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Compositional Signatures of Gold from Different Deposit Types in British Columbia, Canada

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Abstract: A study of both in situ and detrital gold from different deposit types in British Columbia was undertaken to establish deposit-specific compositional characteristics in terms of alloy composition and suites of mineral inclusions. The study is based on 11,840 particles from 160 localities in which nine gold deposit types are represented, although there is a strong bias towards gold of orogenic, low-sulphidation epithermal, and alkalic porphyry origin. In general, Ag values in gold alloys are not a powerful discriminator for deposit type, but minor metals may prove useful where detectable, e.g., Cu in gold from ultramafic associations and Pd and Hg in gold from alkalic porphyry systems. The characterization of inclusion suites is far more illuminating, as they correlate strongly with the mineralogy of auriferous ores from different deposit types. This outcome has confirmed the validity of designing an indicator methodology based on inclusion suites and has permitted the prediction of inclusion suites for gold from other deposit types where data are more scarce. The compositional templates generated in the study were applied to identify the source deposit type(s) of gold from 41 localities (a total of 2916 detrital gold particles) where gold genesis was previously unknown.

Keywords: detrital gold; gold alloy composition; mineral inclusions; indicator minerals; gold deposit types; British Columbia

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1. Introduction

The liberation of mineral particles from host lithologies by weathering generates a mineralogical and geochemical footprint whose extent is governed by transport in the prevailing surficial environment [1,2]. Spatial variations in chemical response or mineral abundance can act as vectors to the in situ source [3], and the approach can be particularly powerful when based on specific mineral-ore deposit style relationships, e.g., kimberlite [4], magmatic Ni–Cu–PGE e.g., [1,5], and gold [6,7]. Particular attention has been given to specific erosional products of copper porphyry mineralization, e.g., magnetite [8,9], apatite [10–12], and tourmaline [13]. These minerals are useful because subtle differences in their chemical composition may be linked to specific settings within a mineralized system, and their physical durability and chemical stability ensure longevity in the surficial environment, such that the geochemical/mineralogical anomaly is not ephemeral.

The presence of detrital gold in surficial sediments is generally accepted as the best evidence for a gold-bearing source, and consideration of the gold morphology and geomorphological process may permit speculation on the likely location of the source [14]. While the characterization of dispersion trains of gold particles in till has successfully been employed as vectors to source [6,15], the composition of gold particles and implications for source type have not found routine application in exploration. In contrast, an increasing number of academic studies have sought to utilize the compositional signatures of placer gold to either illuminate the evolution of economically important placers or speculate on the nature of the source(s). Several placer mining districts in Russia have been the focus of robust studies [16–21], in which distinct signatures of sub-populations of gold have been identified through the study of large numbers of gold particles. Similar approaches have been adopted in remote areas of geological complexity, e.g., South America [22] and Northern Pakistan [23,24]. If gold compositional studies are to find regular application in exploration projects, readily available compositional templates describing the generic features of gold from different deposit types are essential, but these are rarely generated in studies where the focus is a specific placer. In contrast, other studies have sought to identify generic compositional signatures that can subsequently be applied more widely [25–28], and while some clear diagnostic signatures for gold from different deposit types emerged, there are two main knowledge gaps. First, as more data are collected, the potential compositional ranges in gold corresponding to specific deposits are extended; e.g., even large studies of gold particles from different magmatic hydrothermal systems [29] subsequently proved inadequate as compositional templates [30]. Similarly, early attempts to ascribe distinguishing features to gold from a wider range of deposit types [31] were completely revised [32] after a further period in which several relevant studies were published. Second, our understanding of the compositional characteristics and range of gold from some specific deposit types is underrepresented, either as a consequence of a lack of focused studies or because the small particle size of gold commonly associated with some deposit types precludes collection by standard field techniques.

Placer gold is widespread in British Columbia, Canada (BC), as evidenced by the large amount of historical mining activity [33]. However, in many placer gold-producing areas, the in situ source(s) remain undiscovered. Surface exposure is commonly obscured by surficial deposits, and exploration approaches using indicator minerals have found favor [34]. Parallel studies in Yukon, Canada, have demonstrated the potential for placer gold compositions to establish source type and hence contribute to an improved understanding of regional metallogeny [28,35]. The presence of detrital gold, however, is not confined to sites of current or historic placer working, and exploration activities on all scales could collect gold particles and benefit from the interpretation of their compositional signature.

The Cordilleran Orogen that underlies BC is a complex assemblage of terranes that vary considerably in terms of age, composition, and tectonic history. The summary presented here is based on two references that address both tectonic history and metallogeny [36,37]. The region includes "pericratonic" terranes that display a largely continental affinity, some of which (e.g., Yukon–Tanana and Kootenay terranes) are thought to have originally been part of the Northwestern Laurentian margin, as well as continental margin arc terranes (e.g., Stikine and Quesnel terranes), and terranes such as the Cache Creek and Slide Mountain terranes that represent rock units formed in a mainly oceanic environment. These various terranes were assembled into their current configuration through a series of tectonic events that ranged in age from the latest Paleozoic through Early Tertiary time and included both collisions of exotic terranes against the Laurentian margin and each other as well as tectonic shuffling along major, late, dextral (and minor sinistral), crustal-scale strike-slip faults. Individual terranes comprise varying proportions of volcanic and sedimentary rocks and commonly include intrusive rock units that are coeval and comagmatic with the volcanic rocks. In addition, late and post-accretion intrusions are present within most terranes and locally crosscut many of the terrane boundaries. The metamorphic grade that has affected many of the terranes is generally low to moderate.

In addition to the geological complexity of the BC Cordillera, this region also displays a wide range of mineral deposit styles, including many variations on intrusion-related mineralization (porphyry, skarn, epithermal), as well as volcanogenic massive sulphide (VMS) and sedimentary exhalative (SEDEX) deposits and base and precious metal carbonate replacement deposits. The location of the localities mentioned in the text is provided in Figure 1. Gold (and silver) represent the major economic commodities in many of the deposit types in BC, including several subtypes of mainly late-tectonic orogenic gold deposits (e.g., Cariboo, Bralorne, Cassiar, Atlin, and Zeballos camps); epithermal vein deposits (Blackdome, Silbak Premier, Brucejack); and some rare gold-rich VMS deposits (Eskay Creek) [38]. Gold is also an important by-product in a wide variety of other deposit types in BC, including Cu–Au skarns (Hedley), Cu–Au alkalic porphyry deposits (Mt. Milligan, Mt. Polley, Copper Mountain, Galore Creek), and some calc-alkaline porphyry deposits (e.g., Red Chris, Kemess, Highland Valley). Gold is present in at least trace amounts in a very large proportion of mineral deposit types in BC, highlighting its potential to be used as a discriminant between deposit styles.

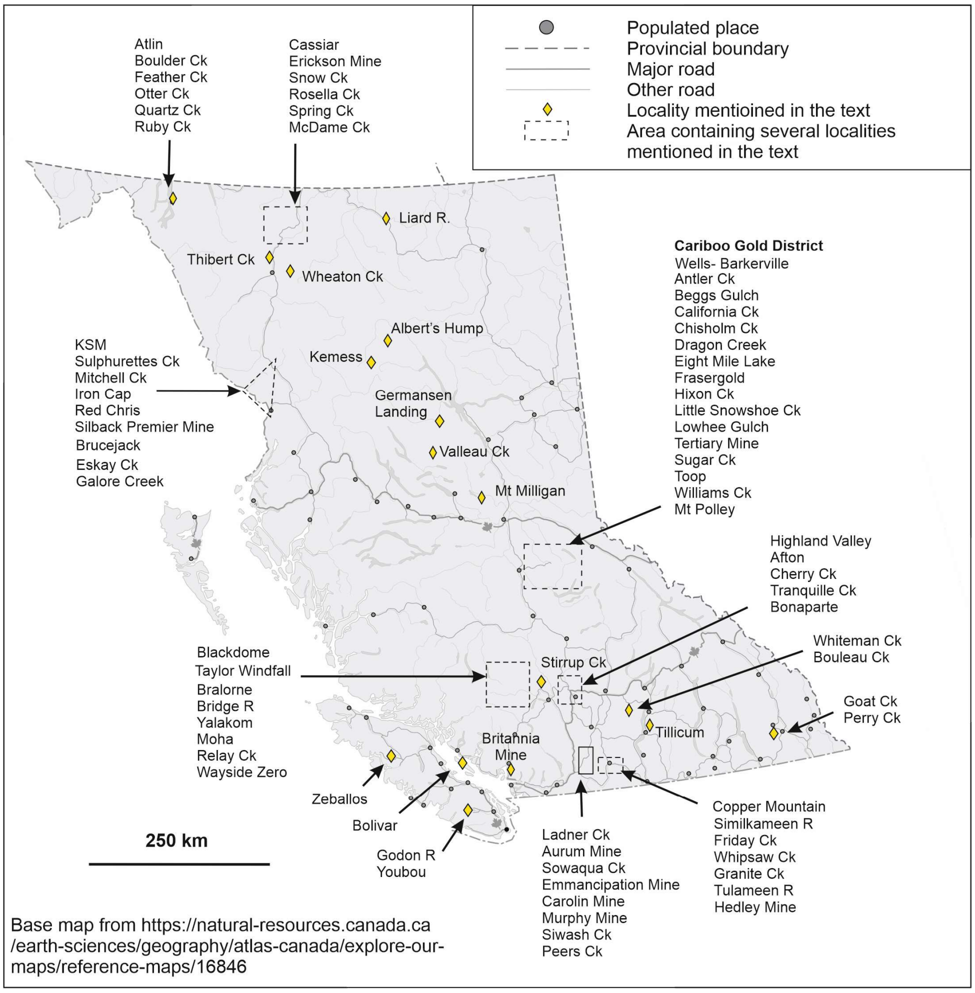

Figure 1. Locations mentioned in the text. Grid references for all sample locations are provided in Appendices A and B.

Gold particles exhibit compositional and microtextural features that are a consequence of their genesis and subsequent residence in their hypogene setting. These features persist post-liberation and erosion and have utility in interpreting the origins of detrital gold particles. This subject has been discussed in detail previously [39,40], and a brief overview is presented here.

Gold is almost always an alloy of Au and Ag, although other minor metals such as Cu and Hg may be detectable by electron microprobe (EMP) analysis. Some gold particles are compositionally homogeneous, but many are heterogeneous due to the presence of microfabrics caused by alloys of different compositions (usually variations in Ag) and/or inclusions of other minerals [32]. The origins of various microfabrics have been classified according to the time of formation with respect to the initial mineralizing event using a dual approach of compositional and crystallographic study [32]. In this way, it has been possible to ensure that the analysis of gold particles generates data pertaining only to the ore-forming stage rather than that resulting from subsequent modifications in residence within either the hypogene or surficial environments.

Differences between the mineralogy of different types of gold mineralization (e.g., low- and high-sulphidation epithermal deposits, calc-alkalic porphyries, and gold from orogenic deposits) are well known, and these are reflected in the suite of mineral inclusions observed in polished sections of gold particles from these different deposit types [32]. Furthermore, the physico-chemical environment of gold precipitation influences the Au–Ag ratio of the resulting alloy [41], together with the concentrations of other minor metals such as Cu, Hg, and Pd [32]. Consequently, the broad controls on ore fluid and mineralization environment (ore deposit type) have a major influence on the gold signature, with further variation arising as a consequence of specific conditions that influence alloy composition. In addition, the temporal and spatial evolution of a hydrothermal mineralizing event can generate a compositional range between gold particles within the overall population, and therefore a sufficient amount must be analyzed to generate a robust compositional signature of gold from a single mineralizing event. The term 'sample population' is used to denote a population of gold particles collected from a specific site. In the overwhelming majority of cases, a sample population exhibits a compositional range, which is effectively a proxy for the stability of the mineralizing environment or an indication of multiple mineralizing episodes.

Gold particle studies may consider sample populations collected either from in situ or placer sources. In situ mineralization may comprise multiple episodes that may or may not have been emplaced under similar conditions. Thus, it is possible that gold from a single in situ locality may exhibit more than one signature [42,43]. Erosion and transport of gold from a single locality generate detrital gold whose composition is faithful to that of the source, but populations of placer gold may contain particles from multiple sources. In order to establish the nature of the contributing gold types, sufficient particles must be available, and these must exhibit sufficient diagnostic criteria to permit interpretation. Despite these challenges, various recent studies have identified groups of compositional characteristics that are exhibited by gold from specific deposit types. Examples include the Pd–Hg inclusions (and alloy) signature of gold from alkalic Cu–Au porphyry systems in BC [26] and the Bi–Te–Pb–S inclusion signature of gold formed in calc-alkalic porphyry systems in Yukon [27]. Gold signatures from mineralized orogenic systems are characterized by a broader array of features within which particular inclusion associations commonly occur, namely a simple base metal signature associated with sulphides $\pm$ (sulpharsenides or tellurides) $\pm$ sulphosalts [28].

Much of the early pioneering work on gold composition was carried out in BC between 1985 and 1993 [44–48]. These studies focused on the relationships between the alloy compositions of gold from known lode sources in Southern and central BC and those of the surrounding placers. The origins of gold in the Fraser River were discussed in terms of potential contributions from the Cariboo Gold District (CGD) and Bridge River area, and a similar approach was applied to the Coquihalla drainage. Two main compositional groups were identified on the basis of Cu and Hg levels in the Au–Ag alloy. The high Cu group was attributed to gold associated with ultrabasic lithologies, whereas the presence of Hg was interpreted as indicative of orogenic gold sources. Within these groups, there were compositional overlaps that could not be resolved through the study of alloy compositions by EMP alone. Nevertheless, examination of microfabrics within the high-Cu population greatly refined the characterization of gold with an ultrabasic association [49].

A study of over 2000 gold particles from placer and lode settings in the CGD [43] augmented the alloy composition data previously reported [47] with both inclusion data for those samples and new material collected for the study. Comparison of mineralogical descriptions of lode occurrences with mineral suites helped refine the classification of gold types in the Wells–Barkerville area, in particular distinguishing between a low-Ag type associated with cosalite inclusions occurring around Wells and a more Ag-rich regional type with an inclusion suite dominated by pyrite and arsenopyrite. The correlation of the Ag contents of these gold types with bulk fineness data from historical placer mining activities permitted the evaluation of the most economically important gold types.

Gold compositional studies in the Northern Cordillera in BC, Yukon, and Alaska have also established generic compositional signatures associated with gold from specific mineralizing environments. Gold from alkalic Cu–Au porphyries in BC yields a Pd–Hg signature [26], while similar work in Yukon showed that gold from calc-alkalic systems shows a Bi–Pb–Te–S signature in the inclusion suite [27]. A perceived disadvantage to this approach was the number of gold particles required to establish the signature, and consequently [50] investigated whether the larger range of detectable elements afforded by the use of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) could generate a consistent signature from fewer gold particles. The aim was to evaluate whether the small number of gold particles generated in stream sediment surveys could find utility in an indicator mineral context. This work developed during the time that the large degree of heterogeneity of trace and ultra-trace elements within gold was becoming clear, and it is now apparent that analysis of only a few particles could produce highly unrepresentative results [40].

The large numbers of gold particles from BC analyzed and inspected prior to the present study revealed internal microfabrics and alloy compositions that were entirely compatible with the detrital model of placer gold, i.e., a model in which eroded gold particles remain largely intact within fluvial sediments. Nevertheless, it is important to note that other workers have reached different conclusions through consideration and interpretation of different information. The apparent discrepancies between both the particle size and bulk fineness of gold in lodes and placers in the Cariboo Gold District have been cited as evidence for gold nugget growth in the supergene environment [51–53]. These assertions resonate with the widely held perception that gold is chemically active in surficial environments to the extent that placer gold may be compositionally distinct from that recovered from the proximal lodes owing to an entirely different genesis. The argument for gold growth in the placer environment has also been advocated more recently in a number of papers, e.g., [54], that propose that the commonly observed micron-scale precipitation of gold onto pre-existing particles through biogenic activity is an ongoing process that results in particle size increases. If gold modification in the surficial environment is widespread and bulk compositions are indeed modified, the potential use of gold as an indicator mineral would be fatally undermined. The subject has recently been discussed at length in a study [39] that considered over 40,000 sections of gold particles from localities worldwide and concluded:

i. Gold particles can increase their mass in specific supergene (not fluvial) settings of circumneutral groundwaters where both Au and Ag are transported as thiosulphate complexes.
ii. Hypogene gold exhibits specific microfabrics and inclusion assemblages, and the identification of these features in placer gold particles confirms a detrital origin.
iii. Gold from the overwhelming majority of placer localities globally exhibits such features, whereas microfabrics consistent with a process of nugget growth have not been recorded in any of the 40,000 placer particles studied.

On the basis of the scale and detail encompassed by this study, we assert that the internal compositions of placer gold particles are faithful to those within the lode source and therefore represent a platform on which to develop a robust indicator methodology.

In this study, we have demonstrated the close correlation between mineral inclusion suites and the mineral assemblages associated with gold in different ore deposit types. In tandem with substantial new alloy and inclusion data describing gold from many localities, we have developed compositional templates for gold from orogenic, low-sulphidation epithermal, and alkalic porphyry settings. There have been substantial advances in characterizing gold from other magmatic hydrothermal and orthomagmatic environments, facilitated both by the data set at our disposal and petrographic studies of auriferous mineralization. The Synthesis of these data sets has generated deposit-specific compositional templates against which 'unknowns' may be compared. In this way, it has been possible to identify the type(s) of source mineralization for some gold localities where this was previously unknown.

2. Materials and Methods

The major objective of producing a database of gold compositions depends on access to sufficient populations of gold particles representing both geological and geographical spread within the province. This project has taken advantage of gold collections from both the University of British Columbia (UBC) and the University of Leeds (UoL), and the geographical spread of gold sample populations examined in the study is shown in Figure 1.

The database describing gold from localities where the deposit type is known comprises 11,520 particles from 133 localities. The UBC collections comprise placer and hypogene gold collected over several years in the 1980s and 1990s. Polished sections of both placer gold populations from specific localities and Au-bearing ore samples were analyzed by EMP at UBC during this period. The initial database was augmented in two ways during the present study. Firstly, the inclusion suites present in each population of gold particles were established by visual examination on the scanning electron microscope (SEM; see below). The incidence of inclusions varies considerably [27,32], and in many cases, the number recorded in sample populations was insufficient to underpin rigorous classification. Secondly, the UBC collections contained additional particles from numerous localities, and these were mounted and analyzed in the present study to improve the quality of the final data set. The remit of the present project to generate a compositional template against which other gold samples may be compared requires gold samples whose deposit type provenance is unambiguous. Samples of placer and lode gold in the UoL collections relate to either locality-specific studies (Cariboo Gold District: [43]; Atlin, [55]) or deposit-type-specific studies (gold from alkalic porphyry systems, [26]). Lode samples are vital in this regard, but in many other cases, the source type of gold placer samples can be established with near certainty, particularly where the signature of the placer gold corresponds to that of proximal lode gold [26,43]. In other cases, the deposit type from which placer gold is derived remains unclear, and such sample populations cannot be used to generate compositional templates. Similarly, placer samples from some (commonly large) drainages may contain gold particles from two or more different deposit types. Around 30% of the gold particles in the UBC collections fall into this category (e.g., gold from the Fraser and Coquihalla river main valleys), because at the time of collection, the drivers for gold collection were to investigate variation in gold signatures between localities rather than to identify compositional signatures for gold from specific deposit types. For the purposes of the present study, the data set has been divided into sample populations where the source deposit type can be ascribed with confidence and others where, although the source deposit type is unclear, there is sufficient compositional information to establish a compositional signature. A full table showing details of the localities for which deposit types may be confidently ascribed is presented in Appendix A, and the data are summarized in Table 1. The data set comprises 11,840 gold particles from 160 localities.

Table 1. Overview of sample suites according to deposit type.

Deposit Type	No. Localities	Total No. Particles
Alkalic porphyry	10	897
Calc-alkalic porphyry	7	551
High sulphidation epithermal	2	40
Low sulphidation epithermal	8	1032
Orogenic	93	8724
Intrusion-related veins	7	38
Skarn	3	93
Ultramafic association	2	107
VMS	1	38

Gold from orogenic settings has the strongest representation in the data set, and this is an inevitable consequence of the amenability of orogenic gold to form placers. It is also clear that several deposit types (high-sulphidation epithermal, VMS, intrusion-related gold, and skarns) are poorly represented. In some cases, it has been possible to partially alleviate this issue by studying samples of polished blocks of ore, where the association of gold with coeval minerals can be used to predict elements of the inclusion signature. In addition, there is a bias in the whole data set according to previous studies in the Province that targeted gold from the Cariboo Gold District [43] and the sample suites describing gold from alkalic porphyry deposits [26].

The suite of samples for which provenance is unknown comprises a total of 2916 gold particles from 41 localities, and details are provided in Appendix B. However, only 8 of these yielded a sufficiently large inclusion suite to permit comparison with deposit-specific compositional templates (Table 2). In addition, sample populations from Bonaparte Mine, Granite Ck, Lilloet, Peers Ck, and Fairless Ck exhibited compositional characteristics that could be informative, and these are mentioned in the text.

Table 2. Details of sample populations where the source is unknown but there is sufficient data to characterize the signature. The 'inclusion tally' refers to the number of particles that contain a useful inclusion.

Location	No. of Particles	Inclusion Tally
Bridge R at Yalakom	88	13
Bridge R above Moha	45	16
Coquihalla R	83	24
Liard R	94	16
Tranquille Ck	164	25
Whipsaw Ck	328	21
Yalakom R	45	10
Ladner Ck	165	24

Polished blocks were inspected using the secondary electron (SE) and back scattered electron (BSE) facilities of a Quanta 650 FEG scanning electron microscope (SEM). Liberated or detrital gold particles are characterized through a combination of alloy profiles (determined by EMP) and inclusion assemblages (determined by visual inspection in both (SE) and (BSE) modes). Both approaches require particles to be sectioned and polished. Alloy analyses of most of the UBC sample suite were carried out at UBC, and all other analyses were carried out at UoL. The compatibility of results from the two analytical facilities was previously established by duplicate analyses of populations of gold particles from localities in Yukon [42]. All analysis regimes included Au, Ag, Cu, and Hg, but the early studies did not include Pd. An overview of the analytical conditions used for gold analysis for the full element range has been described previously [32]. All analyses quoted are mass%.

A summary of the workflow from gold collection to sample preparation is provided in Figure 2. The first stage in the sample characterization was a visual inspection of all gold particle sections. These studies were carried out at UoL using a SEM. Mineral inclusions were identified and chemical analyses generated using the energy dispersive spectrometer (EDS) facility. Mineral speciation was interpreted by comparing the spectra with those of reference minerals. In some cases, a small degree of substitution was observed (e.g., Cu in acanthite or Sb in galena). In these cases, a record was generated that influenced the scoring system used in the generation of radar diagrams, as described previously [28].

Figure 2. Schematic representation of the project workflow for the collection and characterization of gold particles.

3. Results

3.1. Variation in Mineral Assemblages between Gold-Bearing Deposit Types

The generic geological settings in which specific ore deposits form have a substantial influence on the overall deposit mineralogy, particularly regarding the assemblages coeval with gold. Examples of different mineral associations in gold-bearing deposit types are presented in Figure 3. Figure 3A–F shows a range of gold-mineral associations in samples from orogenic gold deposits. The simplest mineralogical associations are gold–quartz (Figure 3A) and gold–quartz–pyrite (Figure 3B). In some samples, abundant Fe oxides are the decomposition products of pyrite (Figure 3C). Common sulphides are important components at some localities, e.g., chalcopyrite (Figure 3C). Gold from Bralorne is an example of a gold ore associated with a range of accessory minerals such as arsenopyrite, galena, sulphosalts, and sphalerite, as illustrated in Figure 3D. Carbonate is an important component at many localities (Figure 3E), and in some cases, gold is associated with alteration products of the mineralizing event (Figure 3F).

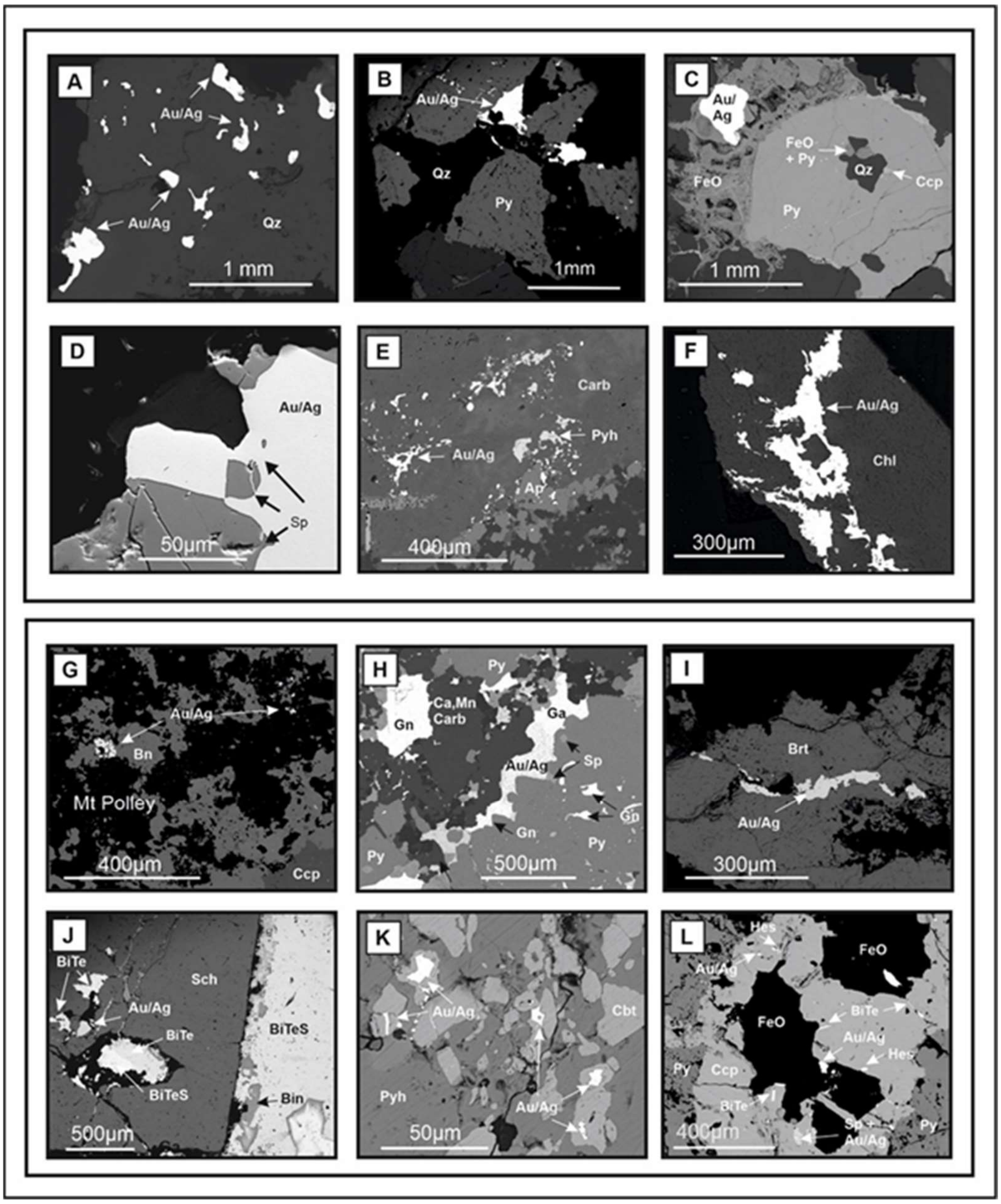

Figure 3. Mineral associations of gold in various deposit types. (**A**–**F**): Orogenic Au. (**A**): Murphy, (**B**): Erickson Eileen Vein, (**C**): Frasergold, (**D**): Bralorne, (**E**): Carolyn, (**F**): Aurum. (**G**–**L**): Gold mineral association in magmatic hydrothermal systems (**G**): Mt Polley Cu–Au alkalic porphyry, (**H**): Silback Premier low-sulphidation Au, (**I**): Albert's Hump High sulphidation Au, (**J**,**K**) Hedley Au skarn, (**L**): Bonaparte intrusion-related veins. Mineral abbreviations in all figures are approved [56], except where speciation is unknown; and in those cases, the elemental components are shown.

Gold from magmatic hydrothermal systems commonly exhibits intimate spatial relationships with a wider range of mineral types, and examples are provided in Figure 3G–L, although these by no means describe the full range of mineral associations for each deposit type. Gold particles associated with the potassic stage of Cu–Au porphyry formation are exolved from either chalcopyrite or bornite and are usually too small to be collected during field sampling using traditional panning techniques. An example of a relatively large Au particle associated with bornite is shown in Figure 3G. Variation between the mineralogy of high- and low-sulphidation epithermal deposits is the basis for their classification, and examples from each ore are depicted in Figure 3H,I. The Ag content of gold from the low-sulphidation ore at the Silback Premier Mine was determined by EDS rather than EMP and contained around 40 wt% Ag. The gold is associated with pyrite, galena, sphalerite, and Mn-bearing carbonates. In contrast, gold from Albert's Hump comprises barytes and a gold alloy containing only 0.5 wt% Ag. Samples of gold-bearing ore from the Hedley skarn deposit (Figure 3I,J) show two auriferous associations: one of around 10 wt% Ag with various minerals in the Bi–Te–S system and scheelite, and the other of around 5 wt% Ag with pyrrhotite and cobaltite. Finally, gold from the Bonaparte intrusion-related gold system is associated with Bi telluride, hessite, chalcopyrite, and pyrite.

3.2. Features of Natural Gold Particles That Permit Compositional Characterization

Gold particles may comprise homogeneous alloys (Figure 4A), but the variation in Ag contents of different homogenous particles may vary widely (Figure 4B). Placer gold particles commonly exhibit an Au-rich (equivalently Ag-depleted) rim typically 2–10 microns in thickness, and examples are visible in Figure 4C, where the particle core is highly heterogeneous, as indicated by the variation in grayscale when viewed in back-scattered electron (BSE) mode. The detailed images of different microfabrics presented in Figure 4C–G are interpreted to indicate modification of pre-existing Au–Ag alloy to Ag-rich alloy in the later stages of the mineralizing event [32]. Modification of the primary alloy by fluid ingress along grain boundaries yields Ag-rich films, which may or may not be associated with heterogeneity, as indicated by the variation in grayscale when viewed in back-scattered electron (BSE) mode. The detailed images of different microfabrics presented in Figure 4C–G are interpreted to indicate modification of pre-existing Au–Ag alloy to Ag-rich alloy in the later stages of the mineralizing event [32]. Modification of the primary alloy by fluid ingress along grain boundaries yields Ag-rich films, which may or may not be associated with grain boundary migration (Figure 4D,E). Where Cu contents in Au–Ag alloys are relatively high, Cu–Au intermetallic compounds exsolve on cooling (Figure 4F). Modifications to gold particles in the surficial environment comprise loss of Ag, sympathetic to grain boundaries in the interior of particles (Figure 4G) and also parallel to the particle surface, to form the Ag-depleted rims described above [39]. In summary, it is important to note that an individual gold particle may exhibit a chemical record of changes in the conditions of precipitation during the mineralization event, which may be subsequently partly altered during residence at or near the surficial environment. In these cases, it is not possible to derive a simple 'signature' from an individual particle without knowledge of the degree and nature of the heterogeneity. For example, spot analysis of the particle shown in Figure 4F could generate alloy compositions ranging from 85.8 wt% Au, 1.62% Ag, and 13.6 wt% Cu in the matrix to 75.7 wt% Au and 24.3 wt% Cu in the exolved laths, showing that in heterogeneous particles, compositional definition by a single measure is meaningless. Similarly, particles with varying Ag content (e.g., Figure 4C) are impossible to characterize with a single value. In these cases, the analysis value relates to the earliest paragenetic stage of the alloy that is identified through mutual spatial relationships within the section. The rationale is that this alloy is most useful in relating particle composition to the main episode of gold deposition. Where particles exhibit exsolution of intermetallic Au–Cu, the composition of the matrix is recorded.

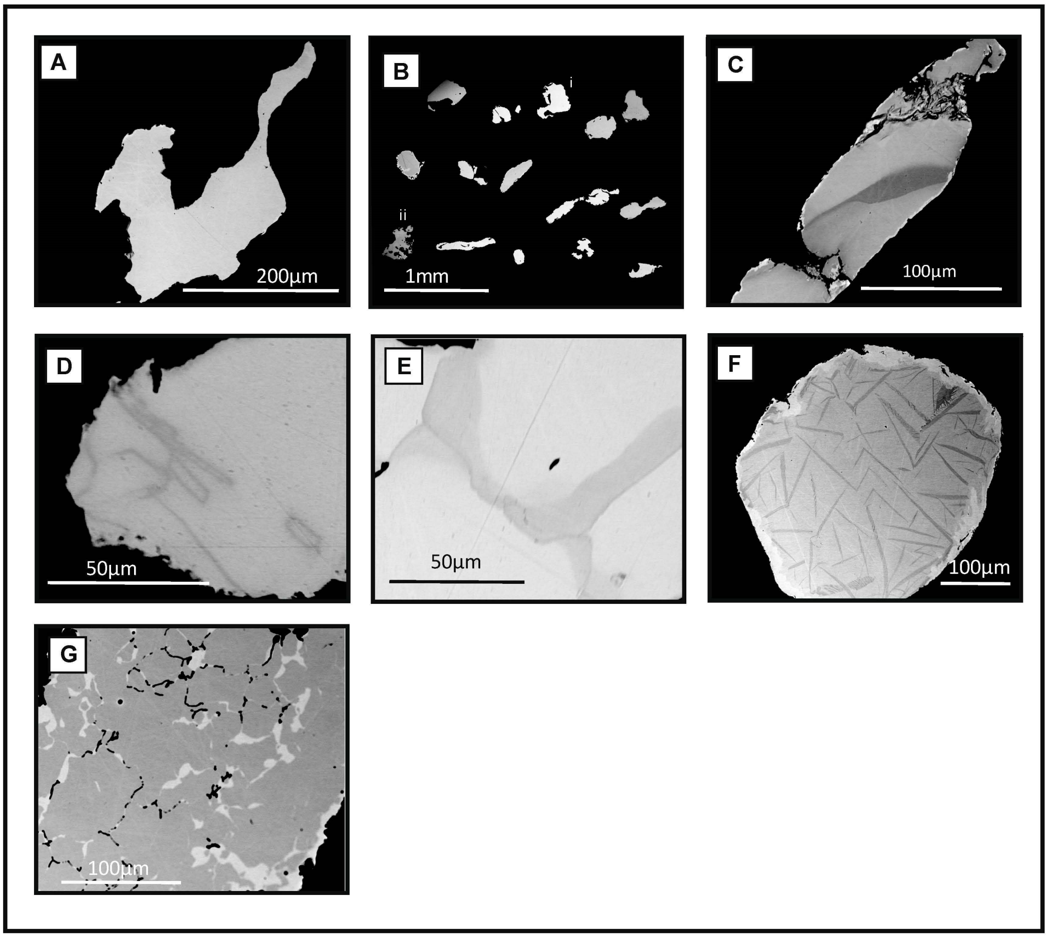

Figure 4. (**A**): Homogenous gold particle (Eight Mile Lake), (**B**): Example of variation in BSE response according to Ag content: range 4.6 wt% Ag (i) to 25.9 wt% Ag (ii) (Antler Creek), (**C**): Heterogeneity within a single particle (Granite Creek), (**D**,**E**): examples of late stage Ag-rich alloy emplaced sympathetic to grain boundaries (Mitchell Creek), (**F**): Exsolution of CuAu intermetallic from Au–Ag–Cu alloy (Coquihalla River), (**G**): Au-rich alloy (pale grey) resulting from Ag removal in the surficial environment in primary relatively Ag-rich gold (dark grey) (Tranquille Creek).

Mineral inclusions typically comprise 2–10 µm particles genetically related to the mineralization stage coeval with gold. They are recorded in gold particles from lode samples (e.g., Figure 3D) and are preserved by their encapsulation within the inert gold particles following erosion. Figure 5A–F shows examples of inclusions commonly found in gold from orogenic settings, where they typically comprise the entire inclusion suite. These minerals also occur in gold from magmatic hydrothermal settings but usually in association with minerals from other classes, e.g., tellurides or selenides. Figure 5E–K provides examples of inclusions observed in gold from magmatic hydrothermal systems. Many mineral species recorded in gold from magmatic hydrothermal deposits are apparently absent or extremely uncommon in gold from orogenic systems. Silver-bearing minerals such as proustite and aguilerite are confined to gold from these deposit types, and minerals in the Bi–Te–S system are very common, whereas they are extremely rare in gold from orogenic systems. Gold from alkalic porphyry systems exhibits a distinctive array of Pd and/or Hg-bearing minerals within the inclusion suite (e.g., Figure 5G). Various Cu sulphides (±Fe) are common in gold associated with ultramafic rocks (e.g., Figure 5L).

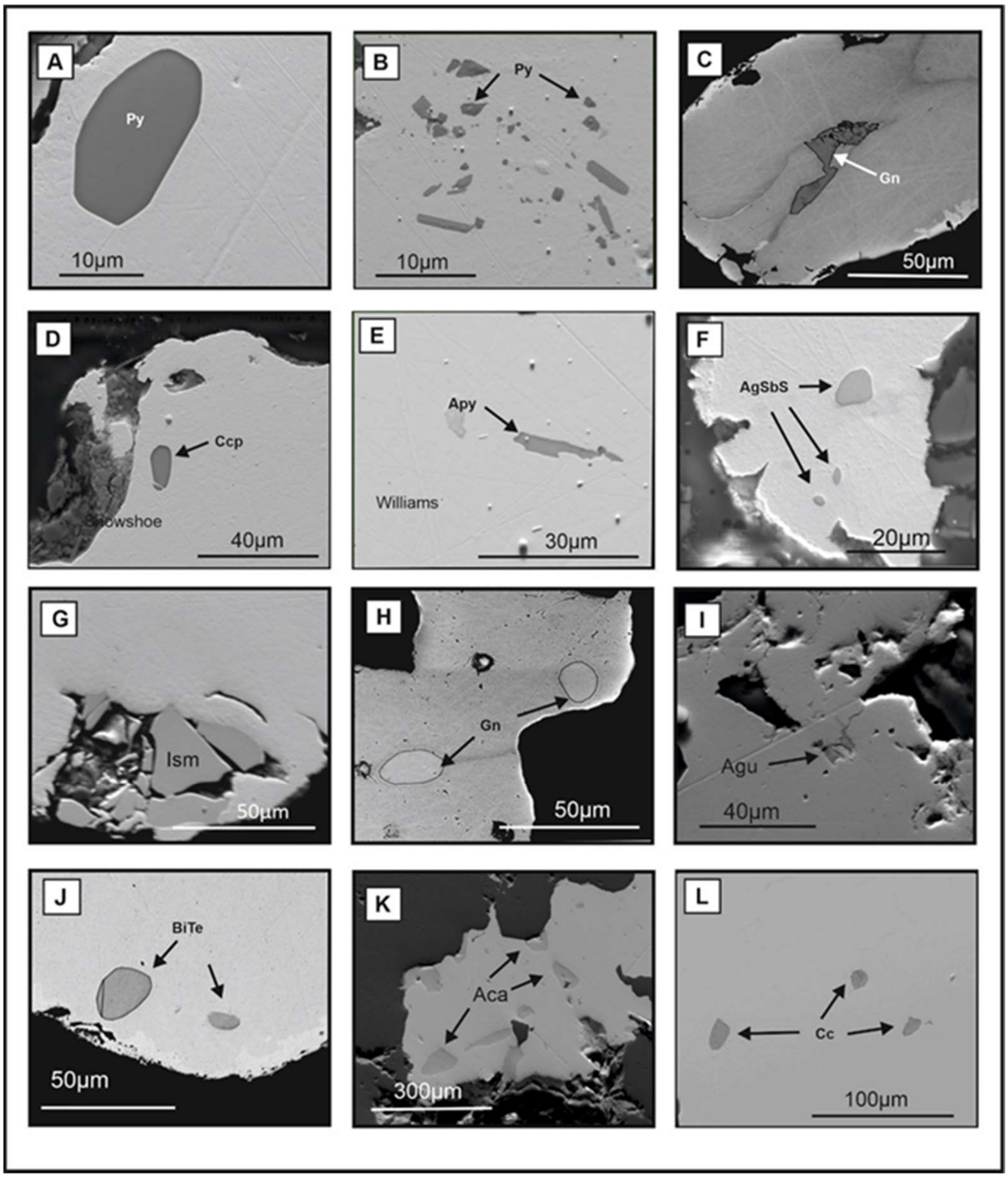

Figure 5. Examples of mineral inclusions. (**A**–**F**): Orogenic gold deposits (**A**), Spring Ck, Cassiar District, (**B**): Chisholm Ck, CGD, (**C**): Tertiary Mine, CGD, (**D**): Little Snowshoe Ck, CGD, (**E**): Williams Ck, CGD. (**F**–**K**): Examples of inclusions in gold from magmatic hydrothermal systems (**F**): Sulphurettes Ck, KSM deposit, (calc alkalic porphyry) (**G**): Friday Ck, Copper Mountain (alkalic porphyry) (**H**–**K**): gold from low-sulphidation epithermal deposits, (**H**,**I**): Blackdome, (**J**): Stirrup Ck, (**K**): Brucejack. (**L**): gold from an ultrabasic association: Wheaton Ck.

3.3. Characterization of Sample Populations

At the outset, it is useful to gain an overall impression of the data available to the study in order to get a sense of the broad differences between the compositional characteristics of gold from different deposit types. Differences in the signatures of gold within individual deposit types are considered subsequently. Figure 6 compares the Ag profiles of all populations whose genetic origins may be confidently ascribed.

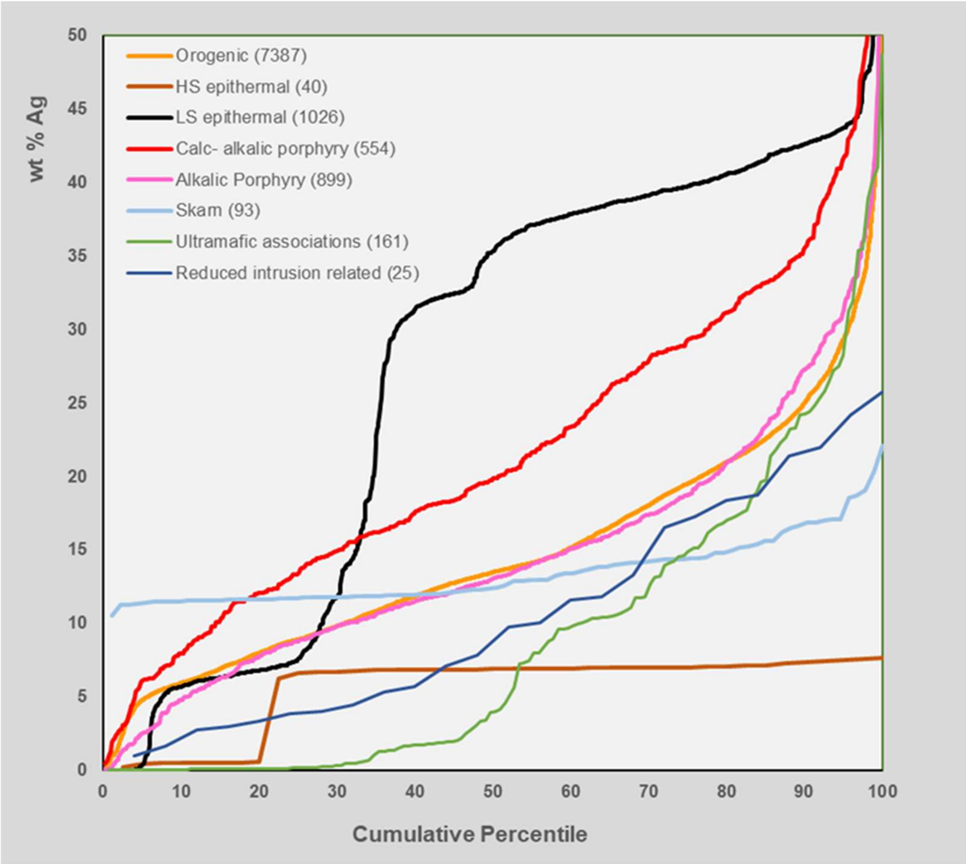

Figure 6. Ag profiles of samples for which the deposit type is known. Figures in parentheses refer to the number of particles within the population.

The majority of gold particles contain between 5 and 30 wt% Ag, irrespective of deposit type. The size of the populations available for study greatly influences confidence in ascribing generic characteristics to particular gold types. Gold from high-sulphidation epithermal, skarn, VMS, and ultramafic associations is relatively underrepresented in the current database. Gold derived from orogenic and porphyry sources generates plots with a continuous increase in Ag, whereas the Ag profile of gold from low-sulphidation epithermal systems typically shows a pronounced step, which is a consequence of the relatively large proportion of Ag-rich particles that all originate from the Blackdome deposit. The curve depicting gold from calc-alkalic porphyry systems is derived solely from sampling alluvial localities in the environs of the KSM porphyry deposit. The small sample set from the Britannia Mine is the only example of gold from a VMS system available for the study. The Ag profile is similar to that exhibited by the far larger sample suite from orogenic systems. Signatures of gold from VMS systems are not considered further in this study as a consequence of the small amount of data available.

The range of Ag contents of the deposit types in Figure 6 is a consequence of the variation in Ag profiles of the constituent populations. Figure 7 compares Ag plots for different individual localities according to deposit type. Individual Ag profiles of gold from orogenic settings (Figure 7A) show various characteristics in sub-populations, as evidenced by portions of the curve with markedly different gradients (e.g., Bralorne Mine and Lowhee Creek). In contrast, gold from the Eileen Lode of the Erickson Mine in the Cassiar area shows two mutually exclusive sub-populations, each displaying a narrow Ag range. Similarly, the gold from low-sulphidation epithermal systems shown in Figure 7B shows different plot forms; some are sub-horizontal, whereas others show profiles containing both shallow and steep gradients. Gold from alkalic porphyry deposits (Figure 7C) all show a continuum of compositions between 0 and 45 wt% Ag. The Ag profiles from some other deposit types are illustrated in Figure 7D–F, and although the data sets are relatively small, some useful observations can be made. Gold from the two skarn deposits (Figure 7D) exhibits curve shapes similar to those observed in gold from other deposit types, and Ag ranges are also comparable. The Ag profiles of gold from populations associated with ultramafic rocks (Figure 7E) exhibit a wide compositional range, including sub-populations where Ag is absent. Finally, the sample populations from intrusion-related systems show a continuum of Ag values from 0 to 25 wt% Ag.

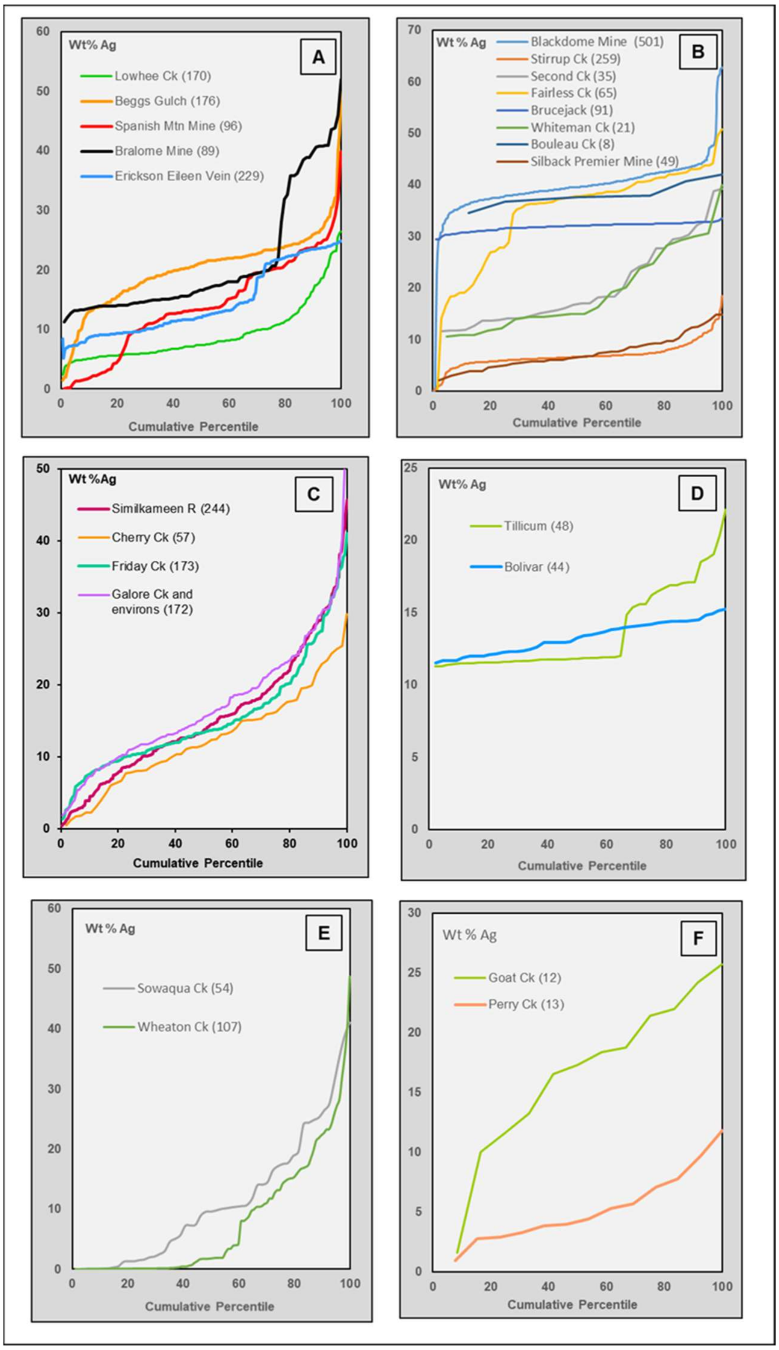

Figure 7. Intra-deposit type Ag comparisons. (**A**): selected Ag profiles from orogenic gold samples: (**B**): Low sulphidation epithermal systems, (**C**): Alkalic porphyries. (**D**): Skarn deposits, (**E**): Ultramafic associations, (**F**): Reduced intrusion associations.

The other minor components of the metal alloys detectable by EMP may, in some cases, be useful discriminants, and Figure 8 shows the concentration ranges of Cu, Hg, and Pd according to deposit type. A small proportion of gold particles from most deposit types may exhibit relatively high (>0.5 wt%) Cu values, but most are below the LOQ of 0.06 wt%. Concentrations of Cu in gold from ultramafic associations are frequently far higher, and compositions often conform to the mineral auricupride (AuCu). These particles are often highly heterogeneous with respect to Cu and Au (see Figure 4F), and the individual analyses that describe a particle are always derived from the low-Cu alloy matrix. The alloy composition and heterogeneous microfabrics observed in these particles are clearly distinctive. Some of the 40 gold particles from the Taylor Windfall high-sulphidation epithermal deposit show Cu values of nearly 1 wt% (Figure 9).

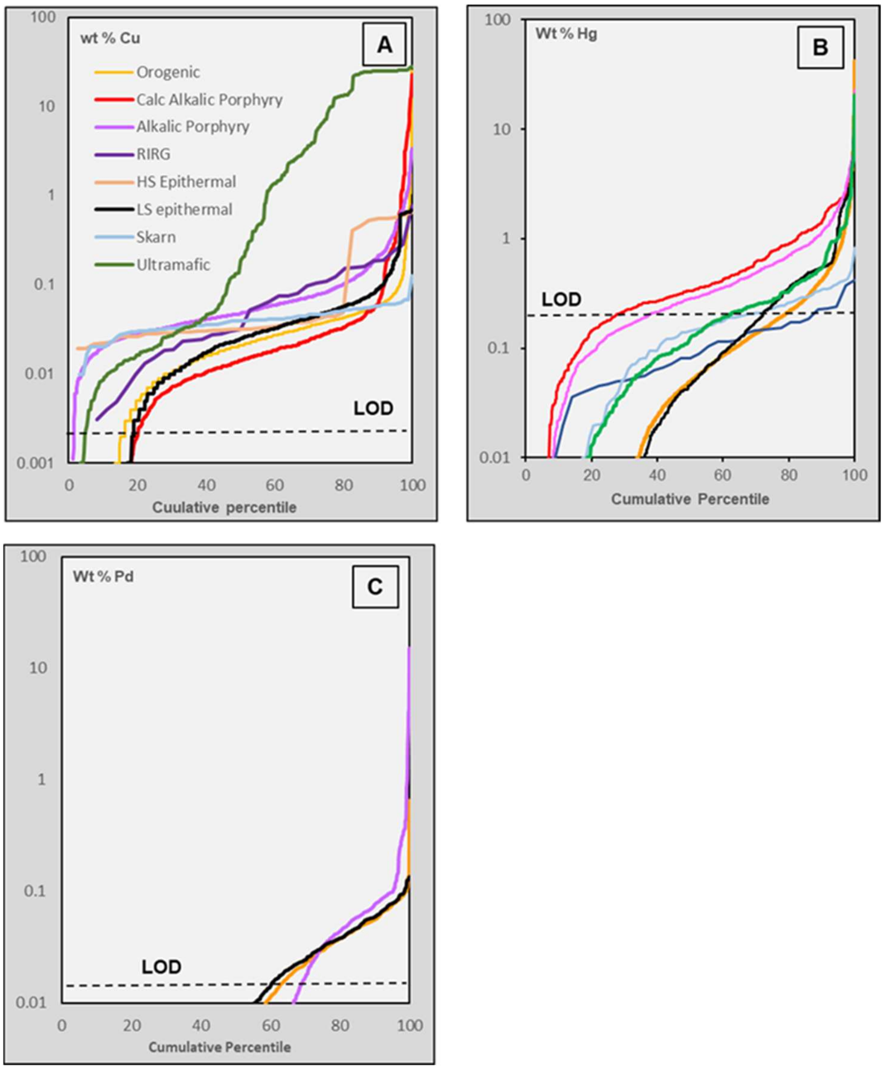

Figure 8. Minor alloy components of gold alloys according to deposit type. (**A**): Cu, (**B**): Hg, and (**C**): Pd. The number of particles in each of the populations is provided in Table 1.

The detection limit of Hg in Au–Ag alloys is relatively high (0.3 wt%), and therefore most of the data points depicted in Figure 8B are below the limit of quantification. The proportion of gold particles from porphyry environments exhibiting detectable Hg appears to be greater than for other deposits, but most deposit types yield some gold particles that exhibit Hg at percent levels.

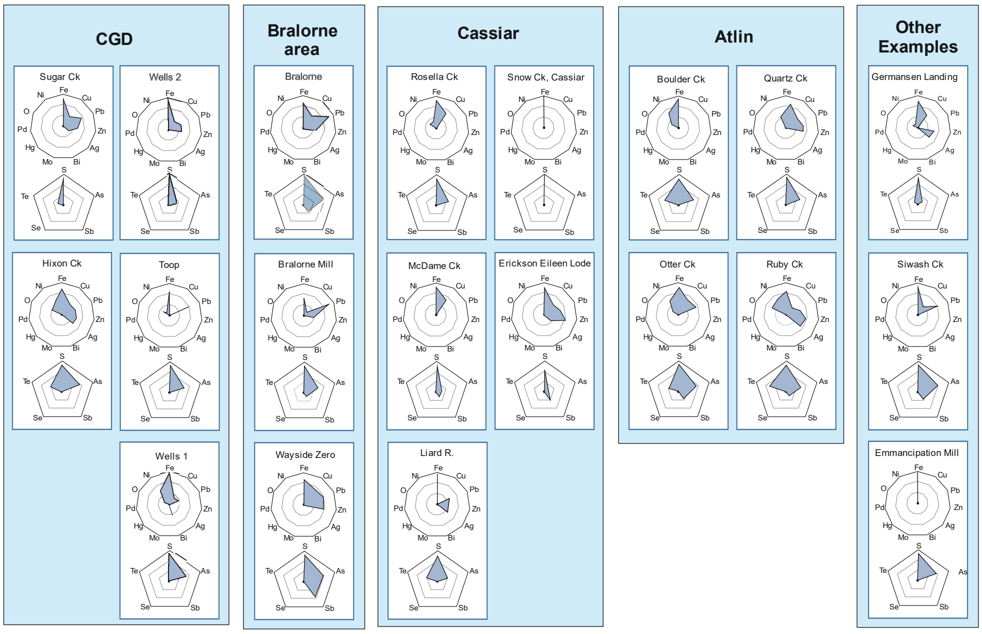

Figure 9. Radar diagrams for inclusion signatures of gold from orogenic settings.

Measurable palladium is confined to gold from alkalic porphyry systems, as previously reported [26], and although it is only detected in around 4% of the particles from each location (Figure 8C), where present, it comprises a clear discriminant.

A previous study of the signatures of gold from throughout the Canadian Cordillera established that inclusion suites were the most powerful tool in establishing deposit type [28]. Around 15 particles containing inclusions are normally required to confidently establish a robust signature, but in the present study, many sample populations have not revealed inclusion suites sufficiently large to permit characterization. Figure 9 shows the radar diagrams relating to samples of orogenic gold. Consideration of such data sets from orogenic gold localities globally showed that the non-metal component was usually most useful to classify gold of orogenic derivation [28]. Common associations are as follows: i. sulphides only; ii. sulphides and sulpharsenides ± minor sulphosalts; iii. sulphides, sulpharsenides, and tellurides; iv. sulphides and tellurides; and v. sulphides, sulpharsenides, tellurides, and sulphosalts. All associations have been observed in sample populations from BC. Figure 9 has grouped inclusion signatures from various localities in the same region, and it can be seen that gold from geographically close areas can exhibit different signatures. For example, two regional signatures in gold from the CGD have been identified [43] (Wells 1′ and Wells 2′, Figure 9), and the new sample from Toop conforms to one of these. Gold from Hixon Creek differs from the Wells 1 signature because it exhibits a Te component, as does gold from Sugar Ck, to the exclusion of As. Similarly, orogenic gold from localities in the Cassiar District conforms to either the S or (S + As ± Sb) signature. Gold from the Liard River could contain a distal component (because of the size of the drainage area), which might account for the presence of Te. The S–As–Sb signature is also observed in all samples from the Bralorne area. Most of the aforementioned inclusion suites comprise simple sulphides such as pyrite, arsenopyrite, galena, chalcopyrite, and sphalerite, but the gold from the four localities within the Atlin camp is the most mineralogically complex. There seem to be minor differences between inclusion suites of gold from different creeks in the Atlin area, although it is recognized that this may be a consequence of some relatively small data sets. In general, the mixed S–As–Te ± Sb signature is accompanied by a strong Ni–Co component (possibly reflecting the dominantly mafic-ultramafic host rocks for most gold occurrences in the Atlin area), and in 3 out of 4 cases, Ag. Unfortunately, no inclusions were observed in the sample population from Feather Ck, as other lines of investigation suggest that gold at this locality is fundamentally different and exhibits a strong association with cassiterite [57].

Radar diagrams describing gold from magmatic hydrothermal systems are presented in Figure 10, and it is immediately apparent that these signatures are more complicated than the signatures of gold from orogenic settings, as illustrated in Figure 9. The diagram includes some examples of gold signatures from calk-alkalic porphyry systems in Yukon (green tiles) because these emphasize generic deposit-type signatures and form useful comparators for the gold sample populations from the KSM drainage available from this study. Similarly, signatures of gold from the Clear Creek and Dublin Gulch intrusion-related systems in Yukon have been included to show their compatibility with the limited amount of mineralogical information available to infer inclusion suites of gold of this type from localities in BC (Figure 3L and Table 3).

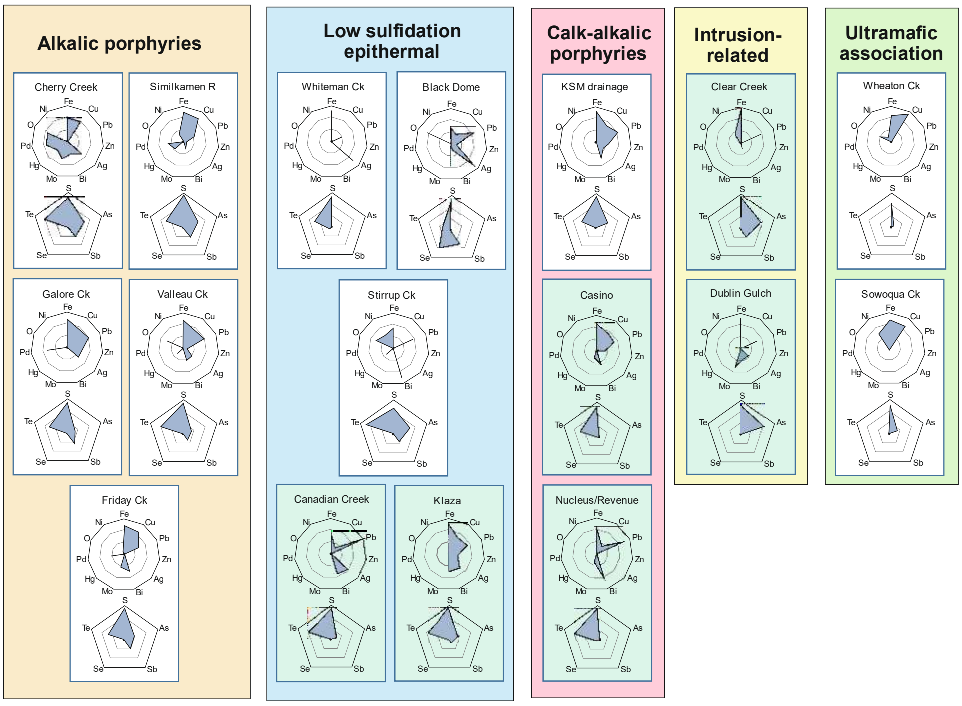

Figure 10. Characterization of inclusion suites in gold from magmatic-related systems. Diagrams in green relate to sample populations from Yukon: included here as further comparatives.

Table 3. Examples of small inclusion suites compatible with generic inclusion signatures.

Location	Inclusions	Deposit Type
Bonaparte	Matildite (AgBiS), undifferentiated Pb, Bi Telluride	IR veins
Brucejack	Acanthite (trace As)	LS epithermal
Silback Premier Mine	Acanthite	LS epithermal
Fairless Ck	Undifferentiated Au–Ag tellurosulphide	LS epithermal

The three inclusion suites derived from low-sulphidation epithermal mineralization are all relatively complex but show clear differences from those from the orogenic gold suite, for example in the relative importance of Ag and Bi. Tellurides are common to all, but gold from Blackdome shows a very strong Se signature. Gold from Stirrup Ck shows a strong similarity to gold from alkalic porphyry systems in the non-metallic components. A complex signature comprising Ag, Bi, and Te is also evident in gold from the Mitchell and Sulphurettes creek drainages at KSM.

Radar diagrams offer many advantages in depicting inclusion suites over other graphical approaches [28], but the elemental signatures provide no information on mineral speciation, which may itself be important. Differentiation between different mineral species can prove useful on a qualitative level; for example, the Cu signature of gold from orogenic settings is almost exclusively a consequence of chalcopyrite, whereas Cu mineral speciation in magmatic hydrothermal systems may also include bornite, chalcocite, and covellite. Gold associated with ultramafic rocks shows a complex Cu-bearing mineralogy, including all the species mentioned above and non-stoichiometric Cu–Fe sulphides. Tellurium-bearing species are encountered in gold from orogenic hydrothermal systems but almost exclusively as a consequence of hessite (Ag_2Te), whereas Bi-tellurides are the most common Te-bearing species in most magmatic hydrothermal systems.

In many cases, sample populations contain a few inclusions but are not sufficient to characterize the suite. However, where unusual inclusions are present, these may provide some useful information (Table 3). The inclusion suite of gold from the Bonaparte deposit (intrusion-related veins) shows an elemental signature suggestive of a magmatic hydrothermal system, although the presence of Te suggests a difference with the gold from intrusion-related systems in Yukon. Gold from the low-sulphidation epithermal occurrences at Brucejack contains inclusions of Ag-bearing minerals, and there is a close association of high (ca. 40 wt% Ag) gold with acanthite in an ore sample from Silback Premier Mine (Figure 3H). The small sample from Fairless Ck, near the Black Dome occurrence, contains Au–Ag sulpho-selenide inclusions, as does the gold from the Black Dome deposit itself.

4. Discussion

The discussion section has been divided into two sections: one reviewing the new data that contributes to refined compositional templates for specific deposit types, and the other applying these to gold from localities where the source deposit type is unknown.

4.1. Compositional Variation in Gold from Different Deposit Types

The data presented in Figure 6 shows that, when considered in isolation, the Ag content of gold alloy within a single particle is not diagnostic for source type. The ranges of Ag contents in gold alloys also vary between deposits of the same type (Figure 7), so it is not possible to make general statements relating Ag range to genesis, although values of >30 wt% appear more common in gold from magmatic hydrothermal systems. Gold from low-sulphidation deposits has been characterized as 'high Ag' (e.g., [57]), and the data depicted in Figure 7B does indeed show that some Ag ranges are notably higher than those in most gold from orogenic systems. However, high Ag contents of over 30 wt% are not a generic feature with gold from Whitman, Fairless, and Second creeks, where Ag ranges are lower and compatible with those of gold alloy from other deposit types. The profile of the Ag curves may either be horizontal/sub-horizontal or exhibit a gradient. These generic shapes of the Ag curve have been discussed in terms of the nature and evolution of the mineralizing hydrothermal system [42,43]. The Au/Ag ratio of the gold alloy is a function of (Au/Ag) (aq), temperature, pH, fS_2^-, and fCl^- [41], and consequently, a low Ag range is most likely indicative of stable conditions of alloy precipitation, whereas a curve with a steeper gradient indicates change in one of more parameters in an evolving system. Hydrothermal systems that comprise multiple episodes of fluid influx may generate sub-populations corresponding to either (or both) of these scenarios. The curves depicted in Figure 7A,B show that gold from orogenic and low-sulphidation epithermal mineralization may conform to either profile form, indicating that the plot shape is not diagnostic for deposit type. A comparison of the Ag ranges of gold from alkalic porphyry systems is shown in Figure 7C. In this case, all curves show Ag values mainly across a range of 0–30 wt%. The detrital gold collected from the environs of the calc-alkalic KSM porphyry exhibits a similar Ag profile (Figure 6). This result may be a consequence of the 'net effect' of sampling placer locations where gold is derived from the various mineralizing environments within the hydrothermal system as a whole. At Copper Mountain (alkalic porphyry), 22 distinct episodes of mineralization were previously reported [58]. The sample from Mitchell Ck (calc-alkalic porphyry) could contain gold particles from both the Mitchell porphyry and the adjacent Iron Cap epithermal deposit. A detailed paragenetic study of mineralization at Iron Cap revealed seven stages of mineralization, five of which contained gold [59], and multiple stages of veining have also been recorded in the Mitchell porphyry [60]. Consequently, the sample population of placer particles from Mitchell Creek almost certainly contains contributions from different mineralizing episodes, and the same is almost certainly true of gold in Sulphurets Creek, which drains the adjacent Kerr and Sulphurets porphyries. Data from gold sample populations from Mitchell and Sulphurrets creeks has been combined to generate a signature of the entire Kerr–Sulphurets–Mitchell (KSM) porphyry system. While this data set cannot identify the nuances between gold formed in individual hydrothermal episodes, it does provide an example of the signature obtained by sampling porphyry-epithermal systems of this type.

Gold particles from the skarn deposits depicted in Figure 7D suggest that conditions for gold precipitation may be variable within the same deposit. A limited amount of data describing gold compositions from the French Mine at Hedley also showed a range of Ag values from 10 to 20 wt% [61]. The very limited amount of data describing gold from high-sulphidation epithermal settings also shows that a compositional range with respect to Ag is possible. Gold particles from mineralization within reduced intrusion deposits are composites from several sampling sites, which may in part account for the range in Ag values. The sample populations from Wheaton and Sowaqua creeks are distinctive because of their very pronounced Cu signature (see below), but they also show a wide range of Ag values. This Ag profile could be explained either by a large variation in the signature of a single source or as a result of a mixture of gold types in a single placer locality. This subject is explored in more detail below.

Concentrations of minor metals have proved useful in some cases. The Cu contents of gold from high-sulphidation epithermal localities suggest that they may be a useful discriminant for gold of this deposit type more widely. Mercury contents of gold alloys are generally higher in gold from porphyry mineralization, but some individual localities in orogenic gold regions also yield gold with Hg at percent levels; for example, Dragon and California creeks in the CGD [43], so in isolation, Hg values are not a diagnostic discriminant. The previous assertion [26] that gold from alkalic porphyry systems exhibits both Hg and Pd-bearing inclusions is partly upheld, with Pd minerals observed in gold from Galore Creek and Hg-bearing minerals recorded in gold from Valleau.

These inclusion signatures recorded in gold from all deposit types are entirely consistent with the range of gold alloy-mineral associations observed in petrographic studies of ore assemblages. The dominance of mineralogically simple inclusion suites in gold from orogenic settings previously reported [28] has been confirmed, and the importance of Ag-bearing minerals in gold from low-sulphidation epithermal systems has been emphasized by the auriferous mineral assemblage of ore from Silback Premier Mine and the few inclusions recorded in gold from the Brucejack Mine and Fairless Creek. At present, there are insufficient data points to generate a robust inclusion template for gold from intrusion-related systems, but consideration of the inclusion suite in gold from the Bonaparte deposit and the minerals associated with gold in ore samples shows that minerals with a Bi–Te–Ag–Pb signature are likely to be important components. Samples of gold-bearing ore from the Hedley skarn deposit show two distinct mineral associations that would likely be represented in local detrital gold. While only a single example of high-sulphidation gold is available for this study, both the alloy and mineral association profiles are unlike any gold from low-sulphidation deposits and occurrences. The distinctive microfabrics in Cu-rich gold derived from ultramafic associations have previously been described [48]. These authors reported the presence of such gold particles in alluvial gold from the Coquihalla River drainage, and these were observed in the same sample set during the present study (Figure 11A). In addition, similar particles were recorded in gold from Bridge River (Figure 11B,C), Relay Ck (Figure 11D), and in one case from the Fraser R. above Williams

Lake (Figure 11E). In addition, around 10% of the sample population from the Bridge River, 1km upstream from Moha, exhibited Cu contents > 2%. In all these cases, many other gold particles in the sample populations contain no detectable Cu and may also exhibit inclusion species commonly associated with orogenic gold deposits. Nevertheless, the identification of specific alloy microfabrics and inclusion suites within gold of ultramafic association provides clear diagnostic markers for gold of this type.

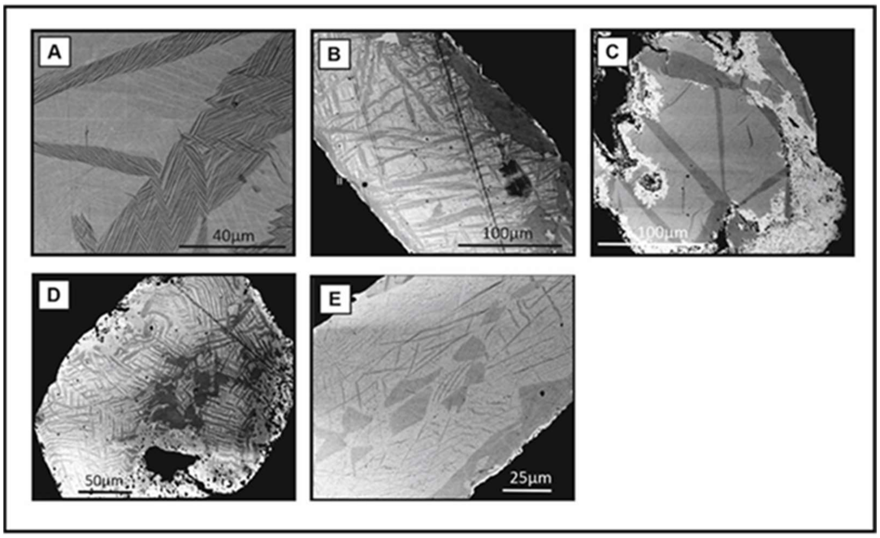

Figure 11. Gold from ultramafic sources identified through microfabrics in which auricupride has exsolved from a Au–Cu–Ag alloy. (**A**); Coquihalla R., (**B**): Bridge R. at Bralorne, (**C**): Bridge River at Yalakom confluence, (**D**): Relay Ck, (**E**): Fraser R. above Williams Lake.

While the focus of the study has been the gold metallogeny of British Columbia, it has been useful to refer to gold signatures derived from studies of deposit types elsewhere, particularly in the contiguous territory of Yukon (see green tiles in Figure 10). The range of signatures observed in orogenic gold in Yukon [28] has also been recorded in BC, and the generic characteristics of gold from porphyry and epithermal environments in Yukon resonate with signatures from those deposit types recorded in the present study. The Bi–Te signature in gold at the Hedley skarn deposit was also reported in gold from Ecuador [62]. Bismuth is a strong component of the inclusion signature in gold from the Wells area in the CGD, where it is present as cosalite ($Pb_2Bi_2S_5$) only, but in all magmatic hydrothermal systems, Bi minerals usually comprise various tellurides and sulphotellurides.

The methodology employed during the study has highlighted some shortcomings of gold characterization work where approaches to sample collection are not specifically designed to permit characterization of the source gold type. The recognition of the limitations of Ag content as a discriminant in this regard and the inability to utilize concentrations of minor metals for characterization as a consequence of their low concentrations and LOQ of the analytical technique hinder further insights into the origins of many of the sample populations studied. In some cases, there are neither sufficient gold particles nor sufficient sample populations (or both) to permit identification of robust compositional signatures (VMS, intrusion-related veins, high-sulphidation epithermal systems), but the data reported here forms a platform for future work. Similarly, the inclusion suites recorded are often too small to facilitate robust interpretation as a consequence of relatively small sample numbers and, most likely, their obliteration by morphological changes to gold particles that accompany fluvial transport. Nevertheless, the databases available to the study have contributed to a more complete understanding of the signatures of gold from deposit types from throughout British Columbia, and a summary of these characteristics is presented in Table 4.

Table 4. Summary of generic compositional characteristics of gold formed in various deposit types.

Deposit Type	Key Distinguishing Features			Comments
	Inclusion Suite Signature		Alloy Composition/Microfabrics	
	Non-Metallic	Metallic		
Orogenic: 1 Orogenic: 2 Orogenic: 3 Orogenic: 4	S S–As ± Sb S–As–Te S–Te	Base metal sulphides, sulparsenides ± sulphosalts or tellurides. Dominated by pyrite	Variable Ag, Cu mostly below LOQ, Hg rarely detectable but in specific cases present to % levels, associated with relatively high Ag (>25 wt%). Where present, Sb and Te are usually minor components of the inclusion signature	Non-metallic signatures replicated at various localities, both within BC and worldwide. Signature type may differ between samples from within a gold camp
Orogenic: 5	S–As–Sb–Te	Ni–Co very strong ± Ag	Wide range of Ag, Hg, and Cu < LOQ	Signature unique to (most) gold from Atlin camp.
Low sulphidation epithermal	S–As–Te ± Se	Ag and or Bi occurring as various minerals Base metal sulphides ± sulpharsenides		Ag ranges in gold from a specific locality may be small, but differences in Ag ranges between deposits can be large.
Alkalic porphyry	S–As–Te–Sb	Pd and or Hg-bearing inclusions plus a wide range of other species	Pd to wt% levels typically in c 4% of particles. Cu > LOQ in c 40% of particles	
Ultramafic association.	S>>As	Dominated by Cu ± minor Ni.	Diagnostic microfabrics of Cu–Au intermetallic exsolving form Au–Ag–Cu alloy	Speciation of Cu minerals distinct from Cu in OGDs: copper sulphides and bornite dominate.
Calc- alkali porphyry	S–As–Te	Base metals, Bi		Sample suite confined to environs of KSM deposit, and may be a mixture of gold from porphyry and epithermal environments. Inclusion signature compatible with that reported in gold of the same type in Yukon.
RIRG	Insufficient data to fully characterize	Bi and Te-bearing minerals identified in gold from Bonaparte	Wide range of Ag values in small sample set studied	Insufficient data to fully characterize, but Bi–Te association is clear
Skarn		BiTe–Au and Au-apy-po associations evident in polished block samples		BiTe–Au and Au-apy-po associations evident in polished block samples from Hedley.
VMS				Single sample population is insufficient to speculate on generic signature
High sulphidation epithermal			Some particles from Taylor–Windfall exhibit Cu values to c. 1 wt%: far higher than observed in any of the samples from low sulphidation epithermal systems	

4.2. Application of Compositional Templates to Characterization of Placer Gold at Localities Where the Deposit Type(s) Are Unknown

A summary of sample populations where the source type is unknown or where mixtures of gold from different gold types are considered likely is presented in Table 2, and details of localities form Appendix B. In this section, we have explored how some of the generic compositional characteristics of gold from specific deposit types have been identified in gold from other populations where the source deposit type is unknown. Given that Ag is not a particularly useful discriminant in this regard and that the main concentration of other alloying elements is below LOQ, there are in general limited characteristics of the population of unknown samples to examine. However, in some cases, inclusion suites and textural information can be applied to advantage, and several short case studies are described below.

Where populations of inclusions are sufficiently large, radar diagrams have been generated for comparison with those of inclusion suites in gold of known origin. 'Unkowns' (in pale red) have been paired with their closest analogues, and Figure 12A shows that the inclusion signature of gold from Lorne Mine is almost identical to others recorded in the Bralorne area. The strong Sb signature of gold from the Tertiary Mine in the Western CDG (Figure 12B) bears a striking resemblance to that previously observed in the Mooosehorn Range of Yukon and Alaska and also the environs of the Coffee Gold property, Yukon [28].

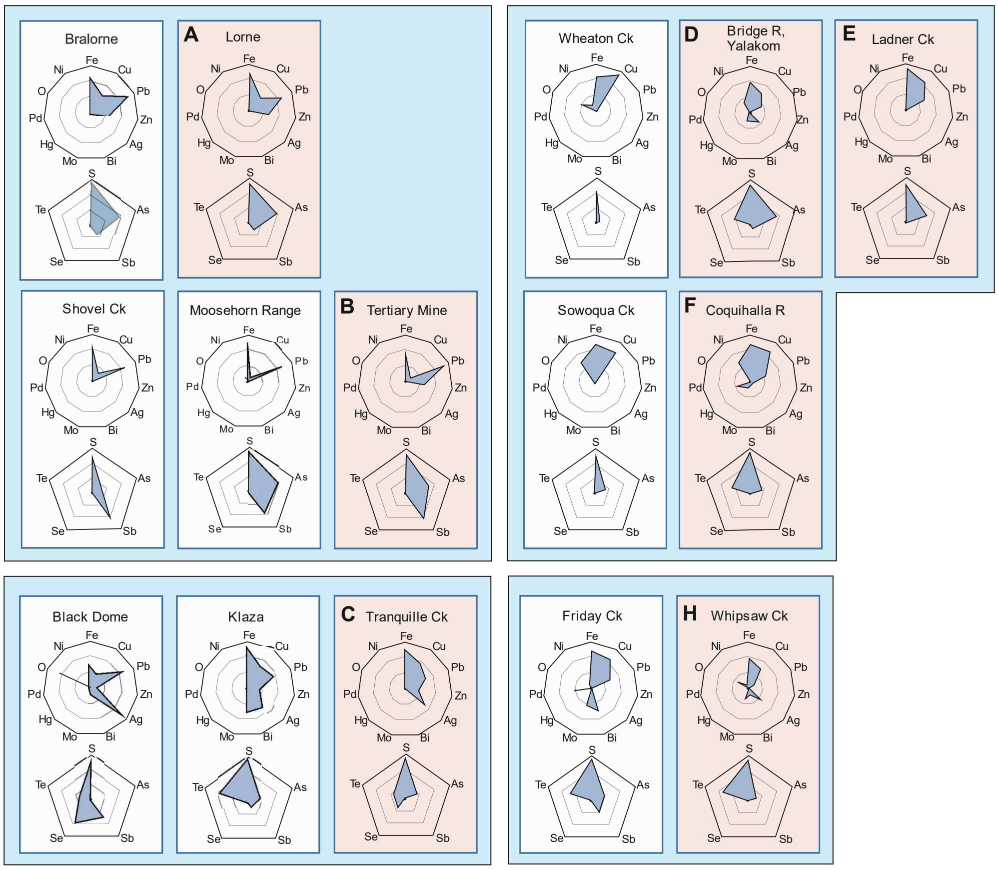

Figure 12. Inclusion assemblage comparisons of samples from 'known' and 'unknown' sources with relevant comparisons indicated by the horizontally adjacent groupings A-H 'Unknown' samples are depicted in pale red tiles and are horizontally adjacent to tiles showing signatures of gold with similar characteristics.

The placer deposit in Tranquille Creek near Kamloops was economically significant [33], although the source of the gold remains unclear. The inclusion assemblage depicted in Figure 12C is most similar to the signature of epithermal gold from Blackdome, which suggests a genetic association with local Eocene volcanic rocks. Gold from the Klaza intermediate sulphidation deposit in Southern Yukon shows a similar signature but contains Bi. Gold from Tranquille Ck contained chalcocite inclusions, which are more commonly associated with porphyry rather than epithermal systems, and consequently, this sample population may itself be a mixture of gold from different episodes within the evolution of a magmatic hydrothermal event.

Other examples of where the few inclusions available are potentially useful in determining the source type are Youbou, Vancouver Island (tsumoite (BiTe), HREE silicate, and loelingite (FeAs) suggesting a low-sulphidation environment), Granite Creek near Princeton (BiPdTe-indicative either of an alkalic porphyry source or perhaps related to the source of platinum in local placers), and the Fraser River at Quesnel Canyon, where a particle containing temagamite ($Pd3HgTe_4$) inclusions was recorded, again suggestive of an alkalic porphyry source.

Individual gold particles derived from ultramafic rocks are distinctive (Figure 11), but the sample populations that contain them often also contain gold particles where Cu is below LOD, and these may host either pyrite or arsenopyrite inclusions, suggesting a different source deposit type. Radar diagrams depicting inclusion suites for sample populations where the distinctive Cu–Au microfabrics were present in some particles are presented in Figure 12, where it can be seen that the strong Cu signature is accompanied by various contributions from As (a minor component of gold from Wheaton and Sowaqua creeks) and Pb (absent in gold from Wheton and Sowaqua creeks). The detailed relationship between inclusion species and host alloy composition is provided in Figure 13, which comprises a bivariate Ag–Co plot with the host alloys of specific inclusion types indicated. shows the relationship of different inclusion species to their alloy host and provides evidence for sample populations of alluvial gold that contain contributions from both gold of ultramafic origin (low Ag, high Cu) and gold from orogenic hydrothermal systems (low Cu, high Ag). There is no necessity for these two populations to be compositionally mutually exclusive, but overall, the compositional fields are clearly distinct. The incidence of the distinctive Cu-rich gold particles is focused around the Bridge River area (Bridge River, Relay Creek) and the Coquihalla and its tributaries (Sowoqua Creek and also Ladner Creek). Gold from Ladner Creek exhibits an inclusion signature that shows a strong resemblance to gold from Sowoqua Creek (Figure 12), but around 20% of the gold particles contain Cu to >2 wt%. Gold from Peers Ck (another tributary of the Coquihalla) also contained relatively Cu-rich particles, but no inclusions were observed. Similarly, gold from Thibert Ck exhibited some very high Cu values, and one of these particles contained a bornite inclusion. However, there were insufficient inclusions present to fully characterize a signature, but it was noted that most other inclusions were either galena or pyrite hosted in gold where Cu was below LOD. Finally, a single particle exhibiting Cu exsolution from a Cu-rich Au–Ag alloy was also recorded in the sample population from the Fraser River above Williams Lake. Variably altered ultramafic rocks occur as small to very extensive fault-bounded bodies within and adjacent to many of the major fault zones in Southwestern BC [63], and these are the likely sources of the distinctive gold particles reported here.

During this study, sample populations from localities that had previously been investigated were augmented to generate more robust data describing the inclusion suites. In the case of Whipsaw Creek near the Copper Mountain alkalic Cu–Au porphyry deposit, new data has permitted a re-evaluation of the previous classification of derivation from an alkalic porphyry source originally proposed because of some shared compositional characteristics with gold from the nearby Friday Creek and Similkameen River localities [26]. Examination of 124 additional gold particles provided a large data set in which neither Pd or Hg-bearing inclusions nor alloys containing detectable Pd were observed (Figure 12D). The inclusion suite differs from that observed in gold from Friday Creek and most likely represents a mixture of gold from different source types, possibly including that present in the drainages of Granite Creek and the Tulameen River to the north. Unfortunately, there is insufficient data to characterize gold from these two drainages to afford a robust comparison. Nevertheless, the availability of a significantly larger data set has permitted refinement of the previous classification.

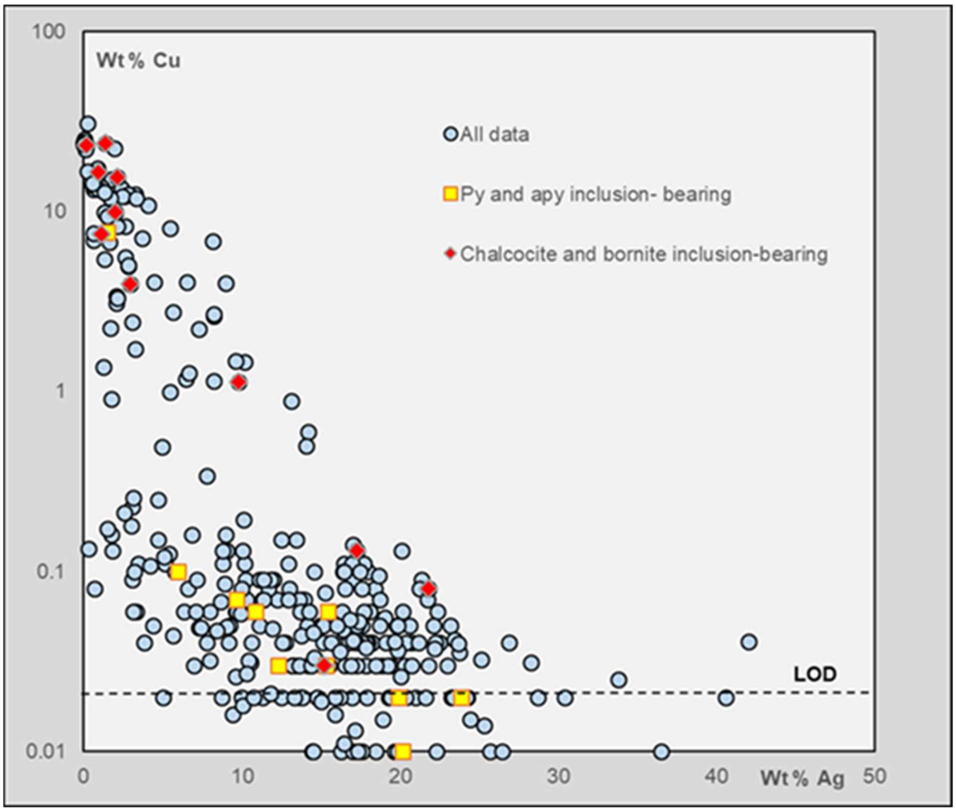

Figure 13. Distribution of inclusion species within different alloy compositional fields. 'All data' corresponds to sample populations from localities in which Cu–Au exsolution microfabrics were observed: Coquihalla R, Bridge River and Yalakom, Sowaqua Ck and Relay Ck.

The characterization of compositional ranges of gold from different deposit types in the Canadian Cordillera is an ongoing endeavor, with various targeted studies [26,27] feeding into a regional consideration [28] that has been expanded in the present study. From a global perspective, interpretations of large data sets such as this can be used to establish generic deposit-type signatures through integration with data sets describing gold from similar tectonic environments elsewhere [28]. The continuation of this work will without doubt involve the characterization of gold from deposit types where compositional data are relatively scarce. In addition, researchers interested in developing regional compositional templates should be aware of other gold signatures specific to specific deposit types, for example, those associated with relatively unusual hydrothermal systems [31] or those associated with a specific sub-class of a broader category [64].

5. Conclusions

This large-scale regional study has greatly increased our understanding of the range of compositional signatures of gold within the complex geological settings in British Columbia. Although the geochemistry and mineralogy of gold grains in the region are certainly far from simple, gold alloy compositions of populations of gold particles together with inclusion suites of opaque minerals have in many cases proven capable of discriminating between gold derived from different types of source deposits. In some cases, the project outcomes have confirmed those of previous work, but new insights have also been generated, principally by combining studies of in situ gold-bearing mineralization with compositional studies of detrital gold particles.

It is important to consider the full range of compositional data available when aiming to identify deposit-type signatures. In this study, the Ag content of the Au–Ag alloy has not proved useful in the majority of cases, as there is substantial overlap in the compositional ranges of gold from different deposit types and between samples from different localities of the same deposit type. Nevertheless, extreme values may prove informative. Where detectable, concentrations of minor metals (Cu, Hg, and Pd) can be useful as strong indicators of gold genesis, but in many cases they are below detection by EMP. The study of the relationship between the mineralogy of the inclusion suite in detrital gold particles and the ore mineralogy itself has proved far more illuminating.

Detailed petrographic studies of samples of gold-bearing ore from various deposit types have confirmed the relationship between ore mineralogy and the compositional signatures of gold particles in their erosional products. The range of well-constrained compositional templates for gold from orogenic and low-sulphidation epithermal systems shows strong similarities with mineralogical associations of gold with other coeval minerals within ore samples of those deposit types. This outcome supports two important claims about gold compositional studies. The first confirms that the inclusion suites of detrital gold from locations where the source is unknown can be used to elucidate the type of that source mineralization, and comparison of deposit-specific inclusion suites with those of gold from other localities in the Canadian Cordillera in neighboring Yukon confirms the generic nature of the signatures. The second has been brought into sharp focus in the present study and shows that an understanding of the mineral associations of gold in a specific deposit type may be used to predict the inclusion suite of any associated detrital gold liberated by erosional processes. Consequently, although there is limited inclusion data describing mineral suites in detrital gold from high-sulphidation, skarn, and intrusion-related deposits, their signature is predictable. Where small inclusion suites are available for comparison, they support this hypothesis.

For some localities in BC where the source of detrital gold is unknown, it has been possible to apply compositional templates to elucidate the source type. The success of this approach depends entirely on the quality of the sample population of the unknown sample in terms of the number of particles available and the degree to which they are representative of the whole population. Donated samples may not fulfill either of these criteria, and projects such as this generally demand dedicated sampling campaigns. This is especially important in regions such as BC, where gold from different source types may be present in a single drainage system, with the result that the detrital gold inventory may contain gold with different compositional signatures. An understanding of the various compositional ranges of gold from different deposit types permits discrimination between sub-populations, an accurate interpretation of local gold metallogeny, and an aid to the design of focused exploration campaigns.

The outcomes of the project can already underpin the examination of new sample suites where the source deposit types are unclear. At the very least, it is possible to clearly discriminate between gold from orogenic and magmatic hydrothermal systems as well as that associated with the ultramafic rocks present at several different localities. Further study is required to gain a better generic compositional template for gold from some deposit types and to identify the compositional nuances between gold from deposit types formed by magmatic hydrothermal systems.

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Appendix A. Summary of Sample Suites Where Source Deposit Type Is Known

Site	Region	Sample Type	No Particles	UTM	E	N
Alkalic porphyries						
Copper Mountain Magnetite Veins Virginia Pit	Similkameen	Hypogene	1	10	679873	5466650
Copper Mountain Pit 3 North Wall	Similkameen	Hypogene	2	10	680075	5466265
Copper Mtn Ingerbelle Pit	Similkameen	Hypogene	2	10	677637	5468093
Friday Ck	Similkameen	Detrital	173	10	674786	5463431
Galore Ck	Skeena	Detrital	55	9	351451	6334803
Galore, Scottsimpson Ck	Skeena	Detrital	95	9	347496	6327746
Mount Polley Springer Pit North West Face	Cariboo	Hypogene	1	10	591942	5822820
Mount Polley Underground Stockpile Wight Pit	Cariboo	Hypogene	1	10	591897	5822842
Mount Polley Wight Pit	Cariboo	hypogene	14	10	592861	5825510
Mount Polley Wight Pit	Cariboo	Detrital	1	10	592861	5825510
Mt Milligan King Richard Creek	Omineca	Detrital	39	10	432688	6108843
Mt Milligan MBX Pit	Omineca	Detrital	2	10	424363	6109380
Mt Milligan MBX Pit	Omineca	Hypogene	8	10	434572	6109300
Mt Milligan MBX Pit	Omineca	Hypogene	12	10	434698	6109460
Mt Milligan MBX Pit Blast hole 82-5522	Omineca	Hypogene	3	10	434669	6109040
New Afton	Kamloops	Hypogene	4	10	683647	5609456
New Afton	Kamloops	Hypogene	2	10	675628	5615087
New Afton Cherry l Ck	Kamloops	Detrital	57	10	672106	5615710
Similkameen River	Similkameen	Detrital	248	10	669117	5485510
Valleau Ck	Omineca	Detrital	177	10	386865	6133372
Calc-alkalic porphyries						
Iron Cap	Skeena	Hypogene	3	9	425500	6267000
Kerr Fan	Skeena	Detrital	5	9	421012	6261191
Mitchell Ck	Skeena	Detrital	164	9	416722	6262775
Relay	Lillooet	Detrital	64	10	509681	5664325
Sowchea	Omineca	Detrital	6	10	408890	6031602
Sulphurets Ck	Skeena	Detrital	304	9	419095	6261371
Tennyson Property	Skeena	Hypogene	5	9	427925	6236028
White Star Mine	Alberni	Hypogene	3	9	656988	5543526
High sulphidation epithermal						
Albert's Hump	Liard	Hypogene	8	9	594716	6371425
Taylor–Windfall	Clinton	Hypogene	32	10	475244	5661693
Low sulphidation epithermal						
Blackdome	Lillooet	Hypogene	501	10	531130	5653664
Bouleau Ck	Vernon	Detrital	8	11	318668	5568633
Brucejack	Skeena	Hypogene	90	9	426958	6258537
Fairless Ck	Lillooet	Detrital	65	10	530860	5653775
Mt Graves property	Omineca	Hypogene	6	9	621942	6361045
Second Ck	Clinton	Detrital	35	10	566452	5658769
Silbak–Premier	Skeena	Hypogene	47	9	500000	6209789
Stirrup Ck	Clinton	Detrital	259	10	557997	5659116
Whiteman–Boule Ck	Vernon	Detrital	21	11	315395	5566256

Site	Region	Sample Type	No Particles	UTM	E	N
Orogenic						
Amador Gulch	Cariboo	Detrital	75	10	588853	5876180
Antler Ck	Cariboo	Detrital	151	10	609056	5888223
Aurum Mine	New Westminster	Hypogene	52	10	623873	5485405
Baldhead Ck	Cariboo	Detrital	16	10	574196	5883884
Ballarat St Georges	Cariboo	Detrital	80	10	600450	5881650
Bassford Ck	Cariboo	Detrital	18	10	582546	5874825
BC Vein	Cariboo	Hypogene	25	10	596343	5883218
Beggs Gulch	Cariboo	Detrital	176	10	605454	5875266
Berube	Liard	Hypogene	29	9	462597	6570816
Boulder Ck	Atlin	Detrital	121	8	589229	6613761
Bralorne	Lillooet	Hypogene	173	10	515477	5623283
BRX Property	Lillooet	Hypogene	10	10	511246	5632230
Burns Ck	Cariboo	Detrital	132	10	590031	5881840
Burns Mountain (Perkins)	Cariboo	Hypogene	155	10	588790	5878034
California Ck	Cariboo	Detrital	101	10	606550	5873800
Cariboo Gold Qtz	Cariboo	Hypogene	20	10	596343	5883219
Cariboo R Bench	Cariboo	Detrital	142	10	602260	5835729
Carolin Mine	New Westminster	Hypogene	23	10	623873	5485405
Cayuse Ck	Lillooet	Detrital	75	10	567021	5610440
Cayuse Ck Balbernie	Lillooet	Detrital	55	10	572670	5613532
Chisholm Ck	Cariboo	Detrital	216	10	586791	5878197
Cottonwood Bar	Cariboo	Detrital	87	10	523229	5886799
Cottonwood R	Cariboo	Detrital	74	10	553205	5881895
Coulter Ck	Cariboo	Detrital	94	10	610550	5868650
Cow Mt	Cariboo	Hypogene	77	10	596343	5883219
Cunningham Ck	Cariboo	Detrital	164	10	606398	5870152
Dennis Ck	Liard	Detrital	39	9	476210	6579070
Devlin Bench	Cariboo	Detrital	35	10	597180	5888057
Dragon Ck	Cariboo	Detrital	193	10	582250	5885000
Eight Mile Lake	Cariboo	Detrital	279	10	597286	5666686
Emancipation_Mill	New Westminster	Hypogene	138	10	625900	5482980
Emancipation_	New Westminster	Hypogene	29	10	625900	5482980
Erickson Jennie	Liard	Hypogene	8	10	623873	5485405
Erickson Vollaug	Liard	Hypogene	2	9	461639	6564403
Erickson_Alison	Liard	Hypogene	18	9	461639	6564403
Erickson_Caitlin	Liard	Hypogene	8	9	461639	6564403
Erickson_Eileen	Liard	Hypogene	227	9	461639	6564403
Feather Ck	Atlin	Detrital	42	8	600785	6600303
Foster's Ledge	Cariboo	Hypogene	5	10	425565	5382210
Frasergold	Cariboo	Hypogene	15	10	579779	6650830
Frye Ck	Cariboo	Detrital	110	10	546145	5880934
Germansen	Omineca	Detrital	297	10	394405	6181362
Hibernia	Cariboo	Hypogene	23	10	586345	6011100
Hixon	Cariboo	Detrital	417	10	531790	5921604
Hurley R	Lillooet	Detrital	220	10	510797	5633030
Island Mt	Cariboo	Hypogene	7	10	594811	5884455
Jerry Ck Strathnaver	Cariboo	Detrital	80	10	558509	5937595
Keighley Ck	Cariboo	Detrital	95	10	604183	5849514
Lightening Ck	Cariboo	Detrital	146	10	561728	5874567
Likely	Cariboo	Detrital	26	10	604917	5828416
Lillooet	Lillooet	Detrital	62	10	576883	5618322
Little Snowshoe Ck	Cariboo	Detrital	35	10	604600	5856500
Lowhee Ck_1	Cariboo	Detrital	143	10	596500	5883750
Lowhee Ck_2	Cariboo	Detrital	28	10	597700	5881550
Manson Ck	Omineca	Detrital	26	10	406679	6170248
Maude Ck	Cariboo	Detrital	101	10	604300	5879450
McDame R	Liard	Detrital	124	9	475208	6570724
McKee Ck	Atlin	Detrital	1	8	581303	6592762

Site	Region	Sample Type	No Particles	UTM	E	N
Midas adit	Cariboo	Hypogene	247	10	606534	5856510
Montgomery Ck	Cariboo	Detrital	48	10	583950	5885450
Moorehead Ck	Cariboo	Detrital	102	10	580981	5833737
Mosquito Ck	Cariboo	Detrital	88	10	594500	5886100
Mosquito Mine	Cariboo	Hypogene	4	10	593903	5885241
Moustique Ck	Cariboo	Detrital	91	10	587500	5654570
Mt Calverly	Cariboo	Hypogene	2	10	604665	5827629
Mt Proserpine	Cariboo	Hypogene	30	10	600772	5877900
Murphy	New Westminster	Hypogene	59	10	613553	5473781
Myrtle	Cariboo	Hypogene	68	10	597414	5881788
Nelson Ck	Cariboo	Detrital	20	10	586700	5881900
Oregon Gulch	Cariboo	Detrital	74	10	586700	5879250
Otter Ck	Atlin	Detrital	306	8	590451	6610413
Perkins Gulch	Cariboo	Detrital	34	10	587655	5876715
Peter Ck	Cariboo	Detrital	42	10	611129	5863278
Pine Ck	Atlin	Detrital	27	8	575126	6603083
Pioneer	Lillooet	Hypogene	30	10	515477	5623283
Quartz Ck	Atlin	Detrital	100	8	600389	6613902
Quesnel Canyon	Cariboo	Detrital	106	10	538806	5872170
Rosella Ck	Liard	Detrital	146	9	478356	6590788
Ruby Ck	Atlin	Detrital	91	8	589293	6613778
Siwash Ck	New Westminster	Detrital	87	10	619497	5493434
Slough Bench	Cariboo	Detrital	96	10	587250	5883100
Snowy Ck placer	Liard	Hypogene	83	9	462875	6569894
Snowy_Crusher	Liard	Hypogene	12	9	463325	6569892
Snowy_Rich Vein	Liard	Hypogene	4	9	462300	6570388
Sooke R	Victoria	Detrital	86	10	447377	5371480
Sovereign Ck	Cariboo	Detrital	145	10	586700	5881900
Spanish Mt	Cariboo	Detrital	23	10	608007	5823814
Spanish Mt	Cariboo	lode	114	10	582763	6046650
Spring Ck	Liard	Detrital	17	9	476617	6582888
Spruce Ck	Atlin	Detrital	79	8	588902	6601480
Sugar Ck	Cariboo	Detrital	284	9	585695	5894707
Summit Ck	Cariboo	Detrital	50	10	589532	6029860
Tame Ck	Liard	Detrital	91	9	479889	6590234
Taurus Mine	Liard	Hypogene	9	9	460706	6570815
Tertiary	Cariboo	Hypogene	144	10	526980	5886565
Toop	Cariboo	Detrital	144	10	561974	5880404
Vancouver Mine	Nelson	Hypogene	6	11	490640	5443120
Warspite	Cariboo	Hypogene	46	10	601518	5876958
Wayside	Lillooet	Hypogene	102	10	512019	5636155
Wayside (Cariboo)	Cariboo	Hypogene	19	10	588155	5971100
Wells Adit	Cariboo	Hypogene	52	10	595950	5883250
Williams Ck	Cariboo	Detrital	54	10	599830	5881613
Wright Ck	Atlin	Detrital	92	8	593989	6607041
Yellowjacket Mine	Atlin	Hypogene	3	8	581908	6607172
Skarn						
Bolivar claim	Nanaimo	Hypogene	44	10	385757	5513482
Molly Claim	Nanaimo	Hypogene	1	10	390463	5509906
Tillicum	Slocan	Hypogene	48	11	449002	5537267
Ultramafic Intrusion related						
Sowaqua Ck	New Westminster	Detrital	54	10	625391	5478035
Thibert Ck	Liard	Detrital	106	9	421961	6522643
Wheaton Ck	Liard	Detrital	107	9	500300	6471824
VMS						
Britannia	Vancouver	Hypogene	38	10	489806	5495403

Site	Region	Sample Type	No Particles	UTM	E	N
Intrusion-related veins						
Bonaparte	Kamloops	Hypogene	4	10	679829	5653693
Bohan	Nelson	Detrital	1	11	546550	5459630
Cranbrook	Fort Steel	Hypogene	5	11	600110	5472550
Goat	Nelson	Detrital	12	11	545436	5465307
Kithchener	Fort Steel	Detrital	1	11	548995	5445300
Lamb	Fort Steel	Detrital	2	11	581529	5464916
Lewis Ck	Fort Steel	Detrital	1	11	568159	5467402
Moyie Lake	Fort Steel	Detrital	2	11	582540	5471680
Perry	Fort Steel	Detrital	14	11	565250	5480050

Appendix B. Summary of Sample Suites for Which Either the Source Deposit Type Is Unknown or Which Are Most Likely Mixtures of Gold Particles Form Different Source Types

Site	Region	No Particles	UTM	E	N
15 Mile	New Westminster	193	10	627488	5483762
Big Bar	Clinton	41	10	561069	5670320
Black Ck	Cariboo	4	10	629950	5797000
Bridge River	Lillooet	20	10	569676	5627361
Bridge–Yalakom	Lillooet	35	10	558221	5634927
Bridge River	Lillooet	119	10	510540	5632938
Canal flats	Golden	2	11	580880	5561320
Chilliwack	New Westminster	81	10	576159	5438322
Chimney Ck	New Westminster	13	10	614722	5506237
Coquihalla R	New Westminster	83	10	625304	5478308
Coquihalla–Dewdeney	New Westminster	3	10	626389	5481613
Elizabeth–Yalakom	Lillooet	4	10	531497	5653411
Findlay Ck	Golden	2	11	568380	5552920
Fountain Bar	Lillooet	143	10	579673	5622274
Fraser R	Clinton	8	10	576135	5650008
Gold Pan	Kamloops	56	10	614002	5579526
Gold Ck	Cariboo	100	10	559062	5910736
Gordon River	Victoria	34	10	402046	5404036
Granite Ck	Similkameen	86	10	667000	5485308
Haney Pit	Vancouver	50	10	547292	5447988
Kanaka Bar	Kamloops	2	10	602627	5552726
Ladner Creek	New Westminster	166	10	627367	5483766
Ladner Creek	New Westminster	40	10	626625	5490192
Liard R	Liard	95	9	497300	6672000
Lorne	Lilloet	90	10	512632	5624910
Lytton	Kamloops	74	10	596648	5572573
McConnel R	Omineca	19	9	655440	6305441
Peers Ck	New Westminster	50	10	622486	5471341
Pend d'Oreille R	Nelson	18	11	454747	5428220
Relay	Lilloet	64	10	509681	5664325
Scuzzy	New Westminster	35	10	607605	5521594
Slate Ck	Omineca	42	10	401829	6170664
Thibert Ck	Liard	106	9	421961	6522643
Tranquille R	Kamloops	164	10	687634	5617654
Tulameen	Similkameen	91	10	660813	5489829
Upper Fraser	Clinton	126	10	549640	5759834
Vedder (Chilliwack) R	New Westminster	23	10	584673	5435977
Whipsaw Creek	Similkameen	328	10	676644	5471200
Yalakom	Lillooet	45	10	535584	5657087
Yale	New Westminster	230	10	613877	5488020
Youbou	Victoria	31	10	412348	5414107

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