

U-Pb Dating of Zircon and $^{40}\text{Ar}/^{39}\text{Ar}$ Dating of Biotite at Bingham, Utah

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Abstract

Uranium-lead dating of zircon and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of biotite provide a new estimate of the age of the Bingham hydrothermal system. The U-Pb age of zircon from the Last Chance monzonite establishes the age of crystallization of this intrusion at 38.55 ± 0.19 Ma (2σ , MSWD = 2.08). The oldest hydrothermal event in the monzonite is dated at 38.40 ± 0.16 Ma and is based on a $^{40}\text{Ar}/^{39}\text{Ar}$ determination plateau age of primary igneous biotite. This age is indistinguishable from the U-Pb zircon age of emplacement of the monzonite. Petrographic and fluid inclusion data show that the biotite-bearing sample was propylitically altered at $\sim 400^\circ\text{C}$, which would reset the $^{40}\text{Ar}/^{39}\text{Ar}$ age within ~ 115 ka. Thus the concordance of the biotite age with the intrusion age of the monzonite suggests that propylitic alteration was essentially contemporaneous with monzonite emplacement. The $^{40}\text{Ar}/^{39}\text{Ar}$ ages from three hydrothermal biotites sampled within the 0.35 percent Cu isopleth in the monzonite overlap within uncertainty and indicate that potassic alteration in monzonite occurred at 37.57 ± 0.11 Ma. The youngest hydrothermal activity is identified from a biotite sample (37.07 ± 0.21 Ma correlation age) in potassically altered quartz monzonite porphyry within the central MoS_2 zone. Hydrothermal biotite within the Bingham deposit was produced over a time period of approximately 0.50 ± 0.32 Ma.

Introduction

THE PORPHYRY-TYPE, Cu-Mo-Au ore deposit at Bingham, Utah, is located in the central Oquirrh Mountains 32 km southwest of Salt Lake City, Utah (Fig. 1A). The ore deposit is largely within, and related to, the hydrothermally altered and mineralized composite Bingham stock (Fig. 1B) (Bray, 1969; Lanier et al., 1978a, b). Preliminary reserves in the Bingham porphyry deposit were 3.1 billion tons, averaging 0.73 percent Cu, 0.043 percent MoS_2 , and 0.013 oz/t Au (Krahulec, 1998). Much of the chronological work on the intrusive aspects of the deposit was done in previous K-Ar studies of the 1970s (Warnaars et al., 1978, and references therein). Warnaars et al. (1978) suggested that Bingham porphyry copper mineralization lasted at least from 38.8 Ma to the youngest hydrothermal biotite at 36.6 Ma, a time span of 2.2 m.y. Lack of precision in the K-Ar age determinations and the fact that biotite was the main mineral that was dated leave considerable uncertainty in the ages of events at Bingham.

Numerical modeling shows that the intrusive heat source of most hydrothermal systems is likely to have cooled in a few tens of thousands of years (Cathles et al., 1997) and that longer lived systems are likely the result of multiple intrusive episodes. Upper limits for the duration of hydrothermal system activity have been estimated by $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology

at Potrerillos, Chile (Marsh et al., 1997). This study showed that the large Cobre porphyry copper deposit hydrothermal system cooled from hornblende closure at 570°C to biotite closure at $\sim 300^\circ\text{C}$ in 230,000 yr or less and that the smaller Norte porphyry copper deposit cooled to plagioclase closure at 250°C in 120,000 yr or less.

The purposes of this paper are to date the emplacement of the Bingham monzonite using U-Pb dating of zircon, and to date hydrothermal biotite using precise $^{40}\text{Ar}/^{39}\text{Ar}$ methods for a better estimate of the timing and duration of porphyry-copper-type mineralization at Bingham.

Geology of the Bingham Mine

Igneous rocks

The Bingham stock is a monzonite that has been intruded by quartz monzonite porphyry in its northwestern part (Fig. 2). The monzonite occurs in two masses that represent one intrusive phase: a southwest portion known as the Last Chance stock is connected to a northeast mass known as the Bingham stock by the Phoenix dike (Lanier et al., 1978b; Phillips et al., 1998). Both monzonite and quartz monzonite porphyry are cut by latite porphyry dikes and later quartz latite porphyry dikes, both of which are altered (Fig. 2). Relatively unaltered plugs of quartz latite porphyry crosscut all of the above intrusive rocks. The disseminated Cu, Mo, and Au

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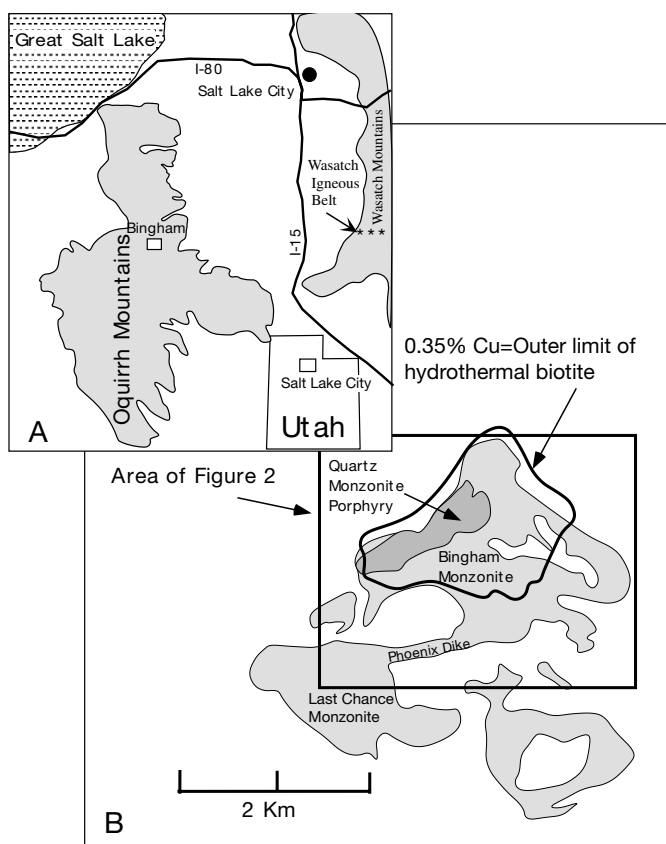


FIG. 1. A. Index map showing the location of Bingham in the Oquirrh Mountains. B. Simplified map of the Bingham intrusive complex showing the outer limit of biotite alteration and the area of Figure 2.

mineralization is associated with zoned hydrothermal alteration that is approximately centered on the quartz monzonite porphyry.

Hydrothermal alteration

Hydrothermal alteration of the igneous rocks at Bingham includes an inner zone of potassic alteration of monzonite and quartz monzonite porphyry, a transition zone where potassic alteration overlaps propylitic alteration, and a peripheral zone of propylitic alteration of monzonite. Intermediate argillic alteration is superimposed on potassically altered quartz monzonite porphyry in the most highly mineralized area of the mine. Illite veins and illite selvages on quartz-pyrite veins form a phyllic alteration zone peripheral to the intermediate argillic zone that is also superimposed on potassic alteration. Generalized distribution of alteration zoning in the Bingham deposit is shown in Figure 2. Mineralogical, textural, and paragenetic relationships from Moore and Nash (1974), Lanier et al. (1978a, b), Moore (1978), Bowman et al. (1987), Babcock et al. (1998), Parry et al. (1998), and Phillips et al. (1998) are summarized in Table 1.

Ore zones

Ore minerals are zoned around a central, low-grade core within quartz monzonite porphyry, which contains less than 0.5 percent pyrite, chalcopyrite, bornite, and molybdenite. A molybdenite zone with more than 0.15 percent MoS_2 surrounds the low-grade core and grades outward into a high-grade bornite and chalcopyrite zone. A peripheral pyrite and chalcopyrite zone with up to 2.5 percent chalcopyrite surrounds the innermost, high-grade zone. The outermost sulfide zone is a pyrite halo with up to 7 percent pyrite where

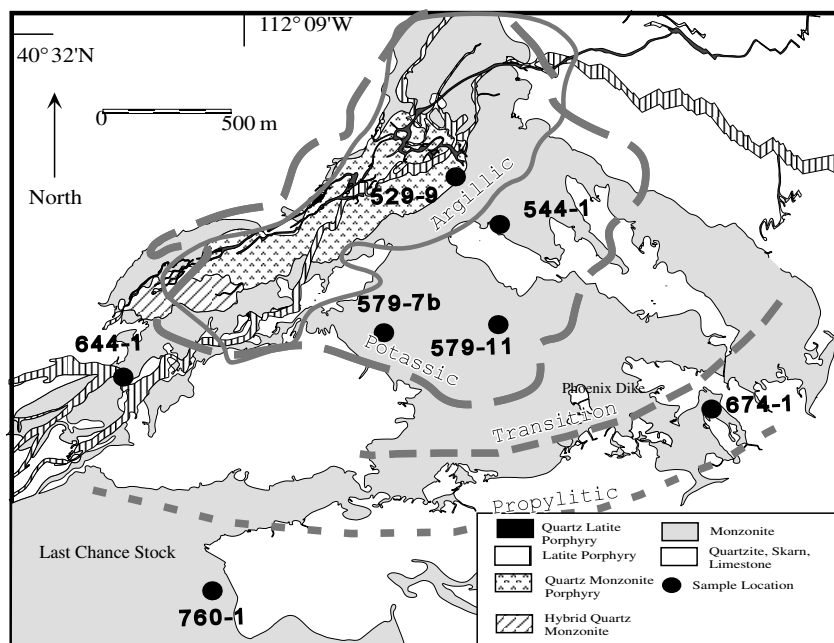


FIG. 2. Generalized and simplified geology of the Bingham mine showing alteration zones and sample locations. The outer limit of potassic alteration approximately corresponds to the 0.35 percent copper isopleth. The mine center is near sample 529-9. Sample location key indicates the first three digits of the pit elevation where the sample was collected. Geology modified from Phillips et al. (1998).

TABLE 1. Alteration Types at Bingham

Alteration type	Rock unit	Alteration mineralogy	Texture	Temperature (°C)	Relative timing
Propylitic	Monzonite	Actinolite + chlorite + epidote 15% ¹	Vein, replacement, disseminated	287–480 ²	Earliest
Transition	Monzonite	Hydrothermal biotite K feldspar Actinolite 10–15%, chlorite, epidote	Vein Vein and vein selvages Vein, replacement, disseminated	337–550 ²	Biotite, K feldspar younger than actinolite, chlorite, epidote
Potassic	Monzonite	Hydrothermal biotite 25–30% K feldspar 20–40%	Vein, replacement, disseminated	300–650 ²	Cuts propylitic alteration
	Quartz Monzonite Porphyry	Hydrothermal biotite 15% or less K feldspar 20–40%	Vein, replacement, disseminated		
Phyllic	Monzonite	Illite, sulfide and sulfosalt traces of smectite and kaolinite	Veins and vein selvages	175–260 ³	Cuts propylitic and potassic alteration
Intermediate argillic	Quartz Monzonite Porphyry	Illite up to 40% smectite up to 20% kaolinite up to 5%	Replacement of plagioclase	175–260 ³	Latest superimposed on potassic alteration

¹ Mineral abundance in volume percent

² Fluid inclusion homogenization temperature from Bowman et al. (1987)

³ Estimate from mineral characteristics from Parry et al. (1998)

disseminated Cu mineralization is below ore grade (John, 1978; Phillips et al., 1998). Highest gold grades are mostly in quartz monzonite porphyry and gold correlates with bornite (Ballantyne et al., 1998; Phillips et al., 1998).

Previous dating studies at the Bingham mine

Conventional K-Ar dates of altered but unmineralized monzonite (not containing ore-grade copper) reported by Moore et al. (1968), McDowell (1971), Moore and Lanphere (1971), Moore (1973), and Warnars et al. (1978) ranged from 38.9 ± 2.0 to 41.4 ± 2.6 Ma (Table 2). All the unmineralized samples came from the propylitic alteration area and contain epidote and other alteration products. The age of intrusion of the monzonite, given by Warnars et al. (1978) as 39.8 ± 0.8 Ma (Table 2), is calculated from the average of six biotite ages and one pyroxene age from unmineralized monzonite.

The oldest of the unmineralized monzonite ages from sample M1 is 41.4 ± 2.6 Ma (Table 2; McDowell, 1971). The sample is a biotite from the Phoenix dike that lies within the propylitic alteration zone. The remaining biotite samples from the monzonite show an increase in apparent age from 37.8 Ma at the quartz monzonite porphyry contact to 39.8 Ma 3 km away from this contact (see fig. 3, p. 1246, Warnars et al., 1978). This systematic variation in apparent age was explained as an effect of the hydrothermal heat aureole around the quartz monzonite porphyry by Warnars et al. (1978).

We have recalculated the data presented in Warnars et al. (1978) by weighting each age by the inverse of the variance. Variance weighted means and 2σ values are shown in Table 2. The weighted mean errors are generally larger than the errors given in the compilation by Warnars et al. (1978). The precision of the data shown in Table 2 does not allow for recognition of discrete igneous events from the samples that they

interpreted as unmineralized igneous rocks. The recalculated error weighted mean age of unmineralized monzonite is 39.7 ± 1.0 Ma. The error weighted mean age of altered rocks is 37.0 ± 0.5 Ma, which is distinguishable from the ages of unmineralized rocks. Inclusion of the two K-Ar ages from altered rocks obtained by Moore and Lanphere (1971) would define a mean age at approximately 36.6 ± 0.6 Ma (sample 20B' in Table 2) that falls near the error weighted mean for the ages of other altered rocks. However, the real uncertainties in sample 20B' are probably greater than estimated by Moore and Lanphere (1971).

Warnars et al. (1978) argue that the copper mineralization ended before the emplacement of quartz latite porphyry plugs in the central pit (38.8 ± 0.6 Ma). Their argument was based on the observation that the plugs are weakly altered, weakly mineralized, and crosscut mineralized quartz veins, intensely mineralized and altered monzonite, and quartz monzonite porphyry.

Evidence for active mineralization lasting until about 37.7 Ma consists of a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 37.72 ± 0.09 Ma for a mineralized quartz latite porphyry dike and an age of 37.74 ± 0.11 Ma for a minette dike in the mine area (Deino and Keith, 1998). An Re-Os age of molybdenite within the quartz monzonite porphyry is 37.00 ± 0.27 Ma (Chesley and Ruiz, 1998). Parry et al. (1998) report a total gas age of 37.97 ± 0.27 Ma for phyllic alteration from the 10- to 20- μm split of vein illite and a highly interpreted age of 37.21 ± 0.56 Ma for argillic alteration from illite replacing plagioclase in quartz monzonite porphyry.

Age Measurements

Dated samples are described in Table 3, and sample locations are shown in Figure 2. Methods of sample collection and analyses are described in Appendix 1.

TABLE 2. K-Ar Data from Table 1 of Warnaars et al. (1978) with Recalculated Error Weighted Mean Ages for Each Group (errors are 2σ calculated from the 1σ errors in Warnaars et al. (1978))

Sample ¹	Age $\pm 2\sigma$ error ² (Ma)	Mean age $\pm 2\sigma$ error ³ (Ma)	Lithology
M1	41.4 \pm 2.6		
1	39.9 \pm 2.4		
2	39.5 \pm 2.6		
3	39.2 \pm 2.6	39.8 \pm 0.8	
4	38.9 \pm 2.0	39.7 \pm 1.0	Unmineralized monzonite
D1-b	39.5 \pm 1.6		
D1-p	40.0 \pm 1.6		
8	38.7 \pm 2.4	38.6 \pm 0.2	
9	38.7 \pm 2.4	38.6 \pm 1.4	Weakly altered monzonite
10	38.4 \pm 2.4		
23A	38.1 \pm 3.8	37.8 \pm 0.4	
23B	37.8 \pm 3.8	37.7 \pm 1.8	Strongly altered monzonite
24	37.5 \pm 2.4		
25	36.9 \pm 3.0	37.5 \pm 0.8	
D2	38.0 \pm 1.6	37.8 \pm 1.6	Strongly mineralized quartz monzonite porphyry
26	36.7 \pm 0.5	36.7 \pm 0.5	Mineralized vein
11A	38.2 \pm 2.4	38.0 \pm 0.4	
11B	38.2 \pm 2.4	38.0 \pm 1.4	Mineralized latite porphyry
M2	37.7 \pm 2.2		
21	38.6 \pm 2.0	37.7 \pm 1.0	
22	36.8 \pm 3.2	37.9 \pm 1.6	Mineralized quartz latite porphyry
M3	37.7 \pm 2.2		
19A	39.2 \pm 3.8	38.8 \pm 0.6	
19B	39.1 \pm 3.8	38.6 \pm 1.6	Weakly mineralized quartz latite porphyry
20A	39.0 \pm 2.6		
20B	37.8 \pm 2.6		
20B'	36.6 \pm 0.6	36.6 \pm 0.6 37.0 \pm 0.5	Hydrothermal biotite Altered rocks

¹ p = pyroxene, all others are biotite² All ages recalculated using the decay constants of Steiger and Jäger (1977)³ Ages and errors in bold type are calculated weighted mean values using the inverse of the variance to weight in each result (Samson and Alexander, 1987)

Uranium-lead

Zircons extracted from the sample are generally small euhedra (100 μ m in average length) that are clear to pale yellow, bipyramidal, and prismatic. Some contain green mineral inclusions, possibly clinopyroxene.

Four multigrain fractions of clear, inclusion- and crack-free zircon were selected for U-Pb isotope analysis (see Table 4 for number of grains and mass of each zircon fraction). Three of these analyses plot concordantly, within error, on a concordia plot (see Fig. 3), indicating reproducible U-Pb ages and a closed isotopic system. The values for the fourth, and largest, zircon fraction (Z3) plot slightly above the other results, indicating the presence of some component of inherited, xenocrystic zircon (likely Paleoproterozoic in age) in that particular fraction. Excluding Z3, the three concordant analyses yield a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 38.55 ± 0.19 Ma (95% confidence, MSWD = 2.08).

$^{40}\text{Ar}/^{39}\text{Ar}$

Five $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating age spectra were obtained on one igneous and three hydrothermal biotite separates

from altered monzonite and one biotite from altered quartz monzonite porphyry (Table 3). Step heating results are shown in Appendix 2.

Biotite samples 674-1, 579-11, 579-7b, and 544-1 from monzonite all yield flat age spectra (Fig. 4) for 100 percent of the total ^{39}Ar released. The oldest plateau age of 38.40 ± 0.16 Ma from igneous phenocrysts in sample 674-1 (Fig. 4A) is indistinguishable from the U-Pb zircon age of 38.55 ± 0.19 Ma. Hydrothermal biotite from samples 579-7b (Fig. 4B), 579-11 (Fig. 4C), and 544-1 (Fig. 4D) all yield analytically indistinguishable plateau ages of 37.45 ± 0.11 , 37.60 ± 0.11 , and 37.57 ± 0.09 Ma, respectively (Table 5).

Isotopic correlation analyses (Fig. 5) yield concordant ages with the plateau ages for these biotites and have trapped initial $^{40}\text{Ar}/^{36}\text{Ar}$ compositions within error of the atmospheric value (Table 5).

The age spectrum for sample 529-9 biotite from quartz monzonite porphyry yields relatively old apparent ages for the initial heating steps, followed by a fairly flat portion for the final 90 percent of gas release (Fig. 6). The minor complexity appears to be caused by excess argon contamination. This is supported by the isotopic correlation analysis (Fig. 7), which

TABLE 3. Description of Dated Samples from the Bingham Porphyry Copper Deposit

Sample	Rock unit	Alteration	Description	Dated material	Method
760-1	Monzonite	Least altered	Epidote and pyrite fill penetrative fractures; 1997 collection	Zircon	U-Pb
674-1	Monzonite	Propylitic	Vein and disseminated actinolite, chlorite, and epidote; actinolite replaces amphibole phenocrysts; hydrothermal biotite rims and replaces amphibole; igneous biotite phenocrysts about 6%; clay replacing hornblende; fluid inclusion homogenization temperatures in quartz 365°–480°C, mean is 403° ± 35°C; 1978 collection	Igneous biotite phenocryst	⁴⁰ Ar/ ³⁹ Ar
579-11	Monzonite	Potassic	Disseminated hydrothermal biotite 35%; igneous biotite 6%; K feldspar replaces plagioclase; 2% disseminated illite; trace chlorite; 1978 collection; 520 m from monzonite-quartz monzonite porphyry contact	Hydrothermal biotite (85%)	⁴⁰ Ar/ ³⁹ Ar
579-7b	Monzonite	Potassic	Disseminated and veinlet hydrothermal biotite 30%; igneous biotite 5% with rutile inclusions; K feldspar + quartz replace plagioclase and matrix; disseminated and vein chlorite; disseminated and vein clay, less than 1% illite; fluid inclusion homogenization temperatures in quartz 368°–600°C, mean is 462° ± 70°C; 1978 collection; 305 m from monzonite-quartz monzonite porphyry contact	Hydrothermal biotite (85%)	⁴⁰ Ar/ ³⁹ Ar
544-1	Monzonite	Potassic	K feldspar, hydrothermal biotite, trace chlorite, epidote, calcite, disseminated illite; vein and disseminated clay; 1978 collection; 290 m from monzonite-quartz monzonite porphyry contact	Hydrothermal biotite (100%)	⁴⁰ Ar/ ³⁹ Ar
529-9	Quartz monzonite porphyry	Potassic	Potassic alteration with superimposed pervasive argillic alteration of plagioclase phenocrysts; 6% illite, 6% smectite, trace kaolinite, 10% hydrothermal biotite	Hydrothermal biotite (100%)	⁴⁰ Ar/ ³⁹ Ar

reveals a very well defined array (MSWD = 1.23) for all but the first heating step and yields an apparent age of 37.07 ± 0.21 Ma and a trapped initial ⁴⁰Ar/³⁶Ar composition of 312.1 ± 3.4. This isotopic correlation age is analytically indistinguishable from the plateau age of 37.25 ± 0.22 Ma given by the final four heating steps. Because the isotopic correlation technique makes no assumptions regarding the composition of the initial argon, and because nearly all of the heating steps are well correlated, the isotopic correlation age is suggested to represent the closure age of the biotite.

Discussion

In the following discussion, we compare the age of intrusion of the monzonite determined by U-Pb zircon dating to

the age of hydrothermal biotite determined by ⁴⁰Ar/³⁹Ar dating. When comparing two age results produced by two methods, the absolute accuracy of the methods becomes a consideration. Analytical errors have decreased dramatically for both the U-Pb and ⁴⁰Ar/³⁹Ar methods. The largest remaining factors contributing to our ability to directly compare results comes from uncertainty in the age of the ⁴⁰Ar/³⁹Ar flux monitor and the ⁴⁰K decay constants (Renne et al., 1998; Lanphere and Dalrymple, 2000; Min et al., 2000; Scaillet, 2000). For purposes of this study the true age of our standard Fish Canyon sanidine is the limiting factor in determining the timing of biotite closure to argon loss relative to the U/Pb zircon-determined intrusion age of the monzonite. Adopting the decay constant and age for Fish Canyon sanidine reported by

TABLE 4. U-Pb Analytical Data for Zircons from Sample 760-1 of the Bingham Monzonite

Fraction	Mass (mg)	U ² (ppm)	Th/U ³	Common Pb (pg) ⁴	²⁰⁶ Pb/ ²⁰⁴ Pb ⁵	²⁰⁶ Pb/ ²³⁸ U ⁶	²⁰⁷ Pb/ ²³⁵ U ⁶	²⁰⁷ Pb/ ²⁰⁶ Pb ⁶	²⁰⁶ Pb/ ²³⁸ U age (Ma)
760-1-z2	0.106	167	1.55	12.8	549	0.006011 ± 16	0.03893 ± 98	0.0467 ± 11	38.63 ± .10
760-1-z1	0.083	320	1.52	5.0	2052	0.005980 ± 36	0.03870 ± 36	0.04694 ± 30	38.43 ± .24
760-1-z3 ¹	0.110	290	1.11	16.2	780	0.006044 ± 14	0.03956 ± 68	0.04747 ± 78	38.84 ± .10
760-1-z4	0.030	363	1.44	1.3	3268	0.005989 ± 18	0.03886 ± 2	0.04706 ± 22	38.50 ± .12

¹ Not included in age calculation

² U concentrations known to be better than 5% for sample weights over 50 mg and about 50% for sample weights below 2 mg

³ Model Th/U inferred from ²⁰⁸Pb/²⁰⁶Pb using the ²⁰⁷Pb/²⁰⁶Pb age

⁴ Total common Pb (corrected for fractionation and spike), assigned to blank and subtracted from total Pb for age calculations

⁵ Corrected for fractionation and spike

⁶ Corrected for fractionation, spike, blank Pb, and initial common Pb if total common Pb > 5pg; initial Pb composition estimated using Stacey and Kramers (1975) model; uncertainty estimated with error propagation procedure that accounts for measurement errors, blank uncertainties, and reproducibility of Pb and U standards and the effect of an uncertainty of ±2% on the initial Pb composition and 1% on the blank Pb composition; uncertainties on ratios and ages are quoted at 2σ level of confidence

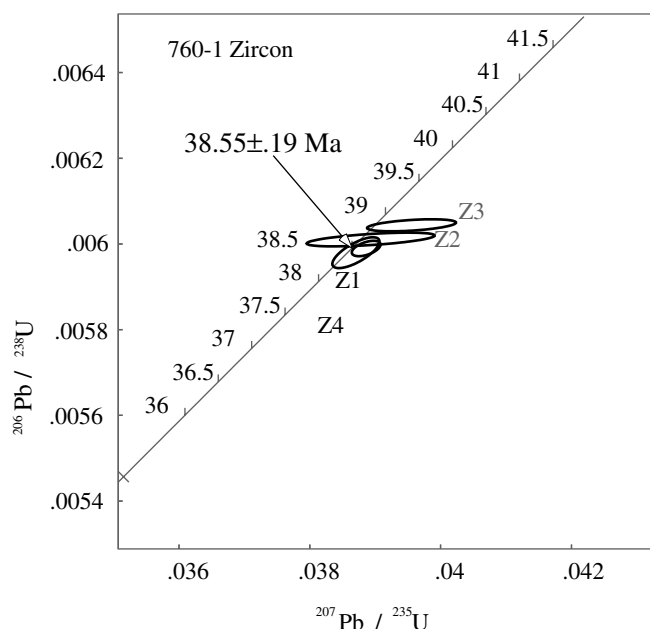


FIG. 3. U-Pb concordia diagram for zircon from the monzonite.

Min et al. (2000) yields an age of 38.69 Ma for sample 674-1 biotite, which is somewhat older than the reported U/Pb age of 38.55 Ma determined for the monzonite in this study. In

contrast, adopting the Fish Canyon age of 27.55 Ma and Steiger and Jäger (1977) decay constants argued for by Lanphere and Dalrymple (2000) yields an age of 38.00 Ma for sample 674-1 biotite, which is somewhat lower than the U-Pb age. We see no compelling reason at this point to change to either of these ages until further resolution of the true age of Fish Canyon sanidine can be obtained. Thus, interpretations for the events at Bingham will be presented based on an age of 27.84 Ma for Fish Canyon sanidine and the decay constants recommended by Steiger and Jäger (1977). Also, the reader should be aware that the relative difference in $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages reported here are not affected by flux monitor ages or decay constants. However, comparison of $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar ages suffers from uncertainty in flux monitor age and spike calibration.

The geologically constrained timing relationships are summarized with the geochronological data in Figure 8. Age results are discussed below and samples chosen for Figure 8 are those that we interpret to have meaningful and accurate measures of discrete events at Bingham.

The U-Pb age of 38.55 ± 0.19 Ma of zircon in sample 760-1 is interpreted to represent the age of crystallization of the zircons and the emplacement age of the Bingham monzonite (Fig. 8). This U-Pb age is 1 m.y. younger than the mean K-Ar age (39.8 ± 0.8 Ma, Table 2) of "unmineralized" monzonite samples calculated by Warnaars et al. (1978).

Biotite sample 674-1 is an igneous phenocryst from within propylitically altered monzonite. Fluid inclusions in quartz

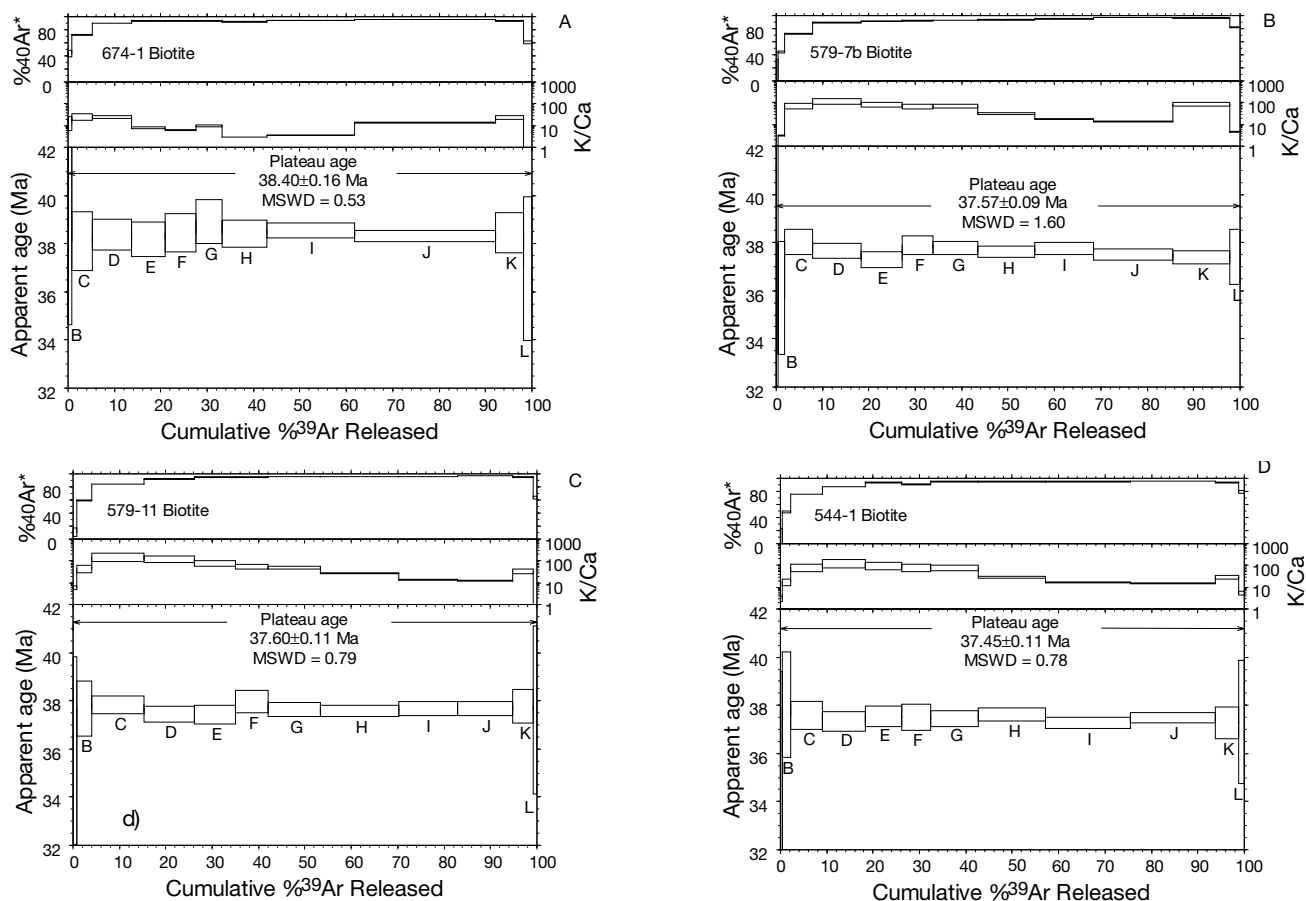


FIG. 4. Ar-Ar spectra for biotite from the monzonite at Bingham, Utah.

TABLE 5. Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronologic Data for Biotite from the Bingham Porphyry Copper Deposit, Utah

Sample	Total gas age (Ma $\pm 2\sigma$)	Plateau age (Ma $\pm 2\sigma$)	^{39}Ar (%) in the plateau or preferred age	Correlation age (Ma $\pm 2\sigma$)	MSWD	Initial $^{40}\text{Ar}/^{36}\text{Ar}$ $\pm 2\sigma$
674-1	38.41 \pm 0.60	38.40 \pm 0.16	100	38.40 \pm 0.23	0.62	295 \pm 20
579-11	37.55 \pm 0.46	37.60 \pm 0.11	100	37.63 \pm 0.13	0.85	292.7 \pm 6.8
579-7b	37.54 \pm 0.52	37.57 \pm 0.09	100	37.55 \pm 0.12	1.84	296.7 \pm 6.6
544-1	37.34 \pm 0.52	37.45 \pm 0.11	100	37.48 \pm 0.13	0.86	292.7 \pm 8.8
529-9	37.78 \pm 0.43	37.25 \pm 0.22	53.8	37.07 \pm 0.21	1.23	312.1 \pm 3.4

from this sample homogenize at 365° to 480°C (mean of 15 measurements is 403° \pm 35°C). The concordance of the biotite (38.40 \pm 0.16 Ma plateau age) with that of the U-Pb zircon age (Fig. 8) suggests that the biotite closed to argon loss soon after intrusion and has not undergone significant argon loss since. Using the reported argon kinetic parameters of Harrison et al. (1985), the effect of propylitic alteration on the apparent age of sample 674-1 biotite can be estimated. At 400°C, the biotite age would be reset in about 115 ka, thus propylitic alteration that occurred significantly later than monzonite intrusion would produce a younger age for sample 674-1. The age of propylitic alteration is indistinguishable from the age of emplacement of the monzonite. Note that if the age for Fish Canyon sanidine standard reported by Lanphere and Dalrymple (2000) were used, the estimated age of propylitic alteration would be ~0.5 Ma after emplacement of

the monzonite. A shorter duration alteration event or a lower temperature event could be significantly younger than the intrusion.

Biotite samples 544-1 (37.45 \pm 0.11 Ma), 579-11 (37.60 \pm 0.11 Ma), and 579-7b (37.57 \pm 0.09 Ma) are hydrothermal biotites from the monzonite. These younger, hydrothermal biotites have a weighted mean age of 37.57 \pm 0.11 Ma (MSWD = 2.2) and are shown in Figure 8. They are all significantly younger than the emplacement age of the monzonite, and their plateau ages are interpreted to record the time when they cooled below ~350°C. In addition, these ages are indistinguishable from the total gas age of crosscutting vein illite (37.97 \pm 0.27 Ma) reported by Parry et al. (1998). In contrast to Warnaars et al. (1978), the ages of hydrothermal biotites in the monzonite do not differ from each other even though the samples are at varying distances

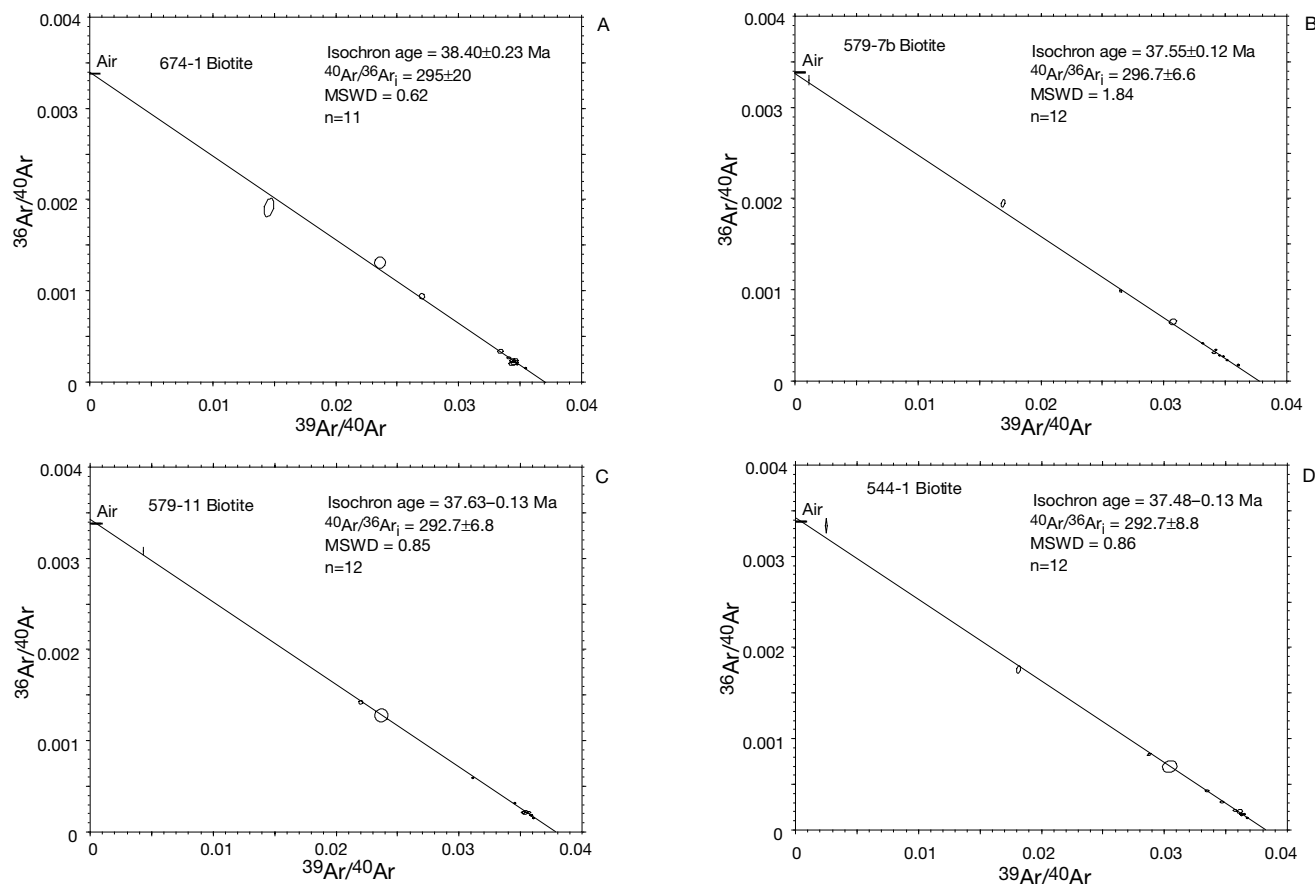


FIG. 5. Inverse correlation plots for biotite from the monzonite and quartz monzonite porphyry at Bingham, Utah.

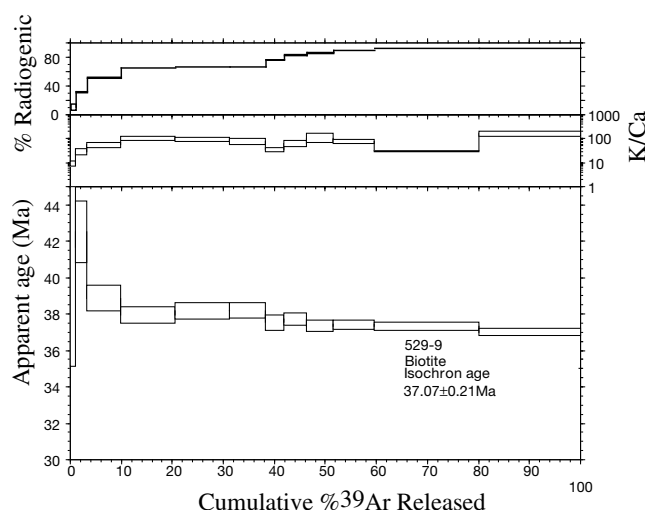


FIG. 6. Ar-Ar spectra for biotite from quartz monzonite porphyry.

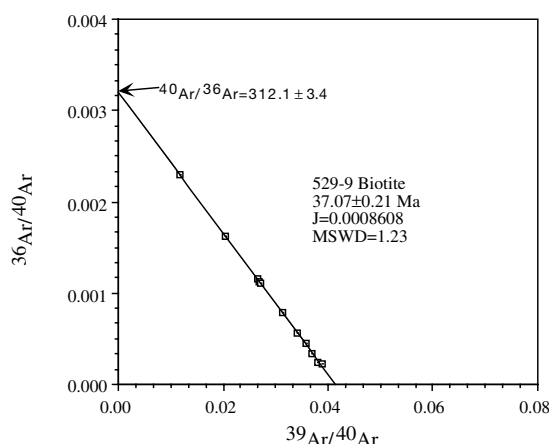


FIG. 7. Inverse correlation plot for biotite from sample 529-9.

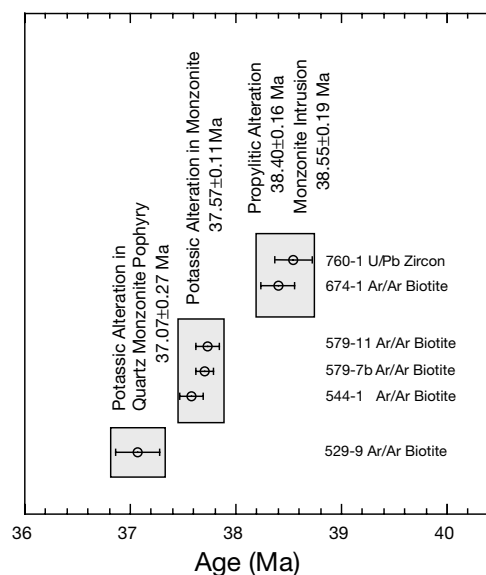


FIG. 8. Summary of the timing of events at Bingham.

(290, 305, and 520 m, respectively) from the quartz monzonite porphyry-monzonite contact. These samples, collected in 1978, are from somewhat deeper exposures, but temperatures and cooling rates were probably similar to the Warnaars et al. (1978) samples. Hydrothermal temperatures in the potassic alteration zone as measured in fluid inclusions in quartz are 300° to 650°C (Bowman et al., 1987). The weighted mean age of these three biotite samples is our preferred age of formation of hydrothermal biotite in the monzonite and the timing of potassic alteration.

Hydrothermal biotite (sample 529-9; 37.07 ± 0.21 Ma) and molybdenite (37.00 ± 0.27 Ma; Chesley and Ruiz, 1998) from the quartz monzonite porphyry have interpreted ages that agree. However, a 1 percent uncertainty in ^{187}Re decay constant (Bergemann et al., 2001) would add an additional 0.37 m.y. to the uncertainty in molybdenite age so that it overlaps all of the hydrothermal biotite ages. The hydrothermal biotite ages (36.7 ± 0.5 , 36.6 ± 0.6 Ma) reported by Moore and Lanphere (1971) from the quartz monzonite porphyry are somewhat younger but do overlap at 2σ with our results from hydrothermal biotite in the quartz monzonite porphyry. Two episodes of formation of hydrothermal biotite are indicated. Hydrothermal biotite in the monzonite may be related to emplacement of the quartz monzonite porphyry, and the biotite in the quartz monzonite porphyry may be related to emplacement of latite porphyry or quartz latite porphyry dikes.

The emplacement age of the quartz monzonite porphyry is constrained by dating of igneous rocks exhibiting crosscutting relationships with the quartz monzonite porphyry. The maximum age of the quartz monzonite porphyry is the 38.55 ± 0.19 Ma U-Pb age of the monzonite intrusion by the quartz monzonite porphyry. The most precise minimum age for the quartz monzonite porphyry is provided by $^{40}\text{Ar}/^{39}\text{Ar}$ ages of crosscutting quartz latite porphyry (37.72 ± 0.09 Ma) and minette dikes (37.74 ± 0.11 Ma; Deino and Keith, 1998). Deino and Keith (1998) used the same flux monitor and age as our study. Therefore, the age of the quartz monzonite porphyry must lie between 38.55 ± 0.19 and 37.73 ± 0.10 Ma.

The duration of hydrothermal activity at Bingham lasted continuously or episodically from crystallization of the monzonite at 38.55 ± 0.19 Ma to formation of hydrothermal biotite in the quartz monzonite porphyry at 37.07 ± 0.21 Ma, a duration of at least ~ 1.48 m.y. Formation of hydrothermal biotite representing potassic alteration in the porphyry-copper style of hydrothermal activity lasted from 37.57 ± 0.11 Ma in the monzonite to 37.07 ± 0.21 Ma in quartz monzonite porphyry, a duration of 0.50 ± 0.32 Ma. Regardless of the uncertainties in comparing Ar/Ar, Re-Os, and U-Pb geochronologic results, this conclusion is upheld because the entire duration is recorded by the biotite Ar/Ar results.

Relationship of Bingham events to the Wasatch igneous belt

The Wasatch igneous belt is a series of stocks, minor intrusions, and volcanic rocks that occur in the central Wasatch Mountains (Fig. 1A). The intrusions of the belt are aligned along the east-west Uinta-Little Cottonwood lineament (Vogel et al., 1998). Bingham occurs farther west and appears to be a continuation of intrusive activity along this belt. Several base and precious metal deposits are associated with the Wasatch igneous belt, including the Park City, Little Cottonwood, and

Big Cottonwood mining districts (John, et al., 1998). These deposits include Ag-Pb-Zn replacements and veins, a low-grade porphyry Cu-Au deposit, a low F porphyry molybdenite deposit, Cu skarns, and quartz-alunite Au deposits.

Igneous rock emplacement ages determined by U-Pb dating of zircon in the belt, from east to west, are Ontario stock, 36.0 ± 2.0 Ma; Clayton Peak stock, 35.5 ± 1.5 Ma; Alta stock, 33.5 ± 1.0 Ma; and Little Cottonwood stock, 30.5 ± 0.6 Ma (Vogel et al., 1998). The ages are successively younger ages to the west. John et al. (1998) propose that igneous emplacement in the Wasatch igneous belt occurred from 41 to 30 Ma. Based on U-Pb dating, Vogel et al. (1998) interpret the Wasatch igneous belt to have been emplaced between 32 to 36 Ma. John et al. (1998) and Vogel et al. (1998) agree that most of the igneous rocks in the western Wasatch igneous belt were emplaced between 30 and 36 Ma and mineral deposits formed between 23.5 and 36 Ma, with most of the mineralization occurring between 31.4 and 36 Ma.

The emplacement of the Bingham stock at 38.55 Ma, determined in this study, is older than the 30 to 36 Ma ages of the Little Cottonwood, Alta, Clayton Peak, and Ontario stocks (John et al., 1998; Vogel et al., 1998). Bingham may be older than all igneous activity in the Wasatch igneous belt. The range in ages of 38.55 and 37 Ma of major hydrothermal-mineralization events at Bingham is older than all mineralization-hydrothermal events in the Wasatch igneous belt.

Conclusions

The results of U-Pb dating of zircon and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of biotite constrain the age of crystallization of the monzonite phase of the Bingham stock and the age of hydrothermal alteration in the monzonite and quartz monzonite porphyry. The U-Pb age of zircon from the monzonite is 38.55 ± 0.19 Ma. The $^{40}\text{Ar}/^{39}\text{Ar}$ age of biotite in the most distal sample in propylitically altered rocks is 38.40 ± 0.16 Ma, which is indistinguishable from the crystallization age. Three hydrothermal biotite samples from potassically altered monzonite have an error weighted mean age of 37.57 ± 0.11 Ma. Hydrothermal biotite from potassically altered quartz monzonite porphyry has an age of 37.07 ± 0.21 Ma. These results suggest a minimum duration of ~1.48 m.y. for the hydrothermal activity at Bingham lasting from emplacement of the monzonite to alteration of the quartz monzonite porphyry. The duration of hydrothermal biotite formation and porphyry-copper-style alteration was 0.50 ± 0.32 Ma.

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REFERENCES

- Babcock, R.L., Jr., Ballantyne, G.H., and Phillips, C.H., 1998, Summary of the geology of the Bingham district, Utah: Society of Economic Geologists Guidebook, v. 29, p. 113–132.
- Ballantyne, G.H., Smith, T.W., and Redmond, P.B., 1998, Distribution and mineralogy of gold and silver in the Bingham Canyon porphyry copper deposit, Utah: Society of Economic Geologists Guidebook, v. 29, p. 147–153.
- Bowman, J.R., Parry, W.T., Kropp, W.P., and Kruer, S.A., 1987, Chemical and isotopic evolution of hydrothermal solutions at Bingham, Utah: *ECONOMIC GEOLOGY*, v. 82, p. 395–428.
- Bray, R.E., 1969, Igneous rocks and hydrothermal alteration at Bingham, Utah: *ECONOMIC GEOLOGY*, v. 64, p. 34–49.
- Cathles, L.M., Erendi, A.H., and Barrie, T., 1997, How long can a hydrothermal system be sustained by a single intrusive event?: *ECONOMIC GEOLOGY*, v. 92, p. 766–771.
- Chesley, J.T. and Ruiz, J., 1998, Preliminary Re-Os dating on molybdenite mineralization from the Bingham Canyon porphyry copper deposit, Utah: Society of Economic Geologists Guidebook, v. 29, p. 165–169.
- Deino, A., and Keith, J.D., 1998, Ages of volcanic and intrusive rocks in the Bingham mining district, Utah: Society of Economic Geologists Guidebook, v. 29, p. 91–100.
- Foster, D. A., Harrison, T. M., Copeland, P. and Heizler, M. T., 1990, Effects of excess argon within large diffusion domains of K-feldspar age spectra: *Geochimica et Cosmochimica Acta*, v. 54, p. 3147–3158.
- Harrison, T.M., Duncan, I., and McDougall, I., 1985, Diffusion of ^{40}Ar in biotite: Temperature, pressure, and compositional effects: *Geochimica et Cosmochimica Acta*, v. 49, p. 2461–2468.
- John, D.A., Turrin, B.D., and Miller, R.J., 1998, New K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of plutonism, hydrothermal alteration, and mineralization in the central Wasatch mountains, Utah: Society of Economic Geologists Guidebook, v. 29, p. 47–57.
- John, E.C., 1978, Mineral zones in the Utah copper orebody: *ECONOMIC GEOLOGY*, v. 73, p. 1250–1259.
- Krahulec, K.A., 1998, History and production of the West Mountain (Bingham) mining district, Utah: Society of Economic Geologists Guidebook, v. 29, p. 189–217.
- Lanier, G., John, E.C., Swensen, A.J., Reid, J., Bard, C.E., Caddey, S.W., and Wilson, J.C., 1978a, General geology of the Bingham mine, Bingham Canyon, Utah: *ECONOMIC GEOLOGY*, v. 73, p. 1228–1241.
- Lanier, G., Raab, W.J., Folsom, R.B., and Cone, S., 1978b, Alteration of equigranular monzonite, Bingham mining district, Utah: *ECONOMIC GEOLOGY*, v. 73, p. 1270–1286.
- Lanphere, M.A., and Dalrymple, G.B., 2000, First-principles calibration of ^{38}Ar traces: Implications for the ages of $^{40}\text{Ar}/^{39}\text{Ar}$ fluence monitors: U.S. Geological Survey Professional Paper 1621, 10 p.
- Mahon, K.I., 1996, The new “York” regression: Application of an improved statistical method to geochemistry: *International Geology Reviews*, v. 38, p. 293–303.
- Marsh, T.M., Einaudi, M.T., and McWilliams, M., 1997, $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of Cu-Au and Au-Ag mineralization in the Potrillo district, Chile: *ECONOMIC GEOLOGY*, v. 92, p. 784–806.
- McDowell, F.W., 1971, K-Ar ages of igneous rocks from the western United States: *Isochron/West*, no. 2, p. 1–16.
- Meyer, C., and Hemley, J. J., 1967, Wall rock alteration, in Barnes, H. L. ed., *Geochemistry of Hydrothermal Ore Deposits*: New York, Holt, Rinehart and Winston, p. 166–235.
- Min, K., Mundil, R., Renne, P.R., and Ludwig, K.R., 2000, A test for systematic errors in $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology through comparison with U/Pb analysis of a 1.1 Ga rhyolite: *Geochimica et Cosmochimica Acta*, v. 64, p. 73–98.
- Moore, W.J., 1973, A summary of radiometric ages of igneous rocks in the Oquirrh Mountains, north-central Utah: *ECONOMIC GEOLOGY*, v. 68, p. 97–101.
- 1978, Chemical characteristics of hydrothermal alteration at Bingham, Utah: *ECONOMIC GEOLOGY*, v. 73, p. 1260–1269.
- Moore, W.J., and Lanphere, M.A., 1971, The age of porphyry-type copper mineralization in the Bingham mining district, Utah: A refined estimate: *ECONOMIC GEOLOGY*, v. 66, p. 331–334.
- Moore, W.J., and Nash, J.T., 1974, Alteration and fluid inclusion studies of the porphyry copper ore body at Bingham, Utah: *ECONOMIC GEOLOGY*, v. 69, p. 631–645.
- Moore, W.J., Lanphere, M.A., and Obradovich, J.D., 1968, Chronology of intrusion, volcanism, and ore deposition at Bingham, Utah: *ECONOMIC GEOLOGY*, v. 63, p. 612–621.

- Moser, D.E., and Heaman, L.M., 1997, Proterozoic zircon growth in Archean lower-crustal xenoliths, southern Superior craton—a consequence of Matachewan ocean opening: *Contributions to Mineralogy and Petrology*, v. 128, p. 164–175.
- Parry, W. T., Ballantyne, G. H., and Wilson, J. C., 1978, Chemistry of biotite and apatite from a vesicular quartz latite porphyry plug at Bingham, Utah: *ECONOMIC GEOLOGY*, v. 73, p. 1308–1314.
- Parry, W.T., Wilson, P.N., Jasumback, M.D., and Heizler, M.T., 1998, Clay mineralogy and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of phyllic and argillic alteration at Bingham, Utah: *Society of Economic Geologists Guidebook*, v. 29, p. 171–188.
- Phillips, C.H., Smith, T.W., and Harrison, E.D., 1998, Alteration, metal zoning, and ore controls in the Bingham Canyon porphyry copper deposit, Utah: *Society of Economic Geologists Guidebook*, v. 29, p. 133–145.
- Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., and DePaolo, D.J., 1998, Intercalibration of standards, absolute ages and uncertainties in $^{40}\text{Ar}/^{39}\text{Ar}$ dating: *Chemical Geology*, v. 145, p. 117–152.
- Samson, S.D., and Alexander, E.C., Jr., 1987, Calibration of the interlaboratory $^{40}\text{Ar}/^{39}\text{Ar}$ dating standard, Mmhb-1: *Chemical Geology Isotope Geoscience*, v. 66, p. 27–34.
- Scaillet, S., 2000, Numerical error analysis in $^{40}\text{Ar}/^{39}\text{Ar}$ dating: *Chemical Geology*, v. 162, p. 269–298.
- Smith, P.E., Evensen, N.M., York, D., 1993, First successful $^{40}\text{Ar}/^{39}\text{Ar}$ dating of glauconies; argon recoil in single grains of cryptocrystalline material: *Geology*, v. 21, p. 41–44.
- Stacey, J.S., and Kramers, J.D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: *Earth and Planetary Science Letters*, v. 26, p. 207–221.
- Steiger, R.H., and Jäger, E., 1977, Subcommittee on geochronology: Convention on the use of decay constants in geo- and cosmochronology: *Earth and Planetary Science Letters*, v. 36, p. 359–362.
- Vogel, T.A., Cambray, F.W., and Feher, L., 1998, Petrochemistry and emplacement history of the Wasatch igneous belt: *Society of Economic Geologists Guidebook*, v. 29, p. 35–46.
- Warnaars, F.W., Smith, W.H., Bray, R.E., Lanier, G., and Shafiquallah, M., 1978, Geochronology of igneous intrusions and porphyry copper mineralization at Bingham, Utah: *ECONOMIC GEOLOGY*, v. 73, p. 1242–1249.
- York, D., 1969, Least squares fitting of a straight line with correlated errors: *Earth and Planetary Science Letters*, v. 5, p. 320–324.

APPENDIX 1

Methods

Sample collection

Samples for this study were collected on pit benches in 1978 to 1979 and in 1996 to 1997. Sample numbering consists of the first three digits of the pit elevation in feet and the sample number at that elevation. Sample locations are plotted on the simplified geologic map of the Bingham mine in Figure 2, and sample descriptions are given in Table 3. Samples were collected to represent least altered, propylitic, potassic, argillic, and phyllic alteration of monzonite and quartz monzonite porphyry along bench traverses.

A 15-kg sample of the least altered, fine-grained monzonite of the Last Chance stock was collected from mine level 7600 for U-Pb analyses (Fig. 2). The outcrop is penetratively fractured (avg fracture spacing of approximately 50 cm), and fracture-filling minerals include epidote and pyrite. Blocks of monzonite were extracted from an area of the outcrop face located 10 m below a 5-m scale calc-silicate xenolith. Efforts were made to collect least altered and least fractured material from areas as far as possible from such xenoliths in order to avoid zones that, during crystallization, may have been richer in xenocrystic zircon.

U-Pb methods

Zircon separation and analyses were carried out at the Royal Ontario Museum geochronology laboratories (Toronto) using methods described by Moser and Heaman (1997) and briefly summarized here. The sample was crushed in a heat-sealed plastic bag and pulverized. Zircons were separated using a Wilfley table, electromagnetic separator, and heavy liquids. Approximately 1 g of zircon was extracted from the sample.

Handpicked, least paramagnetic, best quality zircons were subjected to air abrasion to remove exterior surfaces of the crystals, washed in a primary bath of 4N HNO₃, and heated in a bath of distilled 4N HNO₃. Zircons were then rinsed and ultrasonically cleaned in 2 cycles each of distilled H₂O and distilled acetone. Zircons were then dissolved in Teflon mini-bombs in a mixture of HF and HNO₃ with a measured amount of mixed ²⁰⁵Pb/²³⁵U spike. Sample solutions were evaporated to dryness in bombs on a hot plate. Redissolving of fluoride precipitate and conversion to chloride were achieved by adding distilled 3.2N HCl and returning the bombs to an oven for 24 h. The sample solutions were then passed through precleaned microcolumns containing organic anion exchange resin to extract U and Pb. The U and Pb solutions were evaporated to dryness and converted to phosphate. The samples were then loaded onto Re filaments and ionized under vacuum in a VG M354 thermal ionization mass spectrometer. The Pb isotope ratios generally were measured on a Daly detector, and more intense ion beams were measured using a Faraday detector. All isotopic ratios were measured over a range of temperatures as a check against fractionation and mass interferences.

Measured isotopic ratios were corrected for baseline lift, known mass fractionation, collector bias, Pb introduced in spike, and, in some cases, laboratory blank Pb. Corrected ratios were then used to calculate ²⁰⁶Pb/²³⁸U ages, ²⁰⁷Pb/²³⁵U ages, model ²⁰⁷Pb/²⁰⁶Pb ages, and Th/U ratios.

⁴⁰Ar/³⁹Ar methods

Mineral separates of illite, biotite, and K feldspar were wrapped in copper foil, placed in a machined Al disk, and sealed in evacuated Pyrex tubes along with interlaboratory standard Fish Canyon tuff (age = 27.84 Ma). Samples and standards were irradiated in three separate packages. Irradiation durations were 7.6, 7.0, and 14 h for NM-49, NM-59, and NM-86, respectively. Irradiation took place in the D-3 position of the reactor at the Nuclear Science Center, College Station, Texas. Following irradiation, monitor crystals were placed in a copper planchet. These flux monitors were then fused within an ultra high vacuum argon extraction system with a 10W Synrad CO₂ continuous laser. Evolved gases were purified for 2 min, using a GP-50 SAES getter operated at ~450°C. J factors for the unknowns were determined to 0.1 percent from the known geometry of the monitors relative to the unknown samples.

The samples were incrementally heated within a double vacuum Mo resistance furnace. The evolved gas was cleaned during heating with an SAES GP-50 getter and additionally cleaned for 2 to 5 min following heating with another GP-50 getter. Argon isotope compositions were determined with an MAP 215-50 mass spectrometer operated in electron multiplier mode with an overall sensitivity of 7.0×10^{-17} mol Ar/pA. Extraction system and mass spectrometer blanks and backgrounds were measured numerous times throughout the course of the analyses and were very reproducible. Typical blanks (including mass spectrometer backgrounds) were 900, 1.0, 0.4, 2.0, 5.0×10^{-18} mol at masses 40, 39, 38, 37, 36, respectively.

All errors (including cited literature values) are reported at the 2σ confidence level and the decay constants and isotopic abundances are those suggested by Steiger and Jäger (1977). Plateau ages are calculated for contiguous heating steps that have apparent ages yielding MSWD values that fall within the predicted 95 percent confidence level (see table 1 of Mahon, 1996) for n-1 degrees of freedom. If the MSWD value is above the 95 percent confidence window, the plateau error is multiplied by the square root of the MSWD so that the total error more accurately reflects the data scatter. The plateau or preferred ages are calculated by weighting each step by the inverse variance, and errors were calculated using the equation of Samson and Alexander (1987). Isotopic correlation results are obtained using the regression techniques reported by York (1969).

APPENDIX 2

⁴⁰Ar/³⁹Ar Step Heating Results for Biotite from Bingham, Utah

ID	Temp (°C)	⁴⁰ Ar/ ³⁹ Ar	³⁷ Ar/ ³⁹ Ar	³⁶ Ar/ ³⁹ Ar (× 10 ⁻³)	³⁹ Ar _K (× 10 ⁻¹⁵ mol)	K/Ca	⁴⁰ Ar° (%)	³⁹ Ar (%)	Age (Ma)	± 2σ (Ma)
674-1 biotite, wt = 2.34 mg, J = 0.0007963, NM-86, Lab 8929-02										
B	750	68.47	0.0406	131.2	0.192	12.6	43.4	0.8	42.2	7.6
C	850	37.05	0.0209	34.70	1.12	24.4	72.3	5.1	38.09	1.22
D	920	29.95	0.0209	10.01	2.16	24.4	90.1	13.6	38.37	0.66
E	1000	28.86	0.0651	6.786	1.87	7.8	93.1	20.9	38.18	0.72
F	1075	29.06	0.0815	6.821	1.69	6.3	93.1	27.5	38.45	0.78
G	1110	29.11	0.0542	5.829	1.47	9.4	94.1	33.3	38.92	0.90
H	1180	29.37	0.1728	7.963	2.47	3.0	92.0	42.9	38.42	0.56
I	1210	28.74	0.1428	5.547	4.80	3.6	94.3	61.7	38.54	0.32
J	1250	28.19	0.0386	4.202	7.81	13.2	95.6	92.2	38.31	0.22
K	1300	28.93	0.0218	6.343	1.54	23.4	93.5	98.2	38.45	0.84
L	1650	42.33	1.180	55.65	0.454	0.43	61.4	100.0	37.0	3.0
Total gas age			n = 11		25.6	11.2			38.41	0.60
Plateau age			n = 11	steps B-L	25.6	11.2		100.0	38.40	0.16
579-11 biotite, wt = 3.26 mg, J = 0.0007946, NM-86, Lab 8930-02										
A	650	238.5	0.0949	734.1	0.347	5.4	9.0	0.8	30.7	9.2
B	750	45.70	0.0129	64.86	1.38	39.6	58.1	4.1	37.64	1.16
C	850	32.33	0.0038	19.20	4.69	133.8	82.4	15.3	37.81	0.36
D	920	29.11	0.0046	9.295	4.58	110.0	90.6	26.2	37.41	0.34
E	1000	28.15	0.0073	6.117	3.70	69.9	93.6	35.0	37.38	0.38
F	1075	28.54	0.0103	6.117	2.97	49.5	93.7	42.0	37.92	0.46
G	1110	28.00	0.0112	5.069	4.73	45.6	94.7	53.3	37.60	0.30
H	1180	27.99	0.0215	5.163	7.13	23.8	94.6	70.3	37.54	0.24
I	1210	28.03	0.0414	5.094	5.32	12.3	94.6	82.9	37.63	0.28
J	1250	27.83	0.0466	4.421	4.99	10.9	95.3	94.8	37.64	0.30
K	1300	28.38	0.0172	5.996	1.81	29.6	93.8	99.1	37.75	0.70
L	1650	42.48	0.5684	54.28	0.368	0.90	62.3	100.0	37.6	3.4
Total gas age			n = 12		42.0	51.2			37.55	0.46
Plateau age			n = 12	steps A-L	42.0	51.2		100.0	37.60	0.11
579-7b biotite, wt = 3.91 mg, J = 0.0007943, NM-86, Lab 8931-01										
A	650	881.0	0.4939	2900	0.243	1.0	2.7	0.5	34	40
B	750	59.02	0.1837	114.7	0.666	2.8	42.6	1.7	35.7	2.4
C	850	37.78	0.0078	37.24	3.23	65.5	70.9	7.9	37.98	0.52
D	920	30.18	0.0050	12.33	5.49	102.9	87.9	18.3	37.64	0.32
E	1000	29.21	0.0069	9.988	4.70	73.9	89.9	27.2	37.25	0.32
F	1075	29.34	0.0084	8.988	3.52	60.5	90.9	33.9	37.84	0.40
G	1110	28.96	0.0083	7.956	5.08	61.3	91.9	43.5	37.74	0.28
H	1180	28.73	0.0179	7.550	6.47	28.5	92.2	55.8	37.59	0.24
I	1210	28.47	0.0323	6.362	6.66	15.8	93.4	68.4	37.71	0.24
J	1250	27.75	0.0407	4.505	9.03	12.5	95.2	85.5	37.47	0.22
K	1300	27.75	0.0068	4.780	6.47	75.0	94.9	97.8	37.35	0.26
L	1650	32.56	0.1233	21.07	1.15	4.1	80.9	100.0	37.36	1.14
Total gas age			n = 12		52.7	48.2			37.54	0.52
Plateau age			n = 12	steps A-L	52.7	48.2		100.0	37.567	0.09
544-1 biotite, wt. = 3.26 mg, J = 0.0008011, NM-86, Lab 8947-01										
A	650	410.2	0.1702	1367	0.168	3.0	1.5	0.4	9	30.
B	750	55.27	0.0302	97.05	0.716	16.9	48.1	2.1	38.0	2.2
C	850	34.82	0.0068	28.89	2.87	74.5	75.5	9.0	37.59	0.56
D	920	29.94	0.0042	13.00	3.83	121.9	87.2	18.2	37.33	0.40
E	1000	28.02	0.0055	6.004	3.31	93.0	93.7	26.2	37.53	0.42
F	1075	28.87	0.0066	8.933	2.59	77.7	90.9	32.4	37.51	0.54
G	1110	27.62	0.0068	4.885	4.22	75.1	94.8	42.6	37.44	0.34
H	1180	27.64	0.0174	4.527	6.09	29.3	95.2	57.2	37.62	0.26
I	1210	27.44	0.0319	4.655	7.58	16.0	95.0	75.5	37.28	0.24
J	1250	27.27	0.0338	3.590	7.57	15.1	96.1	93.7	37.49	0.22
K	1300	27.76	0.0178	5.750	2.11	28.7	93.9	98.7	37.28	0.66
L	1650	32.90	0.0945	23.08	0.522	5.4	79.3	100.0	37.3	2.6
Total gas age			n = 12		41.6	48.0			37.34	0.52
Plateau age			n = 12	steps A-L	41.6	48.0		100.0	37.45	0.11

APPENDIX 2 (Cont.)

ID	Temp (°C)	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{36}\text{Ar}/^{39}\text{Ar}$ ($\times 10^{-3}$)	$^{39}\text{Ar}_K$ ($\times 10^{-15}$ mol)	K/Ca	$^{40}\text{Ar}^e$ (%)	^{39}Ar (%)	Age (Ma)	$\pm 2\sigma$ (Ma)
529-9, biotite, 2.52 mg, J = 0.00086082, NM-49, Lab 6528-01										
A	650	233.8	0.0557	699.4	0.783	9.2	11.6	1.1	41.7	6.5
B	750	85.51	0.0177	195.7	1.68	28.9	32.4	3.3	42.5	1.7
C	850	48.77	0.0094	79.42	4.82	54.4	51.9	9.8	38.87	0.72
D	920	37.66	0.0048	43.86	7.95	105.2	65.6	20.4	37.96	0.44
E	1000	37.16	0.0056	41.70	8.03	91.5	66.8	31.2	38.17	0.44
F	1075	36.93	0.0066	40.85	5.20	77.8	67.3	38.2	38.20	0.44
G	1110	31.82	0.0146	25.01	2.68	34.9	76.8	41.8	37.55	0.43
H	1180	29.39	0.0083	16.41	3.26	61.8	83.5	46.2	37.72	0.33
I	1210	28.05	0.0048	12.70	4.03	106.7	86.6	51.6	37.34	0.30
J	1250	27.07	0.0066	9.207	5.99	76.7	90.0	59.6	37.42	0.25
K	1300	26.15	0.0164	6.310	15.3	31.1	92.9	80.2	37.33	0.23
L	1650	25.81	0.0032	5.860	14.8	161.5	93.3	100.0	37.02	0.22
Total gas age			$n = 12$		74.5	85.1			37.78	0.43
Isochron age			$n = 11$	steps B-L					37.07	0.21

Correction factors:

$$(^{39}\text{Ar}/^{37}\text{Ar})\text{Ca} = 0.00070 \pm 0.00005$$

$$(^{36}\text{Ar}/^{37}\text{Ar})\text{Ca} = 0.00026 \pm 0.00002$$

$$(^{40}\text{Ar}/^{39}\text{Ar})\text{K} = 0.0002 \pm 0.0003$$

Notes: n = number of heating steps; isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions; individual analyses show analytical error only; plateau, preferred and total gas age errors include error in J and irradiation parameters; K/Ca = molar ratio calculated from reactor produced $^{39}\text{Ar}_K$ and $^{37}\text{Ar}_{Ca}$

