Pathfinder signatures in placer gold derived from Au-bearing porphyries

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ABSTRACT

Porphyry and epithermal mineralization of early Late Cretaceous (*ca.* 76-74 Ma) at Casino, Revenue/Nucleus, and Sonora Gulch areas in the central and eastern Dawson Range in west-central Yukon is spatially related to numerous placer gold mining areas. Placer-lode relationships have been established through study of gold alloy compositions and associated mineral inclusion assemblages.

At Casino, hypogene gold grains are liberated by erosion and pass into the placer system without compositional modification, as evidenced by the common alloy signatures and a mineral association of Au, (Bi-Pb-Te-S) minerals and chalcopyrite. A second signature of higher-Ag, chalcopyrite-poor gold has been identified in placer populations, but this gold type also exhibited the Bi-Pb-Te-S signature. The results suggest that the placers contain a mixture of gold derived from the porphyry and peripheral or shallow level epithermal mineralization.

The Bi-Pb-Te-S association evident at Casino was also recorded at Revenue/Nucleus and Sonora Gulch. This generic signature of gold in Cu-Mo (-Au) porphyry deposits and their associated distal epithermal manifestations could be applied to exploration in areas where placer-lode relationships are unclear.

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INTRODUCTION

Porphyry mineralization commonly contains various resistive minerals which persist into the secondary environment. Several studies have sought to utilize the occurrence of these mineral grains in stream and glacial sediments to aid in exploration (*e.g.*, Celis *et al.*, 2012). In some cases, the suite of indicator minerals contains native gold (*e.g.*, Kelley *et al.*, 2011), but while Au-bearing porphyries may be spatially associated with placer gold districts, they are also commonly found in areas of complex geology where there may be more than one style of Au-bearing mineralization contributing to the placer inventory. Consequently, the presence of detrital Au may not necessarily invoke a porphyry source.

This paper describes an investigation into the relationship between placer and lode gold surrounding three Au-bearing porphyry systems in the Yukon. The aims of the project were twofold: i. to investigate whether the mineralogical characteristics of gold grains from hypogene porphyry ore persist into grains recovered from the placer environment; and ii. to identify any generic mineralogical signatures within placer gold populations that are diagnostic for this style of mineralization.

Porphyry style copper-gold mineralization has been identified at three localities in the Dawson Range: Nucleus-Revenue, Sonora Gulch, and Casino (Fig. 1). Recent geochronological studies have shown that intrusions and associated mineralization in all three of these localities were formed during an episode of early Late Cretaceous magmatism (76-74 Ma) (Bennett *et al.*, 2010; Allan *et al.*, 2013). A summary of the characteristics of these three systems is provided in Table 1.

While the three intrusive systems share some common metallogenic features, there are important differences in the ore mineralogy (such as the presence of hypogene pyrrhotite at Nucleus), which may be a consequence of a more reduced oxidation state at Revenue-Nucleus and Sonora Gulch, in comparison with Casino.

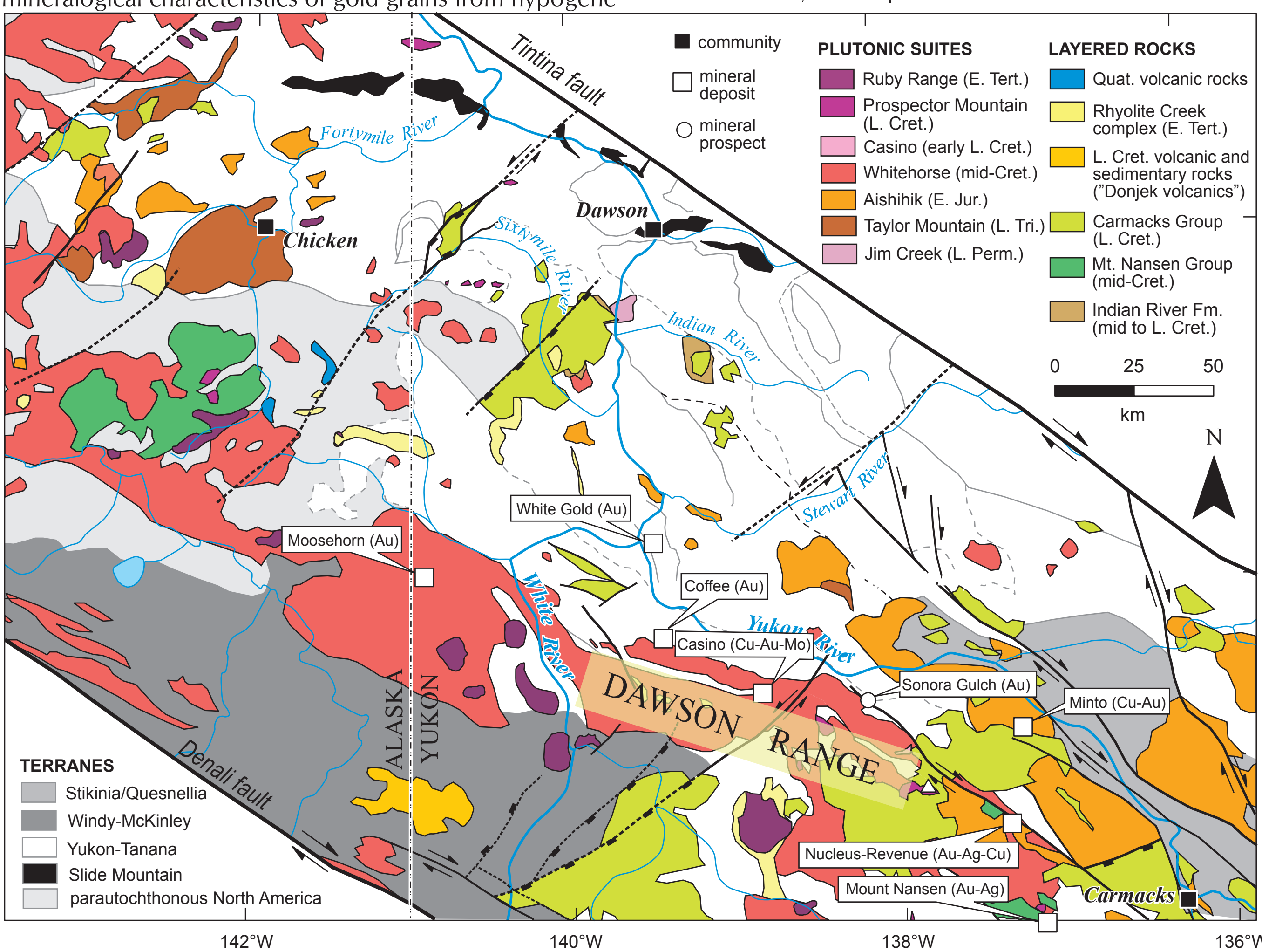

Figure 1. *Geological setting of intrusive rocks in southwest Yukon (adapted from Allan et al., 2013).*

Table 1. *Overview of lithology and mineralogy at the three early Late Cretaceous porphyry systems at Casino, Revenue/Nucleus, and Sonora Gulch.*

Porphyry system	Lithological Description	Mineralogy
Casino	Highly brecciated units of the Dawson Range batholith and the Coffee Creek granite, intruded by the Patton Porphyry[1]	Cpy, Py, Ap, An, Mo, Bi-bearing
Revenue/Nucleus	Revenue breccia complex and related porphyry dike swarm intruding Jurassic to mid-Cretaceous granitoids and Paleozoic metasediments[1]	Py, Po, Cpy, Mo, Ma, Ars
Sonora Gulch	Feldspar porphyry dykes and quartz-feldspar porphyry stocks[2]	i. Tetr, Ars ii. Py, Cpy
[1]Allan *et al*. (2013), [2]Bennett *et al*. (2011)		
Abbreviations used in all Tables and Figures: *An=anhydrite, Ap = apatite, Ars = arsenopyrite, Bi-bearing: unspecified Bi-bearing minerals regardless of stoichiometry and the presence of other elements (principally Pb, Te, S, Sb), Cpy = chalcopyrite, G = galena, Hs = hessite, Ma = marcasite, Mo = molybdenite, Mz = monazite, Po = pyrrhotite, Py = pyrite, Sch = scheelite, Sp = sphalerite Tet = tetrahedrite, Tetr = tetradymite.*		

Each of these centres of bedrock gold mineralization is within a region of placer deposit localities. Placer-lode relationships in the Nucleus-Revenue area were studied by Allan *et al*. (2012) who identified a distinctive suite of Bi-Pb-Te minerals present as inclusions within populations of placer gold grains. In addition to the sample suite from Nucleus-Revenue, small samples of placer gold from Sonora Gulch and Canadian Creek (which drains the Casino deposit area) were studied. Both additional samples exhibited the Bi-Pb-Te association previously recorded at Nucleus-Revenue. The present project was designed to establish whether placer gold derived from these porphyry systems exhibited a distinctive, generic signature. To this end, samples of core, placer, and eluvial gold were collected from the Casino orebody and environs.

FIELDWORK

A suite of placer and lode samples were collected and these are described in Table 2a and b. Placer sample locations are provided in Figure 2. Samples of placer gold were collected using a 'Le Trap River Robber' portable sluice. Material was screened at 1″ prior to sluicing. Samples collected from the leached cap were clay-rich and required dispersion in water prior to sluicing to reduce Au grain loss through entrainment. Placer gold grains were isolated from the heavy sediment concentrates collected in the sluice by hand panning. Sample collection at Casino Creek yielded only a very small number of grains and this sample is not considered further.

ANALYTICAL PROCEDURES AND DATA PRESENTATION

Both placer gold grain populations and polished thin sections of auriferous ore were studied in each of the three areas. Analysis of gold grain particles and gold grains identified in polished thin sections was carried out at the University of Leeds (UoL) to generate the 'microchemical signature', which comprises a combination of data relating to gold alloy composition and mineral inclusion suite. A full description of this methodology is provided in Chapman *et al.* (2010a). Alloy compositions were determined at UoL using a Jeol 8230 Superprobe, and the inclusion suite was established at UoL using the EDS facility of a FEI Quanta 650 FEG-SEM.

The Ag content of populations are presented as cumulative percentile *vs.* increasing Ag plots (*e.g.*, Fig. 5). This approach permits the direct comparison of Ag ranges of populations which contain different numbers of grains. Inclusion suites are defined by the numbers of grains in a population which contain a particular mineral inclusion. Inspection of the inclusion suite usually reveals mineralogical criteria by which different populations may be compared. Data are presented on ternary diagrams (*e.g.*, Fig. 9).

Table 2a. *Placer and elluvial Au collected during fieldwork at Casino (P = placer; E = eluvial).*

Sample	Easting*	Northing*	Site Description	Gold Description
Upper Canadian Creek (P)	609928	6959026	Virgin gravel.	0.5-2 mm mostly rough Au
Potato Gulch (P)	611503	6965042	Side pay on bedrock.	Rough gold grains to 3 mm
Lower Canadian Creek (P)	614300	6965200	Sample donated.	Fine grained gold, mixed morphologies
Casino Creek (P)	612189	6958179	Active channel.	<10 grains to 50 µm
Casino Creek tributary (P)	612160	6958178	Active channel.	10 grains to 50 µm
Rude Creek (P)			Active placer	Many flaky grains
Oxidized Leached Cap (E)	610882	6958295	Material dug from leached cap.	c. 50 grains 50 µm micron - 1 mm
*UTM Zone 7N, NAD83				

Table 2b. *Core samples selected for production of polished sections.*

Drill Hole	Depth (m)		Zone	Mineralogy	
	From	To		Early	Late
94-185	161.54	165.59	Supergene	Cpy, Mo	
CAS 060	160.62	163.62	Hypogene	Bi-bearing in py, Sch, Py, Ap, An	G, Au, Bi- bearing, Cpy, Tet

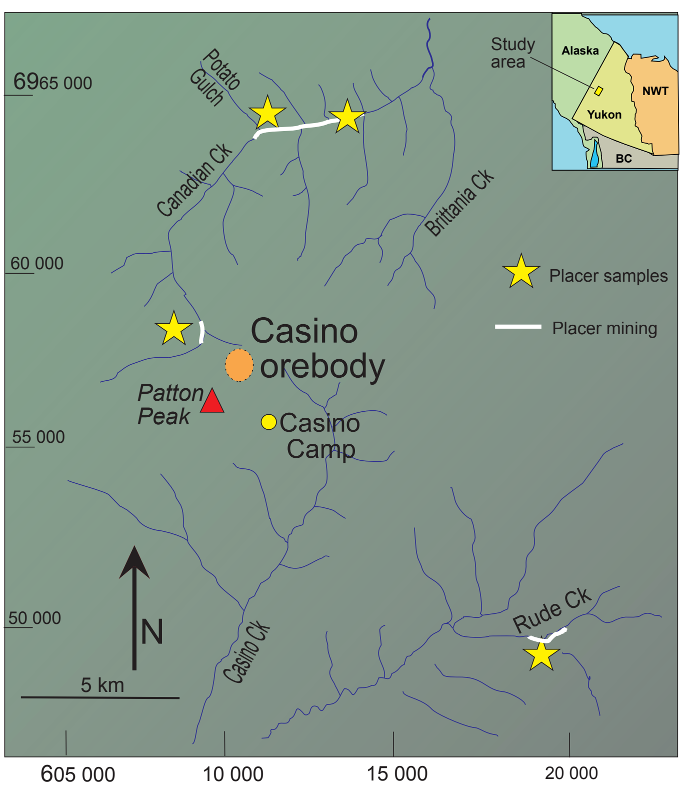

Figure 2. *Details of sampling locations in the Casino area. The locations of hole CAS 060 and the leached cap are within the limits of the Casino orebody. UTM according to NAD83.*

RESULTS

Gold grain compositions and mineral inclusions are presented in Table 3. The samples are considered firstly in terms of the mineralogy observed in polished thin sections and secondly in terms of the alloy and associated inclusion suites within populations of gold grains for the placer and eluvial environment.

GOLD IN SITU

Gold grains were observed in polished thin sections prepared from core in drill hole CAS 060 (hypogene zone) and drill hole 94-185 (supergene zone; Table 2b). Gold grains in the supergene sample were extremely small, and the quantitative data comprised (Au+Ag) totals of much less than 100%. Consequently these data were not included in the interpretation of gold compositions presented below.

The mineralogy of the ore from CAS 060 (Fig. 3) suggests at least two paragenetic stages. Inclusions of anhydrite, apatite, and monazite were observed in pyrite. Gold, galena, and Bi-bearing minerals occurred either infilling the pyrite or as discrete grains within the surrounding quartz.

Table 3. *Sample characteristics.*

Sample	No. grains	Cu mean (%)	Hg-bearing (%)*	Inclusions observed in polished section							
				Py	G	Sp	Cpy	Ars	Tetr	All Bi-bearing	Hs
Leached Cap (E)	34	0.05	0	3			1		1	2	
Upper Canadian Creek(P)	134	0.06	0	5	4	1	8	1	4	5	2
Lower Canadian Creek (P)	39	0.03	0	2	4			1	3	6	2
Potato Gulch (P)	40	0.05	7		7					4	3
Rude Creek (P)	166	0.04	0	5	2		3	1		5	
Gold grains in hole CAS 060	12	0.1	0	N/A							

**'Hg-bearing (%)' refers to the percentage of grains which contain Hg to above the detection limit of 0.3%. See Table 1 for list of mineral name abbreviations. P = placer; E = elluvial*

ELUVIAL GOLD AND PLACER

Details of the morphology and size range of the placer gold samples are presented in Table 2a and images of the different populations are provided in Figure 4. Gold from Rude Creek was mainly flaky, but all other populations contained gold grains which were predominantly rough.

The range of Ag content is depicted in Figure 5, rather than in Table 2, because simple statistical measures are ineffective for comparing the characteristics of different populations. All populations contained small amounts of Cu, commonly above the detection limit of 0.02%. Mercury was largely absent, and is not considered further.

The Ag plots for gold from the hypogene core sample and the grains collected from the leached cap show a very similar range of Ag values (Fig. 5a), with the majority of grains range from 6 to 12% Ag. The sample from upper Canadian Creek comprises three sub populations, one of which conforms to the 6-12% Ag range recorded in the sample from the leached cap. The other two populations contain grains in the Ag ranges 12-17% and 18-26%.

The placer populations from the two Canadian Creek localities and Rude Creek have similar ranges of Ag content, but only one grain in the sample from Potato Gulch returned a value of less than 12.5% Ag.

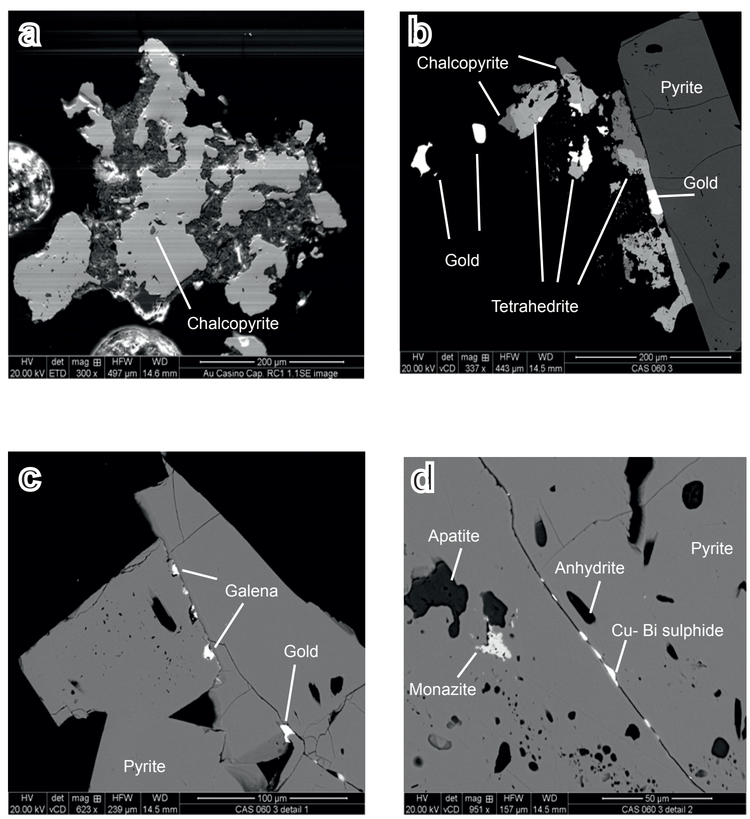

Figure 3*. Features of gold grains. (a) Typical grain from leached cap, with coating of Fe oxide. Inclusion (center) is chalcopyrite. (b) Assemblage in hole CAS 060. Chalcopyrite, tetrahedrite, and Au postdate the pyrite. (c) Galena and Au postdates the pyrite in hole CAS 060. (d) Apatite, anhydrite, and monzanite coeval with pyrite; Bi-Cu sulphide postdates the pyrite.*

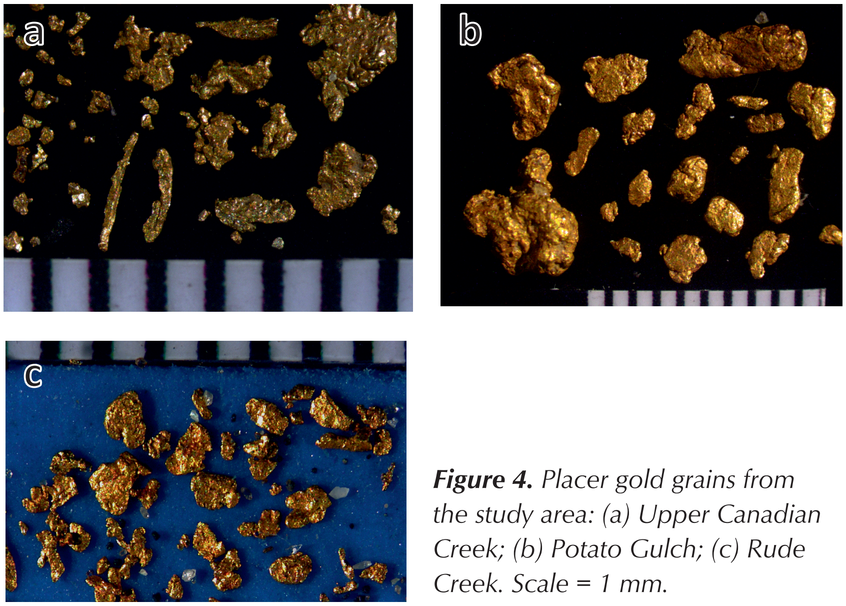

Figure 4. *Placer gold grains from the study area: (a) Upper Canadian Creek; (b) Potato Gulch; (c) Rude Creek. Scale = 1 mm.*

The abundance of mineral inclusions varied widely between samples, but they were more abundant in populations of placer grains from upper Canadian Creek and Potato Gulch. This is probably a consequence of the limited degree of fluvial transport, indicated by the morphology of the grains (Fig. 4). One grain from upper Canadian Creek contained an inclusion of Bi-Pb-Ag sulphosalt and another contained Sn within a Cu-Fe sulphide. Examples of inclusion species recorded in the placer samples are presented in Figure 6. Table 3 shows that all the placer populations contain Bi-bearing minerals as inclusions, although the presence of Bi tellurides at Rude Creek remains to be confirmed. The high incidence of chalcopyrite inclusions in the sample from upper Canadian Creek was not observed in any other of the placer samples.

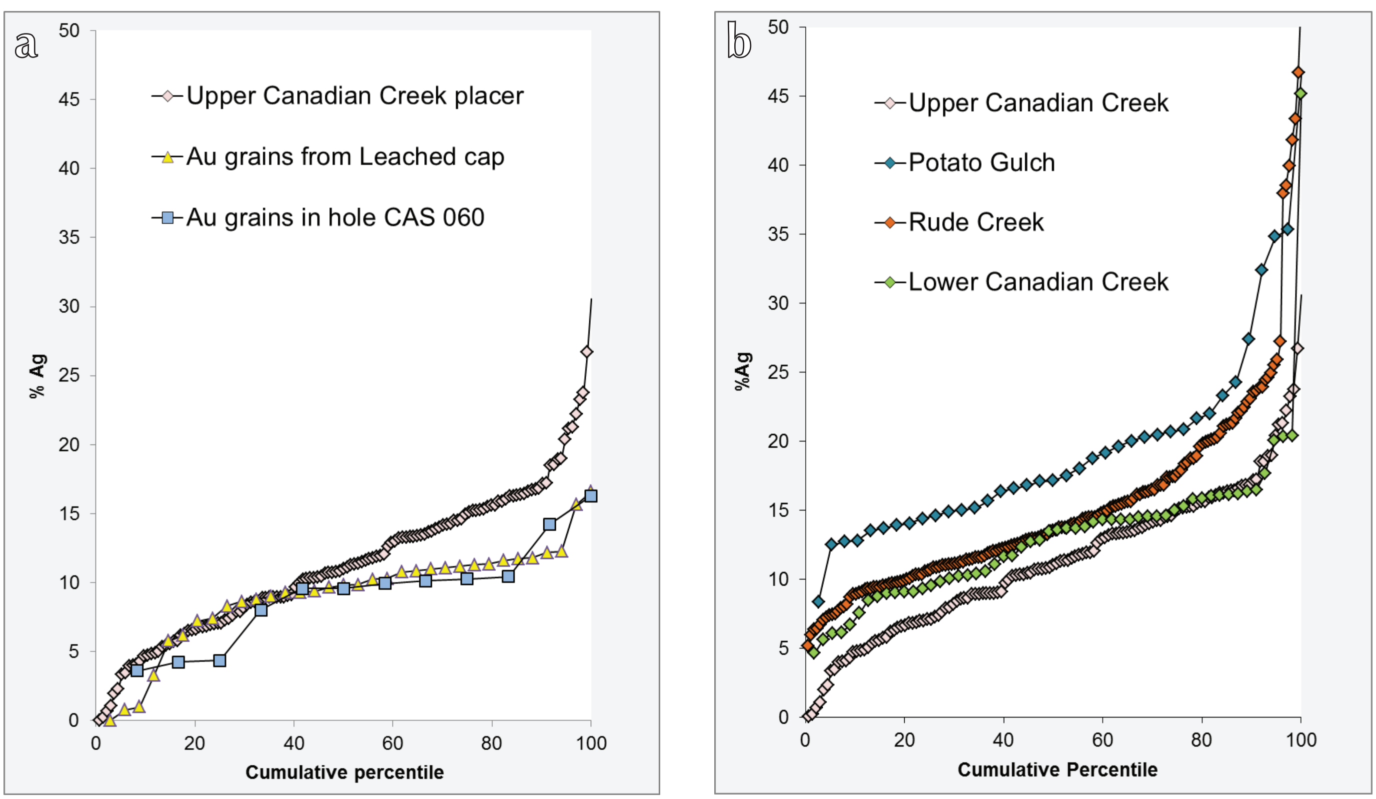

Figure 5. *Silver contents of gold grain populations. A: Casino area: comparison of Ag signatures of gold from the hypogene ore, the leached cap and a nearby placer in upper Canadian Creek. B: comparison of signatures from different placer localities in the study area.*

DISCUSSION

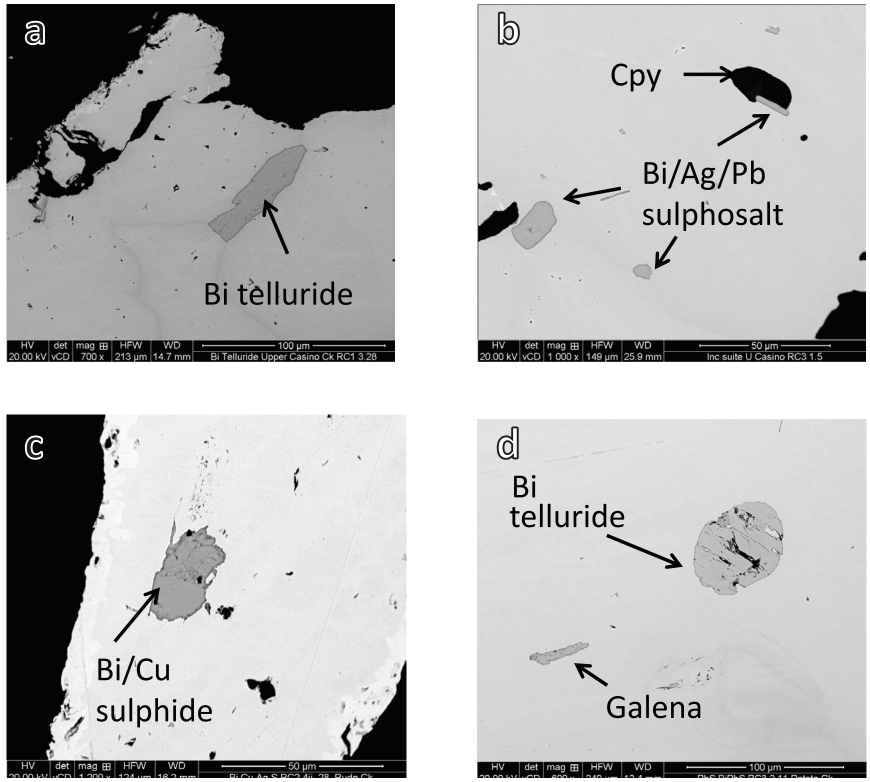

Figure 6. *Examples of mineral inclusions in placer samples from the study area: (a) and (b) Placer grains from upper Canadian Creek; (c) Grains from Rude Creek; (d) Grain from Potato Gulch.*

RELATIONSHIP BETWEEN HYPOGENE, ELUVIAL, AND PLACER GOLD IN CANADIAN CREEK

The alloy composition of gold grains from the hypogene ore corresponds to those obtained from the leached cap. This compositional range is also evident in the placer sample from upper Canadian Creek, where it is augmented by a separate population of gold containing Ag values over 11.9%. This cutoff has been identified by a slight break in the slope of the curve, which is highlighted in Figure 5.

Examination of a limited number of thin sections of hypogene mineralization suggests that gold, chalcopyrite, galena, bismuth minerals, and sulphosalts comprise a second paragenetic stage. This association was also observed within the inclusion assemblages of eluvial grains from the leached cap and in placer grains from upper Canadian Creek. Considered together, these data show that the composition of hypogene gold grains is unaffected by supergene processes or residence within the placer.

The alloy compositions depicted in Figure 5 suggest that two different sources contribute to the placer. In cases such as this, it is informative to examine the compositional range of gold grains according to the contained inclusion species. Figure 7 shows the Ag contents of sub populations of the upper Canadian Creek sample which contain inclusions of chalcopyrite, galena, and Bi-bearing minerals, respectively. The majority of chalcopyrite-bearing grains conform to the lower range of alloy composition, *i.e.*, that observed in the hypogene ore, where chalcopyrite is paragenetically linked with Au. The Bi-bearing minerals and galena, however, are equally abundant across the Ag compositional range. These data strongly suggest that there are two related compositional ranges of gold contributing to the placer inventory of upper Canadian Creek, with a second type entering the surficial system between the leached cap and the upper reaches of the Creek. Bennett *et al*. (2010) described two vein systems form Sonora Gulch, one of which comprises Au-tetradymite mineral assemblages. Placer gold compositions suggest that those similar vein systems are present around the Casino porphyry and contribute Au to the placer inventory. Placers in upper Canadian Creek have been exploited for wolframite (Yukon Placer database 2325, Lebarge, 2007) which occurred with magnetite and hematite particles up to 4cm in diameter. The abundance of these heavy minerals decreased downstream.

ORIGINS OF PLACER GOLD IN LOWER CANADIAN CREEK

The Canadian Creek placers were exploited in two discrete areas, one near the headwaters and the other downstream from the confluence with Potato Gulch (Fig. 2). The abundance of placer gold upstream of this confluence declined significantly (L. Olynek, 2013, pers. comm.), which corresponds to the decrease in concentration of heavy minerals described above. Consequently, it is very unlikely that much, if any, of the gold in the lower section has been transported from the headwaters. The sample from Potato Gulch comprised coarse rough grains (Fig. 3), which, together with the small size of this catchment,

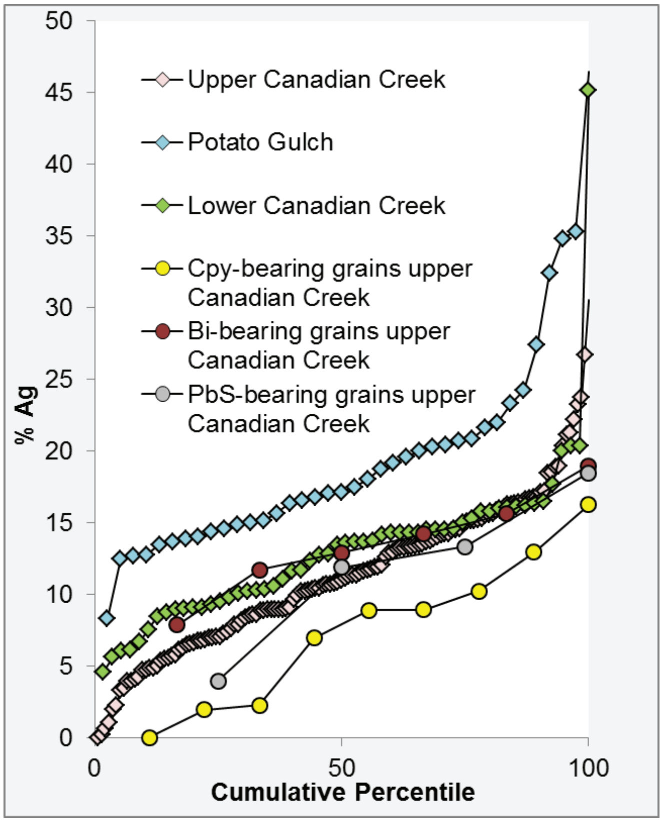

Figure 7. *Analyses of placer gold from upper Canadian Creek in terms of inclusion assemblages and associated alloy compositions.*

suggest a very local source. The relatively narrow range of Ag values is very similar to that observed in the Ag-rich fraction of the placer gold from upper Canadian Creek (described above), and inclusion assemblages of both samples contain galena and Bi-bearing minerals, whereas chalcopyrite is rare or absent in lower Canadian Creek samples. These data are interpreted as indicative of gold influx from sources near the lower placer workings, which are similar and possibly genetically related to the Casino orebody.

Barkhov *et al.* (2008) studied Sn-bearing hematite and associated W-Bi minerals present in the placer deposits in lower Canadian Creek and ascribed their origin to local magmatic hydrothermal systems. It is possible that this hypothesis could also account for Au mineralization in the lower Canadian Creek area. The coarse particle size of gold in Potato Gulch provides a further similarity with gold occurring in the tetradymite vein at Sonora Gulch.

The data presented in this study can be used to develop a hypothesis for placer formation in the Canadian Creek drainage. Gold in upper Canadian Creek is derived from the weathered porphyry, but is augmented by a second type, which appears to be present only in the periphery of the intrusion. The microchemical signature of placer gold from these (inferred) peripheral sources strongly suggests a genetic link with the porphyry mineralization, and it seems likely that they represent related epithermal veins. In situ gold in lower Canadian Creek appears to be wholly derived from such vein mineralization. The degree of transport of gold from the upper to lower sections of the creek is probably small, as evidenced by the absence of placer mining in the middle reaches of the creek and the abrupt influx of coarse gold at Potato Gulch.

ORIGINS OF PLACER GOLD IN RUDE CREEK

The population of placer gold from Rude Creek exhibits a similar range of Ag as the placer samples from Canadian Creek (Fig. 5b) and an inclusion assemblage which contains Bi-bearing minerals, galena, and chalcopyrite. The gold particles are relatively flat (Fig. 4c) and have probably originated some distance upstream of the present placer operation. Consequently, the population could represent gold from multiple sources, and the alloy and inclusion signatures show characteristics of all the populations observed in Canadian Creek. These data suggest that there are undiscovered gold sources feeding the Rude Creek drainage which are very similar to the Casino mineralization. However, the transport distance of the Rude Creek placer gold is greater than that between the Casino orebody and the upper Canadian Creek placers as evidenced by the morphology of gold grains at each locality. Consequently, there may be more placer gold deposits in the Rude Creek drainage of potential economic importance.

RELATIONSHIP TO SIGNATURES OF PLACER GOLD DERIVED FROM OROGENIC MINERALIZATION

Regional surveys of the compositions of placer gold grains have been undertaken in the Klondike (Chapman *et al.*, 2010a,b) and the Indian River/Blackhills Creek drainages (Chapman *et al.*, 2011). In addition, Wrighton (2013) characterized gold from the Sixtymile and White Gold districts. These studies have permitted characterization of gold grain signatures associated with orogenic gold formed during a widespread episode of mineralization in the middle to Late Jurassic (Allan *et al.*, 2013). Two major groups of signatures were recorded, characterized by the presence or absence of Te or As-bearing minerals in the inclusion suites. Only a small number of localities yielded samples in which both elements were present within the inclusions. The large majority of Te-bearing inclusions were (Au+Ag) tellurides and the incidence of Bi tellurides was confined to one tributary of Henderson Creek (White Gold district). The signature of all gold samples from the Casino area including Rude Creek are clearly distinct from the regional orogenic types.

RELATIONSHIP OF AU SIGNATURES AT CASINO WITH THOSE FROM PLACERS NEAR OTHER AU-BEARING PORPHYRIES

Figure 8 shows the relationships between Ag contents of placer samples from the environs of the Revenue-Nucleus Cu-Au porphyry and the Sonora Gulch porphyry compared to that of the gold grains collected from the Casino leached cap. There is a similarity between the Ag contents of the various populations of gold grains from these localities. Furthermore, sample populations of placer gold from the Nucleus/Revenue area and Sonora Gulch contain low, but measurable amounts of Cu (all average 0.04%), in contrast with gold from orogenic sources in which Cu concentrations are typically below detection limit (0.02%) in the large majority of cases. In addition, the Bi-Pb-Te-S signature, which was clearly evident in the placer gold from the Nucleus/Revenue area and Sonora Gulch, was observed in all populations of gold from Casino. Figure 9 shows the proportions of grains which contained Bi-bearing minerals, galena, and chalcopyrite. The low-Ag gold type observed in core, which forms part of the placer inventory in upper Canadian Creek, is characterized by the relatively high incidence of chalcopyrite inclusions. Chalcopyrite is far less abundant in all other samples. The Bi signature is present in all cases, however Pb mineral inclusions were not recorded at Sonora Gulch, but this may be a consequence of the very low sample size.

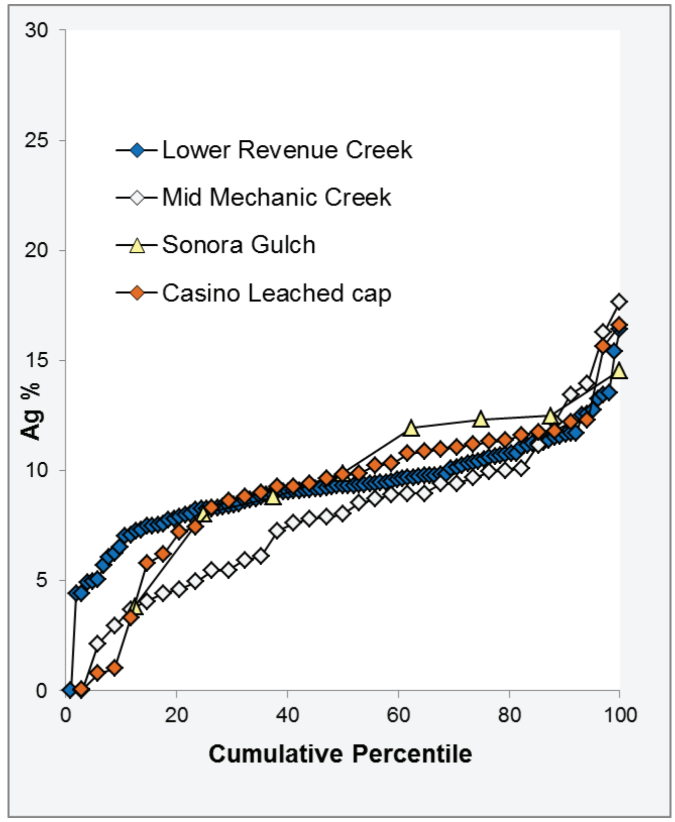

Figure 8. *Ag contents of placer samples from Revenue Creek and Mechanic Creek (which drain the Revenue and Nucleus deposits respectively), and Sonora Gulch, compared to the Ag signature of gold from the leached cap at Casino.*

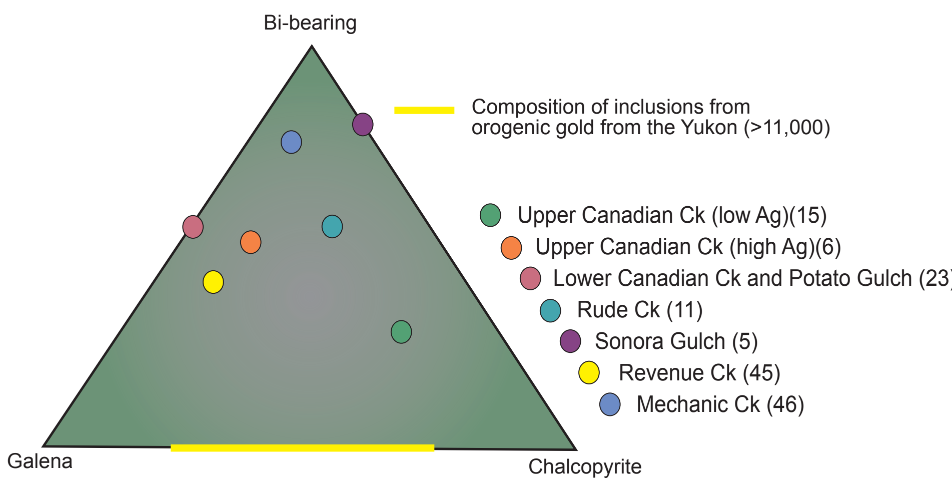

Figure 9. *Ternary plot illustrating abundance of different inclusion species in the sample suite. See methods section for explanation of the derivation of data. The sample from upper Canadian Creek has been subdivided according to Ag range. 'High Ag' refers to values of >11.9% (see Fig. 5). The compositional range of orogenic gold lies along the galena-chalcopyrite tie line. The values in parentheses following each locality refer to the number of inclusions contributing to the plot.*

IMPLICATIONS FOR EXPLORATION

The suite of mineral occurrences associated with early Late Cretaceous intrusions in the eastern and central Dawson Range in Yukon all yield gold particles which exhibit a very similar signature in terms of alloy composition and mineral inclusions. The presence of tetradymite and other minerals in the Bi-Pb-S-Te system are clear indicators for gold derived from these systems and this mineralogical signature is present within both the porphyry mineralization and associated shallow epithermal veins. This clear Bi-Pb-Te-S signature in the inclusion suite distinguishes this gold type from regional orogenic types, which exhibit varying proportions of S-As-Te in their inclusion suites. While Bi-bearing minerals have been recorded in four grains (in around 10 000 analysed) in regions of orogenic gold mineralization (Chapman *et al*., 2011), their incidence in gold derived from Au-bearing porphyry deposits is far higher. In addition, the association with Pb, which manifests either from a high incidence of galena inclusions or Pb-Bi sulphides, provides a further discriminator.

The synthesis of data describing alloy compositions and mineral inclusions appears to discriminate between gold derived from a porphyry environment and that originating from peripheral vein mineralization. The high incidence of chalcopyrite in the gold grains from the leached cap and gold of corresponding composition in the placer is consistent with the mineralogy of the hypogene ore studied here.

The mineral inclusion signatures described herein may find application in an exploration context. Examination of gold grains collected during reconnaissance could yield information on the style of mineralization of the source. Two examples are provided in this report. Firstly, placer gold from Rude Creek clearly exhibits a signature similar to that of the placer gold from upper Canadian Creek; however, the source of this placer gold is currently unclear. Secondly, there is strong evidence for the presence of epithermal mineralization in lower Canadian Creek, which to date has not been the subject of exploration.

CONCLUSIONS

1. Gold associated with porphyry style mineralization at Casino was largely emplaced during a second phase of the paragenesis and is coeval with chalcopyrite, galena, and Bi sulphides and tellurides.
2. The gold signature in the hypogene ore corresponds to that observed in gold grains collected from the leached cap.
3. This signature persists into the placer gold present in upper Canadian Creek where it is augmented by another relatively Ag-rich gold type in which chalcopyrite is absent.
4. Further evidence of two different Au sources in the study area is provided by the signature of gold from Potato Gulch, which corresponds to the ‘high Ag’ component of the upper Canadian Creek sample. It is proposed that the two signatures relate to gold derived from the Casino porphyry and that originating in widespread epithermal veins.
5. Gold in the lower Canadian Creek placer is derived from local sources and is not a distal manifestation of the placer in upper Canadian Creek.
6. There are undiscovered, in situ sources of gold in Rude Creek and lower Canadian Creek.
7. The signature of gold from Canadian Creek shows a close similarity with the signatures of gold from placers surrounding other porphyry deposits of the same age elsewhere in the Dawson Range. Consequently the Bi-Pb-S-Te inclusion signature may be viewed as diagnostic for this style of porphyry mineralization in the Yukon and raises the possibility that a similar approach to define porphyry gold signatures may find value in exploration for porphyries elsewhere.

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