British Columbia Geological Survey
Geological Fieldwork 1990

$^{40}Ar/^{39}Ar$ AGES OF EPITHERMAL ALTERATION AND VOLCANIC ROCKS IN THE TOODOGGONE Au-Ag DISTRICT, NORTH-CENTRAL BRITISH COLUMBIA (94E)

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KEYWORDS: Regional geology, Toodoggone, geochronology, $^{40}Ar/^{39}Ar$, epithermal, gold, silver, alteration, potassium feldspar, adularia, sericite, volcanic, hornblende.

INTRODUCTION

For the past decade, the Toodoggone district has been an active area of mineral exploration, and has recently become an important area of gold and silver production. The district contains one of British Columbia's largest gold-silver mines (Lawyers), as well as smaller scale current and past-producers (Shasta and Baker mines, respectively). Several gold deposits have drill-indicated reserves and await production decisions (*e.g.* Bonanza), and numerous other gold-silver-copper prospects are in various stages of exploration.

The deposits range from gold-rich porphyry-style deposits, to deep-seated precious and base metal bearing stockworks and veins, to near-surface replacement-type gold mineralization. The most economically significant deposits exhibit characteristics typical of epithermal alteration and mineralization of both adularia-sericite and acid-sulphate affinities. The former class of deposits is represented by the Lawyers AGB and Cliff Creek zones and the Shasta deposit, and the latter by the Bonanza deposit. These four deposits also contain most of the known reserves in the district.

The most important lithologic assemblage in the area is the "Toodoggone volcanics" (Carter, 1972). These consist of dominantly andesitic to dacitic pyroclastics and flows of apparent Early to Middle Jurassic age, and have been described by Schroeter (1981; 1982), Panteleyev (1982; 1983), Diakow (1984), Forster (1984), Diakow *et al.* (1985), and Marsden and Moore (1989, 1990). The Toodoggone volcanics are underlain by Upper Triassic mafic to intermediate volcanics of the Stuhini Group, and are overlain by Cretaceous-Tertiary clastic sediments of the Sustut Group. Gold-silver mineralization is primarily hosted by the Toodoggone volcanics, and to a lesser extent, by the Stuhini and Asitka groups, and Lower Jurassic felsic to intermediate intrusive rocks. The major ore deposits in the district have been described by Vulimiri *et al.* (1987; Lawyers), Thiersch and Williams-Jones (1990; Shasta), Clark and Williams-Jones (1986; Bonanza), and Barr (1978; Baker).

The objective of the current study is to clarify the age of the Toodoggone volcanics and the related epithermal gold-silver deposits. This report presents seven new $^{40}Ar/^{39}Ar$ age determinations, and discusses the results in terms of the implications for mineral exploration and metallogeny in the Toodoggone district.

PREVIOUS DETERMINATIONS OF AGE RELATIONSHIPS

Several K-Ar studies have been conducted on the Toodoggone volcanics, and have yielded ages that range from 204 to 182 Ma. When correlated with geological observations, these ages appear divisible into groups that correspond to two stages of volcanism: an older, lower stage with ages of 204±7 Ma (Panteleyev, 1983), 202±7, 200±7, 200±7, 199±7 and 197±7 Ma (Diakow, 1985), and 189±6 Ma (Carter, 1972; age recalculated using the constants of Steiger and Jäger, 1977); and a younger, upper stage with ages of 183±8 and 182±8 Ma (Gabrielse *et al.*, 1980; first value recalculated using constants of Steiger and Jäger, 1977). The lower volcanics are dominantly andesitic pyroclastic and flow rocks, and are characterized by widespread propylitic and zeolitic alteration. The upper volcanics correspond to the "grey dacite" and equivalent units of Diakow *et al.* (1985), and overlying rocks recently mapped by Marsden and Moore (1990). These volcanics consist of dominantly andesitic to dacitic ash-flow tuffs that generally lack significant epithermal alteration. All epithermal gold-silver deposits and prospects discovered thus far in the district are restricted to the lower Toodoggone volcanics and underlying units. On the basis of these geological relationships, Clark and Williams-Jones (1987, 1988) proposed division of the Toodoggone volcanics into two stages, with mineralization having occurred during Stage I and/or between Stages I and II.

The timing of Toodoggone Stage I volcanism is constrained by K-Ar age determinations spanning 204 to 189 Ma. However, the sample of the oldest Stage I rock (204 Ma, Panteleyev, 1983; "Adoogacho Formation" of Diakow *et al.*, 1985) was re-analysed by the $^{40}Ar/^{39}Ar$ method by Shepard (1986) and yielded a plateau age of 197.6±0.5 Ma. This suggested that the Stage I volcanics range between 198 and 189 Ma in age. Toodoggone Stage II volcanics are more poorly constrained by two K-Ar determinations of 183 and 182 Ma. The relatively wide range of K-Ar ages for volcanic rocks in the district is greater than that expected for Hazelton-equivalent volcanism elsewhere in north-central and northwestern British Columbia. There is a clear need for additional high-precision age determinations to elucidate the ages and relationships of the Toodoggone volcanics.

Whereas the ages of the volcanics are at least somewhat constrained, there is poor agreement on the timing of mineralization. Potassium-argon ages of epithermal alteration range from Early to Late Jurassic, and most dates appear to be too young to be geologically reasonable. Schroeter *et al.* (1986) reported K-Ar ages for adularia from the Lawyers AGB deposit (180±6 Ma), the Golden Lion prospect (176±6 Ma) and the Metsantan prospect (168±6 Ma). The K-Ar ages of acid-sulphate alteration and related deposits have been determined for the Alberts Hump alunite zone (190±7 Ma, alunite; Schroeter, 1982), the Jan alunite zone (193±7 Ma, alunite; Clark and Williams-Jones, 1989), and the Bonanza and BV deposits (171±6 and 152±5 Ma, sericite; Clark and Williams-Jones, 1989). Clark and Williams-Jones (1989) suggested that the adularia and sericite dates were minimum ages due to loss of small amounts of radiogenic argon. Whether Toodoggone gold-silver mineralization is restricted to mid-Toarcian (~190 Ma) and older rocks (Clark and Williams-Jones, 1987) or postdates the youngest volcanism in the area by several million years (Schroeter *et al.*, 1986), remains to be clarified by our $^{40}Ar/^{39}Ar$ study.

$^{40}Ar/^{39}Ar$ ANALYSES

Step-heating $^{40}Ar/^{39}Ar$ analyses were conducted on three samples of hornblende separated from Toodoggone volcanic rocks, and four samples of potassium feldspar and sericite separated from hydrothermal alteration zones directly associated with gold-silver mineralization. The samples from volcanic rocks were selected to evaluate the age relationship between the two main stages of Toodoggone volcanism. Samples from ore zones were chosen to accurately date the most important deposits in the area, to provide information on the relationship between deposits associated with both adularia-sericite and acid-sulphate alteration styles, and to constrain metallogenic events in the district.

SAMPLE DESCRIPTIONS

Sample SH-11 is from an andesitic crystal-lapilli tuff unit ("Unit 9" of Marsden and Moore, 1990) located 1.5 kilometres north of the Shasta mine (Figure 2-7-1). The tuff is the youngest unit of the Toodoggone Stage I volcanics in the Jock Creek area. Hornblende comprises 3 per cent of the rock, and consists of euhedral to broken crystals (200-1000 μm) that exhibit no evidence of alteration. Lithic fragments in the tuff sample are similar in composition to the matrix and crystals, and contain optically identical hornblende grains.

Sample BK87-03 was collected from the "Tiger Notch area", 1.8 kilometres north of the Baker mine (Figure 2-7-1). The sample is from the basal part of an andesitic/dacitic ash-flow tuff that forms the major unit of the second stage of the Toodoggone volcanics ("grey dacite" unit of Diakow *et al.*, 1985). Hornblende comprises 5 per cent of the rock and consists of euhedral to broken crystals (200-1500 μm) with slightly oxidized rims (5-10 μm thick).

The material used from sample GSC 76-77 consists of a hornblende separate, part of which has been previously analysed by the K-Ar method. The original sample was obtained from an outcrop mapped by Diakow *et al.* (1985) as part of the "grey dacite" unit, located approximately 9 kilometres north-northeast of the Kemess prospect (Figure 2-7-1). The hornblende gave a K-Ar age of 183±8 Ma (Gabrielse *et al.*, 1980; age recalculated using the constants of Steiger and Jäger, 1977).

Sample LW-037 is from an andesitic/dacitic tuff ("welded trachyte tuff" unit of Vulimiri *et al.*, 1987) exposed in the 1750-level adit of the AGB zone at the Lawyers mine (Figure 2-7-1). The sample exhibits strong potassic alteration, brecciation and gold-silver mineralization. Alteration is complete, and no primary potassium-bearing phases remain from the original tuff. The sample consists of 40 to 50 per cent potassium feldspar as replacements of plagioclase crystals (200-3000 μm), and as alteration of the tuff matrix (20-100 μm). Minor sericite (<3 per cent) occurs as irregular alteration patches in the potassium feldspar, but is considered to be synmineralization in age. Fracture-controlled ankerite alteration locally overprints the potassium feldspar.

A similar sample of material rich in potassium feldspar (LW-011) was obtained from a trench on the Cliff Creek zone at the Lawyers mine (Figure 2-7-1). The sample is from an andesitic/dacitic tuff unit ("upper andesite" of Vulimiri *et al.*, 1987) that has been potassically altered and locally brecciated, and contains gold-silver mineralization. Alteration is complete, and no primary potassic phases remain in the rock. Potassium feldspar comprises 30 to 40 per cent of the sample, and consists of replacements of plagioclase crystals (200-2000 μm) and alteration of the tuff matrix (20-100 μm). Sericitic alteration of the potassium feldspar is minor (<1 per cent), and is considered to be associated with the mineralizing event.

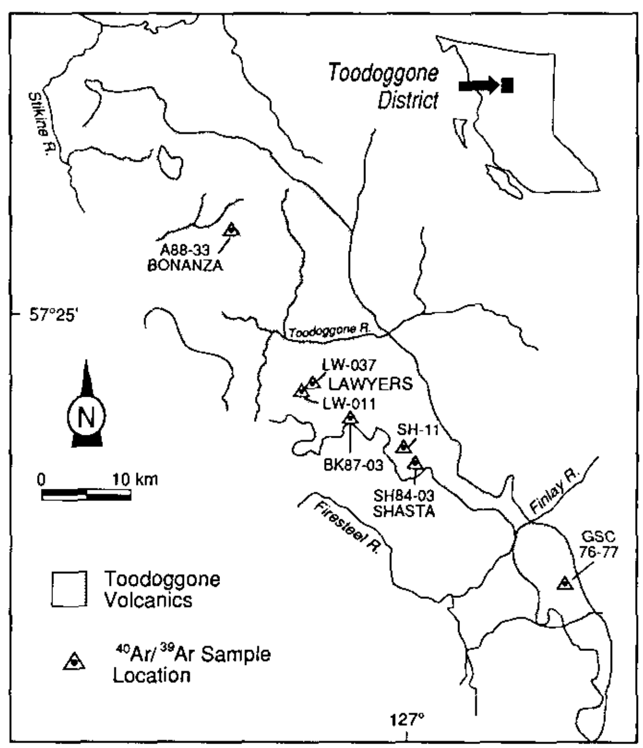

Figure 2-7-1. Distribution of the Toodoggone volcanics and locations of samples used for $^{40}Ar/^{39}Ar$ analyses.

Sample SH84-03 is from 94.5 metres depth in drill hole 84-03 on the Creek zone at the Shasta mine (Figure 2-7-1). The rock is a dacitic ash-flow tuff ("Unit 5" of Marsden and Moore, 1990) that has undergone intense potassic alteration, and contains quartz stockworks and weak gold-silver mineralization. Potassium feldspar in the sample is well crystallized, and generally appears to have been precipitated in open spaces created by an earlier alteration and dissolution event. The potassium feldspar exhibits an adularia-type habit (Felsobanya), and comprises 80 to 90 per cent of the sample. Adularia occurs as euhedral to subhedral grains (50-800 μm) and as fine-grained (<25 μm) flooding of the matrix. Larger grains contain slightly turbid centres due to finely disseminated hematite. Minor sericitic alteration. (<5 per cent) occurs as irregular patches throughout the sample, but is considered to have formed closely after mineralization.

Sample A88-33 is from 73.8 metres depth in drill hole 88-33 on the South Bonanza zone of the Bonanza deposit (Figure 2-7-1). The Bonanza deposit is characterized by acid-sulphate alteration, but locally contains sericite at depth. The hostrock is an andesitic to dacitic ash-flow tuff that has undergone complete alteration to a sericite-quartz-pyrite assemblage that contains gold. The sample consists of 60 to 70 per cent sericite that X-ray diffraction indicates to be dominantly 1M illite. The sericite grains are subhedral (20-200 μm) and generally replace the originally feldspathic components of the tuff. Traces of dickite occur locally in quartz and sericite.

Analytical Methods

Most of the mineral separations, and all the argon determinations were conducted in the Department of Geology, University of Maine at Orono, under the direction of Daniel R. Lux. Samples were crushed and sieved to uniform grain sizes, and standard magnetic and density methods were used to extract hornblende, potassium feldspar and sericite. The mineral separates were encapsulated in foil and sealed in silica-glass tubes, and then irradiated in the HS facility of the Ford nuclear reactor at the University of Michigan. MMhb-1 (Alexander *et al.*, 1978) and several internal standards were used as irradiation monitors. The irradiated samples were heated in molybdenum crucibles in an ultra-high vacuum system using a radio frequency induction furnace. Standard gettering techniques were employed to purify the rare gases from the sample. The argon isotopic compositions were measured with a Nuclide 6-60-SGA mass spectrometer. Peak height-time values were extrapolated to time-zero by both linear and quadratic routines. Aliquots of atmospheric argon were analysed daily in order to determine mass discrimination values. Potassium and calcium salts were analysed with each batch of samples to determine correction factors for unwanted argon irradiation products.

Ages and errors were calculated using the equations of Dalrymple *et al.* (1981), and the decay constants and isotopic compositions of Steiger and Jäger (1977). Errors are given for two standard deviations, plus a 0.5 per cent uncertainty in the irradiation parameter (J). Plateaus were determined using the criteria of Fleck *et al.* (1977), and the critical value test (Dalrymple and Lanphere, 1969) was used to evaluate concordance between successive increments.

Results

The results of the $^{40}Ar/^{39}Ar$ analyses and apparent ages of the gas fractions are given in Table 2-7-1.

Sample SH-11, from the upper strata of the first stage of the Toodoggone volcanics, has a total gas age of 197.9±2.2 Ma. The high ages of the lower temperature gas fractions show that the hornblende contains some excess ^{40}Ar. Standard data treatment yields a plateau age of 195.1±1.6 Ma (Figure 2-7-2a). Use of the isotope correlation data treatment (Fig. 2-7-2b) indicates that the sample has a nonatmospheric $^{40}Ar/^{36}Ar$ ratio of 337±9, which allows calculation of an adjusted plateau age of 193.8±2.6 Ma (Figure 2-7-2c). This result can be considered to approximate the minimum age for the Toodoggone Stage I volcanic rocks.

Hornblende (BK87-03) from near the base of Toodoggone Stage II volcanics also contains minor excess argon, and has a total gas age of 197.8±2.5 Ma. Standard treatment of the data suggests a plateau age of 194.4±1.9 Ma (Figure 2-7-3a). The isotope correlation method indicates a relatively high $^{40}Ar/^{36}Ar$ composition of 349±27 (Figure 2-7-3b), and yields a recalculated plateau age of 192.9±2.7 Ma (Figure 2-7-3c).

In order to check the apparent closeness in age of the upper Stage I and lower Stage II volcanics, we analysed an additional hornblende separate (GSC 76-77) from the "grey dacite" unit. The sample shows evidence of a disturbed argon history in the lower temperature gas fractions which may be due to a superimposed excess ^{40}Ar component and a slight argon loss. The total gas age is 193.0±2.4 Ma, and the plateau age is 193.8±2.5 Ma (Figure 2-7-4a). The isotope correlation treatment indicates a near-atmospheric $^{40}Ar/^{36}Ar$ ratio of 278±12, and a concordant intercept age of 194.2±3.6 Ma (Figure 2-7-4b). The age of the basal Toodoggone Stage II volcanics thus falls in the range of 194 to 193 Ma, and must be only slightly younger than the underlying Stage I rocks.

Sample LW-037, a potassium feldspar separate from the AGB deposit at the Lawyers mine, yields quite straightforward results. The lower temperature steps of the age spectrum show that the feldspar has undergone minor loss of radiogenic argon (^{40}Ar); the sample has a total gas age of 186.0±1.9 Ma. The plateau age is 188.2±2.3 Ma (Figure 2-7-5), and the isotope correlation method indicates an atmospheric $^{40}Ar/^{36}Ar$ composition of 291±77 and an intercept age of 188.0±1.8 Ma.

A potassium feldspar separate (LW-011) from the Cliff Creek zone of the Lawyers mine yields results similar to those for the AGB deposit. There is a very slight ^{40}Ar loss suggested by the lowest temperature gas fractions, and the total gas age is 188.1±3.9 Ma. The plateau age is 189.7±2.6 Ma (Figure 2-7-6). The main orebodies at the Lawyers mine are therefore well constrained, with an age of 190 to 188 Ma.

The results from the Shasta mine adularia sample (SH84-03) are quite similar to those from the Lawyers

TABLE 2-7-1

$^{40}Ar/^{39}Ar$ ANALYTICAL RESULTS AND APPARENT AGES OF MINERALS FROM TOODOGGONE VOLCANIC ROCKS AND EPITHERMAL GOLD-SILVER DEPOSITS.

Temp. °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	^{39}Ar 10^{-13} mol	^{39}Ar % tot.	$^{40}Ar^*$ %	K/Ca	Age±2σ Ma
				SH-11 Hornblende (J=0.006075)				
865	33.39	1.152	0.0372	36.4	2.3	67.3	0.425	231.0±4.1
1015	33.13	1.224	0.0387	76.7	4.8	65.7	0.400	224.3±2.5
1120	27.05	3.007	0.0254	76.7	4.8	73.0	0.163	204.8±2.0
1175	22.38	4.495	0.0128	117.0	7.3	84.7	0.109	197.2±2.2
1220	19.79	5.298	0.0051	321.1	20.1	94.5	0.092	194.7±1.9
1265	19.46	5.386	0.0039	378.3	23.7	96.2	0.091	195.0±2.2
1305	19.47	5.447	0.0038	256.1	16.0	96.4	0.090	195.5±1.9
1345	19.47	5.627	0.0041	161.2	10.1	96.1	0.087	194.8±2.3
FUSE	19.59	5.965	0.0044	175.5	11.0	95.7	0.082	195.2±2.1
Total				1599.0	100.0			197.9±2.2
				BK87-03 Hornblende (J=0.05984)				
865	74.49	16.560	0.1602	23.4	2.1	38.2	0.029	287.0±14.5
975	53.60	11.170	0.1070	26.0	2.3	42.7	0.044	233.0±7.3
1070	22.53	5.302	0.0124	117.0	10.3	85.6	0.092	197.7±2.0
1160	21.73	5.127	0.0094	74.1	6.5	89.0	0.095	198.3±2.3
1235	19.94	4.926	0.0048	140.4	12.3	94.8	0.099	193.9±2.3
1305	19.66	4.889	0.0037	374.4	32.8	96.4	0.100	194.4±2.1
FUSE	20.00	5.224	0.0048	384.8	33.8	94.9	0.093	194.8±2.2
Total				1140.1	100.0			197.8±2.5
				GSC 76-77 Hornblende (J=0.00622)				
650	69.12	0.666	0.1736	22.4	1.0	25.8	0.735	190.1±4.4
740	45.80	0.544	0.0974	31.2	1.3	37.2	0.900	181.8±8.7
830	38.95	0.653	0.0782	27.2	1.2	40.7	0.749	169.9±4.8
900	36.11	1.360	0.0710	20.8	0.9	42.1	0.360	163.4±4.2
970	22.91	4.536	0.0182	149.6	6.5	78.2	0.108	191.3±2.8
1040	20.79	4.846	0.0098	314.4	13.6	88.1	0.101	195.3±2.6
1100	19.92	4.993	0.0076	668.0	28.9	90.8	0.098	193.1±2.0
1170	19.90	5.058	0.0073	612.8	26.5	91.2	0.096	193.7±1.9
FUSE	20.09	5.120	0.0077	467.2	20.2	90.8	0.095	194.6±2.5
Total				2313.6	100.0			193.0±2.4

mine. The lowest temperature gas fractions indicate that there has been minor loss of radiogenic argon; the total gas age is 187.1±1.9 Ma. The standard data treatment yields a plateau age of 188.1±1.8 Ma (Figure 2-7-7a), but the isotope correlation technique suggests a slightly higher than atmospheric $^{40}Ar/^{36}Ar$ ratio of 326±49 and an intercept age of 186.7±2.0 Ma (Figure 2-7-7b). Applying the nonatmospheric $^{40}Ar/^{36}Ar$ composition to the data results in an adjusted plateau age of 186.7±1.7 Ma (Figure 2-7-7c).

Sample A88-33, consisting of sericite from the Bonanza deposit, gives a fairly complicated gas-release pattern. In addition, the sample was heated to relatively high temperatures prior to the first gas analyses, which further complicates interpretation of the results. Most of the argon was released from the sericite in the first three steps, and yielded unexpectedly old apparent ages for these gas fractions. Higher temperature increments give younger ages but involve only small amounts of argon. The total gas age for the sample is 206.8±2.3 Ma, and the plateau age by standard calculation is 207.7±2.7 Ma (Figure 2-7-8a). These ages are geologically unreasonable (*i.e.* older than the host-rocks), as is the intercept age from the isochron diagram. However, the age spectrum only provides a model age, and following the approach of Heizler and Harrison (1988), may be resolved into thermally and compositionally distinct argon components. For example, the last three gas fractions define an isochron which has an atmospheric $^{40}Ar/^{36}Ar$ ratio of 291±23, and an intercept age of 195.9±5.9 Ma (Figure 2-7-8b). Steps 1, 2 and 5 indicate a high $^{40}Ar/^{36}Ar$ ratio of 544±192 and an intercept age of 196.4±4.7 Ma (Figure 2-7-8b). The inclusion of steps 3 and 4 in the treatment of isotope correlation data results in unreasonably old ages. The preferred interpretation for the age of the sericite is thus approximately 196 Ma. As ages older than approximately 197 Ma are not geologically reasonable, the 2σ error limit allows for ages in the range of 197 to 190 Ma.

Sample A88-33 may have been affected by processes that could have disturbed the argon systematics: excess argon, recoil phenomena and mixed phases. Excess argon could have been introduced into the sericite during emplacement of dacitic porphyry dikes thought to postdate, but be closely related to formation of the Bonanza deposit. Two narrow (1-2 m) dikes occur within 10 metres of the sample location, and a larger dike (20-30 m thick) is projected to occur approximately 100 metres away. Argon, with a non-atmospheric $^{40}Ar/^{36}Ar$ signature, may have affected the sericite during the thermal disturbance associated with dike emplacement, and be responsible for the difficulties in inter-

TABLE 2-7-1 — *Continued*

$^{40}Ar/^{39}Ar$ ANALYTICAL RESULTS AND APPARENT AGES OF MINERALS FROM TOODOGGONE VOLCANIC ROCKS AND EPITHERMAL GOLD-SILVER DEPOSITS.

Temp. °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	^{39}Ar 10^{-13} mol	^{39}Ar % tot.	$^{40}Ar^{*}$ %	K/Ca	Age$\pm 2\sigma$ Ma
				LW-037 K-Feldspar (J=0.006145)				
840	18.88	0.0104	0.0072	829.4	9.1	88.6	47.06	176.5±1.7
935	18.55	0.0069	0.0044	1183.0	13.0	92.8	70.64	181.4±1.7
1015	18.51	0.0047	0.0028	750.1	8.2	95.3	104.57	185.7±1.8
1090	18.36	0.0051	0.0017	655.2	7.2	97.1	95.64	187.5±2.6
1160	18.27	0.0032	0.0009	646.1	7.1	98.5	155.29	189.2±1.8
1220	18.23	0.0039	0.0009	770.9	8.4	98.4	125.03	188.6±1.8
1280	18.38	0.0043	0.0016	739.7	8.1	97.3	113.22	188.0±2.1
1335	18.61	0.0037	0.0027	1366.3	15.0	95.6	133.78	187.1±1.8
1385	18.96	0.0035	0.0035	1021.8	11.2	94.4	141.87	188.2±1.8
FUSE	19.09	0.0038	0.0039	1166.1	12.8	93.9	128.43	188.4±1.8
Total				9128.6	100.0			186.0±1.9
				LW-011 K-Feldspar (J=0.006207)				
840	19.69	0.0011	0.0081	843.7	16.3	87.7	427.98	183.8±2.1
935	19.53	0.0007	0.0070	751.4	14.5	89.3	705.65	185.4±2.1
1015	19.26	0.0008	0.0047	464.1	9.0	92.7	627.59	189.5±1.9
1090	19.23	0.0003	0.0042	356.2	6.9	93.4	1549.21	190.7±1.9
1160	19.21	0.0008	0.0041	296.4	5.7	93.5	600.43	190.8±1.9
1220	19.28	0.0010	0.0045	466.7	9.0	92.9	497.52	190.2±1.8
1280	19.64	0.0007	0.0058	608.4	11.7	91.1	750.44	189.9±1.9
1350	19.77	0.0008	0.0068	508.3	9.8	89.7	606.59	188.3±1.8
1450	19.90	0.0008	0.0069	377.0	7.3	89.6	613.73	189.3±1.8
FUSE	20.04	0.0011	0.0074	508.3	9.8	88.9	440.41	189.2±1.8
Total				5180.5	100.0			88.1±3.9
				SH84-03 Adularia (J=0.00619)				
840	22.70	0.004	0.0196	582.4	5.9	74.4	128.32	179.3±2.2
935	21.13	0.003	0.0130	759.2	7.7	81.6	170.57	183.0±2.1
1015	19.62	0.003	0.0069	609.7	6.2	89.4	165.41	186.1±1.9
1090	18.83	0.003	0.0036	595.4	6.1	94.1	166.97	187.8±2.0
1160	18.86	0.003	0.0035	1034.8	10.6	94.3	174.93	188.4±1.8
1220	18.99	0.003	0.0042	1249.3	12.7	93.3	177.77	187.8±1.8
1280	19.09	0.003	0.0045	1353.3	13.8	92.9	162.00	187.9±1.8
1335	19.17	0.003	0.0048	1290.9	13.2	92.5	152.81	187.9±1.8
1385	19.26	0.003	0.0050	1223.3	12.5	92.1	166.72	188.0±1.8
FUSE	19.47	0.003	0.0055	1102.4	11.2	91.6	151.26	188.9±1.8
Total				9800.7	100.0			187.1±1.9
				A88-33 Sericite (J=0.006215)				
840	21.28	0.0071	0.0052	629.2	27.7	92.7	69.23	208.7±2.0
935	20.71	0.0071	0.0038	765.7	33.8	94.5	68.62	207.0±2.0
1015	20.30	0.0070	0.0023	439.4	19.4	96.5	69.96	207.3±2.4
1090	20.14	0.0110	0.0023	249.6	11.0	96.5	44.66	205.7±2.0
1160	20.09	0.0217	0.0030	102.7	4.5	95.5	22.55	203.3±2.7
1220	20.77	0.0592	0.0069	46.8	2.1	90.1	8.27	198.6±3.6
1280	24.99	0.1576	0.0242	19.5	0.9	71.4	3.11	189.7±15.5
FUSE	51.87	0.7206	0.1140	15.6	0.7	35.1	0.68	193.6±10.8
Total				2268.5	100.0			206.8±2.3

preting steps 3 and 4. It is not possible to resolve these steps without an additional heating experiment using a larger number of steps. A less likely problem, but one worth considering, is the possibility of recoil effects during irradiation. For illite, Halliday (1978) has shown that ^{39}Ar can be readily lost from fine-grained (<5 µm) material during irradiation, which leads to anomalously high apparent ages. The illite in sample A88-33 is significantly coarser grained, averaging 20-200 micrometres, but some of the grains at the lower end of this range could have been affected by recoil to some degree. However, the illite in sample A88-33 is dominantly of the 1m polytype, and may be less affected by recoil than more disordered illite. For example, Hunziker *et al.* (1986) found that $2m_1$ illites were more resistant to recoil than 1Md illite, even in similar size fractions. Therefore, recoil effects were probably not sufficient to control the distribution of argon in this sample. A final possible problem with sample A88-33 is the purity of the mineral separate. Although every effort was made to attain a high degree of purity, the drop in calculated potassium/calcium ratios in the last few heating steps suggests degassing of a small amount of a low-potassium mineral phase. The only

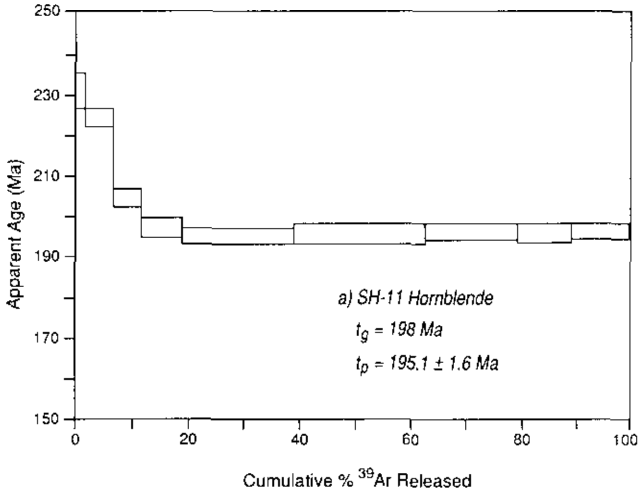

Figure 2-7-2a. Age spectrum for hornblende SH-11, from the upper strata of the Toodoggone Stage I volcanics, calculated assuming an atmospheric composition ($^{40}Ar/^{36}Ar=295.5$) for trapped argon. T_g is the total gas age, and T_p is the plateau age.

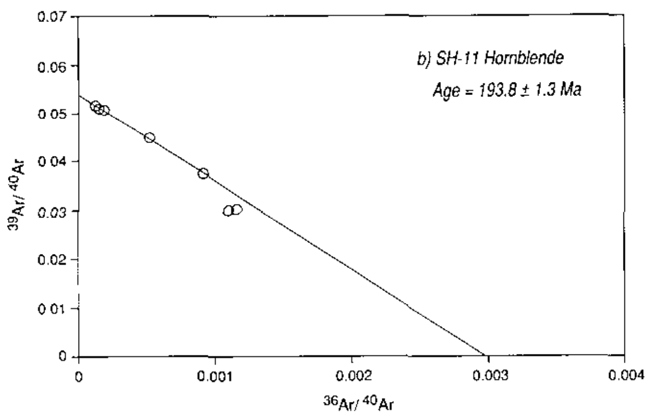

Figure 2-7-2b. Isochron diagram for step-heating data from hornblende SH-11. The $^{40}Ar/^{36}Ar_i=3379$, and the intercept age is 193.8±1.3 Ma (MSWD=2.8).

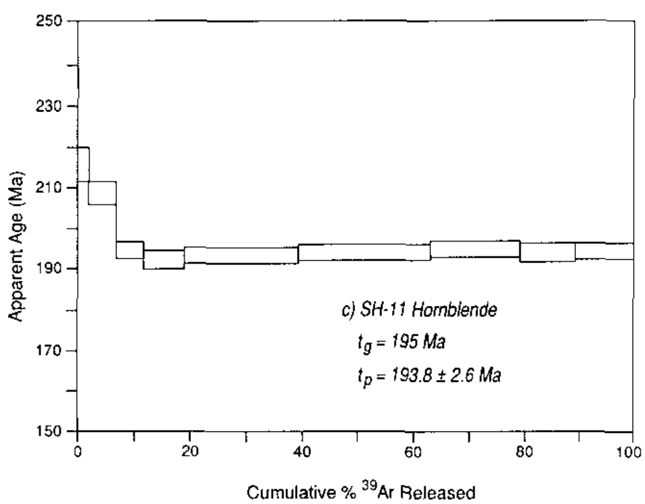

Figure 2-7-2c. Age spectrum for hornblende SH-11 calculated using the trapped $^{40}Ar/^{36}Ar$ ratio indicated by the isotope correlation data treatment.

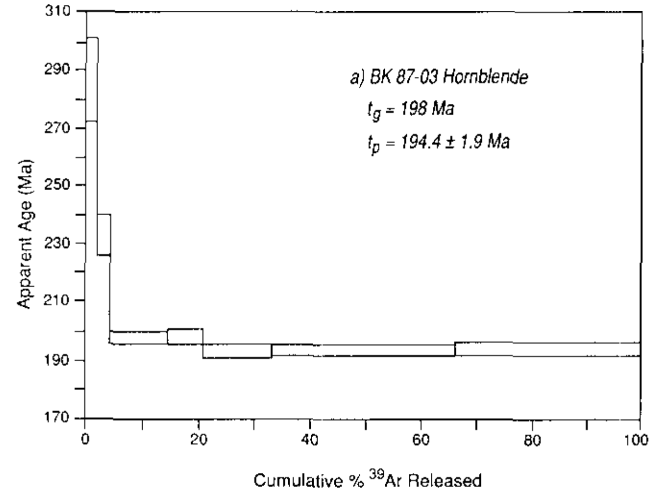

Figure 2-7-3a. Age spectrum for hornblende BK87-03, from the lower strata of the Toodoggone Stage II volcanics, calculated assuming an atmospheric argon composition.

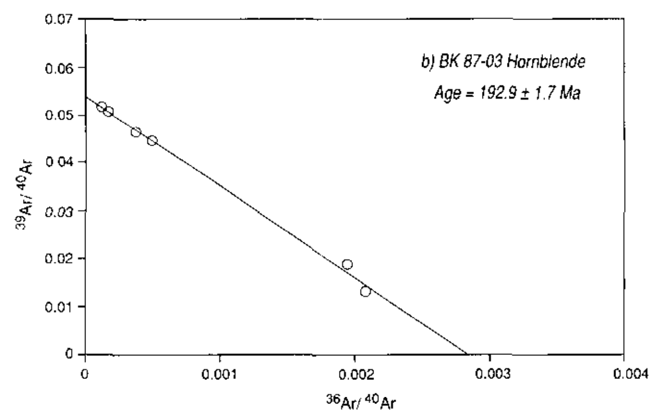

Figure 2-7-3b. Isochron diagram for step-heating data from hornblende BK87-03. The $^{40}Ar/^{36}Ar_i=349\pm27$, and the intercept age is 192.9±1.7 Ma (MSWD=3.3).

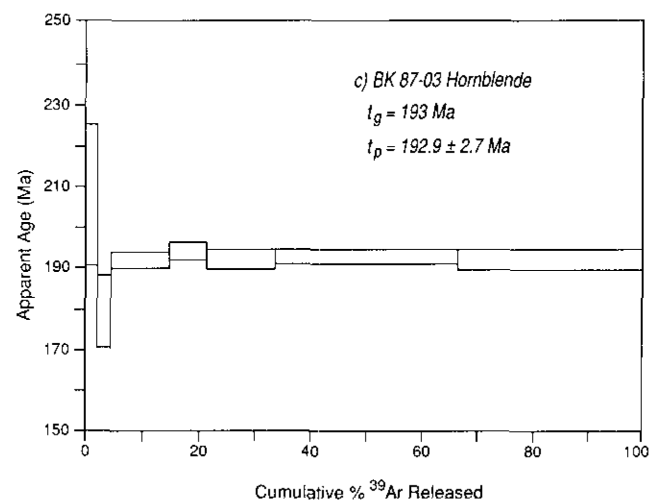

Figure 2-7-3c. Age spectrum for hornblende BK87-03 calculated using the trapped $^{40}Ar/^{36}Ar$ ratio indicated by the isotope correlation data treatment.

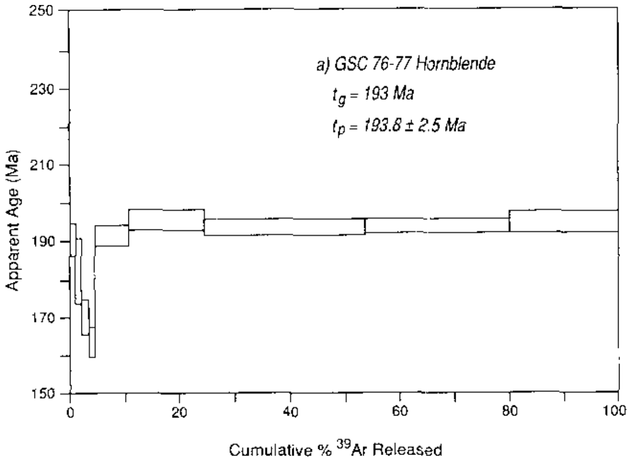

Figure 2-7-4a. Age spectrum for hornblende GSC 76-77, from the Toodoggone Stage II volcanics, calculated assuming an atmospheric composition for trapped argon.

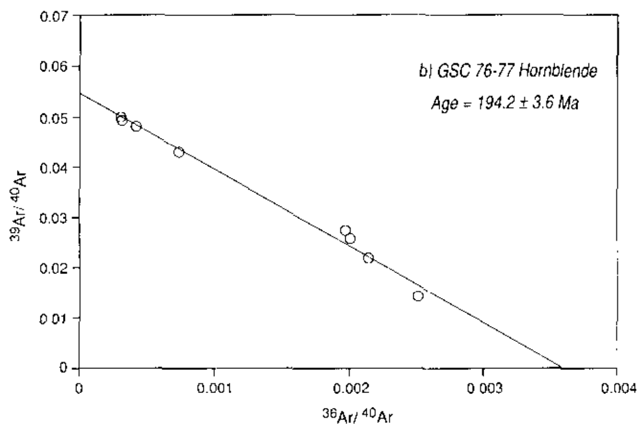

Figure 2-7-4b. Isochron diagram for step-heating data from hornblende GSC 76-77. The $^{40}Ar/^{36}Ar_i = 278 \pm 12$, and the intercept age is 194.2 ± 3.6 Ma (MSWD=2.6).

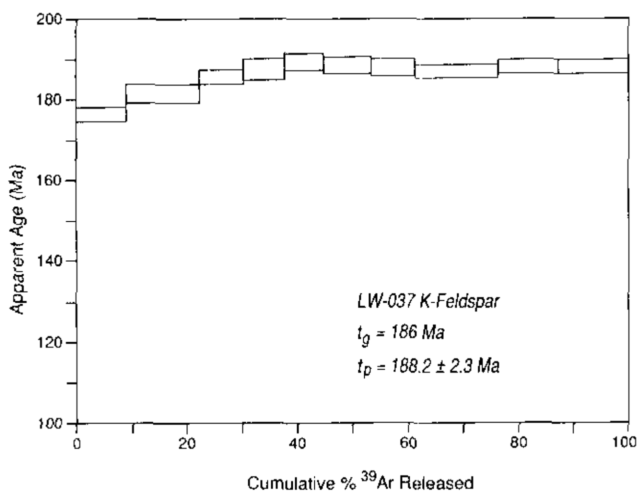

Figure 2-7-5. Age spectrum for potassium feldspar LW-037 from the AGB deposit at the Lawyers mine, calculated using an atmospheric composition for trapped argon.

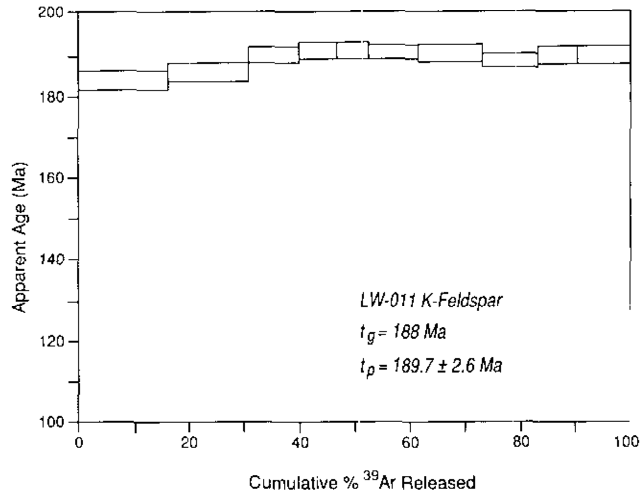

Figure 2-7-6. Age spectrum for potassium feldspar LW-011 from the Cliff Creek deposit at the Lawyers mine, calculated using an atmospheric composition for trapped argon.

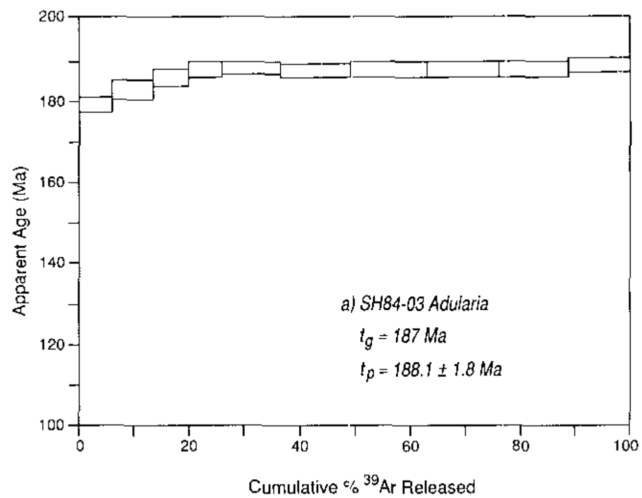

Figure 2-7-7a. Age spectrum for adularia SH84-03, from the Shasta mine, calculated assuming an atmospheric composition for trapped argon.

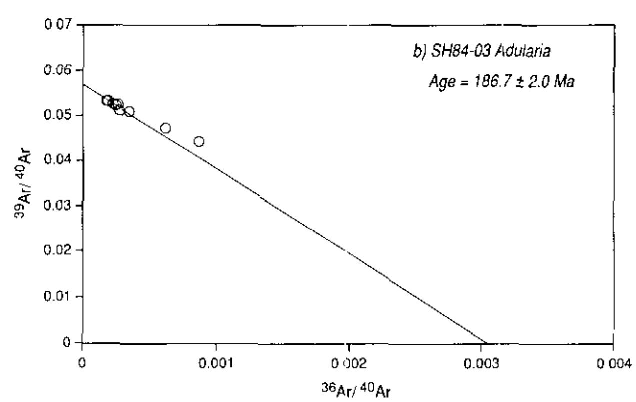

Figure 2-7-7b. Isochron diagram for step-heating data from adularia SH84-03. The $^{40}Ar/^{36}Ar_i = 326 \pm 49$, and the intercept age is 186.7 ± 2.0 Ma (MSWD=2.8).

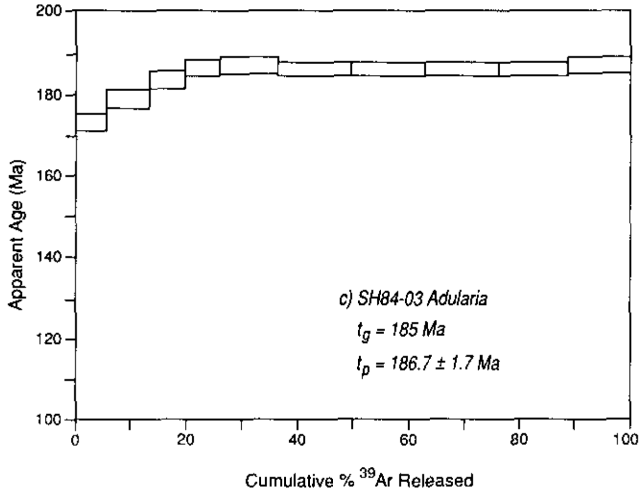

Figure 2-7-7c. Age spectrum for adularia SH84-03 calculated using the trapped $^{40}Ar/^{36}Ar$ ratio indicated by the isotope correlation data treatment.

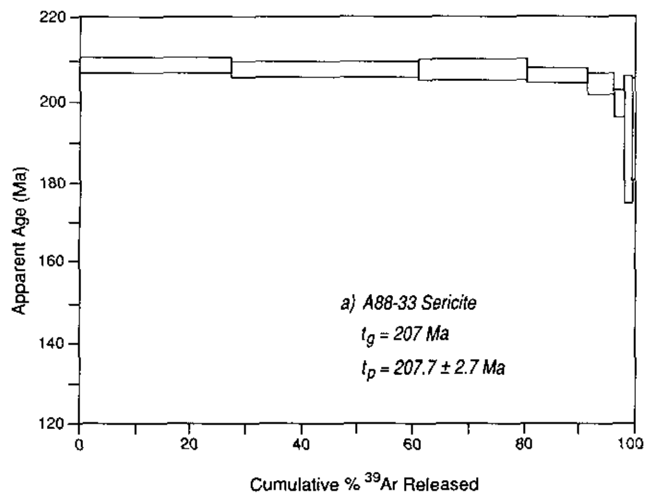

Figure 2-7-8a. Age spectrum for sericite A88-33, from the Bonanza deposit, calculated assuming an atmospheric composition for trapped argon. The total gas and plateau ages are too old to be geologically reasonable.

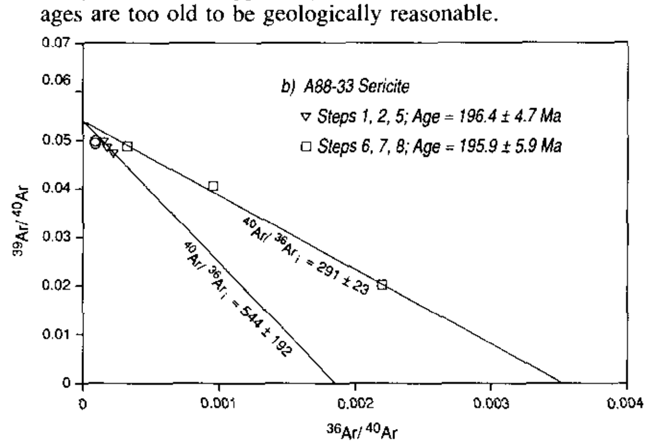

Figure 2-7-8b. Isochron diagram for step-heating data from sericite A88-33. Two linear arrays are defined by the data which yield an age of 196 Ma, but appear to have different trapped $^{40}Ar/^{36}Ar$ ratios of 543±192 (MSWD=6) and 291±23 (MSWD=6). Steps 3 and 4 (circles) cannot be resolved without additional information.

possible contaminants are quartz and dickite. Both these minerals formed contemporaneously with the sericite; trace amounts of potassium from inclusions, and recoil-induced ^{39}Ar may have been released from these minerals during the higher temperature heating steps.

The concordance of isochrons using both low and high-temperature gas fractions (Figure 2-7-8b) suggests that, despite the complications discussed above, the $^{40}Ar/^{39}Ar$ data provide a reasonable estimate of the age of alteration in the Bonanza deposit.

DISCUSSION

The results of this $^{40}Ar/^{39}Ar$ study have important implications for the age of both the Toodoggone volcanics and related epithermal gold-silver deposits.

In general, the Toodoggone volcanics are older than was suggested by previous K-Ar data, and are much more restricted in their range of ages. The basal Toodoggone units have been fixed at ~197.6 Ma by the $^{40}Ar/^{39}Ar$ analysis of Shepard (1986), and the youngest age determined in our study for rocks near the top of the volcanics ("grey dacite" unit) is ~192.9 Ma. Although a small volume of younger volcanics overlying the "grey dacite" unit has been mapped by Marsden and Moore (1990), and erosion has not been taken into account, most of the Toodoggone volcanics appear to have formed during the earliest Pleinsbachian through the earliest Toarcian (*i.e.* entirely Early Jurassic; boundary estimates from Kent and Gradstein, 1985). Within this range it is possible to divide the volcanics into two stages on the basis of geological observations, but the stages cannot be distinguished from the geochronological data alone. Stage I rocks exhibit widespread, low-grade alteration, contain numerous gold-silver showings and range in age between 198 and 194 Ma. Stage II volcanics are less altered than Stage I, are not known to host significant mineralization, and have an age range in of 194 to 193 Ma. The 2σ errors in the $^{40}Ar/^{39}Ar$ ages are large enough to allow a hiatus of up to several million years between stages, but the stages are of essentially the same statistical age. For these reasons, we prefer to retain the division of the Toodoggone volcanics into two stages until such time as data clearly to the contrary become available.

The timing of the gold-silver mineralizing event in the district is significantly older than was suggested by previous K-Ar data. Deposits related to adularia-sericite alteration (*e.g.* Lawyers AGB and Cliff Creek, Shasta) formed between 187 and 190 million years ago, that is up to several million years following cessation of the main part of Toodoggone volcanism. In contrast, deposits associated with acid-sulphate alteration may have formed earlier in the Toodoggone volcanic history. The Bonanza deposit has an age of ~196 Ma and thus formed synchronously with Toodoggone Stage I volcanism. Although alunite $^{40}Ar/^{39}Ar$ ages were not determined in this study, the previous K-Ar ages for alunite of 190±7 Ma (Alberts Hump; Schroeter, 1982) and 193±7 Ma (Jan; Clark and Williams-Jones, 1989) are much older than K-Ar adularia and sericite dates. These alunitic alteration zones may also have formed during Stage I volcanism. A similar relationship, with adularia-sericite-related deposits forming up to several million years after the hostrocks, and acid-sulphate-type deposits forming almost contemporaneously with volcanism, has been documented for a number of other epithermal districts (*cf.* Heald *et al.*, 1987).

In spite of the paucity of alteration and mineralization in the Toodoggone Stage II volcanics, it appears that these rocks do constitute prospective units for exploration for Lawyers-type gold-silver deposits. Our revised metallogenic model suggests that all Toodoggone volcanics, underlying units, and coeval intrusions could contain epithermal mineralization. Regional-scale, low-grade alteration and acid-sulphate style gold mineralization appear to be restricted to the older, Stage I volcanics and possibly underlying units. However, all epithermal gold-silver mineralization in the district appears to have been related to Pleinsbachian to earliest Toarcian volcanic events, and mid-Pleinsbachian to mid-late Toarcian hydrothermal activity.

ACKNOWLEDGMENTS

Most of the $^{40}Ar/^{39}Ar$ analyses were conducted with funding through grant number RG89-17 from the British Columbia Geoscience Research Grant Program. Additional support was provided by the Natural Sciences and Engineering Research Council and Energy, Mines and Resources Canada (AEWJ), and the Ixion Research Group (JRC). Daniel R. Lux directed the $^{40}Ar/^{39}Ar$ analytical work at the University of Maine at Orono, and provided invaluable assistance with data interpretation. We are also grateful to Hugh Gabrielse for donating mineral separate GSC 76-77, and to Peter Thiersch and Henry Marsden for providing samples SH84-03 and SH-11, respectively. The study would not have been possible without the cooperation of Cheni Gold Mines Inc., Homestake Mining Canada Ltd., and Energex Minerals Ltd.

REFERENCES

Alexander, E.C., Mickelson, G.M. and Lanphere, M.A. (1978): MMhb-1: A New $^{40}Ar/^{39}Ar$ Dating Standard; *in* Short Papers of the Fourth International Conference on Geochronology, Cosmochronology and Isotope Geology, *United States Geological Survey*, Open File Report 78-701, pages 6-8.

Barr, D.A. (1978): Chappelle Gold-Silver Deposit, British Columbia; *Canadian Institute of Mining and Metallurgy*, Bulletin, Volume 72, Number 790, pages 66-79.

Carter, N.C. (1972): Toodoggone River Area; *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geology, Exploration and Mining in British Columbia 1971, pages 63-71.

Clark, J.R. and Williams-Jones, A.E. (1986): Geology and Genesis of Epithermal Gold-Barite Mineralization, Verrenass Deposit, Toodoggone District, British Columbia; *Geological Association of Canada*, Program with Abstracts, Volume 11, page 57.

Clark, J.R. and Williams-Jones, A.E. (1987): Metallogenic Implications of Lithotectonic Assemblages in the Toodoggone Au-Ag District, North-central B.C.; *Geological Association of Canada*, Program with Abstracts, Volume 12, page 32.

Clark, J.R. and Williams-Jones, A.E. (1988): A Preliminary Appraisal of the Au-Ag Metallogeny of the Toodoggone District, North-central British Columbia; *in* Geology and Metallogeny of Northwestern British Columbia Workshop, *Smithers Exploration Group – Geological Association of Canada*, Program with Abstracts, pages A33-A37.

Clark, J.R. and Williams-Jones, A.E. (1989): New K-Ar Isotopic Ages of Epithermal Alteration from the Toodoggone River Area, British Columbia (94E); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1988, Paper 1989-1, pages 409-412.

Dalrymple, G.B., Alexander, E.C., Lanphere, M.A. and Kraker, G.P. (1981): Irradiation of Samples for $^{40}Ar/^{39}Ar$ Dating Using the Geological Survey TRIGA Reactor; *United States Geological Survey*, Professional Paper 1176, 55 pages.

Dalrymple, G.B. and Lanphere, M.A. (1969): Potassium-Argon Dating; *W.H. Freeman*, San Francisco, 258 pages.

Diakow, L.J. (1984): Geology between Toodoggone and Chukachida Rivers (94E); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1983, Paper 1984-1, pages 139-145.

Diakow, L.J. (1985): Potassium-Argon Age Determinations from Biotite and Hornblende in Toodoggone Volcanic Rocks (94E); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1984, Paper 1985-1, pages 298-301.

Diakow, L.J., Panteleyev, A. and Schroeter, T.G. (1985): Geology of the Toodoggone River Area (94E); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Preliminary Map 61.

Fleck, R.J., Sutter, J.F. and Elliot, D.H. (1977): Interpretation of Discordant $^{40}Ar/^{39}Ar$ Age Spectra of Mesozoic Tholeiites from Antarctica; *Geochimica et Cosmochimica Acta*, Volume 41, pages 15-32.

Forster, D.B. (1984): Geology, Petrology and Precious Metal Mineralization, Toodoggone River Area, North-central British Columbia; unpublished Ph.D. thesis, *The University of British Columbia*, 223 pages.

Gabrielse, H., Wanless, R.K., Armstrong, R.L. and Erdman, L.R. (1980): Isotopic Dating of Early Jurassic Volcanism and Plutonism in North-central British Columbia; *in* Current Research, Part A, *Geological Survey of Canada*, Paper 80-1A, pages 27-32.

Halliday, A.N. (1978): $^{40}Ar/^{39}Ar$ Stepheating Studies of Clay Concentrates from Irish Orebodies; *Geochimica et Cosmochimica Acta*, Volume 42, pages 1851-1858.

Heald, P., Foley, N.K. and Hayba, D.O. (1987): Comparative Anatomy of Volcanic-hosted Epithermal Deposits: Acid-Sulfate and Adularia-Sericite Types; *Economic Geology*, Volume 82, pages 1-26.

Heizler, M.T. and Harrison, T.M. (1988): Multiple Trapped Argon Isotope Components Revealed by $^{40}Ar/^{39}Ar$ Isochron Analysis; *Geochimica et Cosmochimica Acta*, Volume 52, pages 1295-1303.

Hunziker, J.C., Frey, M., Clauer, N., Dallmeyer, R.D., Friedrichsen, H., Flehmig, W., Hochstrasser, K., Roggwiler, P. and Schwander, H. (1986): The Evolution of Illite to Muscovite: Mineralogical and Isotopic Data from the Glarus Alps, Switzerland; *Contributions to Mineralogy and Petrology*, Volume 92, pages 157-180.

Kent, D.V. and Gradstein, F.M., (1985): A Cretaceous and Jurassic Geochronology; *Geological Society of America Bulletin*, Volume 96, pages 1419-1427.

Marsden, H. and Moore, J.M. (1989): Stratigraphic and Structural Setting of the Shasta Ag-Au Deposit, North-central British Columbia (94E); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1988, Paper 1989-1, pages 395-407.

Marsden, H. and Moore, J.M. (1990): Stratigraphic and Structural Setting of the Shasta Ag-Au Deposit (94E); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1989, Paper 1990-1, pages 305-314.

Panteleyev, A. (1982): Toodoggone Volcanics South of Finlay River (94E/2); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1981, Paper 1982-1, pages 135-141.

Panteleyev, A. (1983): Geology Between Toodoggone and Sturdee Rivers; *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1982, Paper 1983-1, pages 143-148.

Schroeter, T.G. (1981): Toodoggone River Area (94E); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1980, Paper 1981-1, pages 124-131.

Schroeter, T.G. (1982): Toodoggone River Area (94E); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1981, Paper 1982-1, pages 122-133.

Schroeter, T.G., Diakow, L.J. and Panteleyev, A. (1986): Toodoggone River Area (94E); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1985, Paper 1986-1, pages 167-174.

Shepard, J.B. (1986): The Triassic-Jurassic Boundary and the Manicouagan Impact: Implications of $^{40}Ar/^{39}Ar$ Dates on Periodic Extinction Models; unpublished B.Sc. thesis, *Princeton University*, 38 pages.

Steiger, R.H. and Jäger, E. (1977): Subcommission on Geochronology; Convention on the Use of Decay Constants in Geo- and Cosmochronology, *Earth and Planetary Science Letters*, Volume 36, pages 359-362.

Thiersch, P. and Williams-Jones, A.E. (1990): Paragenesis and Ore Controls of the Shasta Ag-Au Deposit, Toodoggone River Area, British Columbia (94E); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1989, Paper 1990-1, pages 315-321.

Vulimiri, M.R., Tegart, P. and Stammers, M.A. (1987): Lawyers Gold-Silver Deposits, British Columbia; *in* Mineral Deposits of the Northern Cordillera, A. Morin, Editor, *Canadian Institute of Mining and Metallurgy*, Special Volume 37, pages 191-201.