Gold, Granites, and Geochronology: Timing of Formation of the Bralorne-Pioneer Gold Orebodies and the Bendor Batholith, Southwestern British Columbia (NTS 092J/15)

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Hart, C.J.R., Goldfarb, R.J, Ullrich, T.D. and Friedman, R. (2008): Gold, granites and geochronology: Timing of formation of the Bralorne-Pioneer gold orebodies and the Bendor batholith, southwestern British Columbia (NTS 092J/15); *in* Geoscience BC, Summary of Activities 2007, Geoscience BC, Report 2008-1, p. 47–54.

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 produced between 1897 and 1971 (Church, 1996). Most production came from the Bralorne-Pioneer vein system that yielded (Leitch, 1990) approximately 7 million tonnes of high grade ores averaging 19.1 g/t (0.58 oz/t). Although the district is dominated by Au veins, it also hosts a large number of Sb-dominant and Hg-dominant mineral occurrences, whose distributions form a general easterly zonation (Pearson, 1975; Woodsworth et al., 1977).

A number of geological models have been proposed to account for both the significant gold enrichments near Bralorne and for the regional metallogenic trends throughout the Bridge River district. Determining the most appropriate model is important as it can influence the types and effectiveness of exploration models and programs that are utilized, as well as influencing decisions about regional prospectivity, targeting and investment. Currently, the integrity of existing models for the Bridge River district suffers from a lack of good geochronological constraints.

The absolute timing of formation of gold orebodies at the Bralorne-Pioneer deposit, as well as for most 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, is not precisely known. In order to establish temporal, and potentially genetic, associations 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 are presented in this paper. Because the Bendor batholith is the nearest, largest, and therefore the most significant magmatic and thermal feature adjacent to the Bralone-Pioneer gold deposit, conventional U-Pb and SHRIMP U-Pb age determinations on zircons, as well as Ar-Ar determinations, are presented to assess the batholith's crystallization and cooling history. These data allow establishment of new constraints on the various interpretative models for the formation of the Bralorne-Pioneer gold veins.

Regional Geology

The Bridge River district is in the structurally complex region between the southeastern Coast Belt and the adjacent intermontane terranes. In this region, the Mississippian to Middle Jurassic accretionary complexes of oceanic basalt and gabbro and related ultramafic rocks, chert, basalt, shale and argillite of the Bridge River Terrane are juxtaposed with Late Triassic to Early Jurassic island arc volcanic rocks and mostly marine, arc-marginal clastic strata of the Cadwallader Terrane. These assemblages are variably overlain, mostly to the north, by clastic, mostly non-marine successions belonging to the Jurassic-Cretaceous Tyaughton Basin.

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

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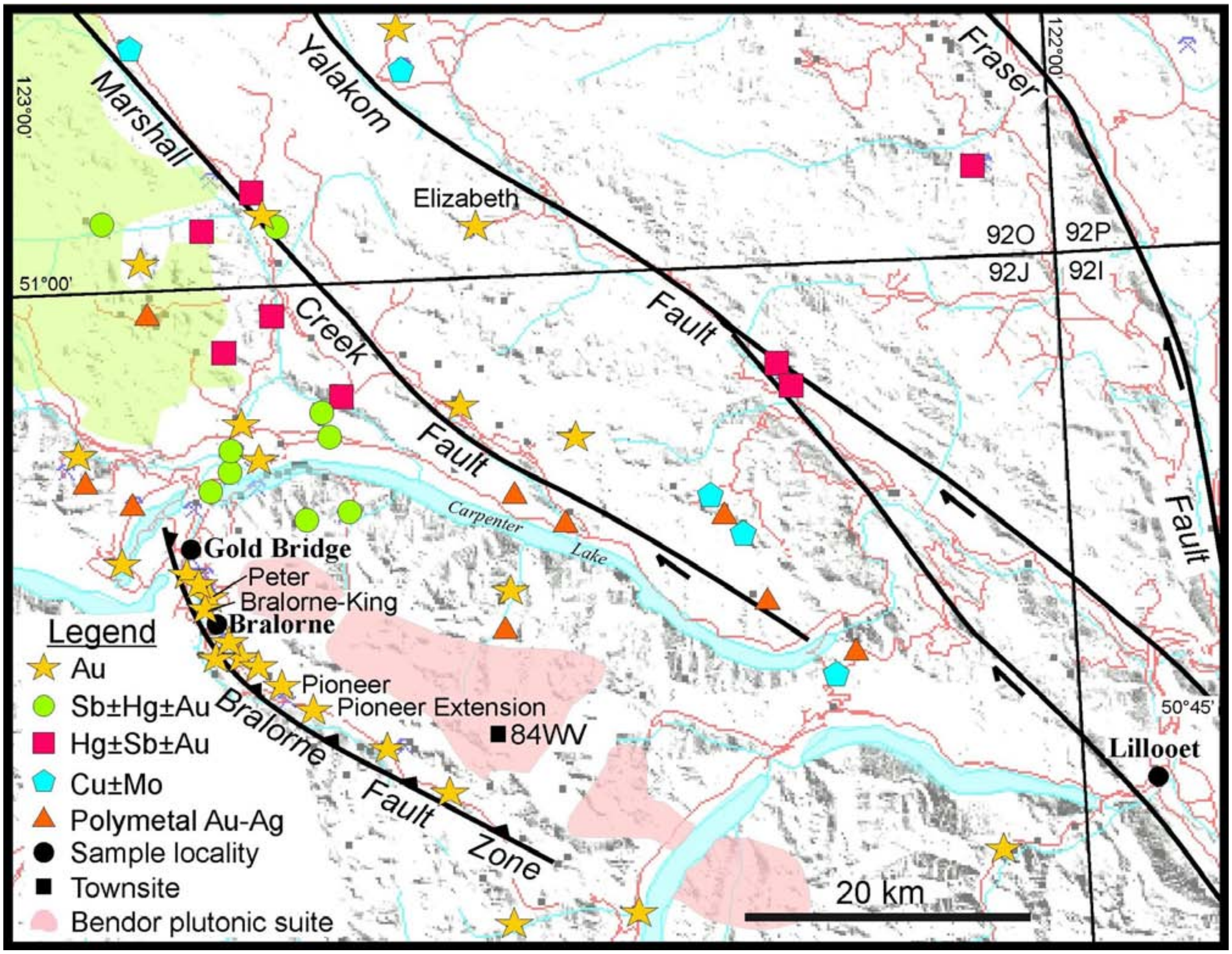

Figure 1. Regional geological setting of the Bridge River camp in southwestern British Columbia showing the major structural features and distribution of mineral deposits. Note the zonation from gold-only to stibnite-dominant, to mercury-dominant deposit types. 84WV is the location of the Bendor Batholith geochronology sample. Shaded area north of Gold Bridge is the Spruce Lake Protected Area.

The region has been intruded and overlain by a wide range of Cretaceous and Tertiary plutonic and volcanic rocks and their hypabyssal equivalents. Most significant among these are the dominantly Cretaceous granitoid bodies that form the Coast Plutonic Complex (CPC), which locally is characterized by the 92 Ma Dickson McClure intrusions (Parrish, 1992) and the large individual bodies of the Late Cretaceous Bendor plutonic suite. The general lack of foliation in all of these igneous rocks indicates their emplacement subsequent to the main regional compressional events along this part of the Cordilleran margin (Armstrong, 1988). Hypabyssal magmatism is reflected by emplacement of porphyritic dikes between 84 and 66 Ma, with the youngest magmatic event being crystallization of 44 Ma lamprophyre dikes (Leitch et al., 1991).

The Bendor plutonic suite consists of a northwest-trending series of plutons that form a belt, perhaps greater than 100 km long from Eldorado mountain in the north to the southeastern Coast Belt towards Hope. These rocks consist mostly of high-standing, resistant, coarse-grained, hornblende>biotite>pyroxene, magnetite-titanite–bearing granodiorite to quartz diorite. Most pertinent to this study is the >20 km-long, northwest-trending Bendor batholith, the major igneous body nearest to the Bralorne-Pioneer deposit, from which previous age determinations range from 139 to 56 Ma (Church, 1996).

The district has been widely deformed by mid-Cretaceous contractional deformation within the westerly-trending Shulaps thrust belt, and by contractional and oblique-sinistral deformation associated with the Bralorne-Eldorado fault system. The Bridge River and Cadwallader terranes were juxtaposed along this fault system, which in the Bralorne area consists of linear, tectonized, and serpentinized slices of late Paleozoic mafic and ultramafic rocks known as the Bralorne-East Liza Lake thrust belt that forms a 1 to 3 km wide zone bounded by the Cadwallader and Fergusson faults (Schiarizza et al., 1997). The timing of this deformation and metamorphism is ca. 130–92 Ma, with synorogenic sedimentary flysch, as young as mid-Cretaceous, 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 and deposition of most of the Bralorne ores (Schiarizza et al., 1997), and thus also much of the local CPC magmatism.

Younger, northwest-trending dextral displacements reactivated many of the older faults and were dominant in the east, particularly along the Marshall Creek and Yalakom faults, and are considered to have controlled mineralization that is located proximal to the faults in these areas (Schiarizza et al., 1997). Dextral deformation is best estimated as having been initiated at or slightly before 67 Ma (Schiarizza et al., 1997).

Deposit Geology

The Bralone-Pioneer vein system 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. The orebodies occur along an approximate 4.5 km strike length, mostly along, adjacent to, or between the Cadwallader and Ferguson faults. Mineralization was interpreted by Leitch (1990) as synkinematic and structurally controlled by secondary fault sets related to westerly-directed, sinistral transpressional movement along faults bounding the Bralorne ophiolite. Veins are preferentially hosted in the more competent, coarse- to medium-grained gabbroic, dioritic, and trondhjemitic phases; less commonly in metabasalt, and rarely in ultramafic rocks (Cairnes, 1937; Ash, 2001). Several unmined and newly discovered veins, which are the focus of recent exploration, are northeast of the main historically mined orebodies. The Peter vein was considered among the most prospective resource of these recently discovered (1987) veins (MINFILE 092JNE 164; MINFILE, 2007).

Veins form in en echelon arrays, with strike lengths of as much as 1 500 m, between bounding structures. Veins extend to at least 2 000 m in depth, with no significant changes in grade recorded. Ores consist mainly of ribboned fissure veins with septa defined by fine-grained chlorite, sericite, graphite or sulphide minerals. Massive white quartz tension veins also comprise some of the ore, although thinner connecting cross-veins are sub-economic. 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 bright green, chrome-bearing phyllosilicate, which occurs in basaltic and ultramafic host rocks. These bright green blebs occur as disseminated fine-grained masses composed of fuchsite, mariposite or Cr-illite. All are referred to herein as fuchsite, irrespective of mineralogy. Notably, this fuchsitic alteration is locally pervasive in some rocks despite being far from the gold-quartz veins. It therefore occurs in response to regional alteration as well as hydrothermal vein formation.

Sulphide 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 fluids at 300 to 400°C and 1.25 to 1.75 kbar (Leitch, 1989). The vein style, structure, mineralogy, and alteration are all similar to those defined for orogenic gold deposits (i.e., Groves et al., 1998).

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 result from fault movement, obduction and emplacement of ophiolite rocks, CPC magmatism, 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.

Magmatic

Several of the historic and some of the most recent models place a large genetic emphasis on the role of magmatic rocks. Past workers have variably considered the CPC, the Bendor batholith, albitite dikes, or the felsic porphyry bodies as the potential source of fluid, metal, and/or heat for the ores in the district.

Many of the early workers (e.g., Cairnes, 1937) developed models that stressed a direct association with the mafic and ultramafic rocks that now are recognized as forming much of the Bralorne ophiolitic assemblage, in particular the various gabbros, trondhjemites, and plagiogranites. However, age determinations have conclusively indicated that these rocks are Permian (Leitch, 1989) and therefore quite a bit older than reasonable age estimates of the age of mineralization (see below).

A genetic association of gold with either the Gwyneth Lake stock or Bralorne batholith was proposed by Church (1996), which was suggested to indicate ca. 90 Ma events based upon the best fit the ages on dikes and intrusions presented by Leitch (1989). Church (1996) further considered that the stress caused by intrusion emplacement provided an extensive fracture system, in particular along the reactivated Cadwallader fault zone, with additional heat and the ore fluids provided from the more distal CPC.

Utilizing geochronology from crosscutting relationships in ore zones, Leitch et al. (1991) constrained the timing of mineralization as between 93 and 42 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 possibly indicated a direct genetic link with the albitite dikes.

Ophiolite

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

Coast Plutonic Complex

Building on the regional metal trends recognized by Pearson (1975), Woodsworth et al. (1977) emphasized a relationship between metal precipitation and the emplacement and cooling of plutons of the CPC. Similarly, an easterly younging of K-Ar ages for mineral occurrences throughout the entire district led Leitch et al. (1991) to suggest the importance of the proximity and cooling of ca. 80 to 59 Ma igneous rocks that form the eastern margin of the CPC. Further dating modified the model, whereby pulses of heat from the CPC resulted in several generations of mineralization, which decrease in age and P-T conditions eastward from the CPC (Leitch et al., 1991).

Fault-Related

Schiarizza et al. (1997) suggested that the metal zonation pattern is the product of different fault systems being active at different times. Specifically, the gold deposits are associated with the Bralorne-Eldorado fault system, the stibnite mineralization is associated with the Castle Pass fault system, and the mercury mineralization is associated with the Marshall Creek and Yalakom–Relay Creek fault systems. Because each of these fault systems is considered to have been active at different times, the logical assumption is that three mineralizing events are necessary to account for the zonation. This conclusion, however, remains based upon limited geochronological data for the mineral deposits in the district.

Geochronology

Three significant orebodies for Ar-Ar geochronological analysis were sampled in this study in order to precisely determine the age of the Bralorne-Pioneer gold deposit,. In each case, the relationship between the dated material and gold ore was clearly evident, in that visible gold was observed in all samples. Appropriate material for isotopic age dating is notoriously difficult to find, which led Leitch et al. (1991) to depend on relationships between crosscutting magmatic phases to constrain the timing of mineralization.

Two analyses were performed at the U.S. Geological Survey's argon geochronology laboratory in Denver. Two argon analyses and the conventional U-Pb analysis were performed at the Pacific Centre for Isotope and Geochemical Research (PCIGR) at the University of British Columbia in Vancouver. Sensitive High-Resolution Ion MicroProbe (SHRIMP) U-Pb analyses were undertaken at the J.D. deLateur Centre at Curtin University in Perth, Australia. All errors are reported to 2σ

The first dated sample (1-BR) was a bright green fuchsitic mica collected from the waste dump immediately below the Pioneer mill and is representative of most vein material found in the King vein system, which was a significant part of the Bralorne orebody. A mass of fuchsitic mica, 1 cm in diameter, was totally contained within massive fine-grained quartz containing free gold. The initial two low-temperature steps yielded anomalous apparent ages and the subsequent steps 2 through 12 yielded older ages, resulting in a step-shaped spectrum from 65.5 to 69 8 Ma (Figure 2a). The initial ^{40}Ar/^{36}Ar ratio derived from the isochron was poorly constrained, but suggested the presence of excess argon. As a result, the isochron age of 67.7 ±0.7 Ma is considered to best represent the timing of mineralization.

A second sample (2-PE) was obtained from the relatively recently discovered 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 2b). As with the sample from the King vein, the isochron indicated the presence of excess argon for steps 2–15 so the isochron age of 66.8 ±0.5 Ma is preferred.

The third sample (P-EXT), collected from the Pioneer Extension adit dump, is of coarse-grained, shiny white muscovite from a small vug in a fine-grained, white quartz vein with carbonaceous and pyrite ribbons. An analysis 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 2c). Unlike 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. Dating of a single muscovite grain also yielded a plateau age at 64.2 ±0.4 Ma comprising eight steps representing 98.3% of

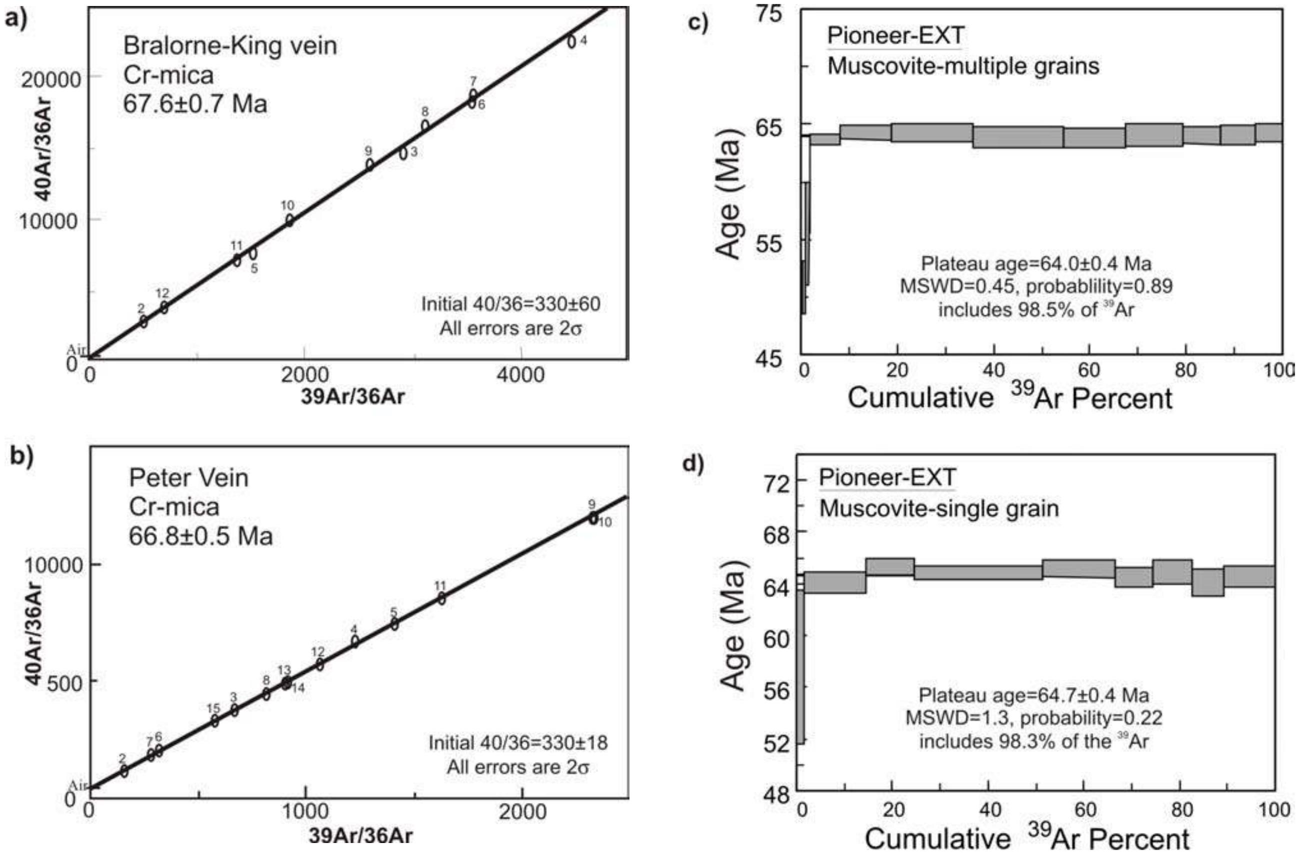

Figure 2. Ar-Ar gas release spectra and isochron plots from the **a**) King (Bralorne), **b**) Peter, **c**) and **d**) Pioneer-Extension veins. All analyses include J-error. MSWD = mean square of weighted deviates.

^{39}Ar released with a matching inverse isochron age of 64.9 ±0.6 Ma.

The age determinations, despite being from three district Bralorne-Pioneer orebodies located more than 10 km apart, yield very similar results that, despite minor analytical complications, confirm that a latest Cretaceous gold deposition event at the Bralorne-Pioneer gold deposit occurred ca. 68–64 Ma.

To establish a precise age of the nearest major intrusive event to the gold ores, a new date for crystallization of the Bendor batholith was also obtained, using a sample (84WV) collected by G.J. Woodsworth of the Geological Survey of Canada in 1984 from approximately 10 km east of the Pioneer deposit.

Conventional U-Pb dating of zircon from the Bendor pluton indicates an age of ca. 65 Ma. Seven analyses include four from Friedman and Armstrong (1995) and three from this study (Figure 3a). The original four fractions are large (1.1–1.7 mg) and give relatively precise data that are difficult to interpret because they lie parallel to, and just off, concordia. The older two of these analyses were abraded and relatively coarse, suggesting that dispersion of the data is due to minor Pb loss. In an attempt to confirm the previous data, three new fractions of 1 to 23 strongly abraded grains (20–35 µg) were analyzed. Although less precise, overlap with the original data and a similar style of dispersion confirm Pb loss and a Cretaceous-Tertiary boundary age. 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.

Eighteen different zircon grains from the sample used for the conventional TIMS U-Pb analysis were analyzed utilizing a SHRIMP. All determinations were on 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 eighteen ^{206}Pb/^{238}U determinations (Figure 3b). The integrity of the data is supported by a sound MSWD of 0.79 and the good correlation with the TIMS determination.

An Ar-Ar determination on well-formed, unaltered, coarse-grained biotite from the same sample yields an excellent plateau from 10 steps at 64.6 ±0.6 Ma that represent 99% of the total gas (Figure 4). The initial ^{40}Ar/^{36}Ar ratio indicated by the isochron was within error of the accepted value and the inverse isochron age was in good agreement with the plateau age.

The geochronological data are summarized in Table 1.

Discussion

The new determinations of the age of mineralization for the Bralorne-Pioneer camp presented above differ significantly from previously reported estimates. Dating of crosscutting dikes from the eighth level of the Bralorne mine by Leitch et al. (1991) 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 K-Ar date of 85.7 ±3 Ma on green hornblende , however, was interpreted by Leitch et al. (1991) as possibly late, intra- to post-ore, and thus perhaps more narrowly constraining the timing of mineralization between 93 and 83 Ma (within the limits of errors). Alternatively, the hornblende date may simply reflect argon loss from ca. 91 Ma, as the hornblende dikes are likely transitional and essentially coeval with the albitite (Leitch et al., 1991). Although the mid-Cretaceous range was favoured by these workers, the uncertainty did not preclude a Late Cretaceous or Tertiary age for gold mineralization.

An Ar-Ar determination on fuchsite from "quartz veined and carbonate altered" metabasalt from the Pioneer orebody dump (Ash, 2001) gave ambiguous results. A single 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, returns a total gas age of 79 ±4 Ma. This latter date was interpreted to represent a lower limit for the age for mineralization (Ash, 2001), although the recognition that the material was from a fine-grained, impure sample that likely endured recoil effects during radiation suggests that the determination cannot be meaningfully interpreted. Two samples of Cr-rich illite, collected from the Cosmopolitan and North veins in the Bralorne-Pioneer deposit, in an area of "sheared, clay-altered zones marginal to pervasively hydrothermally altered felsic dikes along the mineralized quartz-vein structure" (Ash, 2001), yielded a similar spectrum with their ages increasing from ~71 Ma up to 77 Ma. These dates were interpreted to indicate the age of faulting and post-ore hydrothermal alteration. In summary, Ash (2001) interprets the age of Bralorne gold mineralization to be ~86 Ma, presumably in accord with determinations of Leitch et al. (1991), and also interprets the Ar-Ar determinations to represent younger events.

Two age determinations were done in this study on zircons from the Bendor batholith, utilizing different methods. Both methods yielded ages with a high degree of precision, and the similarity of the results indicates a high degree of accuracy with crystallization at ca. 65 Ma. The only slightly younger Ar-Ar age of 64.4 Ma on biotite indicates that the batholith cooled rapidly through ~300° (biotite closure temperature, McDougall and Harrison, 1999).

The Ar-Ar dates of 68 to 64 Ma determined in this study are 20 to 30 Ma younger than previous absolute age estimates for gold mineralization at the Bralorne-Pioneer deposit These data indicate that the Bralorne-Pioneer mineralizing event is significantly younger than juxtaposition of the Cadwallader and Bridge River terranes, and, most specifi-

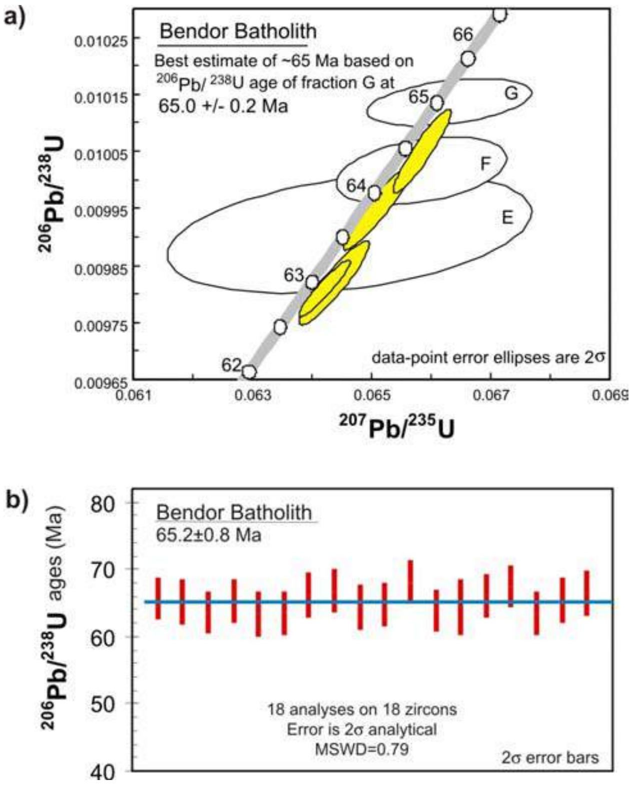

Figure 3. U-Pb plots for Bendor batholith zircon analysis: a) conventional TIMS, **b**) SHRIMP. MSWD = mean square of weighted deviates.

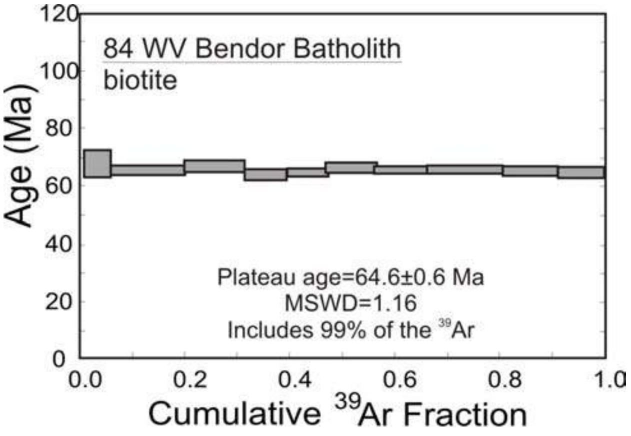

Figure 4. Ar-Ar gas release spectra for Bendor batholith biotite. Plateau steps are filled, rejected steps are open. Box heights are 2σ errors. Error includes J-error of 0.32%. MSWD = mean square of weighted deviates.

Table 1. Compilation of new geochronology for the Bralorne-Pioneer district.

Sample number and source	Sample location	Geochronological technique and sample material	Analyzing laboratory	Date obtained	Interpretation of age
1-BR, King vein (Bralorne)	50.778°N, 122.8208°W	Ar-Ar, fuchsite	United States Geological Survey	67.6 ±0.7 Ma	Age of mineralization
1-PE, Peter vein	50.8621°N, 122.8311°W	Ar-Ar, fuchsite	United States Geological Survey	66.8 ±0.5 Ma	Age of mineralization
P-EXT, Pioneer Extension, vein	50.7542°N, 122.7533°W	Ar-Ar, muscovite, multiple grains	University of British Columbia	64.0 ±0.4 Ma	Age of mineralization
P-EXT, Pioneer Extension, vein	50.7542°N, 122.7533°W	Ar-Ar, muscovite, single grain	University of British Columbia	64.7 ±0.4 Ma	Age of mineralization
84 WV, Bendor batholith	50.7422°N, 122.6166°W	U-Pb TIMS, zircon	University of British Columbia	65.0 ±0.2 Ma	Age of Bendor batholith
84 WV, Bendor batholith	50.7422°N, 122.6166°W	U-Pb SHRIMP, zircon	University of Western Australia	65.2 ±0.8 Ma	Age of Bendor batholith
84 WV, Bendor batholith	50.7422°N, 122.6166°W	Ar-Ar, biotite	University of British Columbia	64.9 ±0.6 Ma	Cooling of Bendor batholith

cally, significantly younger than thrusting and obduction of the ophiolitic rocks. In addition, mineralization is not synchronous with the major contractional and sinistral motion along the Eldorado Fault zone, nor is it coeval with emplacement of the plutons of the CPC.

The new geochronology does indicate temporal association of gold with other events in the district. First, mineralization is synchronous with the emplacement of the Bendor batholith, based upon the new, high-precision dating of the igneous body. Second, the gold event does overlap initiation of dextral strike-slip on the regional fault systems in this part of British Columbia. Finally, given existing K-Ar dates of 69 to 67 Ma for mineralized dikes at the Minto and Congress Sb-Au deposits (Harrop and Sinclair, 1986), and Ar-Ar dates of ca. 70 Ma for the gold-hosting Blue Creek porphyry at the Elizabeth Au deposit (Schiarizza et al., 1977), the possibility now exists that all mineralization in the Bridge River district may reflect a single, latest Cretaceous hydrothermal event. More detailed absolute dating will be needed to confirm this possibility.

Several points indicate that the 68 to 64 Ma dates for mineralization presented here most likely represent the age of gold mineralization at the Bralorne-Pioneer deposit and are not recording any thermal effects from emplacement of the Bendor batholith. First, the analyses for the three new ore-related samples are the best presented to date, and the materials are also the best quality analyzed to date. In particular, the coarse-grained crystalline muscovite from the Pioneer Extension will retain radiogenic argon to temperatures higher than 350°C, and rocks of the batholith may have been cooler than the biotite closure temperature 300°C (McDougall and Harrison, 1999) when the muscovite formed. Second, none of the argon spectra determined in this study are continuously stepped from an older date to a younger, thus reset, date, which would indicate partial resetting by an overprinting thermal event. Lastly, and most importantly, other Ar-Ar and K-Ar determinations in the district give dates that are older than 70 Ma, and thus were not reset by intrusion of the Bendor batholith.

In conclusion, the main gold-forming event in the Bridge River district took place at ca. 68 to 64 Ma at the Bralorne-Pioneer deposit, and other mineralization in the district may also have formed during this same event. The onset of dextral strike-slip in this part of the Cordillera facilitated widespread fluid flow along the reactivated fault systems, as is supported by the abundance of Au, Sb and Hg deposits and occurrences along the various main structures in the district. Geochronological constraints suggest the Bendor batholith was unlikely to have been the source of these ore-forming fluids. The spatial association of the most significant known ore system with a shear zone near the batholith margin, however, suggests that a structurally favourable dilational zone existed adjacent to the recently emplacement igneous body during the onset of latest Cretaceous hydrothermal activity.

Acknowledgments

Funding from this project comes from Geoscience BC, with support from the University of Western Australia and the United States Geological Survey. Conversations with N. Church and P. Schiarizza of the BC Geological Survey about rocks and mineralization in the Bridge River district are appreciated. Information and advice from A. Pettipas of Bralorne Gold Mines Ltd., and T. Illidge of Gold Bridge, BC, are also appreciated. Members of the staff at the Gold Bridge Hotel are thanked for their hospitality.

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