Constraints on the Metallogeny and Geochronology of the Bridge River Gold District and Associated Intrusions, southwestern British Columbia (NTS 092 J/15)

Geoscience BC Report 2017-08

Craig J.R. Hart and Richard J. Goldfarb

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Prepared by MDRU[2]

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Cover image: Looking northeasterly down Carpenter Lake from above the town of Gold Bridge, with the Shulaps mafic-ultramafic complex forming the mountain range on the horizon, and northwesterly-trending faults in the valleys. The Senator-Reliance property underlies the foreground and the Congress and Minto properties are on the north side of the lake.

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Keywords*: orogenic gold, geochronology, gold deposits, gold deposit models*

INTRODUCTION

The Bridge River mining district in southwestern British Columbia (Figure 1) is the largest historical lode gold producer in the Canadian Cordillera, with more than 128 tonnes (4.1 million ounces) of gold production between 1897 and 1971 (Church, 1996; Table 1). Most production came from the Bralorne-Pioneer vein system that yielded approximately 7 million tonnes of high grade ores averaging 19.1 g/t (0.58 oz/t) (Leitch, 1990). Since 1995, surface and underground exploration and minor production have occurred episodically. A 2012 preliminary economic assessment indicated a resource in the Bralorne area of about 400,000t of 9 gpt Au (Beacon Hill Consultants, 2012). Since 2010, a small 100 tonne/day mill has variably operated, producing 3482 ounces of gold in 2014, for example (Avino website, 2016).

Several mineral deposit models have been proposed to explain the significant gold enrichments in the Bralorne-Pioneer deposits, as well as for the numerous epigenetic hydrothermal, variably precious metal-rich mineral deposits and occurrences that occur throughout the Bridge River district. Determining the most appropriate deposit and regional metallogenic model is important because it influences the effectiveness of exploration and decisions related to targeting, property acquisitions and investment. Establishing effective deposit and regional scale metallogenic models for the Bridge River district has been limited by a lack of well-constrained geochronology from host rocks and mineral deposits.

The absolute timing of formation of the Bralorne-Pioneer gold ore bodies, as well as for most other mineral deposits throughout the Bridge River district, is not precisely known. In addition, the timing of some of the numerous and volumetrically significant plutonic events, such as those responsible for the Coast Plutonic Complex and the Bendor Plutonic Suite, which may or may not play a significant role in gold formation, are not precisely known. To establish temporal, and potentially genetic, associations of the ores with regional magmatic, structural, and metamorphic events, and to place constraints on the nature of the geological models responsible for the formation of gold mineralization at Bralorne-Pioneer deposit, new Ar-Ar age determinations on alteration and gangue mineral phases from the gold veins have been obtained.

The Bendor batholith is the nearest, largest, and therefore the most significant magmatic and thermal feature that is adjacent to the Bralorne-Pioneer gold deposits. The timing of batholith emplacement is constrained using conventional TIMS, LA-ICP and SHRIMP U-Pb age determinations on zircons, as well as with Ar-Ar determinations. Comparing these data allow an assessment of the batholith's crystallization and cooling history.

Regional trends in the nature and distribution of the various mineral deposits and occurrences in the district can also provide some regional metallogenic constraints on the nature of the mineralizing systems. These systems can also be evaluated by considering the nature and source of hydrothermal fluids, and of the sulphur, which are both key components in transporting the gold. Combined, several new types of data provide new constraints to determining the most appropriate mineral deposit model for the formation of the Bralorne-Pioneer gold veins and the broader Bridge River mineral district.

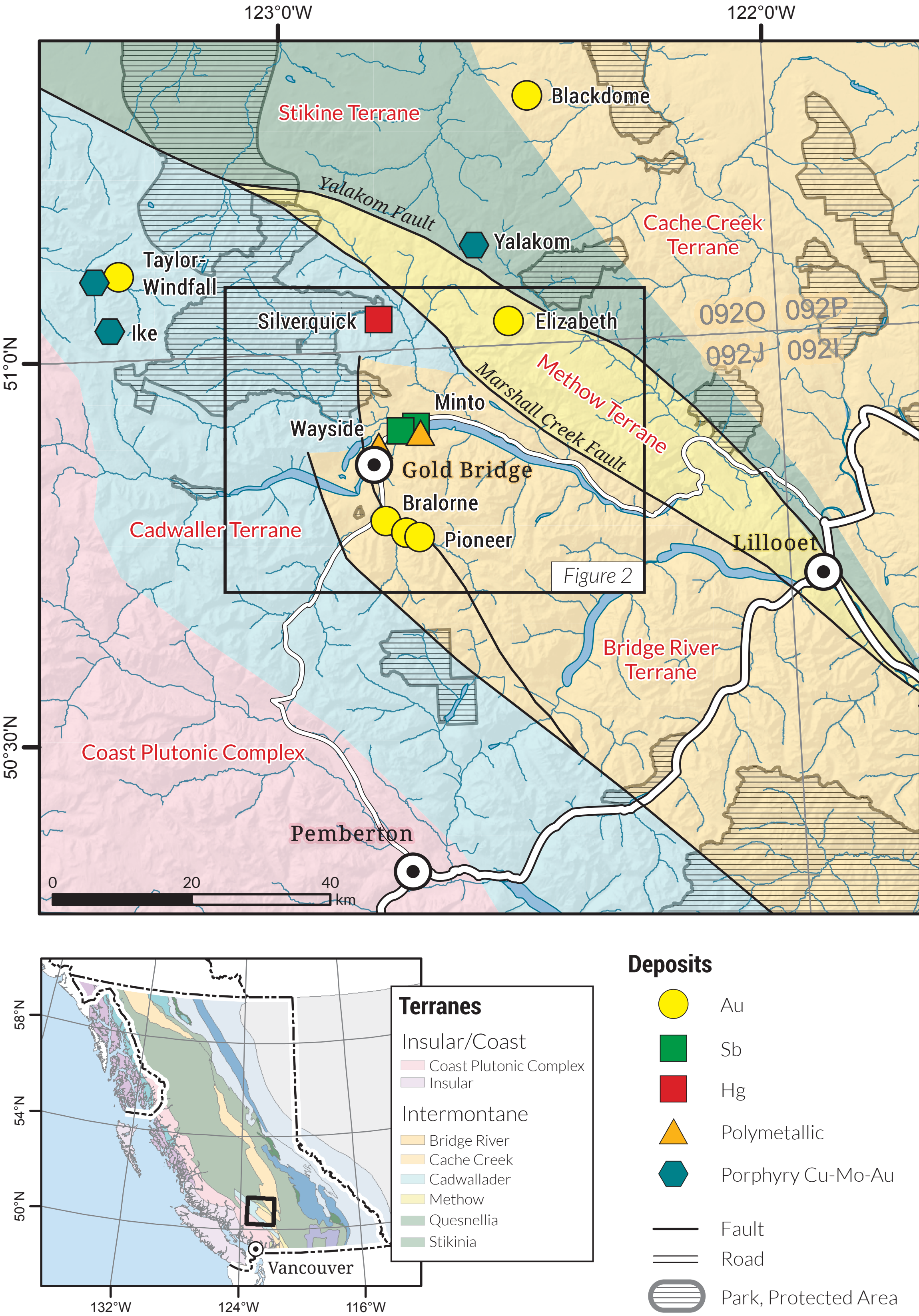

Figure 1: Regional tectonic and geological setting of the Bridge River mining district in southern British Columbia.

Table 1: Production from the Bridge River camp. Modified from Church (1995).

	Mined (t)	Milled (t)	Gold (kg)	Silver (kg)	Au:Ag	Copper (kg)	Lead (kg)	Zinc (kg)
Bralorne	4,981,419	4,954,479	87,643.20	21,969.60	4	-	-	157
Pioneer	2,313,552	2,240,626	41,476.50	7,612.00	5.4		59	139
Minto	80,650	19,073	546.1	1,573.30	0.3	9,673	56,435	-
Wayside	39,094	36,992	166.1	26.1	6.4			-
Congress	943	943	2.6	1.3	2	38	-	-

The region benefits from more than one hundred years of excellent past geological investigations starting with contributions from Drysdale (1915), McCann (1922) and Cairnes (1937, 1943). More modern work advanced the mapping and understanding geological framework and mineral deposits, including contributions by Church (1996), Church and Jones (1999), and Schiarizza et al. (1997). More detailed investigations of the Bralone-Pioneer gold deposits are provided by Leitch, 1989; Leitch, 1990; Leitch et al. (1989, 1991a, b), and on the fluid chemistry and stable isotopes of the regional deposits by Maheux (1989). Investigations on the geology and mineralization in the region since circa 1995 are sparse, perhaps limited to Hart et al. (2008) and Moore et al. (2009), upon which this contribution builds.

REGIONAL GEOLOGY

The Bridge River district is in a northwest-trending, structurally complex region along the western margins of the Intermontane Terranes, adjacent to variably intrusive contacts with the plutonic rocks of the southeastern **Coast Plutonic Complex** to the west (Figure 2). In this region, the Intermontane Terranes consist of structurally interleaved Mississippian to Middle Jurassic **Bridge River Terrane** accretionary complex structurally juxtaposed against Late Triassic to Early Jurassic **Cadwallader Terrane** volcanic rocks and arc-marginal clastic strata. These components were structurally juxtaposed by at least the mid-Cretaceous, but possibly earlier. These assemblages are variably overlain, generally to the north, by clastic, largely non-marine, sedimentary successions of the Jura-Cretaceous **Tyaughton Basin**. The region was subsequently intruded and overlain by a wide range of Cretaceous and Tertiary magmas that form the plutonic and volcanic rocks related to the Coast Plutonic Complex.

The Bridge River Terrane consists mainly of the Bridge River Group (or Complex of previous workers), comprising Mississippian to Middle Jurassic pillowed and massive oceanic basalts and greenstones, with lesser ribbon chert, shale, argillite, and limestone. Locally there are slivers of serpentinite. The stratigraphy of this package has been structurally obliterated. Although sub-greenschist facies metamorphism is pervasive throughout the area, notable localities have preserved sites of blueschist facies metamorphism. Microfossils in sedimentary rocks span the entire range from Mississippian to Middle Jurassic; blueschist facies rocks indicate Late Triassic formation.

The Cadwallader Terrane includes the Late Triassic Cadwallader Group mafic arc tholeiitic volcanic rocks (Pioneer Formation) that are overlain by a thick sequence of Lower and Middle Jurassic Hurley Formation siltstone, sandstone and conglomerate. This terrane also includes the Tyaughton Group (and Last Creek formation), a distinctive succession of Upper Triassic clastic rocks with minor limestone. This group is facies equivalent to the Hurley Formation, but is overlain by Middle Jurassic to Lower Cretaceous Tyaughton Basin strata, including the Relay Mountain, Taylor Creek and Silverquick Formations in the uppermost stratigraphy.

The Bralorne-East Liza Complex consists of greenstone, diorite, gabbro, tonalite and serpentinite that are structurally imbricated within the Cadwallader Terrane, and includes rocks previously identified as part of the “Bralorne intrusions”. These intrusions have highly variable compositional and textural features and have been variously distinguished as trondhjemites, plagiogranites, soda granites and augite diorite. These rocks are dominantly late Paleozoic in age, mostly returning dates of 290 to 270 Ma (Leitch et al., 1991a; Church, 1996). The rocks are similar to the Shulaps ultramafic complex and may have been interleaved during its obduction in the mid-Cretaceous.

The Coast Plutonic Complex is a region underlain by a mostly contiguous and diverse array of granitoid bodies, comprising mid-Cretaceous and older, mid-crustal plutons and batholiths, with contact-metamorphosed country rock pendants indicating intrusion into older, mostly Cadwallader Terrane basement. Notable among the definable plutonic bodies is the Late Cretaceous to Eocene Dickson-McClure batholith, the Bendor batholiths and the Eldorado pluton. These bodies and adjacent country rocks are variably intruded by porphyritic, aplitic, pegmatitic, and mafic dykes ranging to Miocene age.

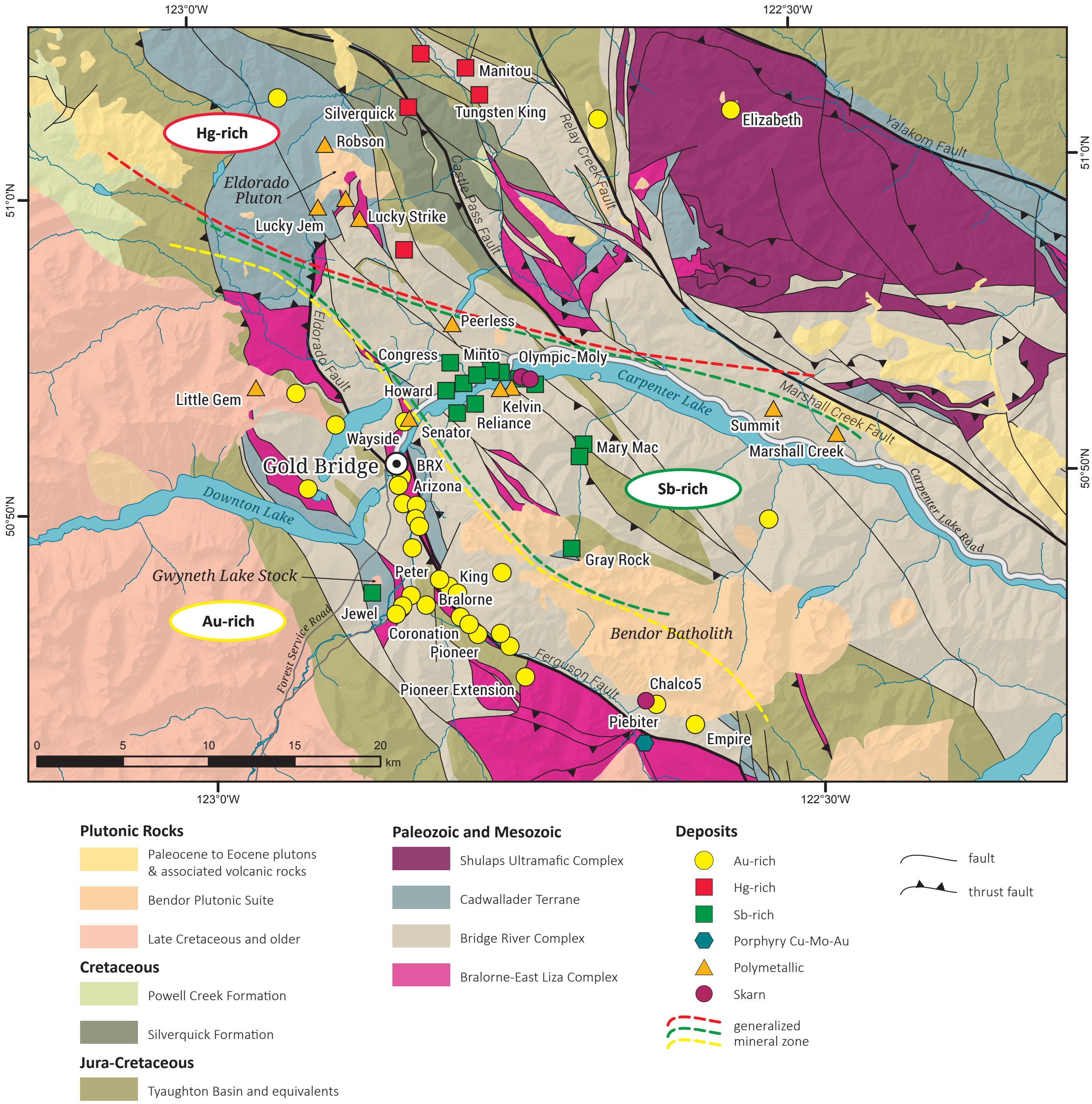

Figure 2: Regional geological setting of the Bridge River district in southwestern British Columbia showing the major structural features and distribution of mineral deposits. Note the zonation from gold-only, to stibnite-dominant, to mercury-dominant deposit types. 84WV is the location of the Bendor Batholith geochronology sample.

Structure and Deformation

The geology of the district is characterized by significant deformation and resultant structural features. The most significant event was the amalgamation of the Bridge River accretionary complex. Locally, blue amphiboles and glaucophane provide evidence for high pressure blueschist facies deformation (Schiarizza et al., 1997). These rocks yield ca. 230 Ma Ar-Ar ages on white mica, and indicate that subduction-related deformation occurred during the late Middle Triassic, and may have continued into the Middle Jurassic, which is the depositional age of the youngest involved chert strata (Schiarizza et al., 1997).

Subsequently, the region was widely affected by mid-Cretaceous contractional deformation that emplaced the westerly-verging Shulaps ultramafic complex above Cadwallader and Bridge River terranes. The same deformation included oblique-sinistral deformation along the northwest-trending Bralorne-Eldorado fault system that juxtaposed and interleaved the Bridge River

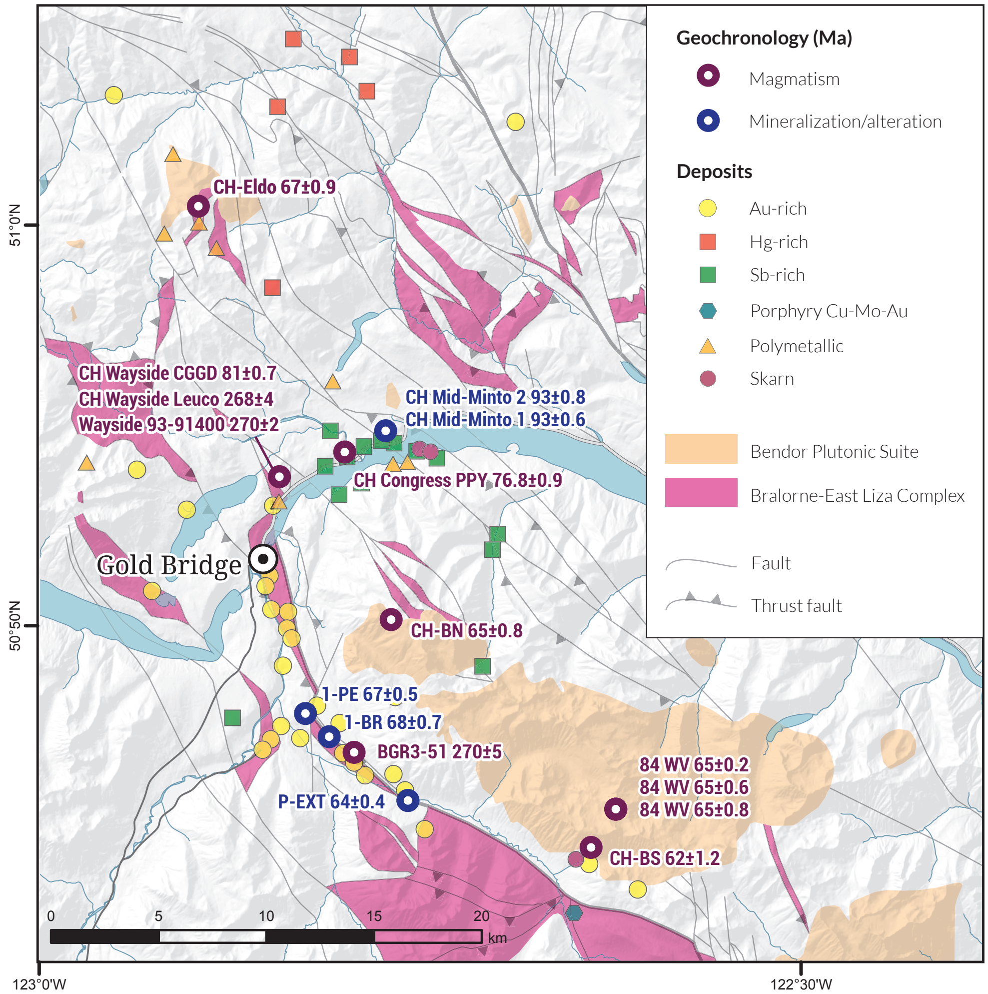

Figure 3: Geochronology results discussed in this report, and also summarized in Table 2.

and Cadwallader terranes. This fault system in the Bridge River district consists of a 1-3 km-wide linear zone of tectonized and serpentinized slices of late Paleozoic mafic and ultramafic Bridge River terrane rocks, known as the Bralorne-East Liza thrust belt, which is bound by the Cadwallader and Fergusson faults (Schiarizza et al., 1997), but becomes the Eldorado fault system further north.

The timing of this deformation and related low grade metamorphism is ca. 130 to 92 Ma, and the deformation events also resulted in the deposition of syn-orogenic sedimentary flysch as young as mid-Cretaceous, which is also cut by the faults (Garver et al., 1989; Schiarizza et al., 1997). Much of the Bralorne-Pioneer vein system occurs along or within these structures, and early Late Cretaceous sinistral movements on the Eldorado fault and the Castle Pass fault system are considered to be coeval with final regional contraction (Schiarizza et al., 1997).

Younger, northwest-trending dextral strike-slip displacements reactivated many of the older faults, particularly the Marshall Creek and Yalakom faults east of the Bralorne district. Dextral deformation is best estimated as having been initiated at or slightly before 67 Ma (Schiarizza et al., 1997), and is considered a primary control on much of the mineralization proximal to the faults in these areas (Schiarizza et al., 1997).

Plutonism

Numerous Cretaceous and Tertiary plutons and smaller intrusions were emplaced throughout the region. Most significant among these are the large, dominantly mid and Late Cretaceous, coarse- and medium-grained, equigranular granitoid bodies that form the bulk of the Coast Plutonic Complex (CPC), located a few kilometers west of the Bridge River district. The most-proximal CPC intrusion is the large Dickson McClure batholith, which consists of greyish, hornblende-biotite granodiorite that yields crystallization ages of ca. 92 Ma ages (Parrish, 1992; Garver et al., 1994; Schiarizza et al., 1997) and cooling ages (Ar-Ar on hornblende and biotite) of 87 to 82 Ma (McMillan, 1983; Archibald et al. 1989).

The Bendor plutonic suite, described in detail below, consists of a series of large (up to 20-km-long) granitoid plutons, as well as the smaller (4-km-long) Eldorado pluton to the north. They

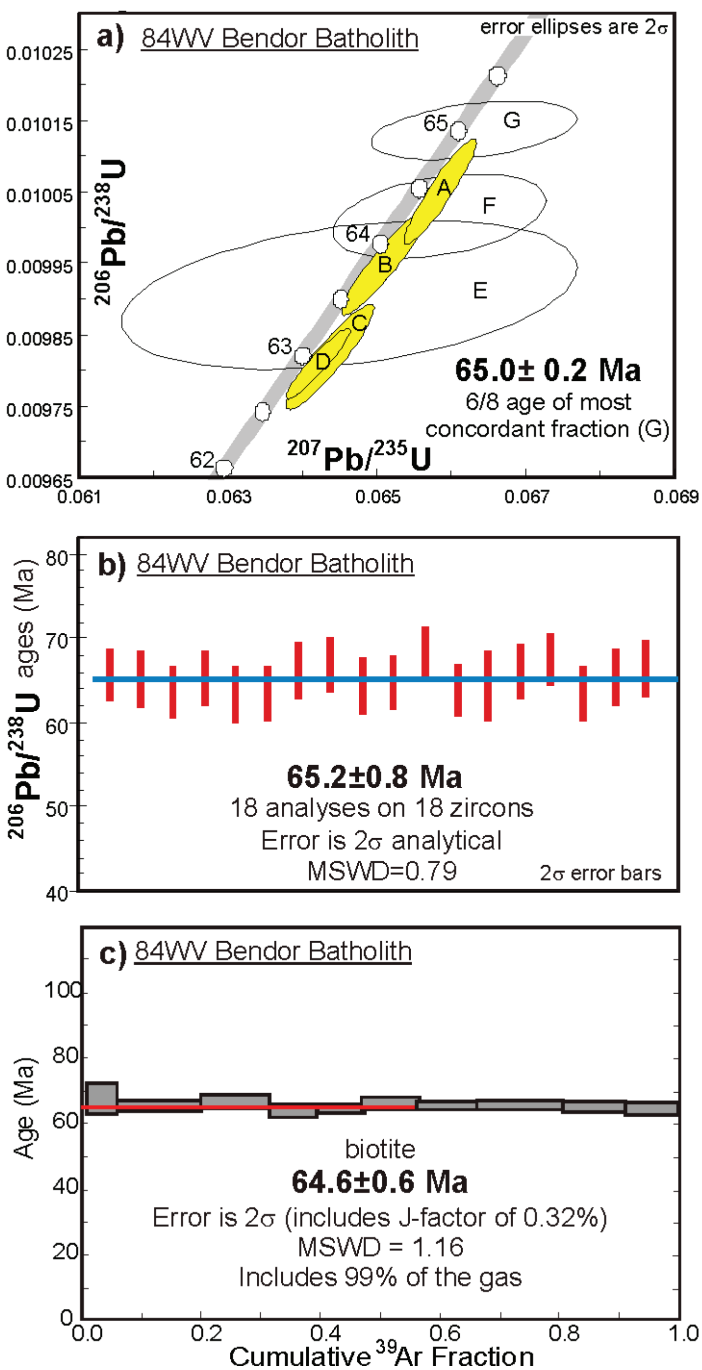

Figure 4: U-Pb plots for Bendor Batholith zircon analysis for sample 84 WV; a) Concordia plot of zircon fractions analysed by conventional TIMS method; b) Weighted mean plot for $^{206}Pb/^{238}U$ plot for analyses by SHRIMP. MSWD = mean square of weighted deviates; c) Ar-Ar gas release spectra for Bendor Batholith biotite. Plateau steps are filled, rejected steps are open. Box heights are 2σ errors. Error includes J-error of 0.32%. MSWD = mean square of weighted deviates.

intrude rocks of the Intermontane terranes in a linear belt just east of the CPC and have ages that are reported as ranging from Late Cretaceous to early Tertiary.

Locally, small hypabyssal stocks and dikes, characterized mostly by porphyritic textures, have reported ages from 84 to 66 Ma. The youngest magmatic event is recorded from lamprophyre dikes at 44 Ma (Leitch et al., 1991a). The general lack of foliation in all igneous rocks, except for the oldest parts of the CPC, indicates their emplacement was subsequent to the main Mesozoic regional deformational events along this part of the Cordilleran margin (Armstrong, 1988).

Bendor Plutonic Suite

The Bendor plutonic suite comprises a northwest-trending series of plutons and batholiths that form a >150-km-long belt along the southeastern side of the CPC from Eldorado Mountain, approx. 15 km north of the town of Gold Bridge, south to Mount Traux, just east of the Bridge River district, and onwards towards the town of Lytton. These rocks consist of high-standing, resistant, coarse-grained, hornblende±biotite±pyroxene, magnetite-titanite–bearing granodiorite to quartz diorite. Most pertinent to this study is the 20km-long, northwest-trending Bendor batholith, the major igneous body nearest to the Bralorne-Pioneer deposits, and a key geological feature in the district.

The intrusive rocks have reported ages mainly ranging from 74 to 58 Ma (e.g., Garver et al., 1994; Wanless et al., 1978; Church, 1996) but also some older U-Pb dates (e.g., 98.4 Ma reported in Church, 1989). This range of ages emphasizes either a diverse and protracted history, or poor geochronological constraints. The most reliable existing date may be a U-Pb TIMS determination of 63±2 Ma from Friedman and Armstrong (1995), but several of the zircon phases showed evidence of Pb-loss and ancient inheritance, which may explain some of the inconsistency in ages.

The Bendor plutonic suite batholiths are the dominant plutonic feature in the Bridge River district and were likely a major contributor of crustal heat throughout the region. A more modern and precise age for this magmatism will allow improved evaluation of the significance of the regional magmatism to the latest Mesozoic-early Tertiary geological evolution of this part of British Columbia, particularly for determination of the temporal-spatial relationships within the plutonic suite, as well as better interpretation of its association with other units and of conflicting existing isotopic dates. It has also been suggested that the Bendor batholith is a potential source of gold mineralization, so this hypothesis must be tested with robust geochronology.

Geochronology of the Bendor Batholith and Bendor Plutonic Suite

To establish a more precise age of crystallization for the Bendor plutonic suite, U-Pb dating was carried out on three samples from the Bendor batholith (Bendor-84WV, Bendor-North, and Bendor-South) and on an additional sample from the Eldorado pluton. All errors for the new geochronology are reported to 2σ.

Sample Bendor-84WV was originally collected by G.J. Woodsworth of the Geological Survey of Canada in 1984 from

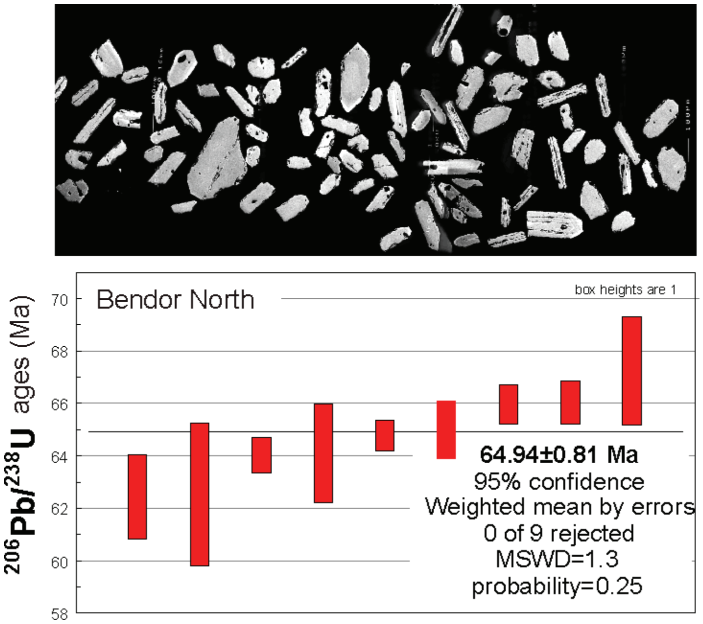

Figure 5: Backscatter SEM image of zircons from Bendor-North (CH-BN) sample site of Bendor batholith [upper], and corresponding U-Pb plot of $^{206}Pb/^{238}U$ ages by SHRIMP [lower].

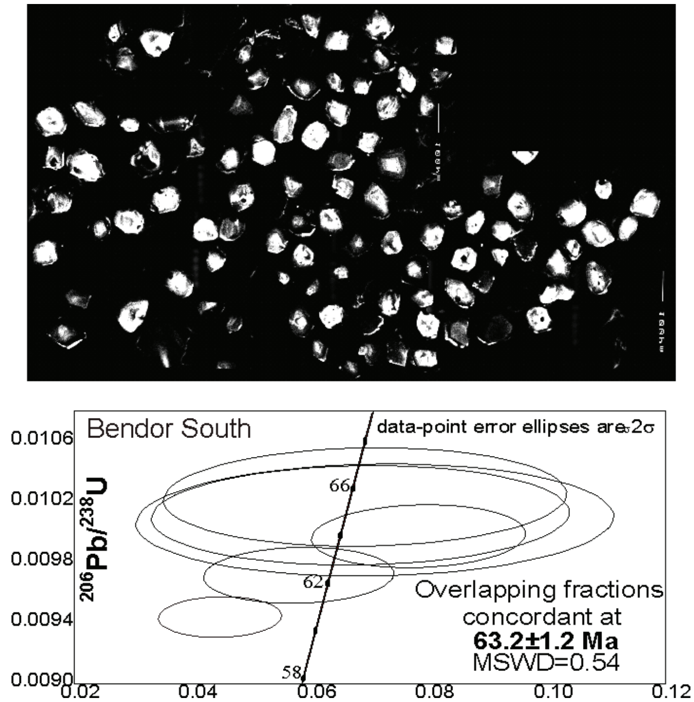

Figure 6: Backscatter SEM image of zircons from the Bendor-South site of Bendor Batholith (CH-BS) [upper], with U-Pb plot of $^{206}Pb/^{238}U$ ages by SHRIMP [lower].

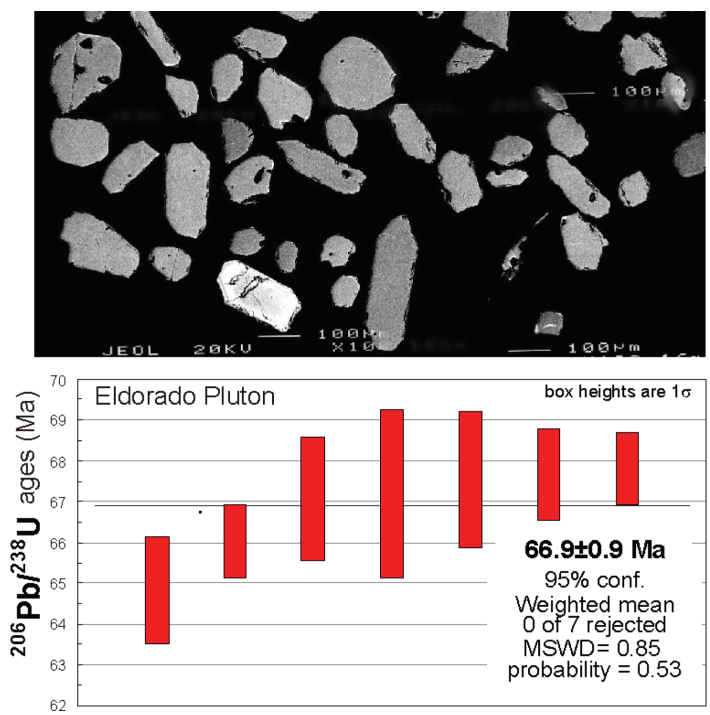

Figure 7: Backscatter SEM image of zircons from the Eldorado Pluton sample CH-Eldo [upper] and U-Pb plot of $^{206}Pb/^{238}U$ ages by SHRIMP [lower].

a site that is approximately 10 km east of the Pioneer deposit. A previous U-Pb date from this sample was obtained from four zircon fractions and analyzed by the TIMS (thermal ionization mass spectrometry) method (Friedman and Armstrong, 1995). We have added additional TIMS U-Pb analyses performed in The University of British Columbia laboratories, using three new fractions, which now provide a combined seven zircon fractions to be considered (Figure 4a).

The original four fractions of 84WV zircons (A-D) included large numbers of zircons (cumulative weight of 1.1–1.7 mg) that gave relatively precise data. But the results are difficult to interpret because the data points lie parallel to, and just off, the Concordia Pb-decay curve. The older two fractions were relatively coarse-grained and were physically abraded, which suggests that dispersion of the data on the Concordia plot is likely due to minor Pb loss from some of the zircons in these fractions. In an attempt to confirm these original data, three new fractions (E, F, G) of 1 to 23 strongly abraded zircon grains (20–35 µg) were analyzed. The best estimate for the age is based on the oldest fraction (G), with a $^{206}Pb/^{238}U$ date of 65.0±0.2 Ma. Although the new analyses are less precise, they overlap with the original data and show a similar style of dispersion that confirms that minor Pb loss is an issue.

Eighteen different zircon grains from the 84WV sample were analyzed with a SHRIMP II Sensitive High-Resolution Ion MicroProbe at the J.D. deLateur Centre at Curtin University in Perth, Australia. All SHRIMP dates presented herein are by the method described in Mair et al., (2006) . All determinations were on selected locations of well-zoned magmatic zircon that lacked inherited cores or radiation damaged regions. A weighted mean of 65.2±0.8 Ma was generated from the 18 $^{206}Pb/^{238}U$ determinations (Figure 4b). The result is supported by a sound MSWD of 0.79, and good correlation with the TIMS determination.

Overlapping ages were determined within error from analyses of the two new sampled batholith sites. The most northerly of the Bendor batholith samples (CH-BN) was also dated using SHRIMP methods from a sample taken on the top of the mountain near the Traux Gold mineral occurrence (Minfile 092JNE060). This Bendor-North pluton yielded an age of 64.9±0.8 Ma (Figure 5). A more southerly locality of the Bendor batholith (CH-BS) that was sampled along Piebiter Creek yielded a SHRIMP U-Pb date of 63.2±1.2 Ma (Figure 6).

An ^{40}Ar-^{39}Ar determination on well-formed, unaltered, coarse-grained biotite from sample 84VW yielded an excellent plateau deduced from ten argon-release steps that represent 99% of the total gas, and gives a date of 64.6±0.6 Ma (Figure 4c). All Ar-Ar dates herein were dated at The University of British Columbia using the method described in Mortensen et al., 2010. The initial $^{40}Ar/^{36}Ar$ ratio indicated by the inverse isochron is within error of the accepted value and the inverse isochron age is in good agreement with the plateau age.

North of Gold Bridge, the Eldorado pluton intrudes the Eldorado fault zone and adjacent rocks of the Hurley Formation, Bralorne East Liza Complex, and Bridge River Complex, west and south of Eldorado Mountain. Similar granitoid dikes, some porphyritic, trend northerly, and are recognized further south to beyond Carpenter Lake (units KTqd and KTp of Schiarizza et al., 1997). A SHRIMP U-Pb determination on zircons from the pluton yields a 66.9±0.9 Ma date (Figure 7), which is within error of a ^{40}Ar-^{39}Ar biotite age of 67.2 ±0.7 Ma (Schiarizza et al, 1997).

Data presented here clearly indicate a crystallization age of 65±1 Ma for the Bendor batholith, but some phases of the plutonic suite may be as young as 63 Ma in Piebiter area, or as old as the 67 Ma Eldorado pluton. Although the precision on the individual analyses is not robust, a southerly-younging trend in magmatism is indicated by the data. Most K-Ar and ^{40}Ar-^{39}Ar dates on biotite and hornblende are similar, or perhaps 1 to 2 million years younger than the U-Pb results (see Garver et al., 1994) indicating that the batholiths cooled and/or were uplifted quickly. Fission-track data from zircons yield dates ca. 53±6 Ma (Garver et al., 1994), suggesting low temperature (approx. 200ºC) cooling or a proximal thermal event near that time.

REGIONAL METALLOGENY AND DISTRICT METAL ZONATION

There is considerable mineralogical diversity in the epigenetic, mostly vein-style, mineral occurrences in the Bridge River district. Previously operating mines in the region include Bralorne, Pioneer, Pioneer-Extension, Wayside, Minto, Congress, and Silverquick, and surrounding these there are more than 60 other mineral occurrences of variable significance. The mineralogical characteristics of the deposits and occurrences are such that they form three regionally distinct zones, comprising mainly Au-dominant, Sb-dominant, or Hg-dominant vein systems. Locally, there are also a few polymetallic sulfide veins and porphyry Cu-Mo mineral occurrences. The Au-dominant occurrences are further divisible into Au-only and Au-Ag-bearing sulfide-rich quartz veins. Many of the Sb-dominant occurrences host Au and Ag enrichments, whereas the Hg-dominant occurrences have only rare precious metal enrichments, but locally contain scheelite.

Regionally, these mineral occurrences form a broad metallogenic zonation with quartz-rich Au occurrences in the west, zoning easterly and northerly towards increasing sulfide-rich Au occurrences, then into an intermediate Sb zone, and then more distally into an eastern and northerly Hg zone. Such zonation patterns were previously recognized by Pearson (1977) and Woodsworth et al., (1977) who utilized the terms Bralorne-type to characterize the Au-zone, and Congress-type to characterize the Sb-zone. It is possible that they represent metal deposition at different crustal levels and temperatures, with the Au-rich occurrences forming deepest and at highest temperatures, and the Hg-rich occurrences forming closest to the surface and at lowest temperatures, which is a model introduced in the later discussion section of the paper.

Gold Zone

The zone of Au-dominant deposits and occurrences form a north-trending area between the Bendor batholith and CPC, mostly within and proximal to the 3-km-wide Bralorne-East Liza fault corridor (Figure 2). The corridor itself is dominated by quartz-rich Au deposits and occurrences, whereas the more distal localities tend to have higher total sulfide contents. The zone includes the main producers for the district, the Bralorne-Pioneer deposits, which will be described specifically in more detail in a following section.

The gold zone is underlain by structurally imbricated Bridge River Complex and Cadwallader terrane sedimentary and volcanic units with faulted slivers of serpentinized ultramafic rocks. Gold-bearing quartz veins dominantly cut the diorite and gabbro intrusions, which are bordered by the serpentinite. The average thickness of the veins is 1 m and they are ribboned with septa of sulfide minerals, sericite, carbonaceous material, and native Au (Leitch et al., 1989) that probably replace reactive wallrock material. Veins often developed along the margins of older albitite dikes and within the extensive network of faults of the Bralorne-East Liza corridor (Leitch, 1991a). Fuchsite alteration is locally a prominent feature within or immediately adjacent to the veins in serpentinite, but also occurs more regionally. The dominant sulfide minerals are arsenopyrite and pyrite, with lesser sphalerite, galena, and chalcopyrite, and rare pyrrhotite and stibnite.

There is a high Au:Ag ratio, with Au occurring as free Au, or with massive arsenopyrite in sulfide-rich veins (Church, 1996). The ore paragenesis begins with deposition of white quartz and minor pyrite and fuchsite alteration of country rock fragments in and adjacent to the vein. The veins are subsequently fractured and a second generation of quartz is deposited with gold and arsenopyrite, with minor sphalerite, galena, chalcopyrite, and tetrahedrite.

Antimony Zone

The Sb zone deposits and occurrences are best characterized by mineralization in the Congress and Minto mines, shown in the central part of the northwest-trending region in Figure 2. They occur mainly to the east and north of the Au-zone veins and are less concentrated in their distribution. They are structurally-hosted in mostly north-trending shear zones that also host porphyry dikes. Some veins are fully or partly dominated by polymetallic metal assemblages, but observations indicate that all the stibnite occurrences are likely part of the same event, regardless of the variable base metal sulfide content (Schiarizza et al., 1997).

Veins in the antimony zone are generally smaller than those in the gold zone, are discontinuous in the shear zones, have relatively lower Au:Ag ratios, and except for the Wayside deposits, contain a larger sulfide mineral volume that typically is dominated by either stibnite or arsenopyrite (Church, 1996). Cairnes (1937) and Maheux (1989) identified two main metallogenic signatures for the Sb-bearing deposits in the antimony zone. One type is characterized by Sb-Au-Ag±Hg with a dominant stibnite phase that is associated with some Au mineralization and a lesser amount of other sulfide phases (e.g., Congress, Howard, Lou, Dauntless). The other type is characterized by Ag-Au±Sb with base-metal and silver enrichments and a wider variety of sulfide mineral phases (e.g., Minto, Olympic). Although this sub-classification works for many deposits and occurrences in this zone, some deposits may have different areas with either metallogenic signature, thus suggesting that local differences in chemical parameters of the fluid (e.g., FO2, pressure, fluid:rock ratios, and/or wallrock composition) may have controlled the metal suite variations deposited from a likely single fluid type.

The volcanic and sedimentary rocks of the Cadwallader Group host the more base-metal-rich, Sb-bearing veins, primarily near the contact between cherty, sedimentary rocks and diorite dikes. The main sulfide minerals include arsenopyrite, pyrite, sphalerite, and jamesonite, with minor galena, chalcopyrite, pyrrhotite and stibnite. The paragenetic sequence of the base-metal-type mineralization begins with deposition of quartz-ankerite and at least two generations of pyrite, arsenopyrite, chalcopyrite, and sphalerite; quartz, Au and minor base-metal sulfide minerals were deposited in a subsequent event.

Mineralization at the Congress and Howard occurrences is hosted in shear zones that are near the contact between sedimentary rocks and volcanic units of the Cadwallader Group. Mineralization is present as fissure fillings and as replacement bodies, and is discontinuous along shear zones. The main sulfide minerals include stibnite, which occurs in clumps with arsenopyrite, pyrite and sphalerite, and minor galena,

Figure 8: Ribboned quartz-sulphide vein view of the roof from underground workings on a portion of the King vein of the Bralorne vein system.

tetrahedrite, chalcopyrite, jamesonite, pyrrhotite, cinnabar, and native Au (Maheux, 1989). The paragenesis starts with first-stage quartz-ankerite±calcite with pyrite and arsenopyrite, then deposition of quartz and massive stibnite, then open-space filling by quartz-carbonate with minor tetrahedrite, sphalerite, jamesonite and cinnabar, and late Au associated with stibnite as fracture fillings and inclusions.

Mercury Zone

Mercury mineralization, characterized by cinnabar, occurs along the Marshall Creek, Relay Creek, and Yalakom fault systems, generally proximal to north- and northwest-trending faults. The sedimentary rocks of the Tyaughton Basin appear to preferentially host these deposits although there are a few Hg-rich mineral occurrences in the Bridge River Complex greenstones. Cinnabar mineralization in brecciated conglomerates at the Silverquick deposit is associated with quartz, calcite, limonite, and clay minerals. Smeared flakes of cinnabar are also present on the walls and gouges of faults (Church, 1996). Stibnite is also associated locally with cinnabar, and together they can occur in quartz veinlets and as disseminated grains, such as at the

Figure 9: Quartz vein material with green fuchsitic mica replacement of wallrock fragment, with sulphide minerals. Such K-bearing alteration material, where occurring with visible gold, are considered as best representatives of the timing of gold mineralization.

Manitou deposit (Schiarizza et al., 1997). The nature of the association of Hg with W, in deposits such as the Tungsten Queen, is uncertain.

BRALORNE-PIONEER DEPOSIT GEOLOGY

The Bralorne-Pioneer vein system in the above described gold zone is hosted in the variably-altered mafic and ultramafic rocks that occur as fault-bounded lenses in a structurally complex zone between the Bridge River and Cadwallader terranes (Figure 2). The orebodies occur along a 4.5 km strike length, mostly along, adjacent to, or between the Cadwallader and Ferguson faults which thus bound the mineralized trend. Several unmined and recently-discovered veins appear northeast of the main historically mined orebodies. The Peter vein (Loco prospect), as well as the Maud, Noelton, and an undeveloped part of the North vein, are among the most prospective of the discoveries made during the past three decades.

The thickest and most continuous veins are preferentially hosted in the more competent, coarse- to medium-grained gabbroic, dioritic, and trondhjemitic phases of the late Paleozoic Bralorne intrusions; less commonly they are hosted in metabasalt, and rarely in serpentinized ultramafic rocks (Cairnes, 1937; Ash, 2001). Veins occur in en echelon arrays, with strike lengths of as much as 1500 m, between bounding structures. The veins continue to at least 2000 m in depth, with no significant changes in gold grade. Ores consist mainly of ribboned fissure veins with septa defined by fine-grained chlorite, sericite, graphite, or sulfide minerals (Figure 8). Massive white quartz tension veins also comprise some of the ore, with sub-economic, thinner connecting cross-veins. The fissure veins tend to be larger, thicker, and host the higher gold grades.

Quartz is the dominant gangue mineral, with lesser calcite, ankerite, and chlorite. The most conspicuous alteration mineral is a bright green, chrome-bearing phyllosilicate, which occurs in basaltic and ultramafic host rocks. Such minerals are referred to herein as fuchsite, although they may be mariposite or Cr-illite. These bright green blebs occur as disseminated fine-grained masses in wall-rock breccia fragments in the veins or in immediate wallrocks (Figure 9). Notably however, this alteration is locally weak but pervasive in numerous localities far from known gold-bearing quartz veins. This suggests that it may have formed in response to a regional alteration event and not solely due to the more-focused hydrothermal activity related to the gold event.

Sulfide mineral volume of the veins is low, consisting of a few percent of pyrite and arsenopyrite with lesser marcasite, pyrrhotite, chalcopyrite, galena, and sphalerite. Gold occurs as free gold, typically in late fractures or along ribbons. The Bralorne-Pioneer gold-bearing veins were deposited from low salinity (4 wt% NaCl eq) fluids at 300 to 400°C and 1.25 to 1.75 kbar (Leitch, 1989).

Mineralization was interpreted by Leitch (1990) as syn-kinematic and structurally controlled by secondary fault sets related to westerly-directed, sinistral transpressional movement along faults bounding the Bralorne ophiolite. The vein style, structure, mineralogy, and alteration are all similar to those defined for orogenic gold deposits (i.e., Groves et al., 1998, 2003; Goldfarb et al., 2005).

GEOCHRONOLOGY OF GOLD MINERALIZATION

Bralorne and Pioneer Deposits

Three significant gold orebodies were sampled for ^{40}Ar-^{39}Ar geochronological analysis to precisely determine the age of the Bralorne-Pioneer gold deposits. In each case, the relationship between the dated material and gold ore was clearly evident; specifically, visible gold was observed in all dated samples. Historically, the veins and the adjacent wallrock alteration assemblages in the host greenstones did not yield abundant hydrothermal minerals to permit isotopic age measurements. It was likely difficult to find such separable mineral grains for dating in these rocks because they were either too fine-grained and (or) not present in sufficient abundance. At the Bralorne deposit, this situation led Leitch et al. (1991a) to utilize cross-cutting magmatic phase relationships to broadly define the timing of the gold event.

Through extensive searching of a great deal of material, samples containing relatively coarse-grained muscovite or fuchsitic micas were found as very local accumulations within auriferous

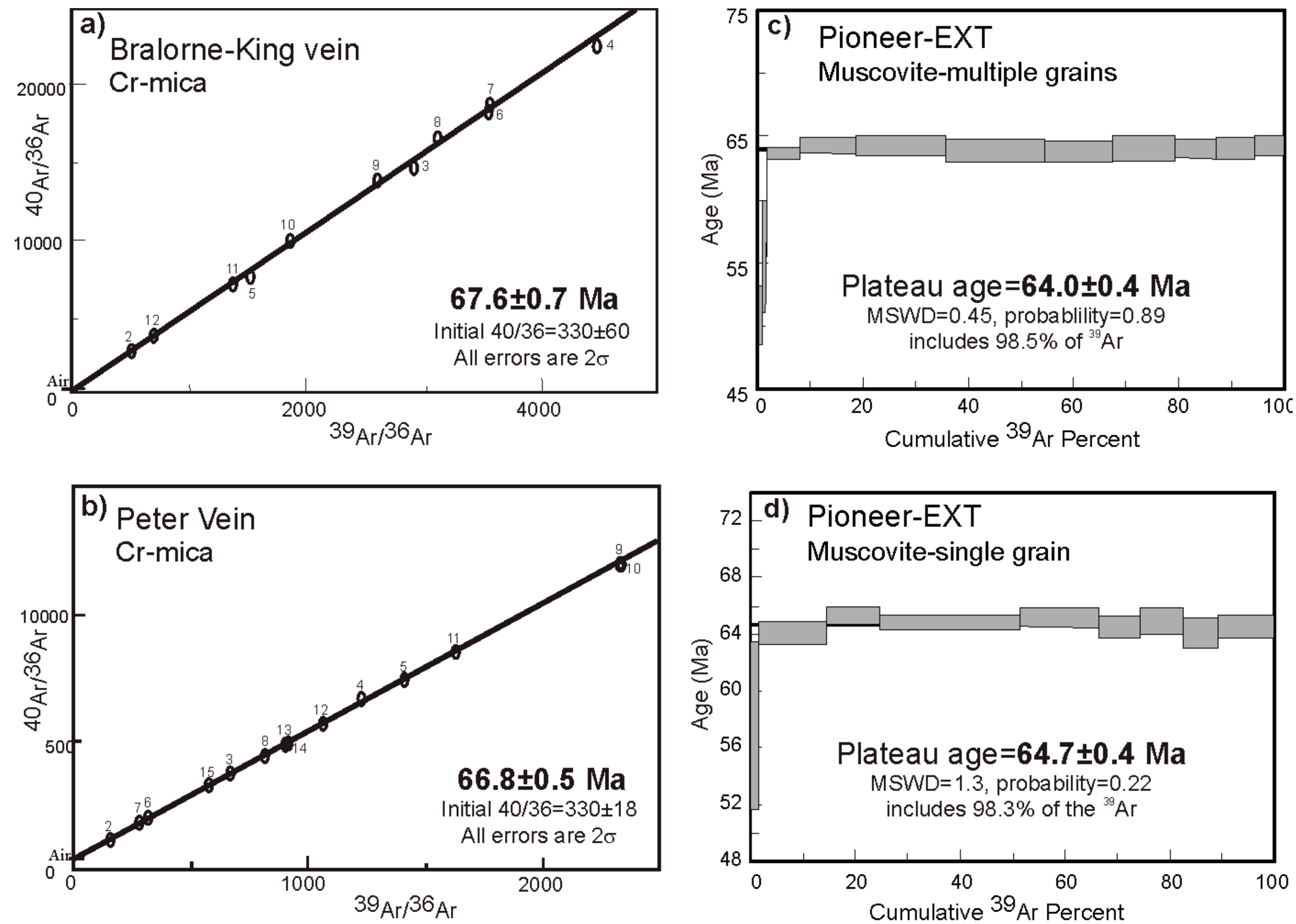

Figure 10: Ar-Ar gas release spectra and isochron plots from hydrothermal micas from the a) King (Bralorne) vein sample 1-BR, b) Peter vein sample 1-PE, c) Pioneer-Extension vein sample P-EXT; and d) Pioneer-Extension vein single muscovite grain (P-EXT2). All analyses include J-error. MSWD= mean square of weighted deviates.

quartz, likely having formed as alteration of entrained wall-rock fragments. Four Ar-Ar measurements were carried out on three samples. Two analyses were performed at the U.S. Geological Survey's argon geochronology laboratory in Denver; analytical procedures are described in Snee (2002). The other two argon analyses were performed at The University of British Columbia in Vancouver. All errors are reported to 2σ.

Sample 1-BR was a bright green fuchsitic mica collected from the waste dump immediately below the Pioneer mill and local mine geologists confirmed that it is representative of most Bralorne vein material from the King vein system, which was a significant part of the Bralorne orebody that was milled at Pioneer. A mass of fuchsitic mica, 1 cm in diameter, was totally contained within massive fine-grained quartz containing free gold. The first two low-temperature steps of the heating experiment yielded anomalous apparent ages and the subsequent steps 3 through 12 yielded increasingly older ages, resulting in an upward stepping spectrum from 65.5 to 69.8 Ma (Figure 10a). The initial $^{40}Ar/^{36}Ar$ ratio derived from the isochron was poorly constrained, but suggests the presence of excess argon. As a result, the isochron age of 67.6±0.7 Ma is considered to best represent the timing of mineralization.

Sample 1-PE was obtained directly from exposed surface trenches of the Peter vein, and consisted of both fuchsitic alteration developed in strongly-altered adjacent wallrock and fragments of wallrock that were entrained in the quartz vein. This sample is from a high-grade ore zone that also contained pyrite and sphalerite. The analysis yielded a disturbed spectrum with anomalously young apparent ages in the initial low temperature steps. The remaining steps yielded ages between 69.2 and 65.4 Ma (Figure 10b). As with the sample from the King vein, the isochron indicates the presence of excess argon (in steps 2–15), so the isochron age of 66.8±0.5 Ma is preferred.

Sample P-EXT was collected from the Pioneer Extension adit dump. It is coarse-grained, shiny, white muscovite from a small vug in a fine-grained, white quartz vein with carbonaceous and pyrite ribbons. A measurement on multiple muscovite grains yielded an excellent plateau at 64.0±0.4 Ma comprising nine steps representing 98.5% of the ^{39}Ar (Figure 10c). Unlike data from the other two samples, there is no indication of excess argon, and the inverse isochron age of 64.2±0.6 Ma is in agreement with the plateau age. An additional analysis of a single muscovite grain from this sample (P-EXT2) also yielded a plateau age at 64.2±0.4 Ma, comprising eight steps representing

Table 2: New geochronological data[1] presented in this report. Abbreviations: TIMS-thermal ionization mass spectrometry; SHRIMP-sensitive high-resolution ion micro-probe; UBC-University of British Columbia (Vancouver) ; JdLC-John de Laeter Center, Curtin University (Perth); USGS-United States Geological Survey (Denver).

Sample	Locality	Lat Long	Rock Description	Method, material; lab	Date (Ma)	Note
			Igneous Rocks			
84 WV	Bendor batholith	50.7422° -122.6166°	Coarse-grained quartz-rich biotite granitoid	U-Pb TIMS, zircon; UBC	65.0±0.2	Crystallization age of Bendor batholith
84 WV	Bendor batholith	50.7422° -122.6166°	Coarse-grained quartz-rich biotite granitoid	U-Pb SHRIMP, zircon; JdLC	65.2±0.8	Crystallization age of Bendor batholith
84 WV	Bendor batholith	50.7422° -122.6166°	Coarse-grained quartz-rich biotite granitoid	Ar-Ar, biotite; UBC	64.9±0.6	Cooling age of Bendor batholith
CH-BN	Bendor batholith, north	50.8255° -122.7587°	Coarse-grained quartz-rich biotite granitoid	U-Pb SHRIMP, zircon; JdLC	64.9±0.8	Crystallization age of Bendor batholith
CH-BS	Bendor batholith, south	50.7210° -122.6380°	Coarse-grained quartz-rich biotite granitoid, weak foliation from Piebiter Ck.	U-Pb SHRIMP, zircon; JdLC	63.2±1.2	Crystallization age of batholith
CH-Eldo	Eldorado pluton	51.0011° -122.8737°	Porphyritic textured, coarse-grained quartz-rich biotite granitoid	U-Pb SHRIMP, zircon; JdLC	66.9±0.9	Crystallization age of pluton
CH Congress PPY	Congress	50.8900° -122.783°	Andesitic feldspar porphyry, probably a dyke, from mine dump	U-Pb SHRIMP, zircon; JdLC	71.2±1.5	Crystallization age of host dyke, probably constrains maximum age for mineralization
CH Wayside CGGD	Wayside	50.8900° -122.8280°	Coarse-grained tonalite, probably a dyke, collected from mine dump	U-Pb SHRIMP, zircon; JdLC	81.0±0.7	Crystallization age of host dyke, probably constrains maximum age for mineralization
BGR3-51	51 Vein	50.7710° -122.7870°	Leucodiorite host rocks to 51 vein, from mine dump	U-Pb SHRIMP, zircon; JdLC	270±5	Crystallization age of Bralorne intrusion, host rocks
CH Wayside Leuco	Wayside	50.8900° -122.8280°	Coarse grained leucocratic diorite, from mine dump	U-Pb SHRIMP, zircon; JdLC	268±4	Crystallization age of Bralorne intrusion, host rocks
Wayside 93-91400	Wayside	50.8900° -122.8280°	Coarse grained leucogabbro, core from mine dump	U-Pb SHRIMP, zircon; JdLC	270±2	Crystallization age of Bralorne intrusion, host rocks
			Mineralization and Alteration			
1-BR	Bralorne, King vein	50.778° -122.803°	Auriferous quartz vein with fuchsite in wall-rock fragments	Ar-Ar, fuchsite; USGS	67.6±0.7	Age of hydrothermal mineralization
1-PE	Bralorne, Peter vein	50.788° -122.818°	Auriferous quartz vein with fuchsite in wall-rock fragments	Ar-Ar, fuchsite; USGS	66.8±0.5	Age of hydrothermal mineralization
P-EXT	Pioneer Extension vein	50.750° -122.7533°	Auriferous quartz vein with muscovite replacing encapsulated wall-rock fragments, from mine dump	Ar-Ar, muscovite, multiple grains; UBC	64.0±0.4	Plateau, 98% of gas. Age of hydrothermal mineralization
P-EXT2	Pioneer Extension vein	50.750° -122.7533°	Auriferous quartz vein with muscovite replacing encapsulated wall-rock fragments, from mine dump	Ar-Ar, muscovite, single grain; UBC	64.7±0.4	Plateau, 98% of gas. Age of hydrothermal mineralization
CH Mid-Minto 1	Minto	50.900° -122.7520°	foliated greenstone with fuchsite alteration	Ar-Ar, fuchsite; UBC	93.2±0.6	Plateau, 87% of gas, probable age of formation or cooling of fuchsite
CH Mid-Minto 2	Minto	50.900° -122.7520°	foliated greenstone with fuchsite alteration	Ar-Ar, fuchsite; UBC	92.8±0.8	Plateau, 75% of gas, probable age of formation of fuchsite, or cooling age

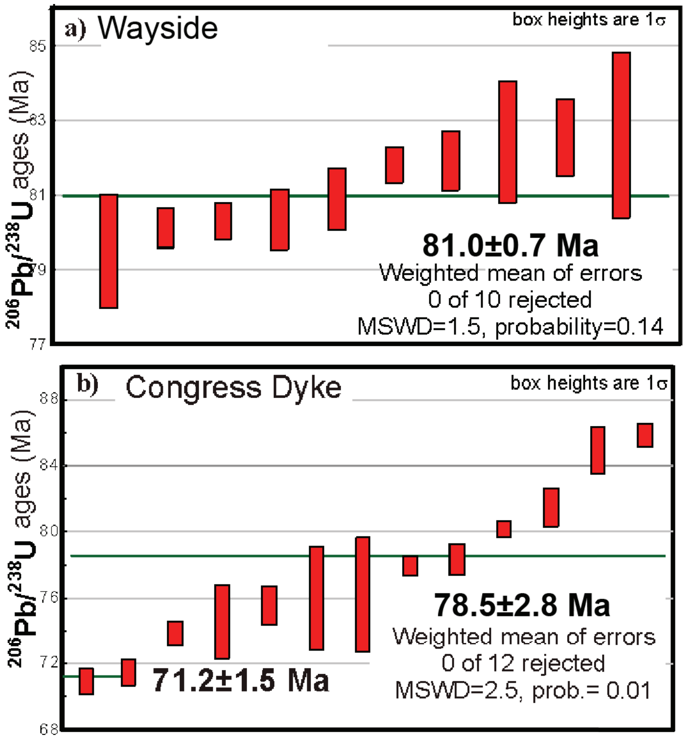

Figure 11: a) U-Pb plot of $^{206}Pb/^{238}U$ ages of zircons by SHRIMP, from dike material from the Wayside deposit. B) U-Pb plot of $^{206}Pb/^{238}U$ ages of zircons by SHRIMP, from dike material from the Congress deposit.

98.3% of ^{39}Ar released, with a slightly older inverse isochron age of 64.7±0.6 Ma (Figure 10d).

The age determinations, despite being from three district Bralorne-Pioneer orebodies located more than 10 km apart, yield similar results that, despite minor analytical complications, confirm a latest Cretaceous gold deposition event within the range of 68.4 to 63.6 Ma.

Deposits in the Sb Zone

Ages for the deposits in the Sb and Hg zones have been notoriously difficult to obtain, most likely because their temperature of formation was too low to have formed hydrothermal micas that are appropriate for dating or, if present, any such alteration minerals are too fine-grained to separate. Thus, to at least broadly constrain the timing of mineralization, we dated the host rocks and cross-cutting intrusive units, mainly dikes, to provide maximum and minimum ages. Although detailed cross-cutting relationships have been well documented by past workers, because the underground workings are no longer accessible, direct observations of such relationships were impossible to re-document during our field sampling.

Samples of porphyritic and intermediate dikes from historic underground mining are variably available from ore dumps and unconstrained drill core samples remaining at the surface in the Sb zone. The Wayside deposit (MINFILE 092JNE030) is mostly hosted in shears cutting the various phases of the Bralorne gabbro intrusion and volcanic rocks of the Cadwallader Group. At the Wayside mine dump, numerous samples of weakly mineralized and altered intrusive rocks and core were available to sample. Samples of leuco(plagio)granite and coarsely porphyritic granodiorite host rocks yielded ages of 268±4 Ma and 270±2 Ma. A coarse-grained granodiorite that is weakly altered and mineralized (sample CH Wayside CGGD) yielded a weighted mean age from 10 similarly aged zircons, of 81.0±0.7 Ma (Figure 11a). This provides a maximum age for the mineralization.

The Congress mine (MINFILE 092JNE029) ore dump yields porphyritic dacite that is well documented to occur in the underground workings as dikes (i.e., Church and Jones, 1999) that cross-cut the pillowed greenstones, argillite and chert host rocks, as well as the ore-bearing veins. Sixteen zircons from the dacite (sample CH Congress PPY) gave a range of dates from 92.5 to 71 Ma indicating that it hosts older zircons that were entrained in its magma. Excluding the older results, a weighted mean of 78.5±2.8 Ma can be achieved, however the two youngest zircon results near 71.2 Ma represent the most probable age of this rock, because small clusters of zircon populations at 75.5, 78, and 87 Ma likely represent xenocrystic populations (Figure 11b). Overall, these constraints from the Sb zone indicate that Wayside deposit cannot be older than 81 Ma and that Congress is likely 71 Ma or younger.

DISCUSSION

Previous Estimates of Timing of Gold Deposition in the Bridge River District

Our new determinations on the age of mineralization for the Bralorne-Pioneer deposits are distinctly younger than previously reported estimates. Dating of cross-cutting dikes from the eighth level of the Bralorne mine by Leitch et al. (1991a) broadly constrained the age of mineralization with a date of 91.4±1.4 Ma (U-Pb zircon) on a pre-ore, strongly-altered albitite dike, and a date of 43.5±1.5 Ma (K-Ar biotite) on a post-ore lamprophyre. A late, intra- to post-ore hornblende-bearing dike yielded a K-Ar date of 85.7±3.0 Ma on green hornblende that was interpreted by Leitch et al. (1991a) as possibly, and thus perhaps more narrowly, constraining the timing of mineralization to between 93 and 83 Ma within the limits of errors. Alternatively, the date on the hornblende could be interpreted to have resulted from argon loss from a ca. 91 Ma crystallization, as the hornblende dikes are likely transitional and essentially coeval with the albitite dikes (Leitch et al., 1991a). Although the mid-Cretaceous age range for mineralization was favored by these workers, the uncertainty in the sampling and analyses does not exclude Late Cretaceous or Tertiary ages (to as young as 44 Ma) for gold mineralization.

A previous ^{40}Ar-^{39}Ar determination on fuchsite from "quartz veined and carbonate altered" metabasalt from the Pioneer orebody dump (Ash, 2001) gave ambiguous results. A single

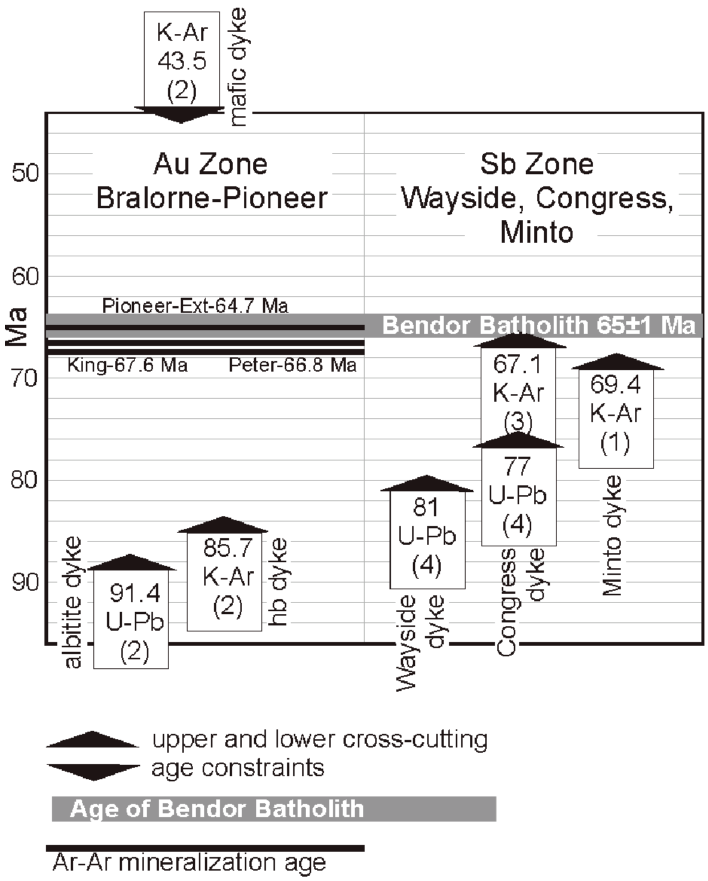

Figure 12: Summary diagram compiling the various geochronological constraints for the timing of Bridge River district mineralization emphasizing the similar window during with both gold and Sb-rich deposits formed.

step representing 75% of the total gas gave a date of 87 Ma which, when mixed with higher temperature steps that yielded 60–50 Ma ages, returned a mixed, total gas age of 79±4 Ma which was interpreted to represent a lower limit for the timing of mineralization (Ash, 2001). However, the mixed age and the nature of the Ar release spectrum from this fine-grained, impure sample suggests that the material likely endured recoil effects (a net loss of ^{39}Ar) during irradiation, indicating that an absolute date cannot be meaningfully interpreted from this analysis.

Two samples of Cr-rich illite, from the Cosmopolitan and North veins in the Bralorne-Pioneer deposits, in an area of "sheared, clay-altered zones marginal to pervasively hydrothermally altered felsic dikes along the mineralized quartz-vein structure" (Ash, 2001), yielded disturbed spectra with their ages increasing from approx. 71 to 77 Ma. These dates were interpreted to indicate the age of faulting and post-ore hydrothermal alteration. Overall, Ash (2001) interpreted the age of Bralorne gold mineralization to be approx. 86 Ma, presumably in accord with determinations of Leitch et al. (1991a), and interpreted the 40Ar-39Ar determinations to represent younger events.

Bendor Batholith Timing Relationship to Bralorne-Pioneer Mineralization

Uranium-Pb zircon dates presented herein from the Bendor batholith, utilizing different methods (SHRIMP, TIMS and 40Ar-39Ar), all yield complimentary ages indicating magma crystallization at 64 Ma, and are compiled in Figure 12 with other constraining dates. The similarity of the ^{40}Ar-^{39}Ar dates with the more robust U-Pb zircon dates indicates that the batholith cooled rapidly through approx. 300ºC shortly after emplacement, and was not subsequently thermally affected.

The ca. 68 to 64 Ma dates presented herein for the timing of gold mineralization of the Bralorne-Pioneer deposit suggest that the deposits slightly predate to overlap the emplacement of the Bendor batholith magmas. Analyses of the three ore-related samples are the most reliable age estimates defined to date, and the minerals dated were syn-gold. In particular, at least the coarse-grained crystalline muscovite from the Pioneer Extension will retain its radiogenic argon to temperatures higher than 350ºC (McDougall and Harrison, 1999).

The ^{40}Ar-^{39}Ar systematics do not indicate that the measured dates were reset from a significantly older gold deposition event. Although there may be slight argon loss, none of the argon spectra determined in this study are continuously stepped from an older, thus reset, date, which would indicate partial resetting by an overprinting thermal event. In addition, many other ^{40}Ar-^{39}Ar and K-Ar determinations from rocks in the district give dates that are older than 70 Ma, such as the 92 to 80 Ma dates on biotite for the CPC plutons (Pearson, 1977; Church, 1996; Schiarriza et al., 1997) and dates as old as 284 Ma on hornblende from the Bralorne diorite (Leitch et al., 1991a). Although a complete resetting of these Ar-Ar dates from an older age cannot be entirely ignored, the data indicate that the thermal effects associated with the emplacement of the Bendor plutonic suite were not widespread. The 64.7 Ma date from the most southerly, Pioneer-Extension deposit could be reset because it is both the youngest of the mineralized dates, and its age is similar to the Bralorne batholith. Nevertheless, we believe this to approximate the true age of the hydrothermal event.

Ages from Other Deposits

In the Sb zone, the Minto deposit has a previously reported age of 69.4±2.4 Ma (K-Ar whole rock) on the Minto dike, and an anomalously young date of 45 Ma for vein-related sericite (Pearson, 1977; Harrop and Sinclair, 1986). The Congress deposit has a published K-Ar whole rock date of 67.1 Ma on a dike spatially associated with mineralization (Pearson, 1977). More distally, the Robson polymetallic mineral occurrence is hosted in and adjacent to a small intrusion that is spatially near and lithologically similar to the Eldorado Pluton, and yields a similar K-Ar age of 63.7±2.2 Ma on biotite (Leitch et al., 1991a) that provides a possible maximum age for this mineralization. The Lucky Gem vein yielded poor quality sericite that gave a K-Ar date of 57.7±2.2 Ma.

Combined with constraints presented above for Wayside (< 81 Ma) and Congress (< 71 Ma) deposits, the plurality of dates here indicates that the Sb zone mineralization may have formed within the period of 71 to 64 Ma. This time window is essentially the same age range as the Au-dominant zone mineralization in the Bralorne-Pioneer system. This suggests that there was a single, broad, latest Cretaceous hydrothermal episode that continued from a few million years prior to until the emplacement of the Bendor plutonic suite.

Relationships between Au-Sb-Hg Mineralization and Other Events

The 71 to 64 Ma dates favored here for a widespread mineralization event are 10 to 30 million years younger than previous age interpretations for gold mineralization at the Bralorne-Pioneer deposits (Leitch et al., 1991a; Schiarizza et al., 1997). These new data indicate that the Bralorne-Pioneer mineralizing event is significantly younger than mid-Cretaceous juxtaposition of the Cadwallader and Bridge River terranes, and therefore significantly younger than, and not related to, the thrusting and obduction of the ophiolitic rocks. In addition, mineralization is also apparently younger than the major contractional and sinistral motion along the Bralorne Fault zone, and it is coeval with emplacement of the plutons of the CPC.

The new geochronology indicates the temporal association of gold and other mineral occurrences with the initiation of dextral strike-slip motion on the regional fault systems in this part of British Columbia, such as the Marshall and Yalakom Faults, as documented by Schiarizza et al. (1997). Furthermore, this strike-slip event overlapped a major period of exhumation, as supported by rapid cooling of the Bendor batholith. Such exhumation would have enhanced hydrofracturing and fluid flow along the regional faults. A similar scenario was presented by Harlan et al. (2017) in the Willow Creek district of south-central Alaska and by Taylor et al. (2015) in central California, where gold-bearing quartz vein formation, local batholith emplacement, translation along pre-existing deep-crustal fault systems, and rapid exhumation were coeval events.

METALLOGENIC MODELS

Numerous geological models have been put forth to describe the origin of the metallogenic features observed in the Bridge River district. Most of the models attribute gold deposit formation to a specific generation of fault movement, obduction and emplacement of ophiolite rocks, magmatism, and (or) a combination of these events. Some models attempt to directly address the formation of the Bralorne-Pioneer gold ores, whereas others consider the district-wide metallogenic variations and zonation. In light of new geochronological constraints, and the sulfur isotope data and interpretations from Moore et al. (2009), these various models are considered.

Magmatic Model

Several of the historic and some of the most recently considered models put a large ore genesis emphasis on the role of magmatic rocks. Past workers have proposed that the host gabbros, the intrusions of the CPC, the Bendor batholith, albitite dikes, or the felsic porphyry bodies were source of fluids, metals, and (or) heat for generating the ores in the district.

Many of the early workers (e.g., Cairnes, 1937; Cleveland, 1938) developed models that stressed a direct association with the mafic and ultramafic rocks that form much of the Bralorne-East Liza assemblage, in particular, the various gabbros (including the trondhjemites, plagiogranites and soda granites). However, age determinations have conclusively indicated that these rocks are Permian (Leitch et al., 1991a) and therefore too old to be causative intrusions to the mineralization.

A genetic association of gold with the magmas that formed the Gwyneth Lake stock, 2 km west of Bralorne, was proposed by Gaba and Church (1988) and Church (1996). Available data indicate that the dikes and larger intrusions are ca. 86 Ma (Church, 1996; Leitch, 1989) and may be coeval with the albite dykes. Church (1996) further considered that the stress caused by such intrusion emplacement could have created an extensive fracture system along a reactivated Cadwallader fault zone, with additional heat and the ore fluids provided from the more distal bodies of the CPC.

Utilizing geochronology from cross-cutting relationships in ore zones, Leitch et al. (1991a) constrained the timing of mineralization to between 93 and 44 Ma. They emphasized, however, that an altered 86 Ma dike could represent a better minimum age constraint to provide a narrower potential age range of 93 to 86 Ma for formation of the Bralorne-Pioneer deposit, and thereby indicating a direct genetic link with the albitite dikes.

Building on the regional metallogenic trends recognized by Pearson (1975), Woodsworth et al. (1977) emphasized a relationship between the regional mineral deposit zonation and the emplacement and cooling of plutons of the CPC. Similarly, an apparent easterly-younging of available K-Ar ages for mineral occurrences throughout the entire district, combined with decreasing temperatures of the mineralizing systems, led Leitch et al. (1989, 1991a) to suggest the importance of the CPC as the main heat source responsible for mineralization. Different episodes of mineralization were attributed to different pulses of heat from the CPC (Leitch et al., 1991a).

Ophiolite Obduction Model

An association between ophiolitic rocks and gold mineralization at the Bralorne-Pioneer deposits, as well as throughout much of the North American Cordillera, was emphasized by Ash (2001). He suggested that gold formation at Bralorne occurred during regional, mid-Cretaceous obduction, tectonic imbrication, and stacking of the Paleozoic oceanic lithosphere (e.g., Shulaps and Bralorne-East Liza ultramafic rocks of Schiarizza et al., 1997). Ash (2001) also emphasized the important role of "felsic dike rocks" that are coeval with early magmatic phases of the CPC.

Protracted-Episodic Deformation-related Model

Schiarizza et al. (1997) suggested that the metal zonation pattern is the product of various mineralizing events that operated contemporaneously with different fault systems. Specifically, they favored a model in which the gold deposition is associated with the timing of movement along the Bralorne-Eldorado fault system, which was active with west-directed thrusts between 91 and 86 Ma. Stibnite-associated mineralization was said to be associated with movement along the Castle Pass fault system that was active from 69–64 Ma. Mercury-associated mineralization was stated to be associated with the strike-slip offsets along Marshall Creek and Yalakom–Relay Creek fault systems that were active at 70 Ma. Because each of these fault systems was active at a different time, three different mineralizing episodes were necessary to account for the zonation. This conclusion has its strength in the foundational relationship of the fault systems to the metal zones, but is based upon limited geochronological data for only few of the mineral deposits in the district.

Orogenic Continuum Model

A model not previously considered, but that builds on previous observations, is that the regional metallogenic pattern reflects the exposure of a single, widespread crustal fluid mineralizing event that deposited different metals at different temperatures and at different crustal depths. Although orogenic gold systems are well-known features forming anywhere between about 3 and 20 km depth, their crustal scale fault systems continue to the surface and fluid migration may continue into the upper 3 km crust, where the mineral occurrences will characterized by different metal assemblages reflecting deposition at lower temperatures (Groves et al., 1998). Thus, although gold may no longer be soluble in these typically relatively S-rich, Cl-poor type of crustal fluid, sulfur complexing of Sb and Hg will carry these metals upward into the shallowest parts of the crust. This crustal continuum of orogenic gold system requires that the range of mineral deposits and occurrences are essentially the same age, but that their exposure at the same current level is a result of differential uplift or tilting.

Constraints presented or compiled and interpreted herein indicate that many of the significant deposits within the Sb zone are similar in age to those in the Au zone. It has been well documented that the fluids depositing metals in the Au and Sb zones are both similarly enriched in $\delta^{18}O$ and are aqueous-carbonic, but that those in the Sb zone were cooler and formed at lower pressure (i.e., emplaced at shallower depths) (Maheux, 1989). When the S isotope patterns (Moore et al., 2009) are combined with the cooling temperature trend of mineralizing fluids, there is unequivocal evidence for a single fluid type for formation of the Au, Sb, and Hg mineralization in the district.

The exploration implications for such a crustal continuum model are that those Sb- and Hg-rich mineral occurrences are the epizonal equivalents of Au systems which may exist at depth, most likely, and are presently closest to the surface beneath the Sb zone mineral occurrences rather than the more shallowly formed Hg occurrences. Therefore, understanding the thermal history of the region and the hydrothermal systems could provide important information for future exploration decision-making.

CONCLUSIONS

The main gold-forming event in the Bridge River district is constrained by four new ^{40}Ar-^{39}Ar dates that indicate mineralization ca. 68–64 Ma within the Bralorne-Pioneer gold system. This timing complements other constraints, such as those determined by dating of pre-mineral and cross-cutting dikes. Mineralization in the adjacent Sb zone, characterized by Sb-bearing and polymetallic mineralogy, has age constraints that mostly come from pre-mineral dikes, but similarly require that the veins are no older than ca. 67 Ma. The Bendor batholith was emplaced at 65 Ma, and pre-dates to overlaps Bralorne-Pioneer mineralization, but related dikes exploit structures hosting some of the Sb zone veins.

The onset of dextral strike-slip faulting in this part of the Cordillera facilitated regional uplift and widespread fluid flow along the reactivated, crustal-scale fault systems, emplacing gold mineralization at deeper crustal levels, and more epizonal Sb, polymetallic and Hg deposits at shallower crustal levels. The resultant broad metallogenic zonation patterns may be a primary feature of the thermal regime associated with the emplacement of the mineralization, or there may have been subsequent uplift in the west to expose deeper levels.

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