$^{40}Ar/^{39}Ar$ Geochronology Results from the Cogswell Point, Dog Valley Peak, Little Drum Pass, Red Ridge, Rex Reservoir, Sage Valley, and Smelter Knolls West Quadrangles, Utah

by

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Bibliographic citation for this data report:

Utah Geological Survey and New Mexico Geochronology Research Laboratory, 2008, $^{40}Ar/^{39}Ar$ geochronology results from the Cogswell Point, Dog Valley Peak, Little Drum Pass, Red Ridge, Rex Reservoir, Sage Valley, and Smelter Knolls West quadrangles, Utah: Utah Geological Survey Open-File Report 522, variously paginated, also available online, <http://geology.utah.gov/online/ofr/ofr-522.pdf>.

OPEN-FILE REPORT 522
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
2008

This Open-File Report makes available raw analytical data from laboratory procedures completed to determine the age of rock samples collected during geologic mapping funded or partially supported by the Utah Geological Survey (UGS). The references listed in table 1 report the age of the samples and provide additional information such as the sample location, geologic setting, and significance or interpretation of the samples in the context of the area in which they were collected. This report was prepared by the New Mexico Geochronology Research Laboratory under contract to the UGS. These data are highly technical in nature and proper interpretation requires considerable training in the applicable geochronologic techniques.

Disclaimer

References that Cite or Explain Rock Units Analyzed in this Report

Biek, R.F., and Hylland, M.D., 2007, Geologic map of the Cogswell Point quadrangle, Washington, Kane, and Iron Counties, Utah: Utah Geological Survey Map 221, 2 plates, scale 1:24,000.

Clark, D.L., 2003, Geologic map of the Sage Valley quadrangle, Juab County, Utah: Utah Geological Survey Miscellaneous Publication 03-2, 57 p., 2 plates, scale 1:24,000.

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County and parts of Beaver, Piute, and Sevier Counties, Utah: Utah Geological Survey Map 195, 2 plates, scale 1:100,000.

Hintze, L.F., Davis, F.D., Rowley, P.D., Cunningham, C.G., Steven, T.A., and Willis, G.C., 2008, Geologic map of the Richfield 30'x60' quadrangle, southeast Millard County and parts of Beaver, Piute, and Sevier Counties, Utah (digital GIS files): Utah Geological Survey Map 195DM, 2 plates, scale 1:100,000.

Corrections and Clarifications

In the technical report section, on the first page, Marysvale is correct (not Marysville).

The age for sample CP62001-3 was mistakenly not reported in Biek and Hylland (2007); the sample is from the Horse Knoll lava flow, from the same location as the 0.81 ± 0.05 Ma K-Ar age reported by Best and others (1980).

Notes

(also see discussion on reliability and preferred ages in technical report section)

S-40 **–** Volcanic clast from conglomerate of West Fork Reservoir.

RR0001 **–** White, pumice- and ash-rich, poorly welded, volcaniclastic sandstone from unit tentatively identified as Dipping Vat Formation. Collected near Little Lost Creek.

DV0021 **–** From unit labeled Dog Valley Tuff (Tdv) in Hintze and others (2003). Collected from head of small canyon in saddle about 800 meters southeast of the top of Dog Valley Peak. Section is not surveyed on USGS 7.5' quadrangle map, and thus stated location is approximate; however, sample was collected about 10 meters above base of Tdv, just above top of the unit mapped as Aurora Formation (Tau).

DV0003 **–** Moderately dense lithic tuff with abundant biotite and hornblende. Collected near top of unit mapped as tuff of Dog Valley (Tdv). Location is near a mapped fault; however, biotite and hornblende suggest unit likely is tuff of Dog Valley.

Table 1. **Sample numbers and locations.**				
Sample #	**7.5' quadrangle**	**Latitude (N)**	**Longitude (W)**	**Reference**
S-40	Sage Valley	39°32'59"	112°06'52"	Clark, 2003
CP62001-3	Cogswell Point	37°26'12"	112°52'42"	Biek and Hylland (2007)
Latitude and longitude in NAD27.				
Sample #	**7.5' quadrangle**	**Location**		**Reference**
RR0001	Rex Reservoir	SE ¼ of SE ¼ of NW 1/4 of section 31, T. 23 S., R. 1 E.		unpublished
DV0021	Dog Valley Peak	NE ¼ of NE ¼ of NE ¼ of section 16, T. 25 S., R. 6 W.		Hintze and others, 2003
DV0003	Red Ridge	NW ¼ of NE ¼ of NE ¼ of section 26, T. 24 S., R. 5 W.		Hintze and others, 2003

Table 2. Summary of $^{40}Ar/^{39}Ar$ ages from Little Drum Pass (samples UGS 2,3,4,5,6,8,9,10,11) and Smelter Knolls West (sample UGS 12) quadrangles. Drum Mountains Rhyodacite and volcanic sequence of Dennison Canyon are coeval. Samples collected by Lehi F. Hintze and reported in Hintze (2003).

Sample number	Unit (map symbol)	Mineral	Date and error (Ma)	Notes	Location (NAD 27): Latitude Longitude
UGS 2	Latite of Black Point (Tbp)	groundmass concentrate	38.80± 0.43	Likely not accurate	39° 29' 43" N 113° 07' 28" W
UGS 3	Mt Laird intrusive (Timl)	biotite, single crystal	37.07±0.28	Cuts Tdr near UGS 4 sample site	39° 29' 22" N 113° 06' 33" W
UGS 4	Drum Mtns Rhyodacite (Tdr)	hornblende	36.68±0.22		39° 29' 32" N 113° 06' 20" W
UGS 5	Drum Mtns Rhyodacite (Tdr)	hornblende	36.93±0.22		39° 27' 42" N 113° 06' 59" W
UGS 6	Latite of Horse Canyon, top unit (Th_3)	hornblende, single crystal	35.1±2.1	Underlying unit (Th_2) overlies Red Knolls Tuff	39° 27' 51" N 113° 04' 16" W
UGS 8	Red Knolls Tuff (Trk)	hornblende biotite	36.47±0.81 36.48±0.12	Unit overlies Mt Laird Tuff in Drum Mountains	39° 26' 05" N 113° 03' 43" W
UGS 9	Volcanics of Dennison Canyon, top unit (Td_3)	hornblende	36.66±0.37		39° 25' 08" N 113° 03' 42" W
UGS 10	Little Drum Formation, member 11 (Tl_{11})	biotite	37.62±0.41		39° 23' 38" N 113° 00' 03" W
UGS 11	Volcanics of Dennison Canyon, basal unit (Td_1)	hornblende biotite	37.05±0.18 37.47±0.19		39° 25' 27" W 113° 00' 18" W
UGS 12	Little Drum Formation, member 2 (Tl_2)	hornblende biotite	38.52±0.60 38.62±0.37	likely not accurate	39° 26' 01" N 112° 58' 38" W

Ar/ Ar Geochronology Results from the Marysville Volcanic Pile and the Little Drum Pass Area

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JULY 9, 2002

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Introduction

Twelve volcanic samples (UGS 1-12) from the Little Drum Pass area of Millard County, Utah, three tuffs from the Marysville volcanic pile, a basalt from Zion National Park and a volcanic clast from Sevier Canyon were submitted for analysis by Bob Biek of the Utah Geological Survey. Mineral separates were prepared for all samples except for UGS 1 that was considered too altered to analyze and UGS 7 that contained no datable mineral phases.

$^{40}Ar/^{39}Ar$ Analytical Methods and Results

The sanidine separate from RR0001 and hornblende from UGS6 were analyzed by the single crystal total fusion method. Biotite from UGS 3 and UGS 10 was step-heated as single crystals. Both of these micas as well as the rest of the biotite, hornblende and groundmass concentrates were analyzed as bulk separates with the furnace incremental-heating age spectrum method. Abbreviated analytical methods for the dated samples are given in Table 1. The $^{40}Ar/^{39}Ar$ analytical results are given in Tables 2-5. Details of the overall operation of the New Mexico Geochronology Research Laboratory are provided in the Appendix. A summary of the $^{40}Ar/^{39}Ar$ ages can be found in Table 1.

Thirteen crystals of sanidine from sample RR0001 were analyzed (Figure 1, Table 2). All thirteen were used to calculate a weighted mean age of 34.64±0.13 Ma. The MSWD is outside the 95% confidence interval so the error has been increased accordingly.

Three of the samples, UGS 4 (hornblende), UGS 10 (biotite) and DV 003 (groundmass concentrate), yielded concordant age spectra (Figures 2a-4a, Table 3). Weighted mean ages for these samples are calculated from all heating steps (36.68±0.22 Ma, UGS 4; 37.62±0.41 Ma, UGS 10; 34.26±0.23 Ma, DV 003). As expected with a concordant age spectrum, the inverse isochron analysis of these samples reveals isochron ages that agree within error to the weighted mean ages calculated from the age spectra (Figures 2b-4b).

Hornblende separated from UGS 5 yielded a nearly concordant age spectrum (Figure 5a, Table 3). Low apparent ages and radiogenic yields in the first 2.5% of ^{39}Ar released suggest slight alteration of the sample. A weighted mean age of 36.93±0.22 Ma is calculated from the remaining 97.5% of the ^{39}Ar released during heating. Inverse isochron analysis reveals a $^{40}Ar/^{36}Ar$ intercept within error of atmosphere and an isochron age within error of the weighted mean age (Figure 5b).

CP62001-3 groundmass yielded an age spectrum concordant over the first ~85% of the ^{39}Ar released during heating (Figure 6a, Table 3), a weighted mean age of 0.73±0.02 Ma is calculated from this portion of the age spectrum. The remaining 15% of ^{39}Ar released reveals a decrease in radiogenic yields, a drop in K/Ca ratio and a dramatic increase in apparent age followed by drop in apparent age. This type of rapid increase in apparent age is commonly attributed to early formed, excess Ar containing phenocrysts such as olivine and pyroxene. Steps A-G were evaluated with the inverse isochron technique and found to have an atmospheric intercept (Figure 6b).

UGS 8 biotite and hornblende yield similar age spectra with somewhat higher apparent ages and low radiogenic yields in the first 10-20% of the ^{39}Ar released (Figures 7a and 8a, Table 3). It is noted that the weighted mean ages calculated for UGS 8 biotite (36.48±0.12 Ma, steps F-G) and UGS 8 hornblende (36.47±0.81 Ma, steps A-L) agree within error. The inverse isochron analysis of these separates suggests slight excess Ar although the $^{40}Ar/^{36}Ar$ for the hornblende analysis is within error of the atmospheric intercept (Figures 7b and 8b).

Biotite and hornblende were also both analyzed for samples UGS 11 and UGS 12. All four age spectra reveal low apparent ages and low radiogenic yields in the first ~5-20% of the ^{39}Ar released during heating (Figures 9a, 10a, 11a and 12a, Table 3). This is suggestive of slight alteration of the samples. The age spectra for UGS 12 also yield a drop in apparent age in the last ~5% of ^{39}Ar released during heating. This drop in apparent age is correlated with a drop in K/Ca ratio, which suggests these samples may have undergone ^{39}Ar recoil during irradiation from high potassium phases to lower K phases (Figure 13). Evaluation of this data with the inverse isochron technique reveals that all samples except UGS 12 biotite have atmospheric intercepts (Figures 9b, 10b, 11b and 12b). Steps C-H of UGS 12 biotite reveal a $^{40}Ar/^{36}Ar$ intercept of 310±6 (above the atmospheric intercept of 295.5). It is noted that all ages calculated for UGS 12 agree within error, but the weighted mean age calculated for UGS 11 biotite is slightly higher than the weighted mean age calculated for UGS 11 hornblende.

Biotite from sample UGS 3 and hornblende from UGS 6 yielded disturbed age spectra (Figures 14a and 15a, Table 3). Old apparent ages are revealed in the low temperature heating step of UGS 3 (~500 Ma) followed by a drop in apparent ages to 60-70 Ma in the mid-temperature steps and finally a rapid increase in the final steps to ~840 Ma. Old apparent ages (~635 Ma and less) are also revealed in the first ~22% of ^{39}Ar released from UGS 6, this followed by a decrease in ages to ~36 Ma. This data was plotted on an inverse isochron and found to be non-isochronous (Figures 14b and 15b). These types of discordant age spectra, are often indicative of xenocrystic contamination, thus these two samples were reanalyzed as single crystals (Figure 16a and 17a, Tables 2, 4 and 5). Eight UGS 3 biotite grains were analyzed in two steps. The more radiogenic and thus more precise B steps yield a weighted mean age of 37.07±0.28 Ma. Ten single crystals of hornblende from UGS 6 were fused in a single step yield an apparent age of 35.1±2.1 Ma. Isochron analysis of these single crystal analyses reveal atmospheric intercepts (Figures 16b and 17b).

UGS 9 hornblende yielded a somewhat disturbed age spectra (Figure 18a, Table 3) with increasing radiogenic yields and apparent ages and decreasing K/Ca ratios over the first ~35% of the ^{39}Ar released during the heating of this sample. A weighted mean age of 36.66±0.37 Ma is calculated from the remaining portion of the age spectra. Inverse isochron analysis of this sample (Figure 18b) reveals an atmospheric intercept.

Groundmass from samples UGS 2 and S-40 yield similar age spectra with increasing apparent ages and radiogenic yields over the first ~25% of the ^{39}Ar released during the heating of these samples (Figures19a and 20a, Table 3). This is followed by a decrease in radiogenic yield and K/Ca ratio and a continued increase in apparent age over the remainder of the age spectra. Alteration combined with either recoil or excess Ar in early formed, calcium rich phases such as pyroxene and olivine could result in this type of age spectra. Inverse isochron analysis of these samples (Figures 19b and 20b) reveals ^{40}Ar/^{36}Ar intercepts within error of the atmospheric ratio (295.5).

Groundmass concentrate from sample DV 0021 yields a disturbed age spectrum with increasing radiogenic yields and apparent ages and decreasing K/Ca ratios over the first ~35% of ^{39}Ar released during heating (Figure 21a, Table 3) followed by decreasing apparent ages, radiogenic yields and K/Ca ratios over the remainder of the age spectrum. Alteration combined with ^{39}Ar recoil may explain this behavior. Those heating steps affected by either alteration and/or recoil would not be expected to fall on the same isochron as the other steps. Steps B-F plotted on an inverse isochron reveal an atmospheric intercept (Figure 21b).

Discussion

Most samples in this study provided low complexity results that can be interpreted in a straightforward manner (UGS4, UGS 10, DV003, UGS 5, CP62001-3, UGS 8, UGS 11, UGS 12, and UGS 3). The apparent age assigned to UGS 6 (35.1±2.1 Ma is most likely accurate although of much lower precision than the other ages assigned in this study.

We have much lower confidence in the ages assigned to the remainder of the samples (UGS 2, 38.80±0.43 Ma; S-40, 35.72±0.61 Ma and DV0021, 33.52±0.38 Ma). The oldest apparent age revealed by an age spectrum will be assigned as a minimum age for a sample suspected of having undergone alteration. The integrated age would be our best estimate of the age of a sample that has undergone recoil and anomalously old high temperature heating steps would not be used to assign an age if excess Ar was suspected. Samples UGS 2 and S-40 are probably affected by some combination of these so the age we have assigned is simply our best estimate of the age of these samples and the quoted error may not adequately reflect the range in possible age assignments resultant from other interpretations. The age spectrum for sample DV0021 is a classic example of an age spectrum disturbed by a combination of alteration and recoil, and therefore the integrated age is our best estimate of the eruption age.

The ages assigned to the samples from the Little Drum Pass Area and those from the Marysville volcanic pile have been plotted on summary diagrams (Figures 22 and 23). The ages of the Little Drum Pass samples are fairly evenly distributed from the imprecise age of UGS 6 (35.1±2.1 Ma) up to the age assigned to UGS 2 (38.80±0.43 Ma). Those from the Marysville volcanic pile are also evenly distributed from DV003 at 34.26±0.23 Ma to RR0001 at 34.64±0.13 Ma.

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Table 1. Summary of $^{40}Ar/^{39}Ar$ data and analytical methods.

Sample	Unit/Location	Irradiation	mineral	analysis	# of steps/crystals	MSWD	K/Ca	Age	±2s	Comments
RR0001	Marysville Volcanic Pile	NM-144	sanidine	laser total fusion	13	2.6**		34.64	0.13	
UGS 2	latite of Black Point	NM-144	groundmass concentrate	furnace step-heat	7	6.0**		38.80	0.43	disturbed age spectrum
UGS 3	Mt. Laird intrusive	NM-144	biotite	laser step-heat	8	2.3		37.07	0.28	
UGS 4	latite of Black Point	NM-144	hornblende	furnace step-heat	11	0.70		36.68	0.22	
UGS 5	Dennsion Canyon	NM-144	honrblende	furnace step-heat	7	1.5		36.93	0.22	
UGS 6	Dennsion Canyon	NM-144	hornblende	laser total fusion	10	1.1		35.1	2.1	
UGS 8	Red Knolls Tuff	NM-144	biotite	furnace step-heat	7	1.5		36.48	0.12	
UGS 9	Dennsion Canyon	NM-144	hornblende	furnace step-heat	3	2.7		36.66	0.37	minimum age
UGS 10	Little Drum Formation	NM-144	biotite	furnace step-heat	11	1.9		37.62	0.41	
UGS 11	Dennsion Canyon	NM-144	biotite	furnace step-heat	5	1.7		37.47	0.19	
UGS 12	Little Drum Formation	NM-144	biotite	furnace step-heat	6	6.3**		38.62	0.37	
DV0021	Marysville Volcanic Pile	NM-144	groundmass concentrate	furnace step-heat	5	5.4**		34.50	0.28	disturbed age spectrum, integrated age
S-40	Conglomerate of Sevier Canyon	NM-144	groundmass concentrate	furnace step-heat	6	4.7**		35.72	0.61	somewhat disturbed age spectrum
DV0003	Marysville Volcanic Pile	NM-144	hornblende	furnace step-heat	12	1.4		34.26	0.23	
CP2001-3	Zion National Park	NM-150	groundmass concentrate	furnace step-heat	7	1.5		0.73	0.02	

** MSWD outside 95% confidence interval

Notes:

Sample preparation and irradiation:

Mineral separates were prepared using standard crushing, dilute acid treatment and hand-picking techniques.

Mineral separates were loaded into a machined Al disc and irradiated for 7 hours in NM-144 or 1 hour for NM-150 in the D-3 position, Nuclear Science Center, College Station, TX.

Neutron flux monitor Fish Canyon Tuff sanidine (FC-1). Assigned age = 27.84 Ma (Deino and Potts, 1990)
relative to Mmhb-1 at 520.4 Ma (Samson and Alexander, 1987).

Instrumentation:

Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system.

Groundmass concentrate, hornblende and biotite separates were step-heated using a Mo double-vacuum resistance furnace. Heating duration in the furnace was 9 minutes.

Reactive gases removed during furnace analysis by reaction with 3 SAES GP-50 getters, 2 operated at ~450°C and
1 at 20°C. Gas also exposed to a W filiment operated at ~2000°C.

Single crystal sanidine and hornblende were fused by a 50 watt Synrad CO_2 laser. Single crystal biotite step-heated with same laser.

Reactive gases removed during a reaction with 2 SAES GP-50 getters, 1 operated at ~450°C and
1 at 20°C (2 minutes for sanidine, 5 minutes for hornblende and biotite). Gas also exposed to a W filament operated at ~2000°C and a cold finger operated at -140°C.

Analytical parameters:

Electron multiplier sensitivities: 1.75×10^{-16} moles /pA for furnace analyses, 9.42×10^{-17} moles /pA for laser analyses.

Total system blank and background for furnace analyses averaged 709, 1.3 , 0.5 , 1.5, 3.1×10^{-18} moles at masses 40, 39, 38, 37, and 36, respectively.
and 44, 0.4, 0.3, 1.3, 0.4×10^{-18} moles at masses 40, 39, 38, 37, and 36, respectively for laser analyses.

J-factors determined to a precision of ± 0.1% by CO_2 laser-fusion of 4 single crystals from each of 6 or 4 radial positions around the irradiation tray.

Correction factors for interfering nuclear reactions were determined using K-glass and CaF_2 and are as follows:
$(^{40}Ar/^{39}Ar)_K = 0.0002 \pm 0.0003$; $(^{36}Ar/^{37}Ar)_{Ca} = 0.00028 \pm 0.000005$; and $(^{39}Ar/^{37}Ar)_{Ca} = 0.0007 \pm 0.00002$.

Age calculations:

Total gas age and error calculated by weighting individual steps by the fraction of ^{39}Ar released.

MSWD values are evaluated for n-1 degrees of freedom for weighted mean age.

$^{40}Ar/^{36}Ar_i$ and MSWD values calculated from regression results obtained by the methods of York (1969).

If the MSWD is outside the 95% confidence window (cf. Mahon, 1996; Table 1), the error is multiplied by the square root of the MSWD.

Decay constants and isotopic abundances after Steiger and Jäger (1977).

All final errors reported at ±2s, unless otherwise noted.

Table 2. Argon isotopic results for laser total fusion analyses.

ID	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	$\%^{40}Ar^*$	Age (Ma)	±1s (Ma)
RR0001, single crystal sanidine, J=0.0007666, NM-144, Lab#=52663								
09	*51.98*	*5.557*	*97.61*	*0.243*	*0.092*	*45.4*	*32.47*	*0.79*
12	26.87	0.0049	5.741	4.49	103.9	93.7	34.49	0.09
11	25.51	0.0053	1.046	2.09	96.6	98.8	34.52	0.10
05	25.59	0.0052	1.293	4.74	98.3	98.5	34.52	0.08
06	25.47	0.0049	0.8899	5.45	104.1	99.0	34.53	0.07
02	25.42	0.0064	0.6909	5.07	80.3	99.2	34.54	0.08
08	25.41	0.0042	0.6313	3.18	121.7	99.3	34.55	0.08
03	25.45	0.0057	0.7112	4.75	89.7	99.2	34.58	0.08
07	25.73	0.0059	1.442	3.89	86.4	98.3	34.67	0.08
14	25.83	0.0019	1.576	2.23	265.2	98.2	34.75	0.10
15	25.78	0.0033	1.295	3.61	156.1	98.5	34.79	0.09
13	25.50	0.0031	0.3067	3.98	166.7	99.6	34.80	0.09
04	25.71	0.0061	1.026	4.35	83.8	98.8	34.80	0.08
10	25.75	0.0068	0.9918	4.12	75.1	98.9	34.87	0.09
weighted mean	MSWD = 2.6**	n=13			117.5 ±52.4		34.64	0.13*
UGS-6, single crystal hornblende, J=0.0007747, NM-144, Lab#=52722								
27	60.66	1.397	133.5	0.104	0.37	35.2	29.6	3.9
25	128.2	1.297	361.2	0.168	0.39	16.8	29.9	2.8
29	46.02	1.323	74.90	0.061	0.39	52.1	33.3	6.9
24	82.58	1.018	198.0	0.159	0.50	29.2	33.5	3.0
28	42.99	1.578	62.61	0.057	0.32	57.3	34.1	7.1
21	109.0	1.328	283.7	0.218	0.38	23.2	35.0	2.6
20	87.85	1.099	205.3	0.188	0.46	31.1	37.8	2.7
22	96.78	1.326	234.3	0.202	0.38	28.6	38.3	2.5
23	70.64	1.264	145.8	0.131	0.40	39.2	38.3	3.1
26	234.6	1.251	698.9	0.135	0.41	12.0	38.9	5.1
weighted mean	MSWD = 1.1	n=10			0.40 ±0.05		35.1	2.1*

Notes:
Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interferring reactions.
Individual analyses show analytical error only; plateau and total gas age errors include error in J and irradiation parameters.
n= number of heating steps
K/Ca = molar ratio calculated from reactor produced $^{39}Ar_K$ and $^{37}Ar_{Ca}$.

* 2s error

** MSWD outside 95% confidence interval

Table 3. Argon isotopic results for furnace step-heating analyses.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-16} mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1s (Ma)
UGS2, 11.77 mg groundmass concentrate, J=0.0007541, NM-144, Lab#=52695-01										
A	*700*	*110.2*	*0.2478*	*303.4*	*37.2*	*2.1*	*18.7*	*5.3*	*27.84*	*0.86*
B	*775*	*33.54*	*0.2991*	*20.80*	*78.1*	*1.7*	*81.7*	*16.5*	*36.93*	*0.14*
C	825	35.12	0.3652	21.87	71.2	1.4	81.7	26.7	38.63	0.15
D	875	36.89	0.4144	27.83	73.2	1.2	77.8	37.2	38.65	0.17
E	950	39.20	0.4685	34.44	93.8	1.1	74.1	50.6	39.12	0.17
F	1050	46.20	0.4960	60.97	101.4	1.0	61.1	65.1	38.02	0.23
G	1150	59.26	0.4476	103.5	109.9	1.1	48.4	80.8	38.65	0.31
H	1325	66.37	0.7808	124.8	91.6	0.65	44.5	93.9	39.81	0.38
I	1725	51.02	2.072	73.17	42.3	0.25	58.0	100.0	39.85	0.31
total gas age			n=9		698.8	1.1			38.08	0.54*
plateau		MSWD = 6.0**	n=7	steps C-I	583.5	1.0		83.5	38.80	0.43*
UGS3, 2.83 mg biotite, J=0.0007663, NM-144, Lab#=52662-01										
A	725	510.7	0.9743	345.9	1.24	0.52	80.0	2.3	491.7	2.9
B	825	55.87	0.7934	8.988	1.98	0.64	95.4	6.0	72.23	0.54
C	925	53.47	0.3824	7.130	3.91	1.3	96.1	13.3	69.70	0.36
D	995	46.99	0.1851	6.556	4.12	2.8	95.9	20.9	61.25	0.31
E	1075	66.06	0.1354	13.17	5.62	3.8	94.1	31.3	83.97	0.34
F	1150	105.0	0.1544	11.35	7.33	3.3	96.8	44.9	135.34	0.39
G	1185	121.1	0.1275	24.45	3.08	4.0	94.0	50.7	151.01	0.60
H	1255	63.30	0.0926	4.236	20.4	5.5	98.0	88.5	83.82	0.19
I	1285	172.7	0.0318	19.22	3.68	16.1	96.7	95.3	217.25	0.69
J	1325	563.2	0.0890	38.05	1.21	5.7	98.0	97.6	636.3	3.9
K	1375	803.4	0.1154	89.98	1.03	4.4	96.7	99.5	842.6	4.4
L	1700	442.5	3.215	243.4	0.262	0.16	83.8	100.0	452.1	7.8
total gas age			n=12		53.9	4.8			138.77	1.2*
UGS4, 10.99 mg hornblende, J=0.0007749, NM-144, Lab#=52721-01										
A	875	301.2	1.291	928.8	2.94	0.40	8.9	7.0	37.2	1.2
B	975	89.24	1.297	208.3	1.08	0.39	31.1	9.6	38.5	1.1
C	1075	77.08	1.977	171.9	0.931	0.26	34.3	11.8	36.6	1.5
D	1105	70.80	3.784	149.8	0.562	0.13	37.9	13.1	37.2	1.9
E	1135	45.27	5.022	66.25	4.94	0.10	57.7	24.8	36.26	0.37
F	1165	36.92	5.079	36.40	3.21	0.10	72.0	32.5	36.92	0.41
G	1195	37.94	5.293	40.67	6.69	0.096	69.5	48.4	36.61	0.25
H	1245	32.64	5.275	22.83	14.1	0.097	80.7	81.9	36.58	0.17
I	1275	33.86	5.584	26.29	6.52	0.091	78.4	97.4	36.88	0.23
J	1325	32.47	6.156	20.18	1.01	0.083	83.2	99.8	37.54	0.81
L	1725	272.1	23.08	847.3	0.084	0.022	8.7	100.0	33.2	10.0
total gas age			n=11		42.1	0.13			36.73	0.84*
plateau		MSWD = 0.70	n=11	steps A-L	42.1	0.13		100.0	36.68	0.22*

Table 3. Argon isotopic results for furnace step-heating analyses.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-16} mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1s (Ma)
UGS5, 11.10 mg hornblende, J=0.0007628, NM-144, Lab#=52674-01										
A	*875*	*351.1*	*2.665*	*1139.9*	*0.716*	*0.19*	*4.1*	*2.5*	*19.9*	*3.2*
B	975	87.85	1.605	195.5	0.303	0.32	34.4	3.6	41.2	2.9
C	1075	72.24	2.942	144.1	0.431	0.17	41.4	5.1	40.8	2.7
D	1105	39.84	3.782	49.24	0.295	0.13	64.3	6.1	35.0	3.3
E	1135	31.02	5.703	17.27	2.82	0.089	85.1	16.0	36.10	0.40
F	1165	26.86	6.030	0.0672	2.49	0.085	101.8	24.8	37.39	0.40
G	1195	30.26	5.973	12.28	3.28	0.085	89.6	36.3	37.11	0.28
H	1245	30.73	5.952	14.11	13.4	0.086	88.0	83.3	37.00	0.13
I	1275	31.06	6.137	16.28	4.27	0.083	86.1	98.3	36.61	0.26
J	1325	33.63	9.452	23.67	0.345	0.054	81.5	99.5	37.6	2.0
K	*1375*	*43.27*	*27.94*	*-214.9769*	*0.024*	*0.018*	*252.1*	*99.6*	*147.0*	*31.2*
L	*1725*	*116.5*	*14.09*	*272.8*	*0.124*	*0.036*	*31.8*	*100.0*	*50.7*	*6.0*
total gas age			n=12		28.5	0.092			36.71	0.96*
plateau		MSWD = 1.5	n=9	steps B-J	27.6	0.090		97.0	36.93	0.22*
UGS6, 10.86 mg hornblende, J=0.0007747, NM-144, Lab#=52722-01										
A	875	920.3	3.058	1275.5	2.16	0.17	59.1	6.7	635.2	3.3
B	975	296.4	1.419	70.96	1.88	0.36	93.0	12.6	349.3	1.7
C	1075	347.1	1.845	50.30	2.13	0.28	95.8	19.2	413.8	1.6
D	1105	223.9	3.476	129.2	0.973	0.15	83.1	22.2	243.4	1.7
E	1135	56.31	5.253	30.00	3.82	0.097	85.0	34.0	65.95	0.30
F	1165	45.67	5.972	41.11	1.86	0.085	74.5	39.8	47.12	0.45
G	1195	51.11	6.214	22.94	2.07	0.082	87.7	46.2	61.88	0.44
H	1245	35.79	6.478	22.34	16.0	0.079	83.0	95.8	41.25	0.16
I	1275	35.76	7.466	34.17	1.40	0.068	73.5	100.1	36.54	0.60
J	1325	126.8	26.00	289.0	0.036	0.020	34.3	100.2	61.0	19.3
K	1375	8.939	5.166	-52.7920	-0.114	0.099	279.3	99.9	34.7	5.4
L	1725	510.7	42.70	1656.1	0.034	0.012	4.9	100.0	35.5	21.4
total gas age			n=12		32.2	0.12			134.3	1.4*
UGS8, 2.78 mg biotite, J=0.0007621, NM-144, Lab#=52670-01										
A	*725*	*147.5*	*0.1150*	*400.9*	*3.63*	*4.4*	*19.7*	*0.9*	*39.49*	*2.65*
B	*825*	*38.98*	*0.0388*	*35.67*	*5.68*	*13.2*	*73.0*	*2.3*	*38.69*	*1.02*
C	*925*	*34.45*	*0.0190*	*18.90*	*9.65*	*26.8*	*83.8*	*4.6*	*39.26*	*0.61*
D	*995*	*31.30*	*0.0292*	*8.618*	*9.60*	*17.5*	*91.9*	*7.0*	*39.11*	*0.52*
E	*1075*	*29.34*	*0.0393*	*5.749*	*21.5*	*13.0*	*94.2*	*12.3*	*37.61*	*0.25*
F	1150	28.28	0.0799	4.136	35.5	6.4	95.7	20.9	36.83	0.17
G	1185	29.64	0.0351	9.123	32.2	14.6	90.9	28.8	36.68	0.19
H	1255	27.92	0.0211	3.902	232.5	24.2	95.9	85.7	36.44	0.05
I	1285	27.53	0.0080	2.604	56.1	63.5	97.2	99.5	36.42	0.11
J	1325	89.31	0.0219	212.2	0.549	23.2	29.8	99.6	36.20	8.12
K	1375	-47.8440	0.2747	-286.9099	0.348	1.9	-77.2	99.7	50.13	12.06
L	1700	89.57	1.609	222.7	1.35	0.32	26.7	100.0	32.61	3.74
total gas age			n=12		408.6	26.2			36.74	0.38*
plateau		MSWD = 1.5	n=7	steps F-L	358.5	27.6		87.7	36.48	0.12*

Table 3. Argon isotopic results for furnace step-heating analyses.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-16} mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1s (Ma)
UGS8, 4.03 mg hornblende, J=0.0007618, NM-144, Lab#=52671-01										
A	875	202.3	0.8088	586.8	1.19	0.63	14.3	7.7	39.4	1.6
B	975	88.87	0.6870	192.0	0.484	0.74	36.2	10.8	43.7	2.6
C	1075	44.59	1.753	57.77	1.02	0.29	62.0	17.4	37.7	1.0
D	1105	45.76	4.007	67.55	0.961	0.13	57.1	23.7	35.66	0.99
E	1135	55.19	4.882	94.95	2.49	0.10	49.9	39.8	37.58	0.60
F	1165	42.83	4.744	59.50	3.67	0.11	59.9	63.6	35.02	0.40
G	1195	34.48	3.668	29.63	0.806	0.14	75.5	68.8	35.52	0.96
H	1245	38.88	4.519	41.89	3.38	0.11	69.1	90.7	36.68	0.36
I	1275	43.82	5.342	55.58	1.04	0.096	63.5	97.4	38.00	0.80
J	1325	53.84	6.060	73.82	0.187	0.084	60.4	98.6	44.3	4.3
K	1375	61.91	6.555	105.4	0.072	0.078	50.6	99.1	42.7	9.3
L	1725	218.5	6.241	653.8	0.139	0.082	11.8	100.0	35.2	8.1
total gas age			n=12		15.4	0.18			37.0	1.8*
plateau		MSWD = 3.5**	n=12	steps A-L	15.4	0.18		100.0	36.47	0.81*
UGS9, 10.12 mg hornblende, J=0.0007745, NM-144, Lab#=52723-01										
A	*875*	*361.4*	*2.101*	*1146.4*	*1.36*	*0.24*	*6.3*	*5.9*	*31.7*	*2.3*
B	*975*	*75.27*	*1.739*	*164.6*	*0.672*	*0.29*	*35.6*	*8.9*	*37.1*	*1.7*
C	*1075*	*66.43*	*2.425*	*145.1*	*0.708*	*0.21*	*35.8*	*12.0*	*32.9*	*1.3*
D	*1105*	*65.95*	*3.482*	*147.3*	*0.357*	*0.15*	*34.4*	*13.5*	*31.5*	*2.1*
E	*1135*	*50.65*	*5.069*	*88.24*	*1.29*	*0.10*	*49.3*	*19.2*	*34.71*	*0.80*
F	*1165*	*43.20*	*5.908*	*61.53*	*4.02*	*0.086*	*59.0*	*36.8*	*35.44*	*0.35*
G	1195	43.21	6.019	56.61	4.17	0.085	62.4	55.0	37.47	0.39
H	1245	37.33	6.356	39.31	9.74	0.080	70.3	97.6	36.46	0.21
I	1275	43.19	9.660	60.77	0.544	0.053	60.3	100.0	36.3	1.3
total gas age			n=9		22.9	0.10			35.91	1.1*
plateau		MSWD = 2.7**	n=3	steps G-I	14.5	0.08		63.2	36.66	0.37*
UGS10, 1.28 mg biotite, J=0.0007745, NM-144, Lab#=52628-01										
A	725	1414.3	0.0420	4685.4	25.7	12.1	2.1	19.1	41.1	3.9
B	825	76.76	0.0257	167.6	26.7	19.9	35.5	39.0	37.65	0.56
C	925	61.30	0.0267	116.4	33.6	19.1	43.9	64.0	37.22	0.32
D	995	52.48	0.0253	86.11	16.3	20.2	51.5	76.2	37.39	0.54
E	1075	48.59	0.0188	70.46	15.6	27.1	57.2	87.7	38.39	0.45
F	1150	37.52	0.0207	35.05	6.55	24.6	72.4	92.6	37.57	0.80
G	1185	38.07	0.0377	41.11	3.97	13.5	68.1	95.6	35.9	1.2
H	1255	34.47	0.0388	20.31	4.93	13.1	82.6	99.3	39.35	0.92
I	1285	113.6	0.2173	313.0	0.483	2.3	18.6	99.6	29.3	8.6
J	1325	377.2	1.051	1167.9	0.147	0.49	8.5	99.7	44.5	28.1
L	1700	249.3	2.923	746.7	0.376	0.17	11.6	100.0	40.1	11.7
total gas age			n=11		134.3	18.7			38.3	2.4*
plateau		MSWD = 1.2	n=11	steps A-L	134.3	18.7		100.0	37.62	0.41*

Table 3. Argon isotopic results for furnace step-heating analyses.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-16} mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1s (Ma)
UGS11, 11.04 mg hornblende, J=0.0007631, NM-144, Lab#=52669-01										
A	*875*	*192.9*	*1.059*	*576.5*	*6.90*	*0.48*	*11.7*	*13.2*	*30.91*	*0.73*
B	975	45.86	0.0844	62.23	5.26	6.0	59.9	23.3	37.44	0.31
C	1075	34.25	3.036	25.69	10.6	0.17	78.6	43.7	36.75	0.19
D	1105	29.18	4.825	8.803	13.2	0.11	92.5	69.0	36.88	0.13
E	1135	30.12	4.598	10.94	8.05	0.11	90.5	84.5	37.28	0.18
F	1165	31.44	4.919	17.63	1.63	0.10	84.7	87.6	36.43	0.53
G	1195	52.30	4.372	84.95	0.625	0.12	52.7	88.8	37.7	1.3
H	1245	29.65	5.396	9.283	4.49	0.095	92.3	97.4	37.41	0.22
I	1275	34.68	5.971	24.65	0.879	0.085	80.4	99.1	38.15	0.80
J	1325	68.70	6.272	131.4	0.262	0.081	44.2	99.6	41.5	2.8
K	1375	89.24	6.660	171.9	0.070	0.077	43.7	99.7	53.1	9.0
L	1725	152.0	5.502	436.6	0.146	0.093	15.4	100.0	32.1	5.7
total gas age			n=12		52.1	0.77			36.27	0.66*
plateau		MSWD = 2.0	n=11	steps B-L	45.2	0.81		86.8	37.05	0.18*
UGS11, 2.80 mg biotite, J=0.0007659, NM-144, Lab#=52666-01										
A	*725*	*475.4*	*0.2630*	*1556.9*	*6.14*	*1.9*	*3.2*	*7.5*	*21.1*	*1.8*
B	*825*	*52.05*	*0.1466*	*91.71*	*7.08*	*3.5*	*48.0*	*16.0*	*34.17*	*0.36*
C	*925*	*48.70*	*0.0181*	*74.72*	*16.2*	*28.2*	*54.7*	*35.7*	*36.41*	*0.23*
D	*995*	*41.08*	*0.0114*	*48.14*	*13.7*	*44.8*	*65.4*	*52.3*	*36.73*	*0.20*
E	1075	37.89	0.0290	34.83	15.5	17.6	72.8	71.1	37.74	0.15
F	1150	35.40	0.0876	27.07	7.94	5.8	77.4	80.7	37.49	0.18
G	1185	29.29	0.0598	6.786	4.06	8.5	93.2	85.6	37.32	0.30
H	1255	30.47	0.0984	10.93	10.0	5.2	89.4	97.8	37.26	0.16
I	1285	26.16	0.0405	-2.2477	1.59	12.6	102.6	99.7	36.70	0.57
J	*1325*	*-6.4646*	*0.8776*	*-53.5056*	*0.037*	*0.58*	*-145.7*	*99.8*	*13.0*	*23.7*
K	*1375*	*54.27*	*0.4034*	*106.6*	*0.129*	*1.3*	*42.0*	*99.9*	*31.2*	*7.5*
L	*1700*	*309.6*	*13.09*	*1099.9*	*0.073*	*0.039*	*-4.6*	*100.0*	*-20.1*	*16.1*
total gas age			n=12		82.4	18.6			35.57	0.74*
plateau		MSWD = 1.7	n=5	steps E-I	39.1	10.9		47.4	37.47	0.19*
UGS12, 11.16 mg hornblende, J=0.000762, NM-144, Lab#=52673-01										
A	*875*	*304.6*	*1.884*	*964.2*	*0.856*	*0.27*	*6.5*	*3.2*	*27.1*	*3.2*
B	975	45.58	0.6380	71.86	0.364	0.80	53.5	4.6	33.2	2.7
C	1075	41.09	4.256	48.25	1.92	0.12	66.2	11.9	37.10	0.45
D	1105	32.98	6.638	19.19	3.10	0.077	84.5	23.6	38.07	0.28
E	1135	32.89	6.673	16.55	12.3	0.076	86.8	70.2	39.00	0.15
F	1165	32.46	6.281	15.99	1.35	0.081	87.0	75.3	38.60	0.50
G	1195	32.49	6.192	22.93	1.05	0.082	80.7	79.3	35.85	0.63
H	1245	35.18	6.719	25.40	3.12	0.076	80.2	91.1	38.58	0.32
I	1275	38.98	7.149	38.00	1.57	0.071	72.7	97.0	38.74	0.52
J	1325	45.88	7.329	79.47	0.362	0.070	50.1	98.4	31.5	1.9
K	1375	35.24	10.23	33.01	0.300	0.050	74.7	99.5	36.1	2.3
L	*1725*	*238.1*	*9.139*	*777.7*	*0.122*	*0.056*	*3.8*	*100.0*	*12.5*	*8.3*
total gas age			n=12		26.4	0.096			37.82	0.98*
plateau			n=10	steps B-K	25.4	0.090		96.3	38.52	0.60*

Table 3. Argon isotopic results for furnace step-heating analyses.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-16} mol)	K/Ca	^{40}Ar* (%)	^{39}Ar (%)	Age (Ma)	±1s (Ma)
UGS12, 2.81 mg biotite, J=0.0007617, NM-144, Lab#=52672-01										
A	*725*	*1077.0*	*0.1496*	*3607.0*	*2.03*	*3.4*	*1.0*	*2.6*	*15.3*	*4.5*
B	*825*	*77.03*	*0.0466*	*169.8*	*2.16*	*10.9*	*34.9*	*5.4*	*36.55*	*0.92*
C	925	48.93	0.0177	67.85	5.66	28.9	59.0	12.7	39.27	0.30
D	995	38.15	0.0127	31.31	9.52	40.1	75.8	24.9	39.28	0.19
E	1075	34.28	0.0363	19.27	16.1	14.1	83.4	45.7	38.87	0.13
F	1150	33.15	0.4672	17.21	10.1	1.1	84.8	58.7	38.22	0.17
G	1185	31.07	0.1690	9.413	5.29	3.0	91.1	65.5	38.48	0.22
H	1255	29.54	0.1278	4.458	24.5	4.0	95.6	97.0	38.39	0.10
I	*1285*	*32.03*	*0.1658*	*19.01*	*1.65*	*3.1*	*82.5*	*99.1*	*35.96*	*0.57*
J	*1325*	*58.93*	*0.6991*	*145.0*	*0.160*	*0.73*	*27.4*	*99.4*	*22.1*	*4.7*
K	*1375*	*45.64*	*0.5611*	*90.32*	*0.215*	*0.91*	*41.6*	*99.6*	*25.9*	*3.9*
L	*1700*	*110.1*	*2.649*	*305.8*	*0.286*	*0.19*	*18.1*	*100.0*	*27.3*	*3.5*
total gas age			n=12		77.7	12.0			37.83	0.66*
plateau		MSWD = 6.3**	n=6	steps C-H	71.2	12.6		91.6	38.62	0.37*
DV 0021, 11.78 mg groundmass concentrate, J=0.0007533, NM-144, Lab#=52696-01										
A	*700*	*177.5*	*0.0855*	*525.9*	*74.8*	*6.0*	*12.4*	*9.6*	*29.71*	*1.24*
B	775	30.62	0.1281	16.98	125.4	4.0	83.7	25.7	34.49	0.11
C	825	28.30	0.1313	8.855	89.9	3.9	90.8	37.2	34.59	0.10
D	875	29.79	0.1913	13.35	82.4	2.7	86.8	47.7	34.80	0.11
E	950	29.28	0.2453	12.64	102.8	2.1	87.3	60.9	34.41	0.11
F	1050	33.29	0.2319	27.25	148.7	2.2	75.9	79.9	34.01	0.14
G	*1150*	*43.14*	*0.3510*	*63.45*	*94.8*	*1.5*	*56.6*	*92.1*	*32.89*	*0.23*
H	*1325*	*44.31*	*0.9623*	*76.70*	*37.5*	*0.53*	*49.0*	*96.9*	*29.30*	*0.32*
I	*1725*	*64.60*	*1.452*	*155.7*	*24.2*	*0.35*	*29.0*	*100.0*	*25.29*	*0.65*
total gas age			n=9		780.6	2.8			33.25	0.54*
plateau		MSWD = 5.4**	n=5	steps B-F	549.2	2.9		70.4	34.50	0.28*
S-40, 11.97 mg groundmass concentrate, J=0.0007535, NM-144, Lab#=52697-01										
A	*700*	*251.3*	*0.2351*	*786.8*	*61.2*	*2.2*	*7.5*	*11.7*	*25.44*	*1.83*
B	775	44.53	0.3056	62.89	79.2	1.7	58.3	26.8	34.97	0.24
C	825	51.31	0.4147	83.29	63.7	1.2	52.1	39.0	35.99	0.30
D	875	54.09	0.5368	90.76	54.4	0.95	50.5	49.4	36.76	0.33
E	950	57.58	0.7424	105.0	54.2	0.69	46.2	59.7	35.82	0.40
F	1050	73.34	0.9610	160.0	43.6	0.53	35.6	68.1	35.21	0.47
G	1150	74.67	0.6838	161.7	118.3	0.75	36.1	90.6	36.26	0.49
H	*1325*	*68.97*	*2.033*	*139.7*	*38.4*	*0.25*	*40.4*	*98.0*	*37.53*	*0.55*
I	*1725*	*81.04*	*5.277*	*177.5*	*10.6*	*0.097*	*35.8*	*100.0*	*39.17*	*1.04*
total gas age			n=9		523.7	1.1			34.84	1.4*
plateau		MSWD = 4.7**	n=6	steps B-G	413.4	1.0		78.9	35.72	0.61*

Table 3. Argon isotopic results for furnace step-heating analyses.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-16} mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1s (Ma)
DV 0003, 10.68 mg hornblende, J=0.0007648, NM-144, Lab#=52667-01										
A	875	211.2	0.4311	629.3	0.702	1.2	12.0	2.0	34.6	2.8
B	975	79.87	0.6895	199.5	0.454	0.74	26.3	3.3	28.7	2.3
C	1075	43.11	2.273	63.65	1.20	0.22	56.8	6.8	33.52	0.81
D	1105	30.16	6.468	19.54	6.49	0.079	82.6	25.5	34.21	0.20
E	1135	35.22	6.172	35.90	9.70	0.083	71.3	53.4	34.48	0.23
F	1165	37.86	5.237	45.08	2.75	0.097	66.0	61.3	34.25	0.47
G	1195	36.10	4.601	37.38	2.50	0.11	70.5	68.5	34.87	0.43
H	1245	31.26	3.866	22.41	6.26	0.13	79.8	86.5	34.20	0.23
I	1275	34.49	5.982	35.53	3.40	0.085	71.0	96.3	33.61	0.36
J	1325	36.87	6.802	39.38	1.13	0.075	70.0	99.5	35.41	0.83
K	1375	259.2	6.167	786.8	0.047	0.083	10.5	99.6	37.4	18.2
L	1725	148.9	7.171	433.3	0.123	0.071	14.4	100.0	29.5	6.6
total gas age			n=12		34.8	0.13			34.22	0.88*
plateau		MSWD = 1.4	n=12	steps A-L	34.8	0.13		100.0	34.26	0.23*
CP2001-3, 202.82 mg groundmass concentrate, J=0.0001098, NM-150, Lab#=53053-01										
A	625	5083.5	1.793	17060.4	3.99	0.28	0.8	0.4	8.4	5.8
B	700	40.49	0.9019	126.2	141.7	0.57	8.1	15.7	0.65	0.04
C	750	14.90	0.6717	37.74	61.3	0.76	25.5	22.3	0.75	0.02
D	800	12.58	0.5517	30.32	192.5	0.92	29.1	43.0	0.73	0.01
E	875	13.43	0.5997	33.09	155.8	0.85	27.6	59.7	0.73	0.02
F	975	17.63	0.8873	47.22	116.7	0.58	21.2	72.3	0.74	0.03
G	1075	21.69	0.9785	60.33	101.8	0.52	18.2	83.3	0.78	0.03
H	*1250*	*63.38*	*7.122*	*194.0*	*116.9*	*0.072*	*10.5*	*95.8*	*1.32*	*0.07*
I	*1680*	*133.7*	*8.636*	*445.4*	*38.7*	*0.059*	*2.1*	*100.0*	*0.57*	*0.17*
total gas age			n=9		929.4	0.61			0.83	0.12*
plateau		MSWD = 1.5	n=7	steps A-G	773.8	0.72		83.3	0.73	0.02*

Notes:
Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interferring reactions.
Individual analyses show analytical error only; plateau and total gas age errors include error in J and irradiation parameters.
n= number of heating steps
K/Ca = molar ratio calculated from reactor produced $^{39}Ar_K$ and $^{37}Ar_{Ca}$.

* 2s error
** MSWD outside 95% confidence interval

Table 4. Argon isotopic results for B-steps of single crystal biotite step-heating analyses.

ID	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ ($x 10^{-3}$)	$^{39}Ar_K$ ($x 10^{-15}$ mol)	K/Ca	$\%^{40}Ar^*$	Age (Ma)	±1s (Ma)
UGS-3, single crystal biotite, J=0.0007659, NM-144, Lab#=52662								
22B	28.64	0.0923	7.510	0.211	5.5	92.3	36.16	0.33
23B	32.86	0.1077	20.09	0.125	4.7	82.0	36.84	0.56
26B	29.09	0.0387	7.176	0.355	13.2	92.7	36.89	0.33
27B	28.66	0.0797	5.724	0.308	6.4	94.1	36.90	0.33
24B	29.01	0.1158	5.989	0.168	4.4	93.9	37.27	0.48
21B	61.16	0.0214	114.6	0.064	23.9	44.6	37.3	1.2
20B	31.09	0.0523	12.73	0.634	9.7	87.9	37.38	0.30
25B	28.97	0.0616	4.273	0.368	8.3	95.7	37.89	0.32
weighted mean		**MSWD = 2.3****	n=8		9.5 ±6.5		37.07	0.28*

Notes:

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interferring reactions.
Individual analyses show analytical error only; plateau and total gas age errors include error in J and irradiation parameters.
n= number of heating steps
K/Ca = molar ratio calculated from reactor produced $^{39}Ar_K$ and $^{37}Ar_{Ca}$.

* 2s error

** MSWD outside 95% confidence interval

Table 5. Argon isotopic data for single crystal biotite step-heating analyses.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-16} mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1s (Ma)
UGS-3, single crystal biotite, J=0.0007659, D=1.00712, NM-144, Lab#=52662-20										
A	4	48.54	0.4116	74.27	9.27	1.2	54.9	37.2	36.43	0.44
B	10	31.09	0.0523	12.73	15.7	9.7	87.9	100.0	37.38	0.16
total gas age			n=2		24.9	6.6			37.02	0.26
plateau			n=2	steps A-B	24.9	6.6		100.0	37.27	0.34
UGS-3, single crystal biotite, J=0.0007659, D=1.00712, NM-144, Lab#=52662-21										
A	4	35.17	0.1880	24.11	15.6	2.7	79.8	90.8	38.37	0.18
B	10	61.16	0.0214	114.6	1.58	23.9	44.6	100.0	37.3	1.1
total gas age			n=2		17.1	4.7			38.27	0.26
plateau			n=2	steps A-B	17.1	4.7		100.0	38.34	0.23
UGS-3, single crystal biotite, J=0.0007659, D=1.00712, NM-144, Lab#=52662-22										
A	2	35.70	0.4324	28.21	1.85	1.2	76.7	26.2	37.48	0.70
B	10	28.64	0.0923	7.510	5.21	5.5	92.3	100.0	36.16	0.23
total gas age			n=2		7.06	4.4			36.50	0.36
plateau			n=2	steps A-B	7.06	4.4		100.0	36.29	0.45
UGS-3, single crystal biotite, J=0.0007659, D=1.00712, NM-144, Lab#=52662-23										
A	2	43.97	0.4507	56.48	0.742	1.1	62.1	19.4	37.4	1.7
B	10	32.86	0.1077	20.09	3.08	4.7	82.0	100.0	36.84	0.49
total gas age			n=2		3.83	4.0			36.94	0.72
plateau			n=2	steps A-B	3.83	4.0		100.0	36.88	0.49
UGS-3, single crystal biotite, J=0.0007659, D=1.00712, NM-144, Lab#=52662-24										
A	2	37.19	0.2993	24.17	1.58	1.7	80.9	27.6	41.09	0.95
B	10	29.01	0.1158	5.989	4.15	4.4	93.9	100.0	37.27	0.42
total gas age			n=2		5.73	3.7			38.33	0.56
plateau			n=2	steps A-B	5.73	3.7		100.0	37.9	1.5
UGS-3, single crystal biotite, J=0.0007659, D=1.00712, NM-144, Lab#=52662-25										
A	2	53.06	0.2206	85.33	3.16	2.3	52.5	25.8	38.10	0.68
B	10	28.97	0.0616	4.273	9.10	8.3	95.7	100.0	37.89	0.21
total gas age			n=2		12.3	6.7			37.94	0.33
plateau			n=2	steps A-B	12.3	6.7		100.0	37.91	0.21
UGS-3, single crystal biotite, J=0.0007659, D=1.00712, NM-144, Lab#=52662-26										
A	2	46.59	0.2290	61.85	1.71	2.2	60.8	16.4	38.74	0.97
B	10	29.09	0.0387	7.176	8.76	13.2	92.7	100.0	36.89	0.22
total gas age			n=2		10.5	11.4			37.19	0.35
plateau			n=2	steps A-B	10.5	11.4		100.0	36.98	0.46
UGS-3, single crystal biotite, J=0.0007659, D=1.00712, NM-144, Lab#=52662-27										
A	2	46.64	0.5708	65.24	1.57	0.89	58.8	17.1	37.5	1.1
B	10	28.66	0.0797	5.724	7.61	6.4	94.1	100.0	36.90	0.23
total gas age			n=2		9.18	5.5			37.00	0.39
plateau			n=2	steps A-B	9.18	5.5		100.0	36.92	0.26

Notes:
Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interferring reactions.
Individual analyses show analytical error only; plateau and total gas age errors include error in J and irradiation parameters.
n= number of heating steps

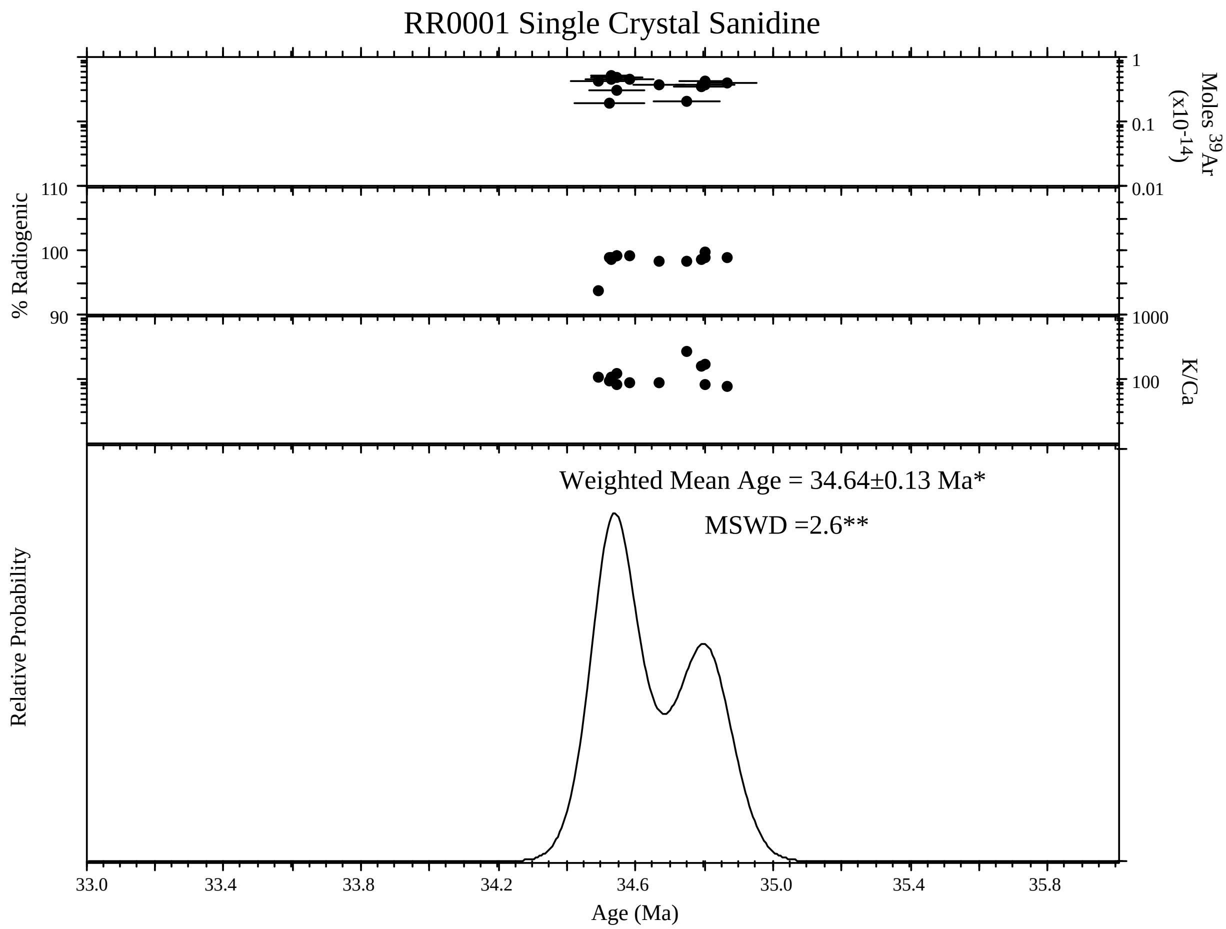


Figure 1. Age probability distribution diagram for sample RR0001 sanidine. *2σ
** MSWD outside 95% confidence interval

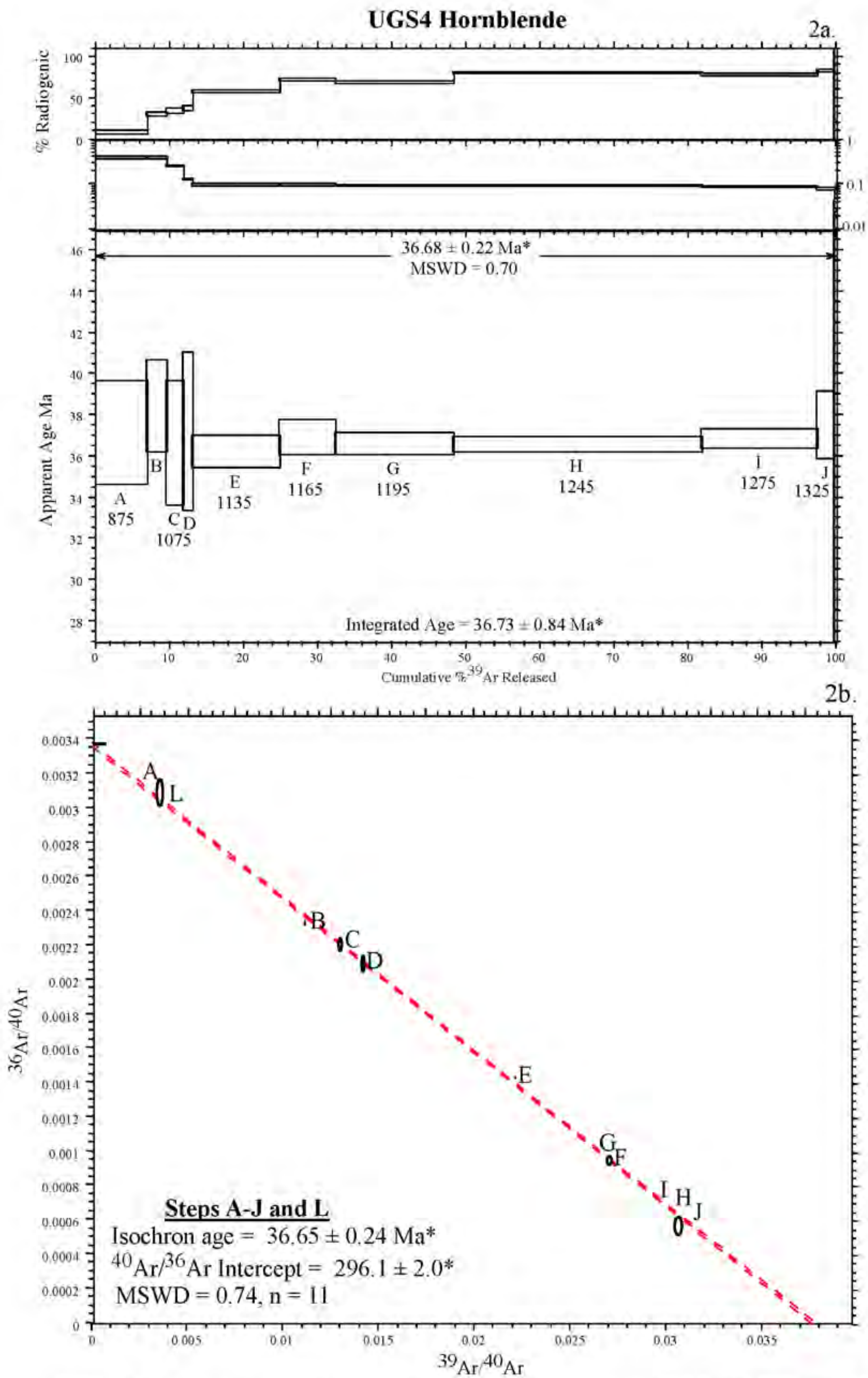
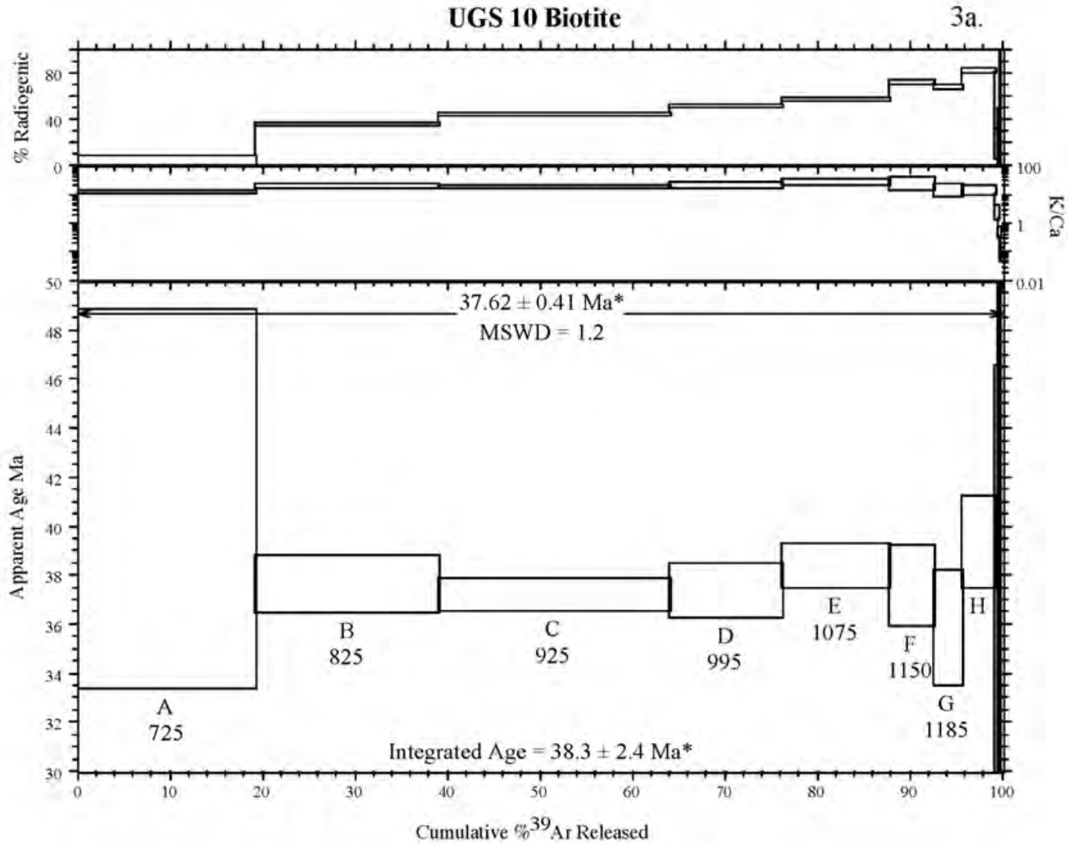


Figure 2. Age spectrum (2a) and isochron (2b) for sample UGS4 hornblende. $^{*}2\sigma$



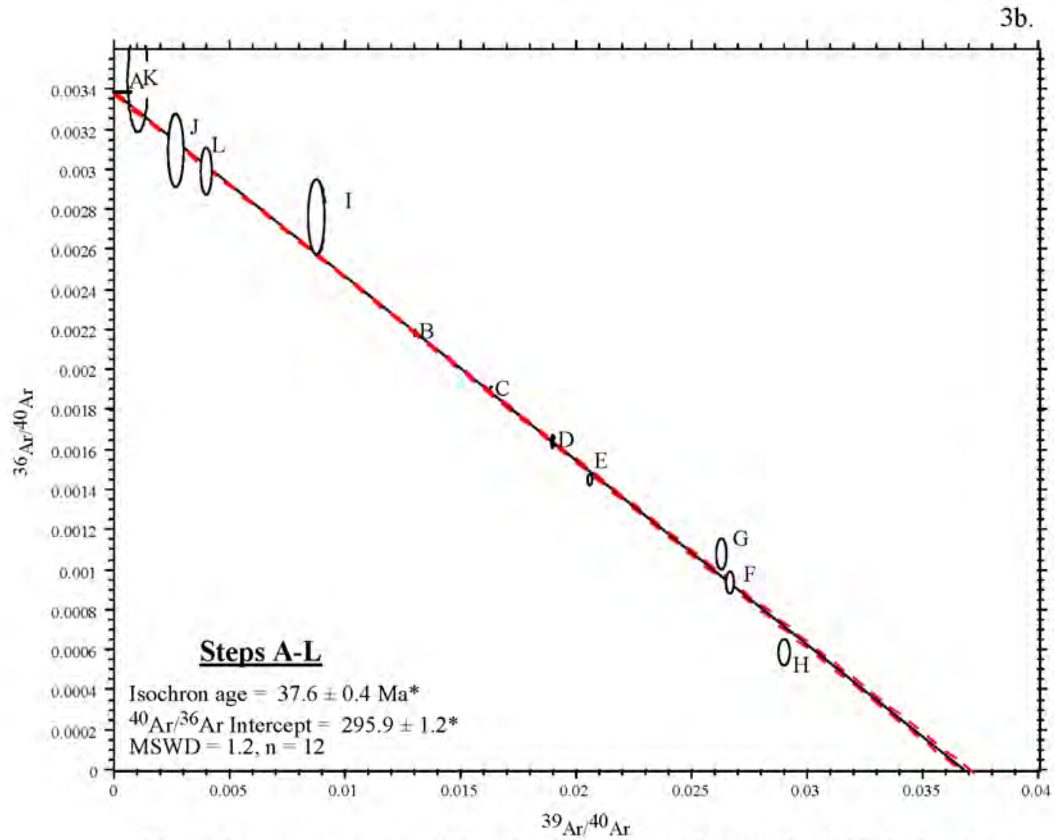


Figure 3. Age spectrum (3a) and isochron (3b) for sample UGS 10 biotite.
*2σ **outside 95% confidence interval

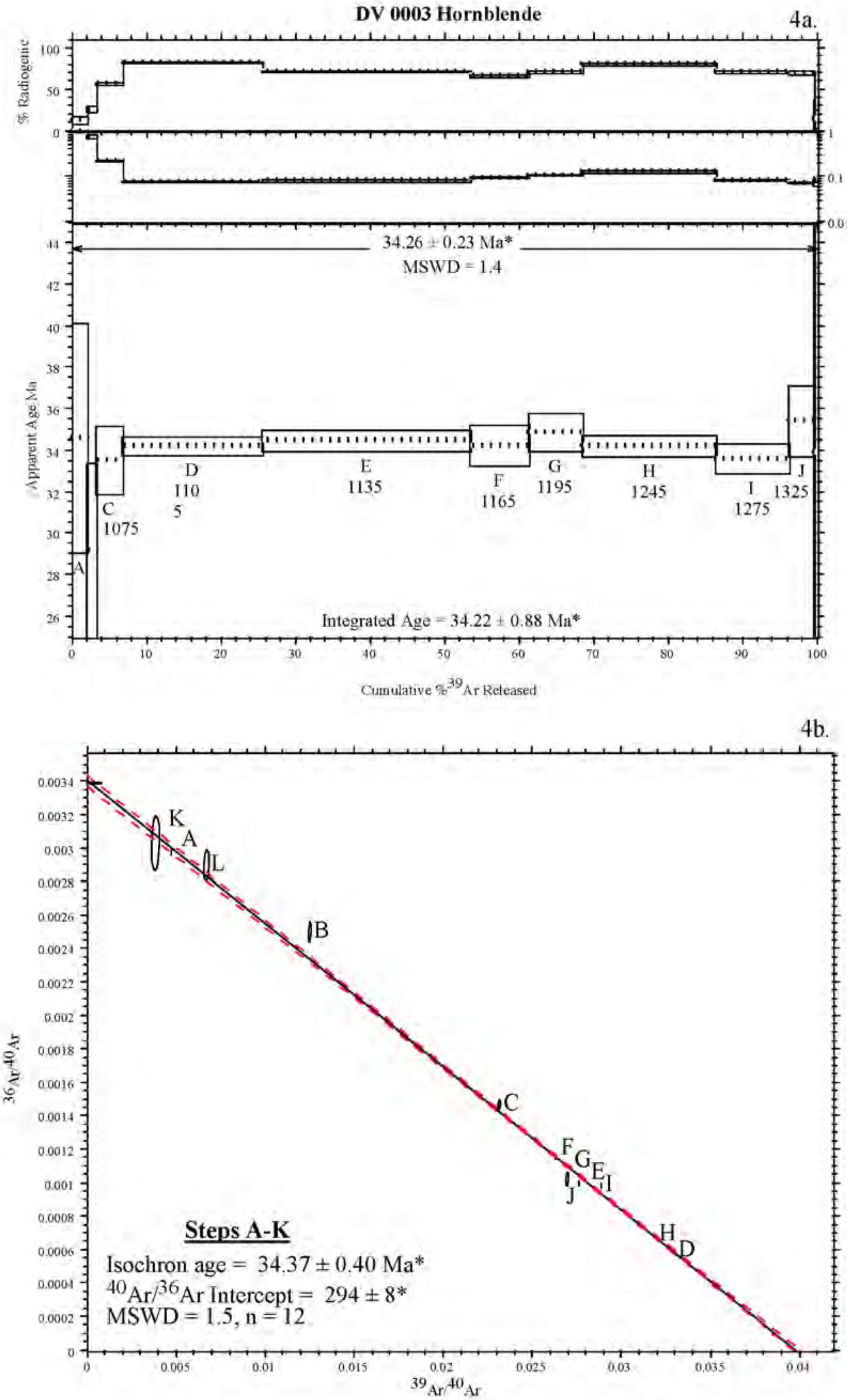


Figure 4. Age spectrum (4a) and isochron (4b) for sample DV 0003 hornblende.
*2σ ** outside 95% confidence interval

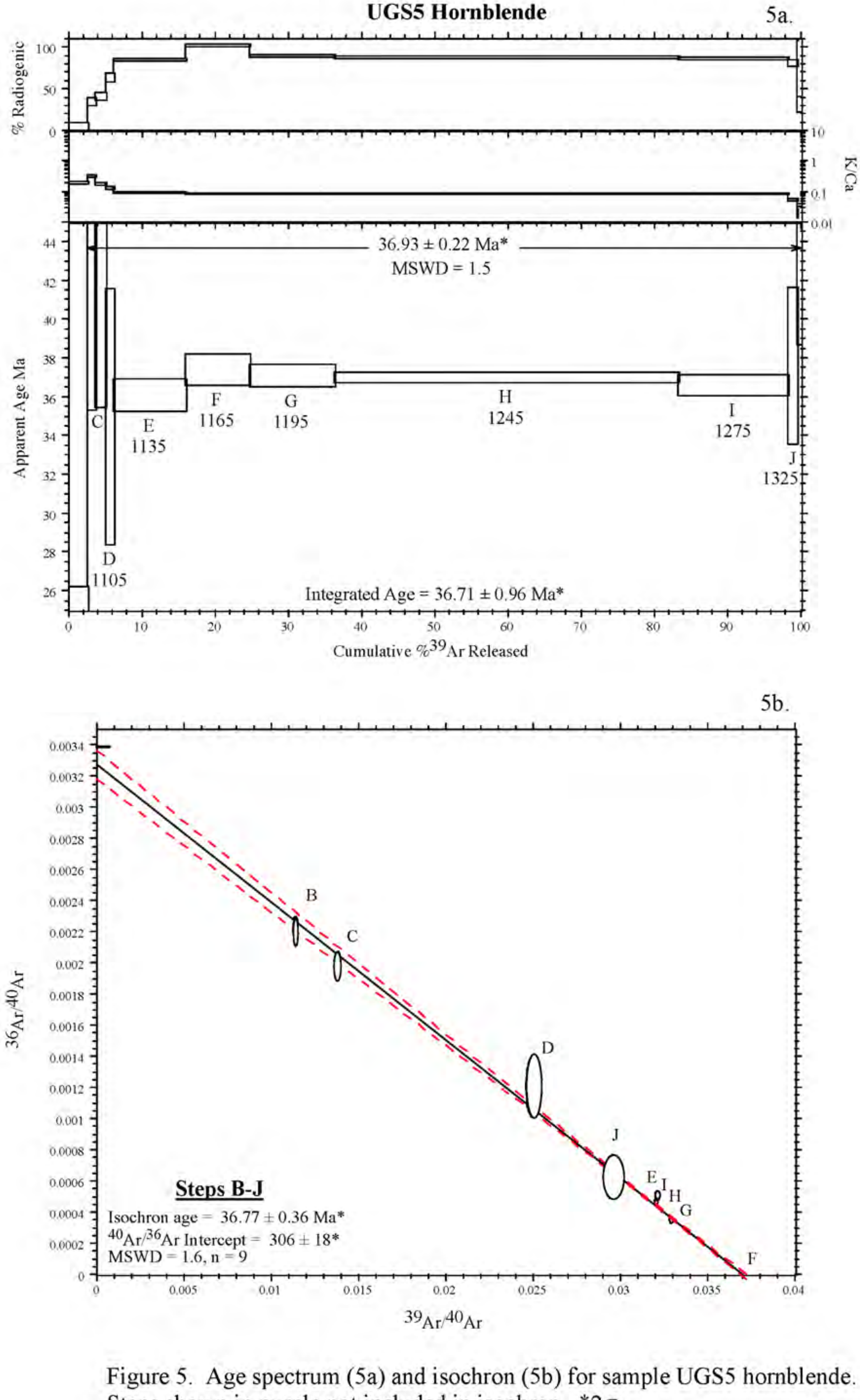


Figure 5. Age spectrum (5a) and isochron (5b) for sample UGS5 hornblende. Steps shown in purple not included in isochron. *2σ

CP62001-3 Groundmass Concentrate

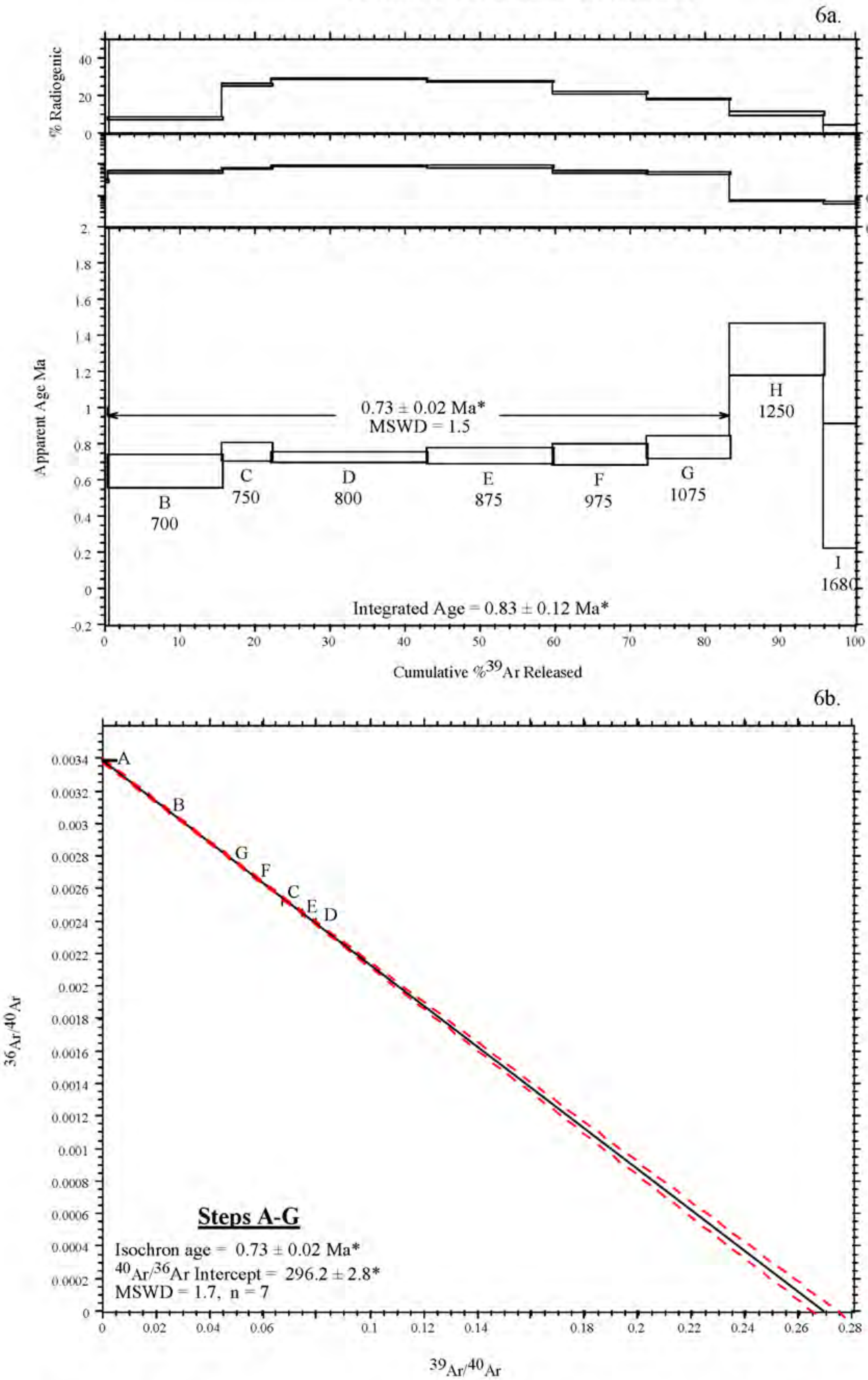


Figure 6. Age spectrum (6a) and isochron (6b) for sample CP62001-3 groundmass concentrate.
*2σ **outside 95% confidence interval

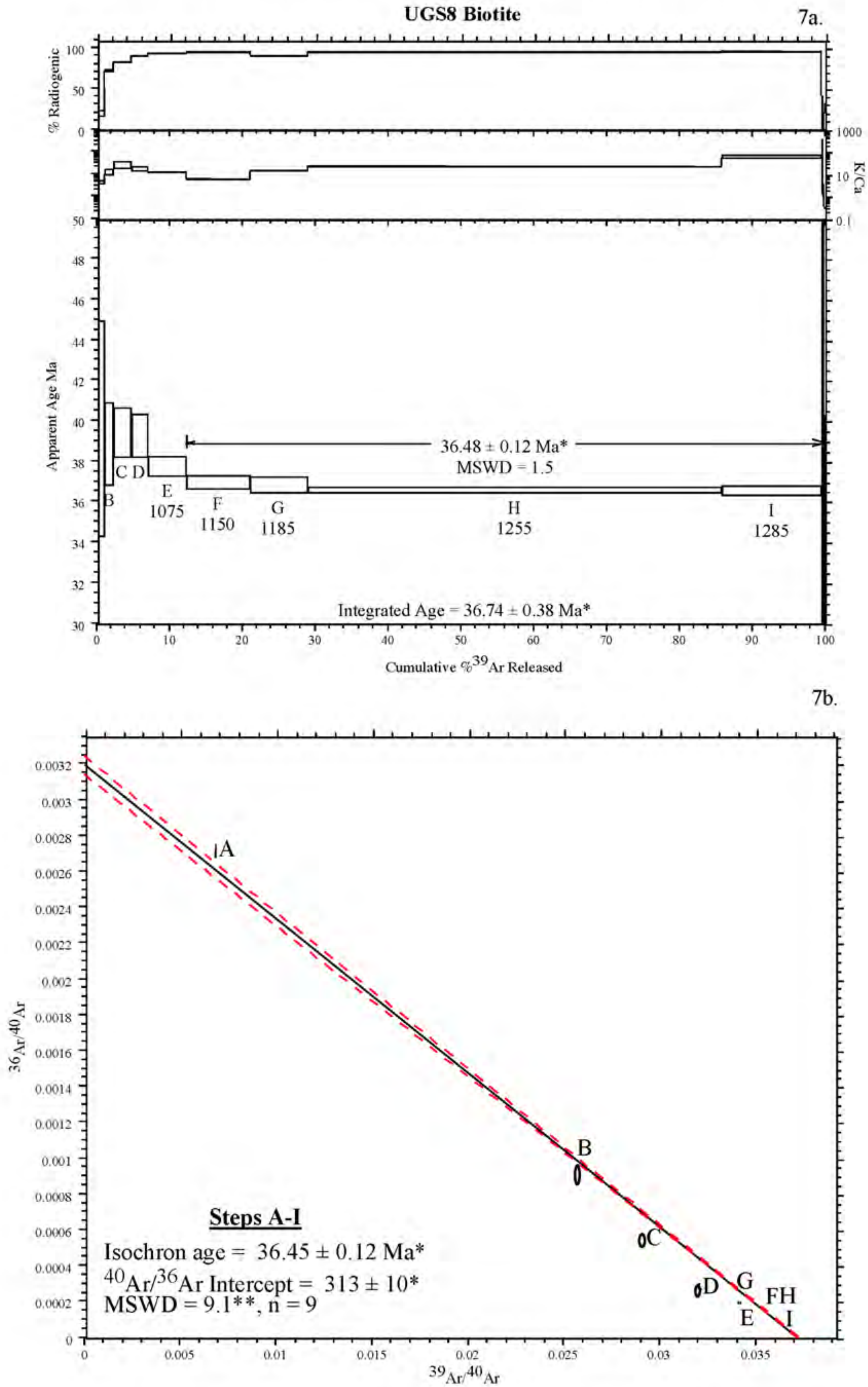
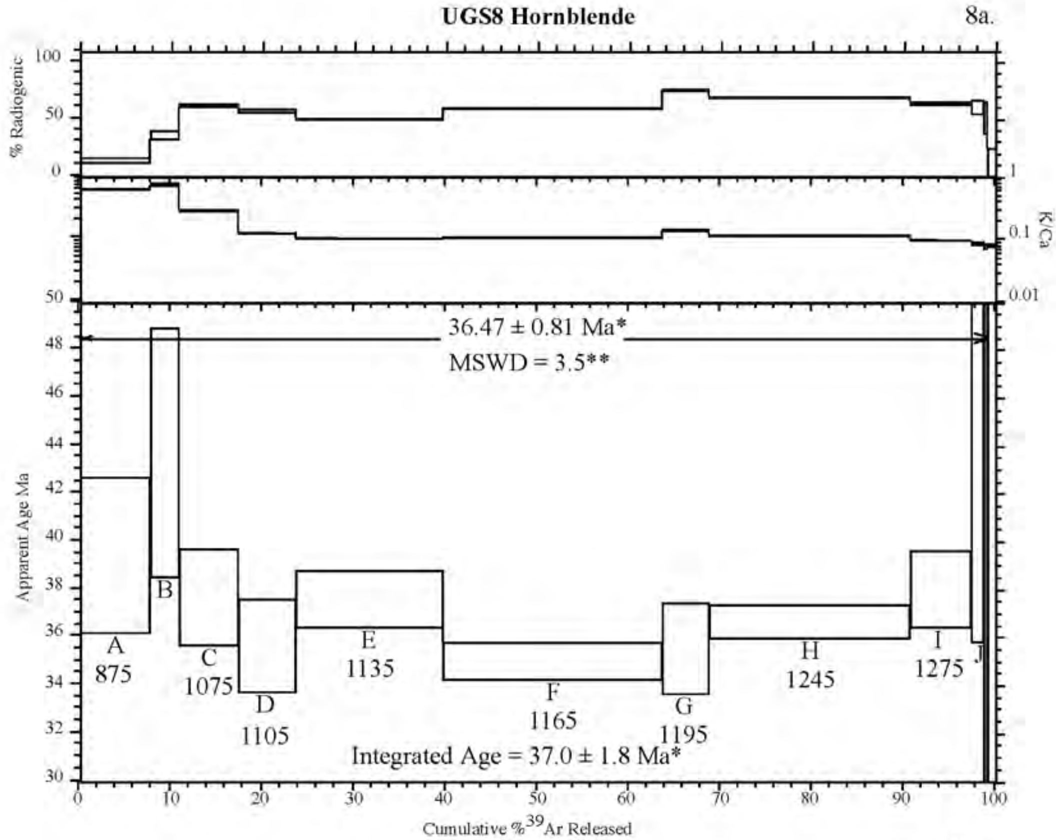


Figure 7. Age spectrum (7a) and isochron (7b) for sample UGS8 Biotite.
*2σ **outside 95% confidence interval



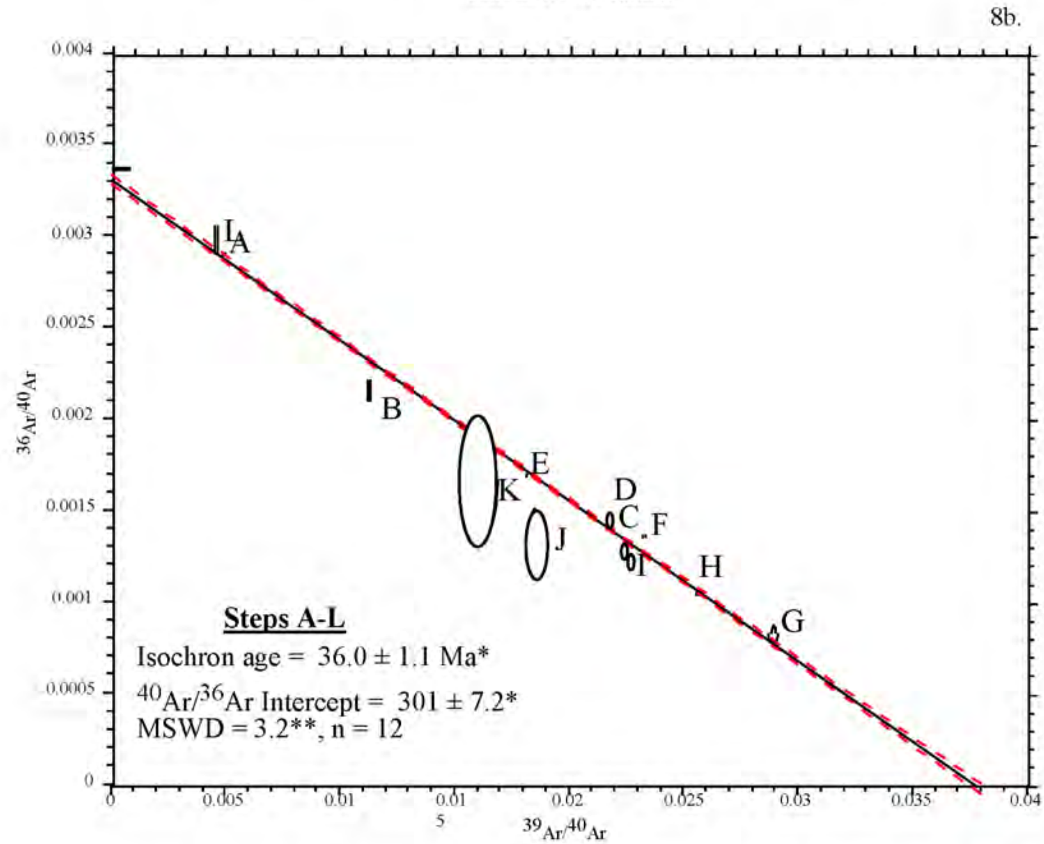
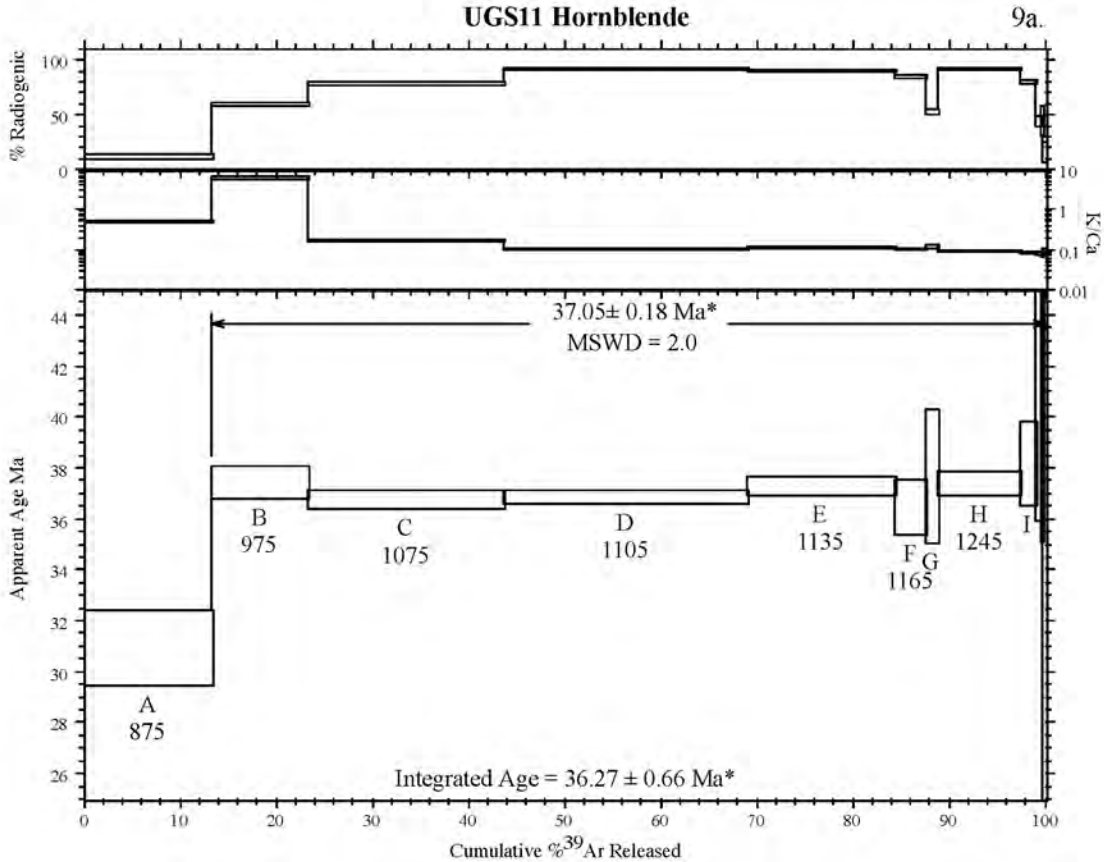


Figure 8. Age spectrum (8a) and isochron (8b) for sample UGS8 hornblende.
*2σ **outside 95% confidence interval



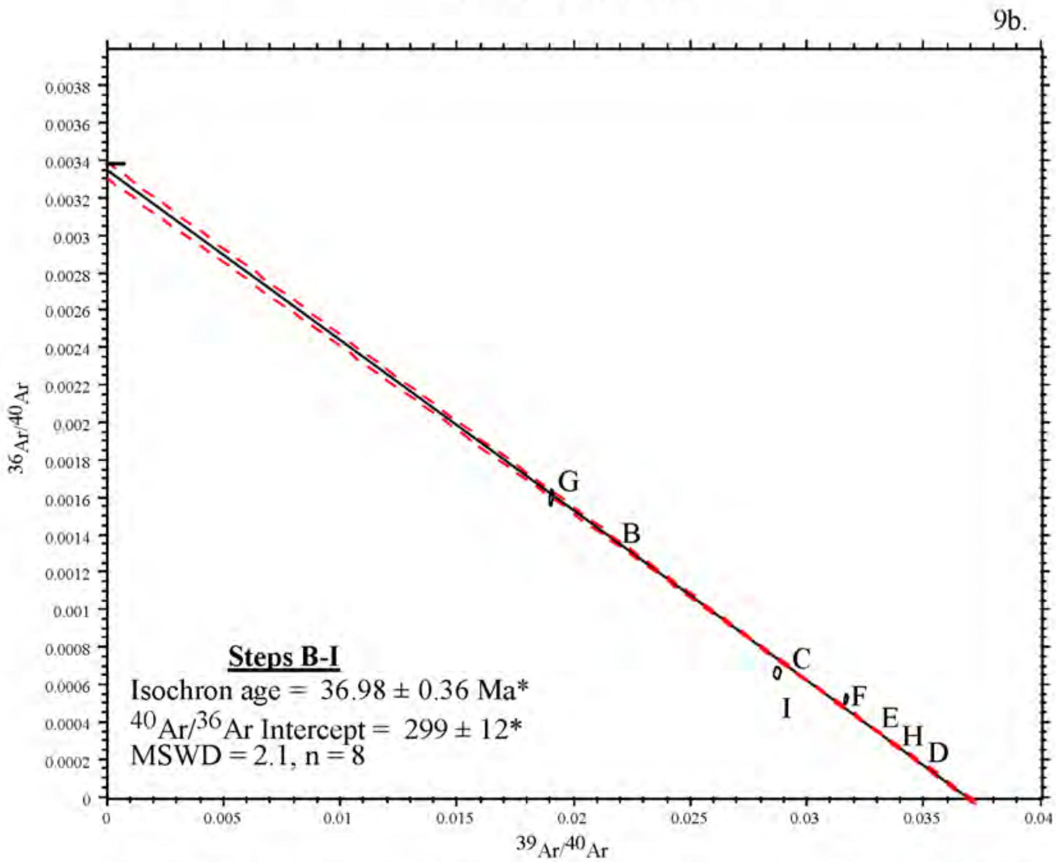


Figure 9. Age spectrum (9a) and isochron (9b) for sample UGS11 hornblende.
*2σ

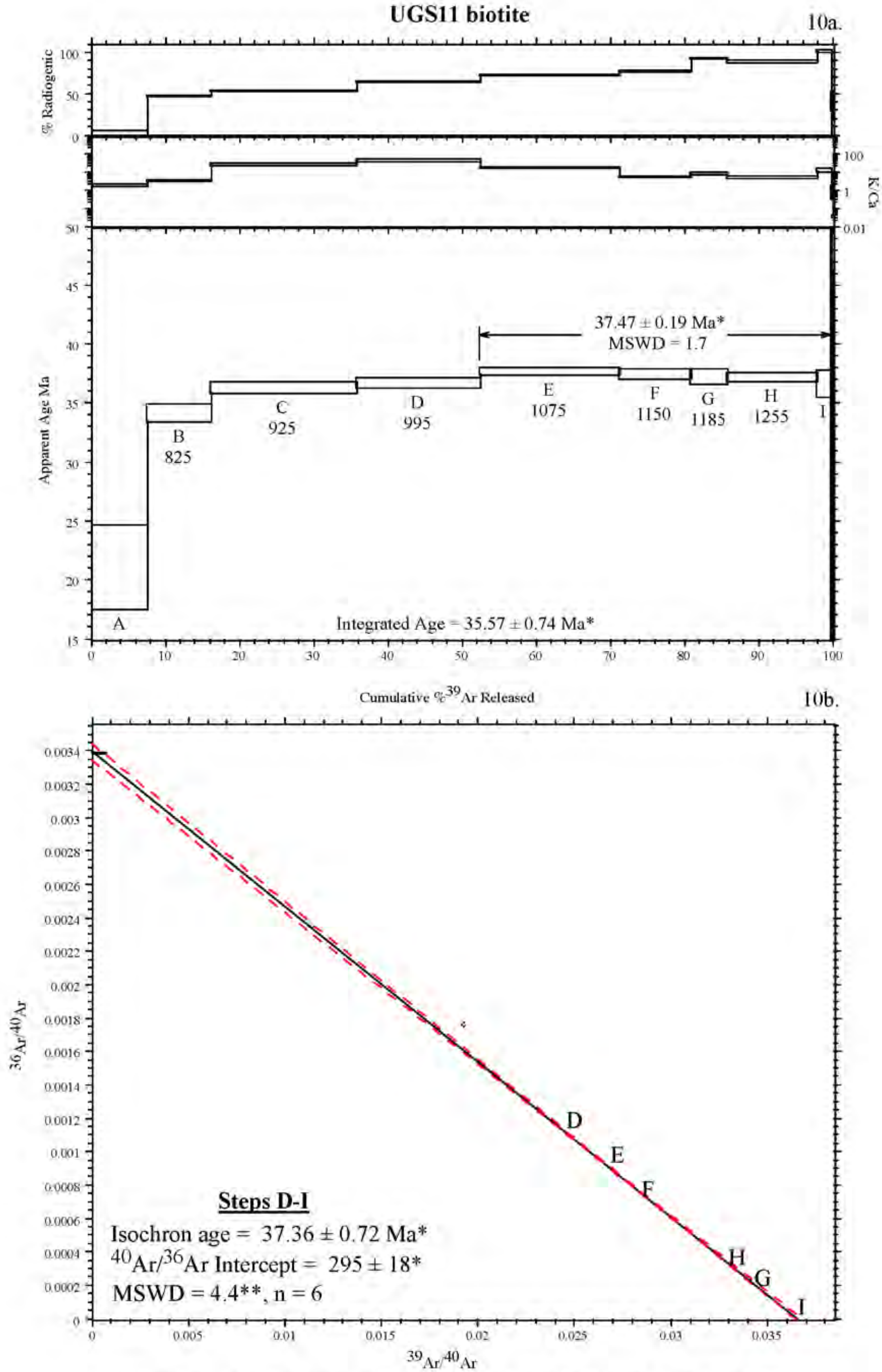
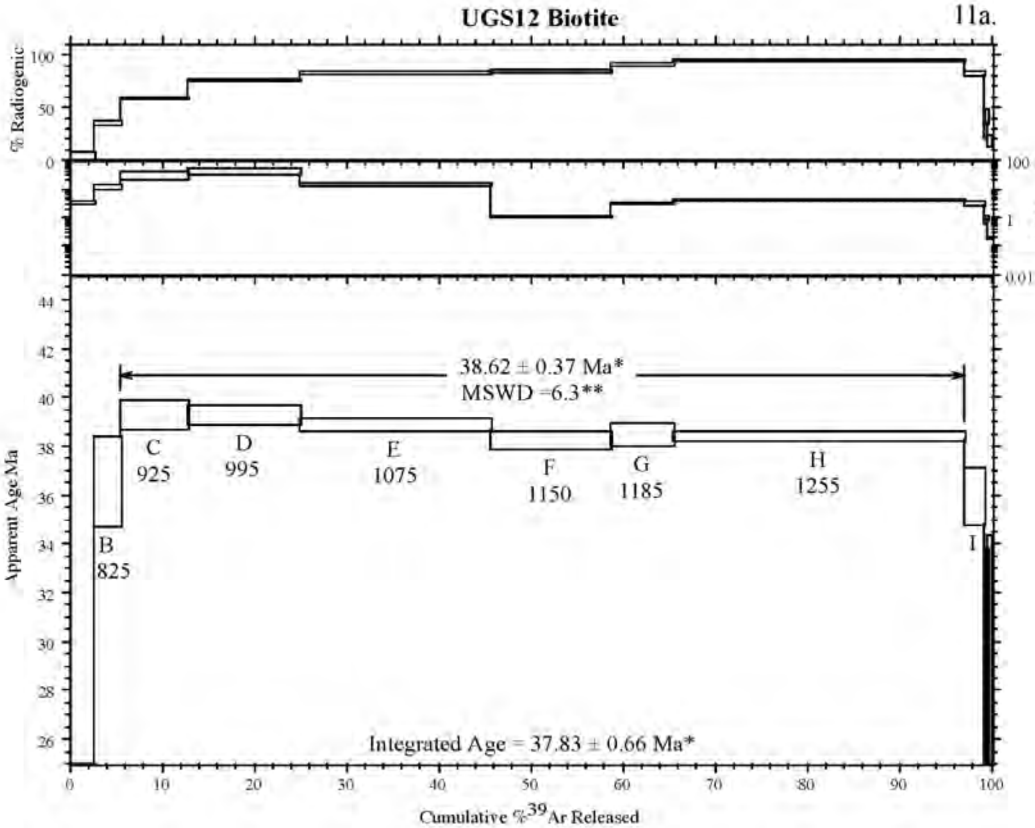


Figure 10. Age spectrum (10a) and isochron (10b) for sample UGS11 biotite.
*2σ ** outside 95% confidence interval



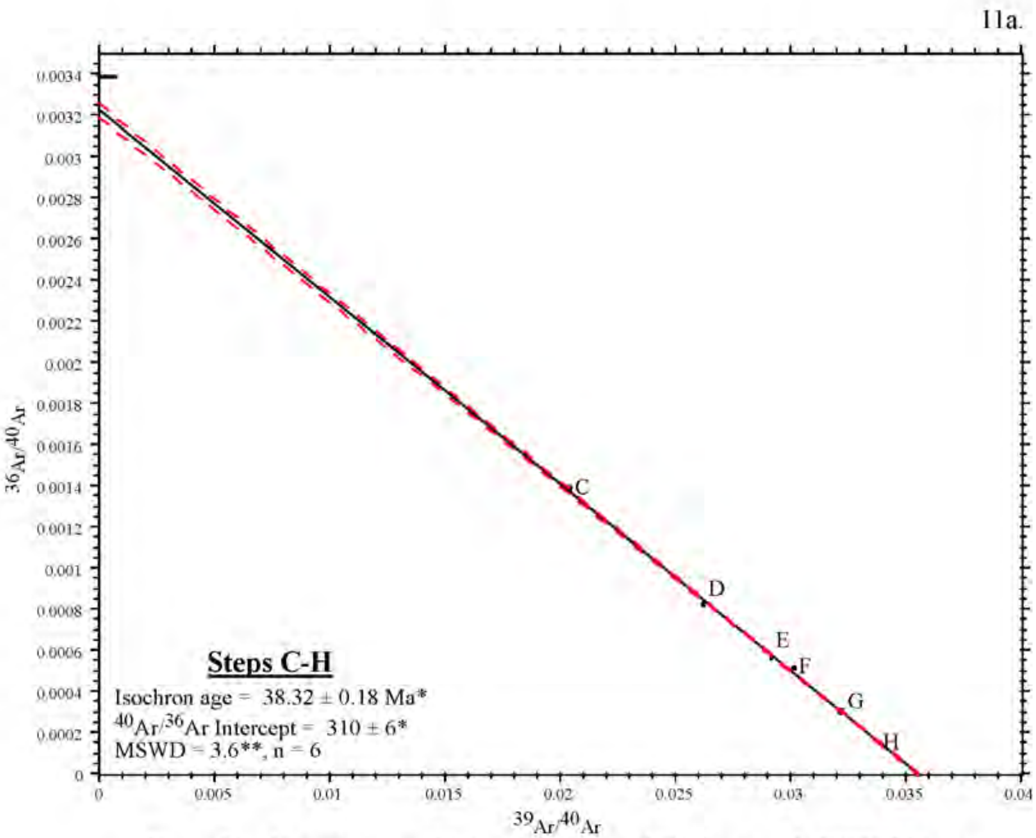
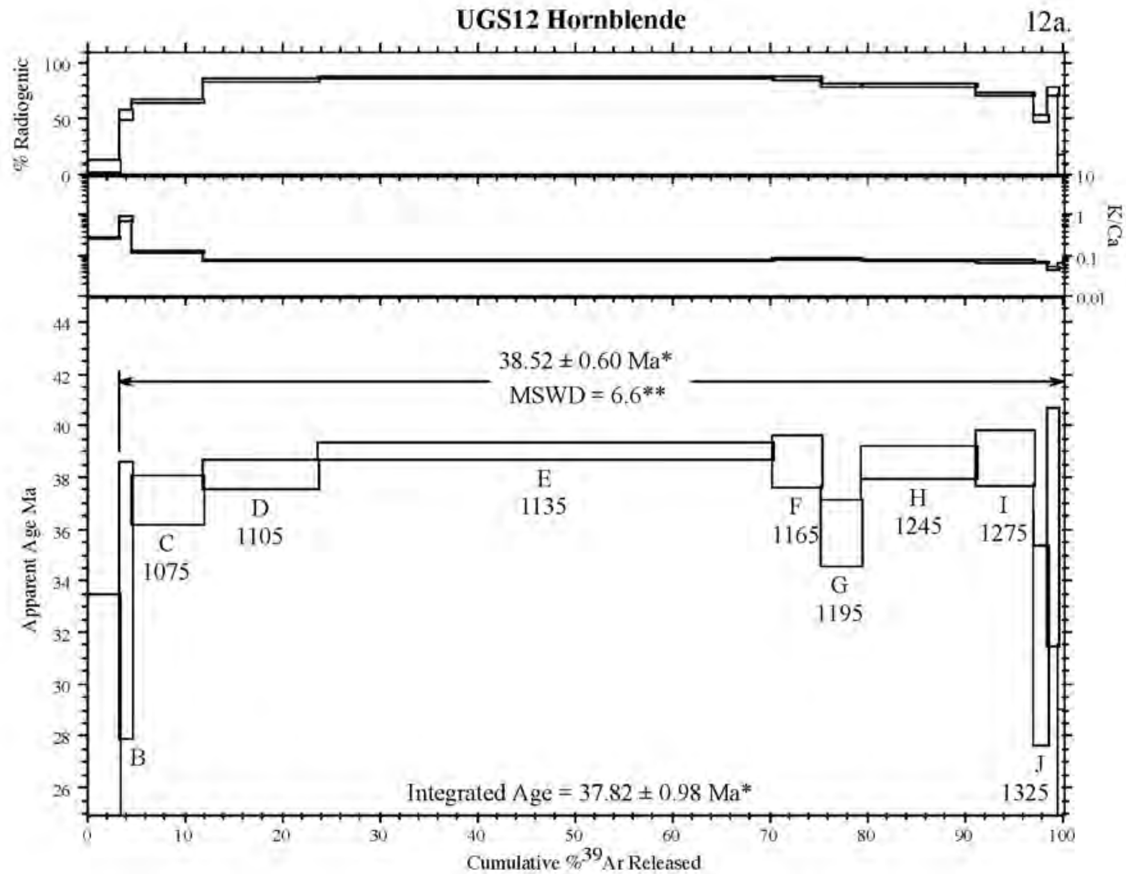


Figure11. Age spectrum (11a) and isochron (11b) for sample UGS12 biotite.
*2σ **outside 95% confidence interval



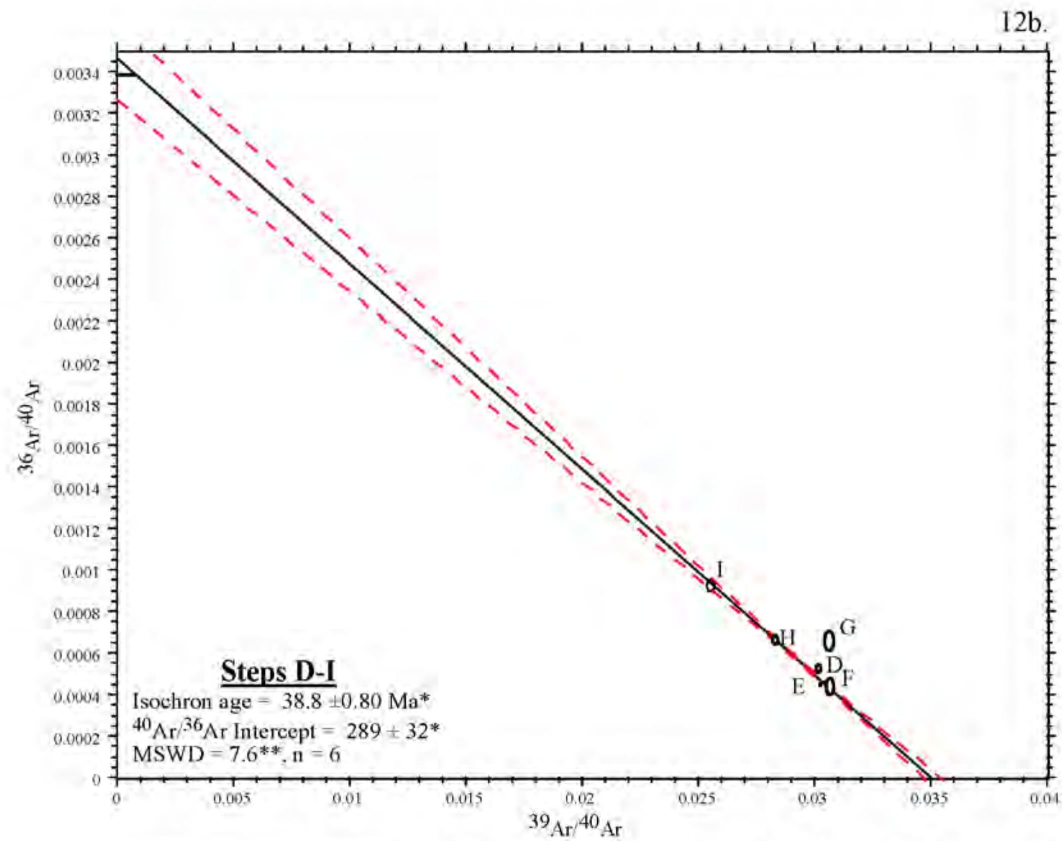


Figure 12. Age spectrum (12a) and isochron (12b) for sample UGS12 hornblende.
*2σ **outside 95% confidence interval

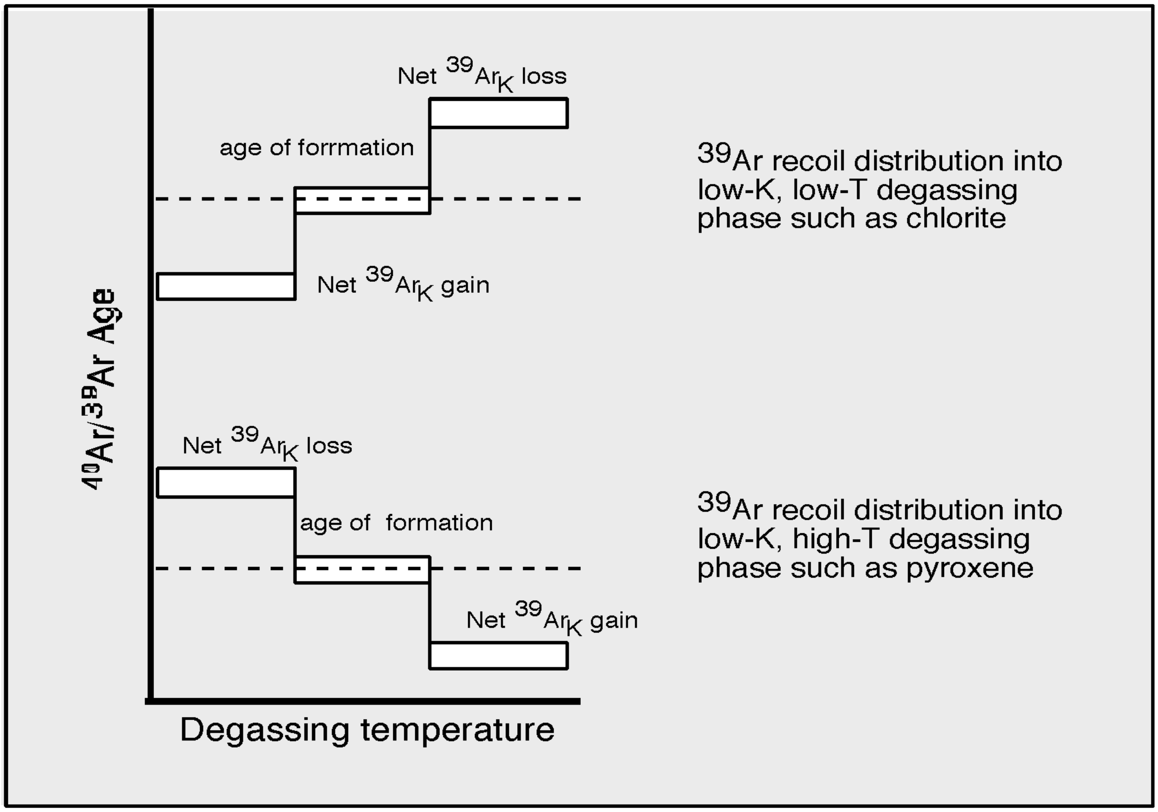
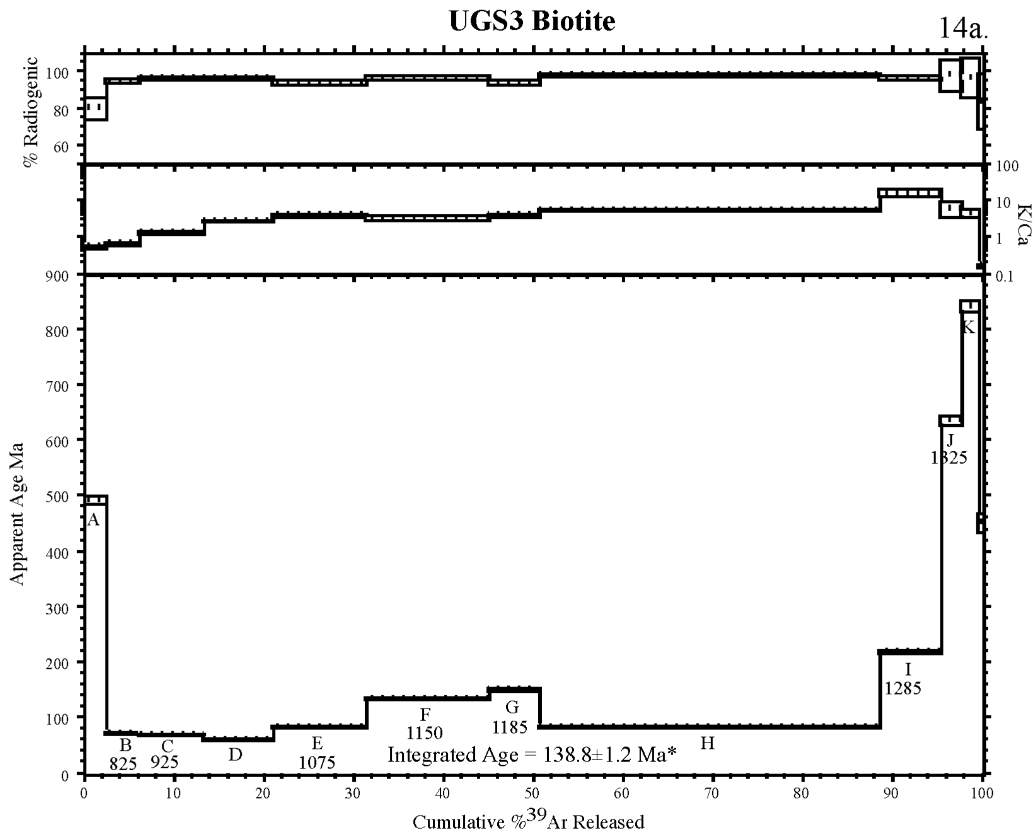


Figure 13. Cartoon showing potential effects of ^{39}Ar recoil on an otherwise flat age spectrum.



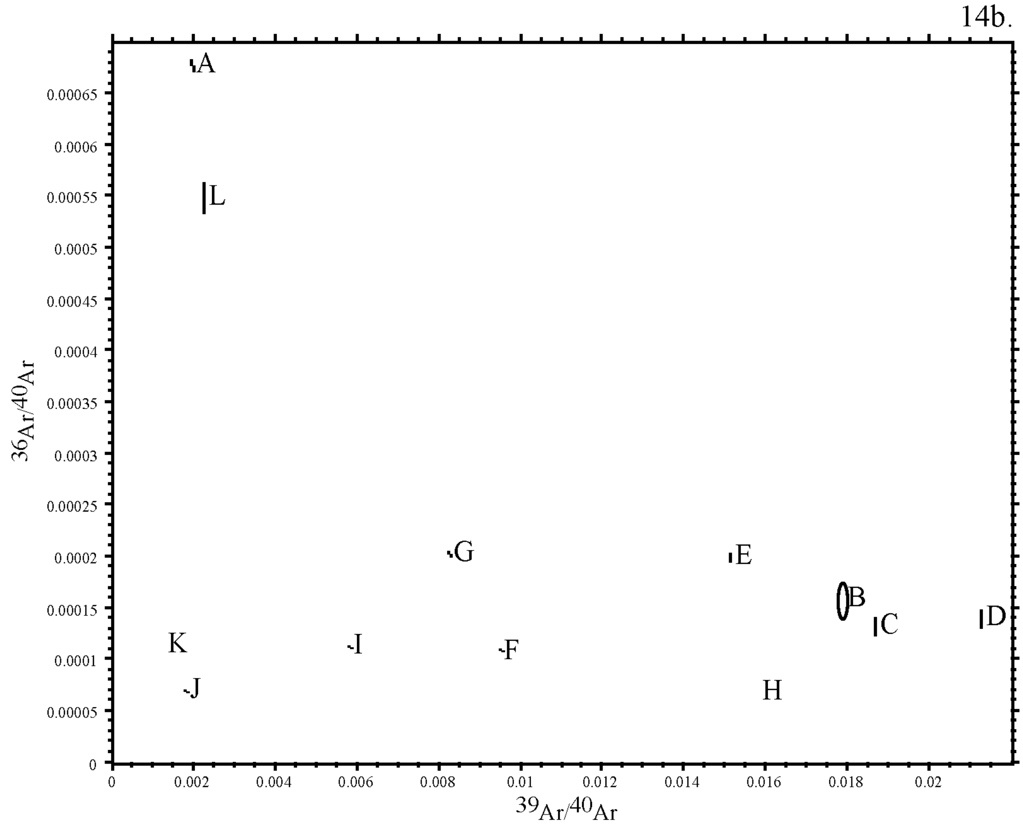
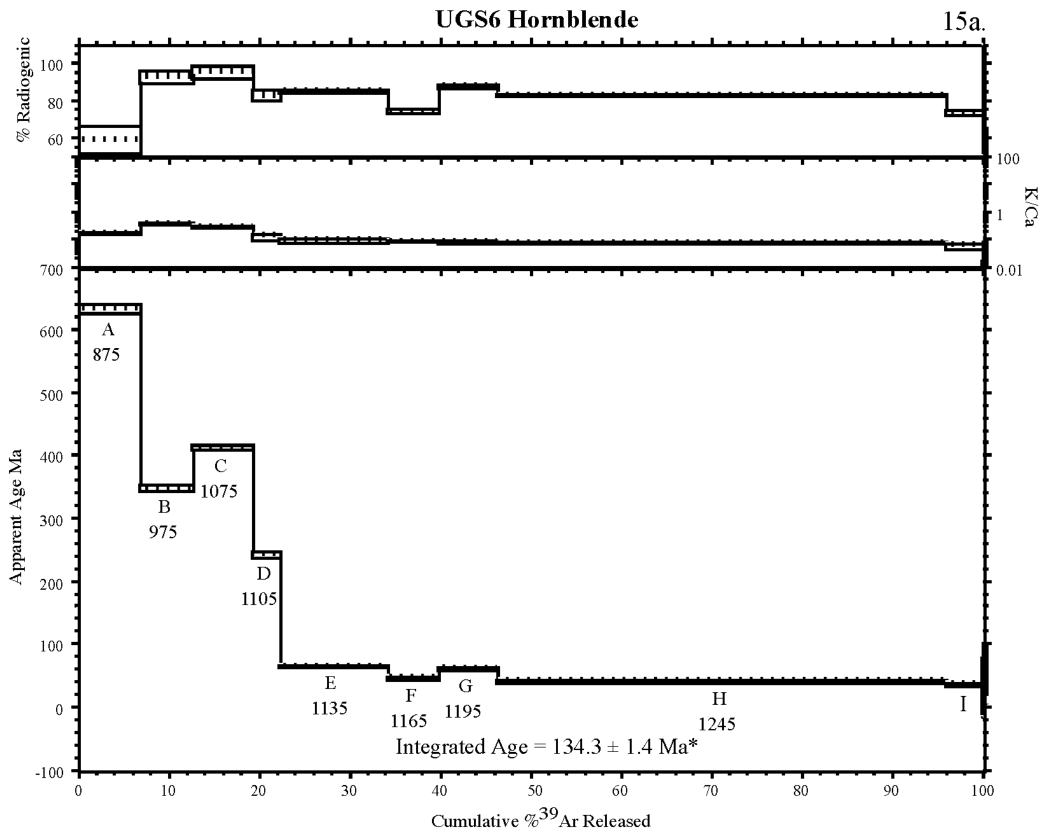


Figure 14. Age spectrum (14a) and isochron (14b) for sample UGS3 biotite.
*2σ



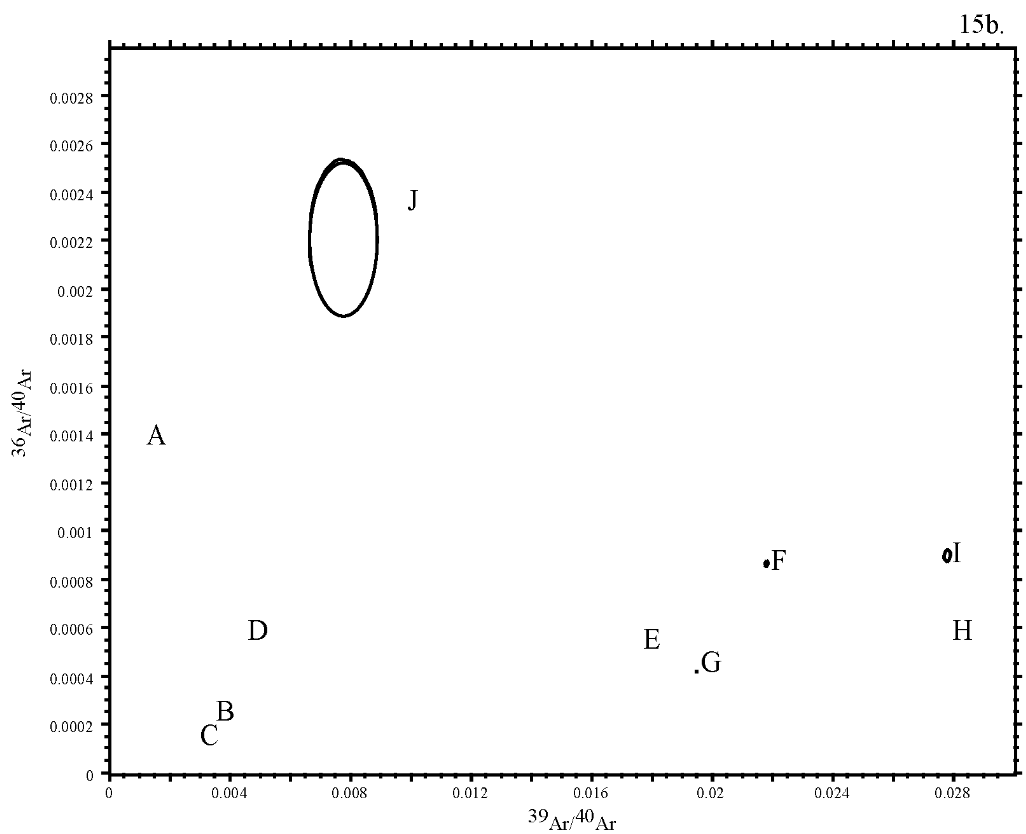
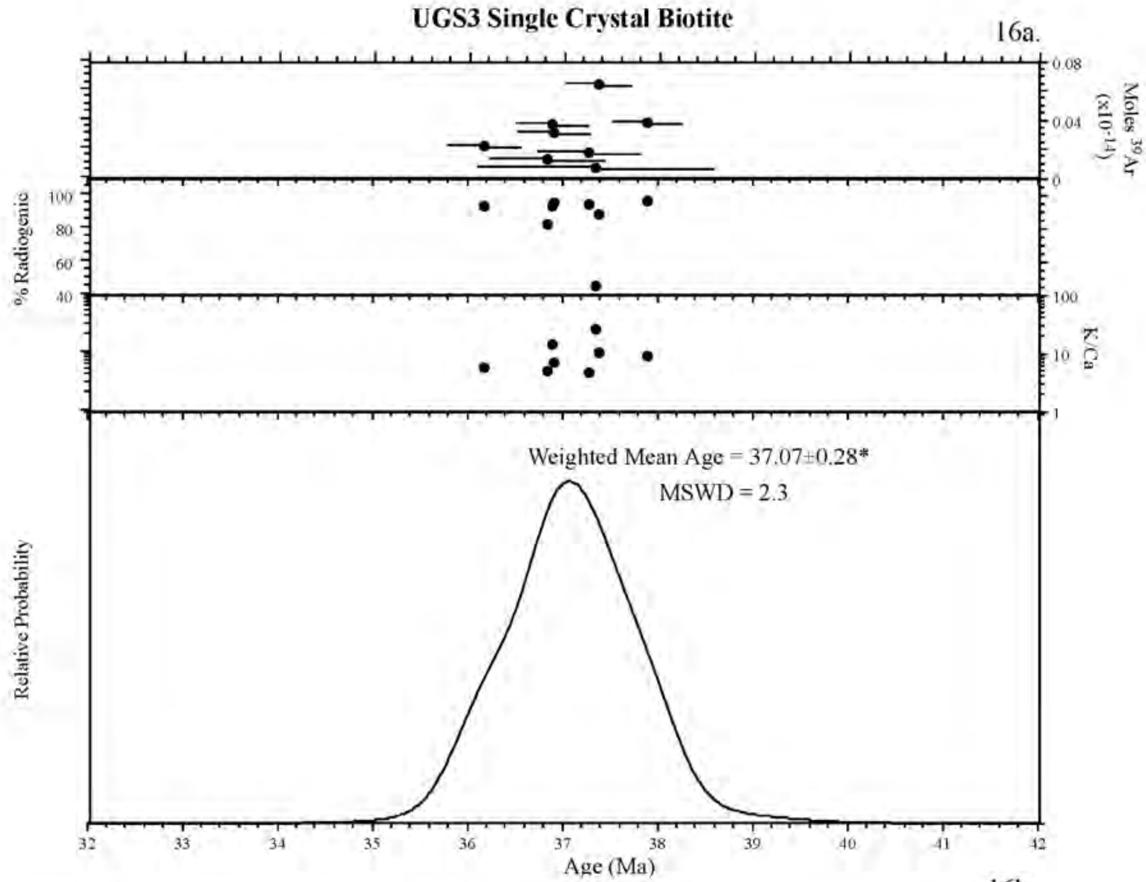


Figure 15. Age spectrum (15a) and isochron (15b) for sample UGS6 hornblende.
*2σ

16a.



16b.

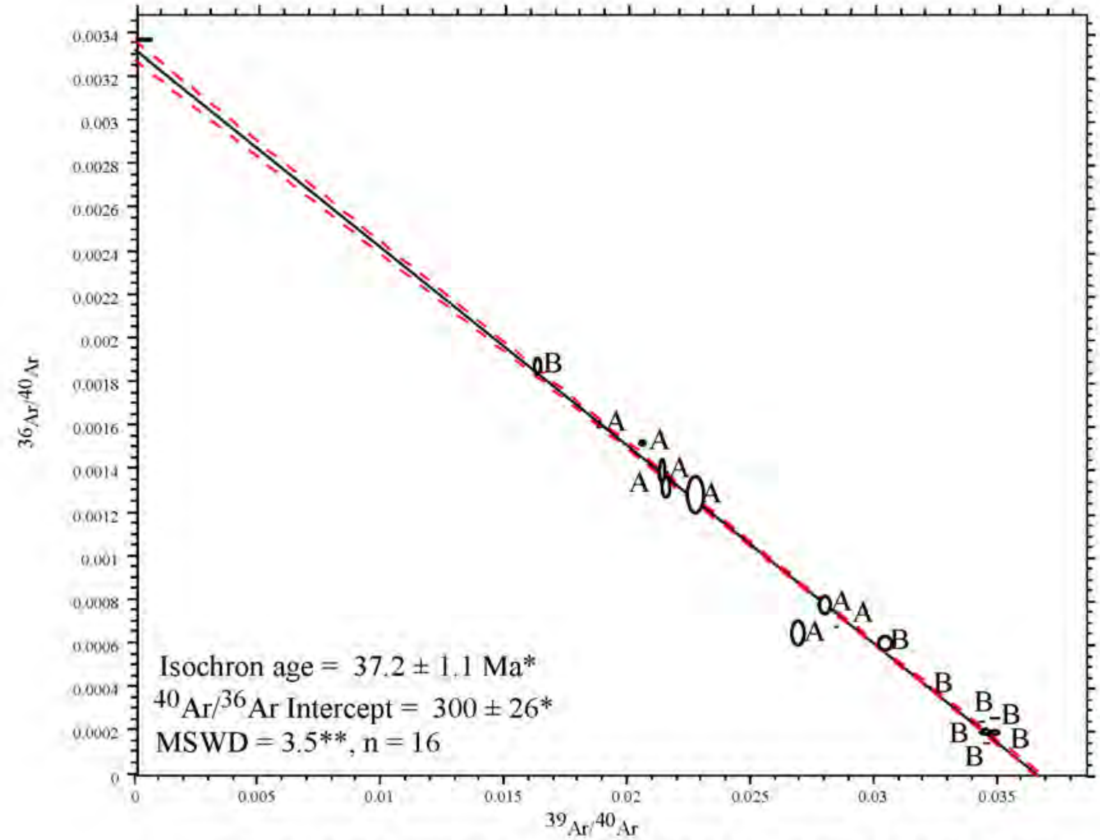
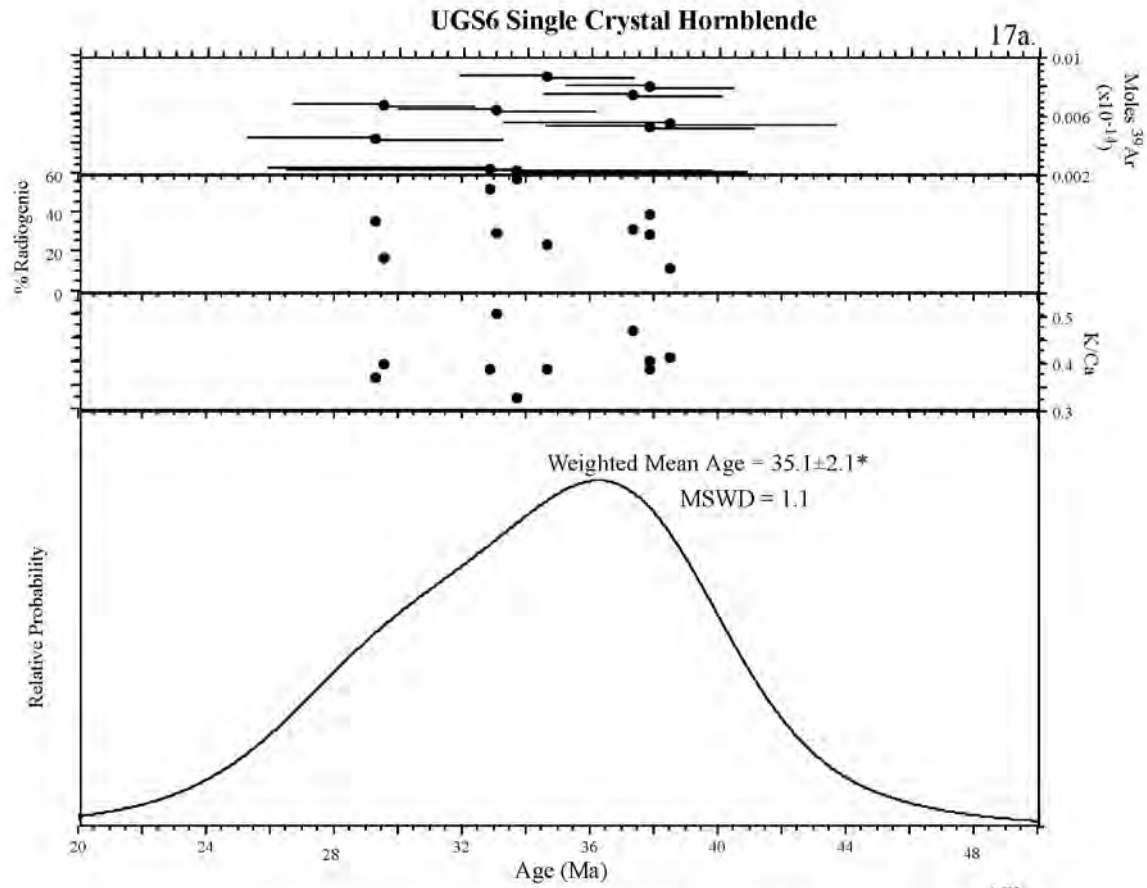


Figure 16. Age spectrum (16a) and isochron (16b) for sample UGS3 biotite.
*2σ ** outside 95% confidence interval



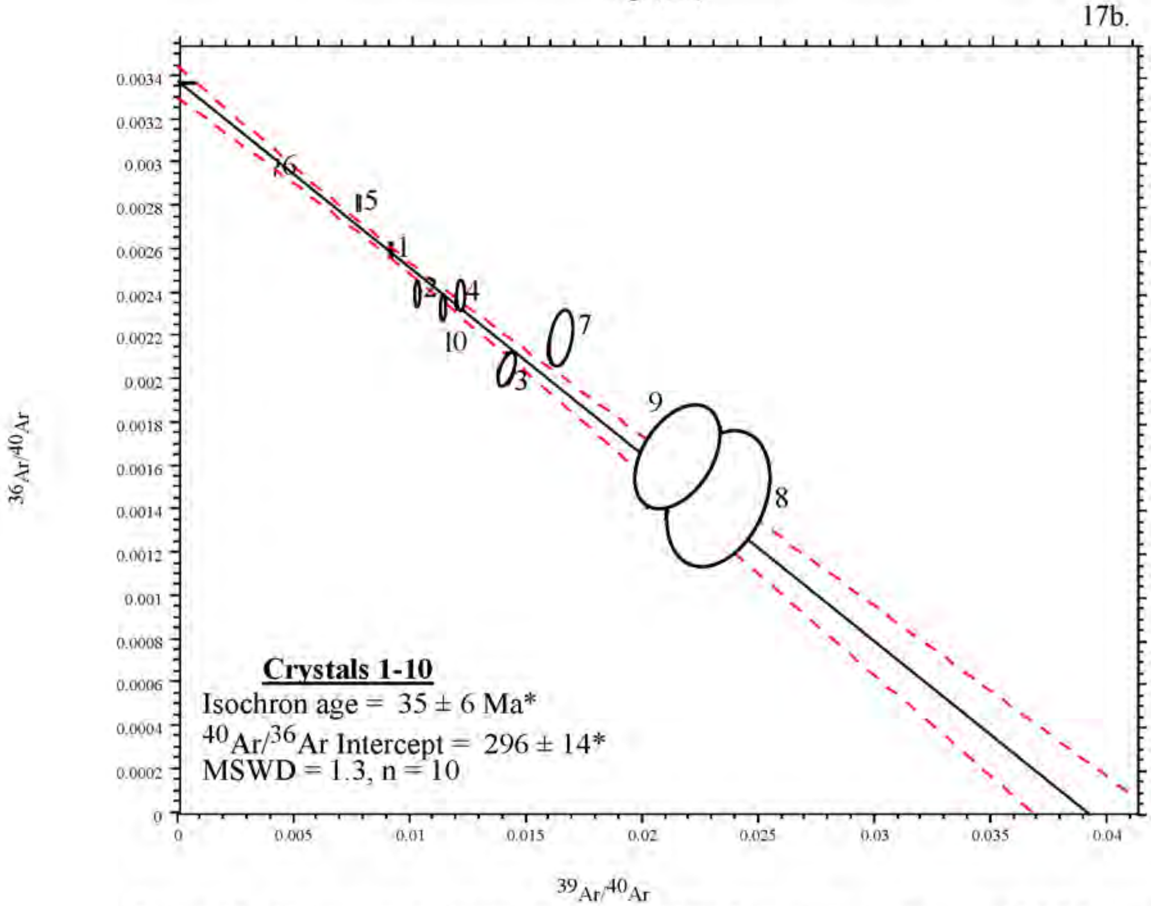


Figure 17. Age spectrum (17a) and isochron (17b) for sample single crystal UGS6 hornblende. *2σ

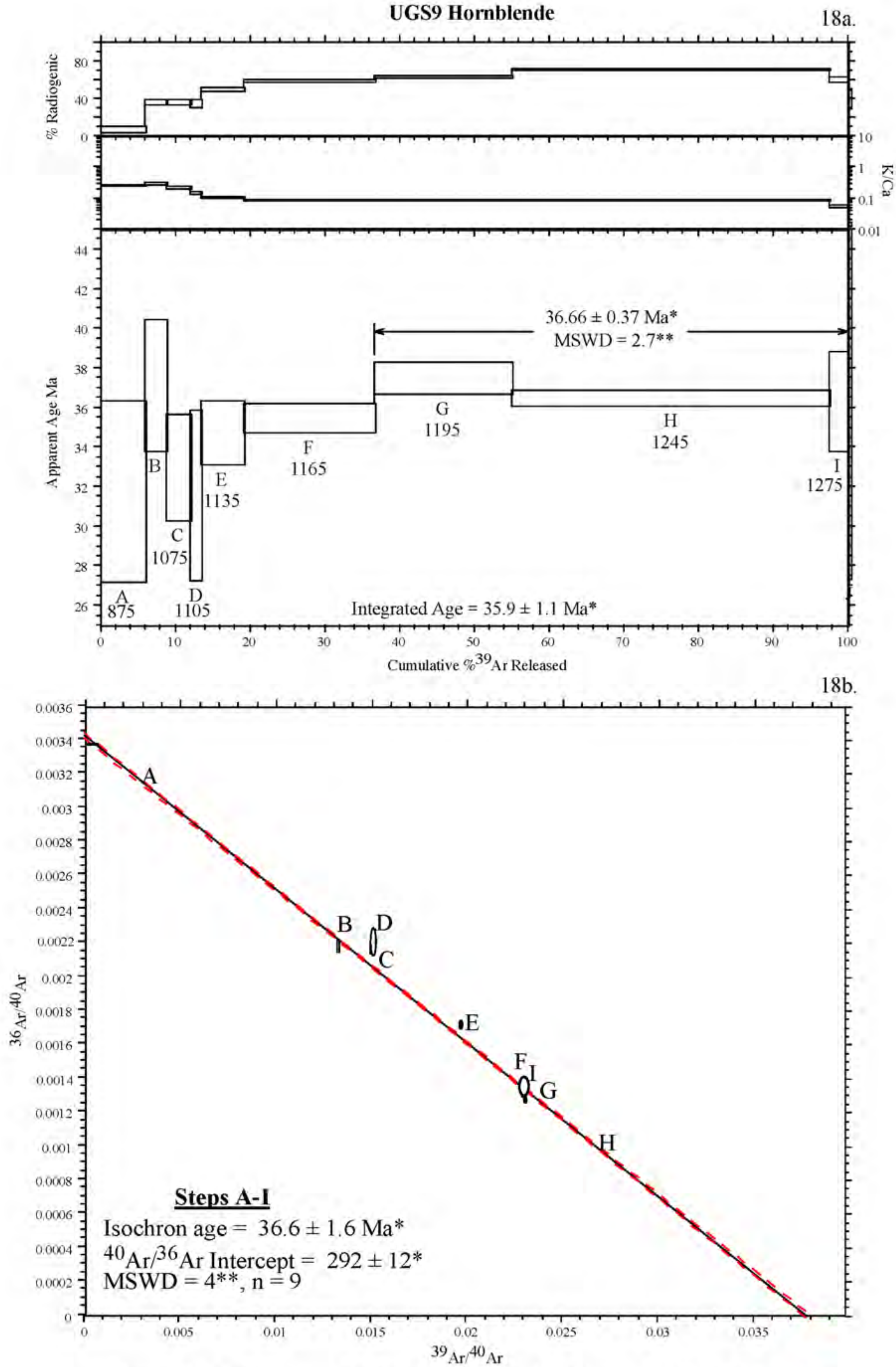
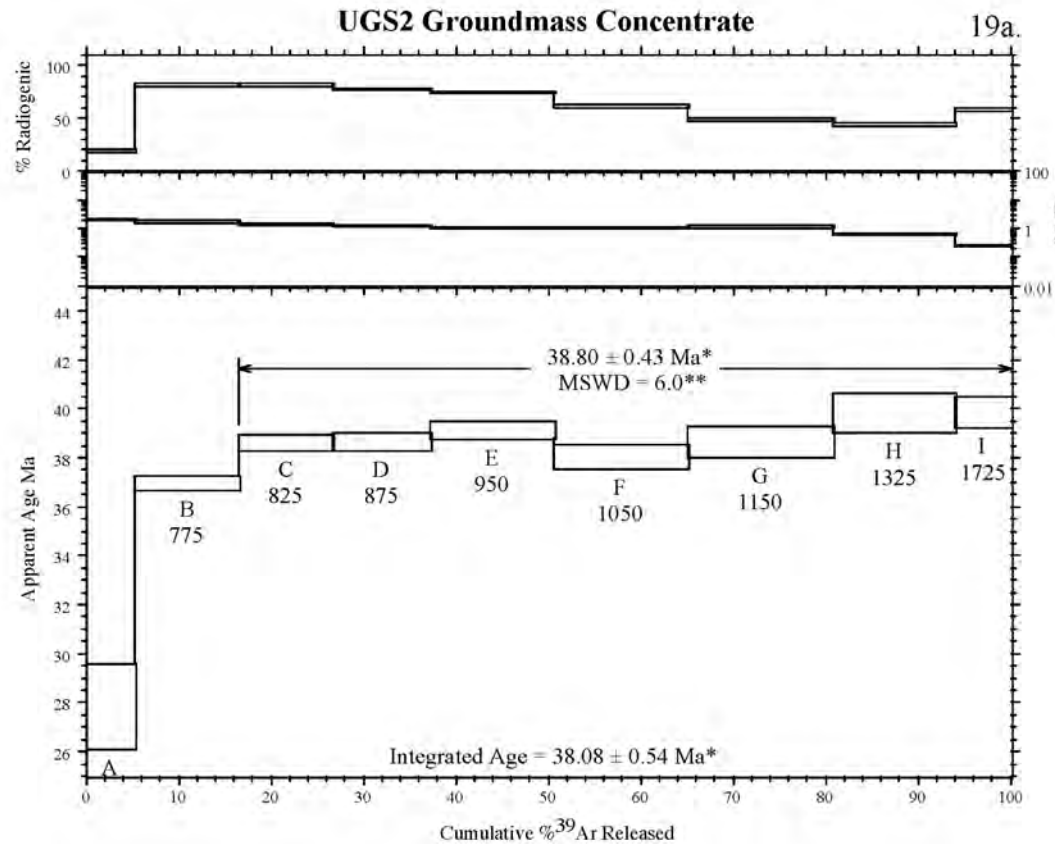


Figure 18. Age spectrum (18a) and isochron (18b) for sample UGS9 hornblende.
*2σ **outside 95% confidence interval



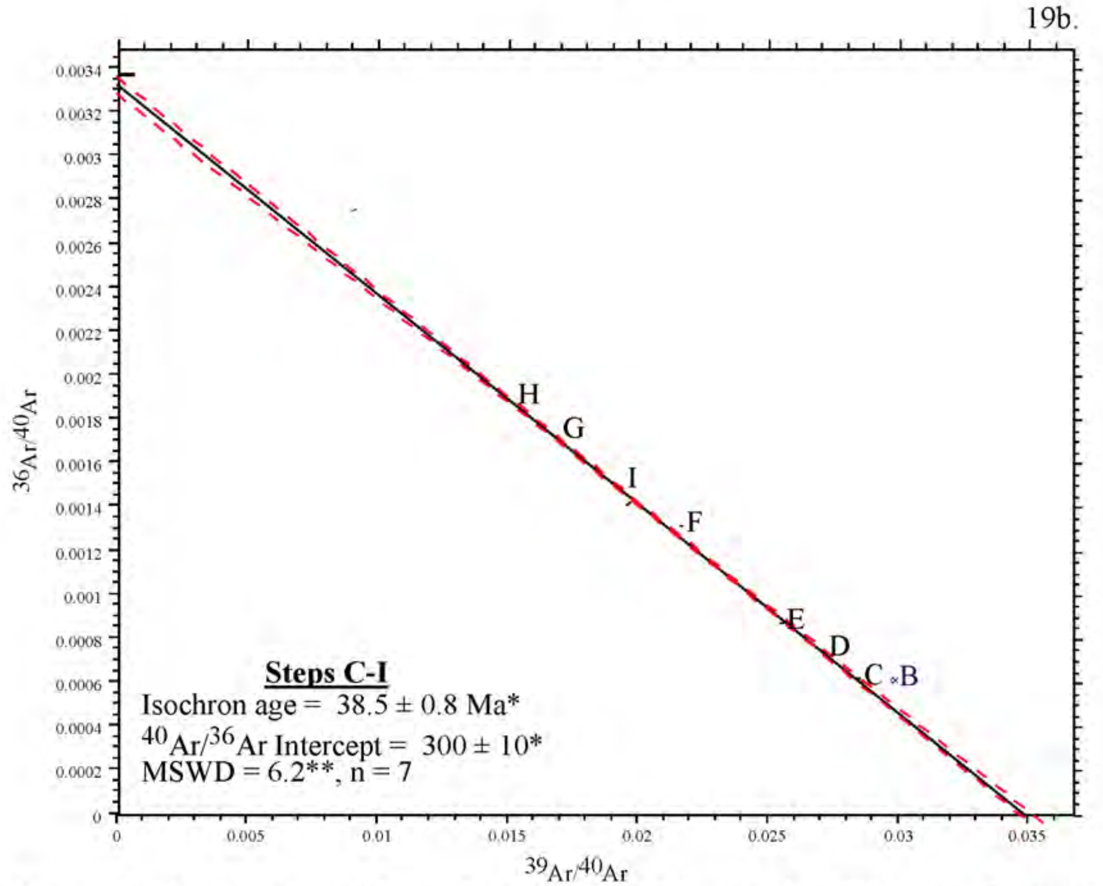
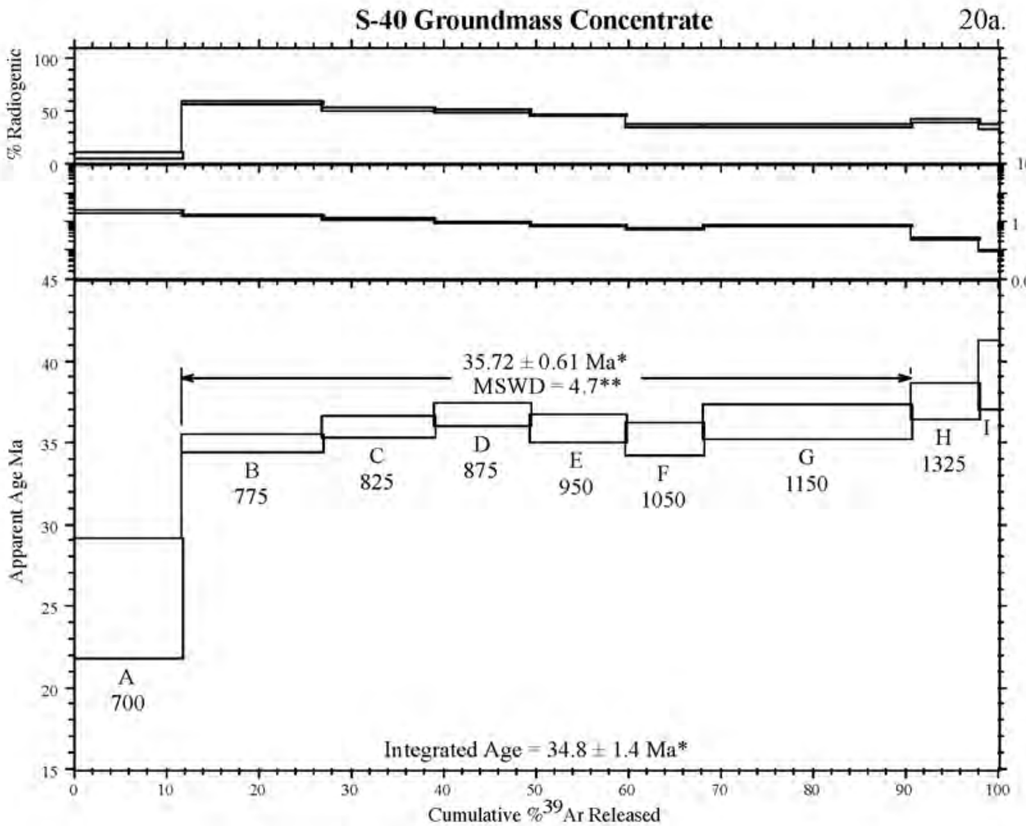


Figure 19. Age spectrum (19a) and isochron (19b) for sample UGS2 groundmass concentrate. Steps shown in purple not included in isochron. *2σ



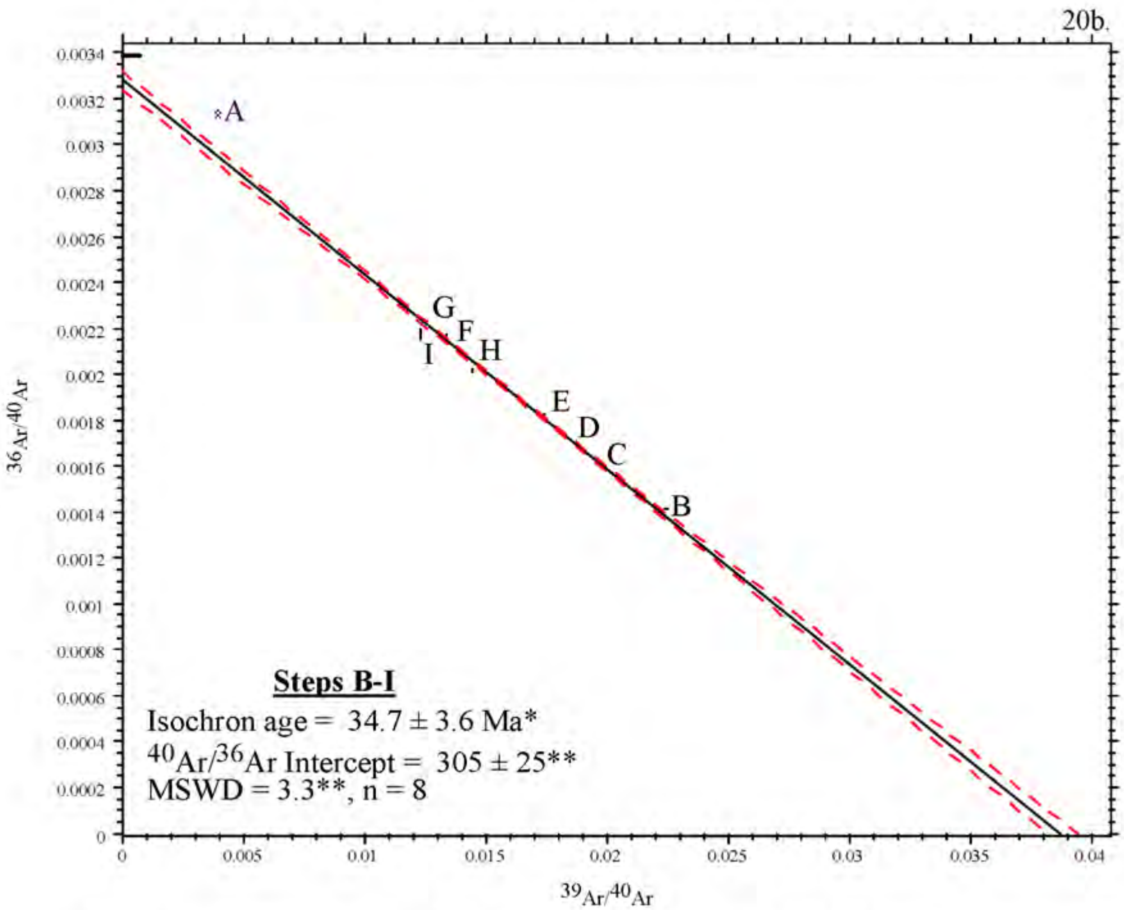


Figure 20. Age spectrum (20a) and isochron (20b) for sample S-40 groundmass concentrate. *2σ ** outside 95% confidence interval

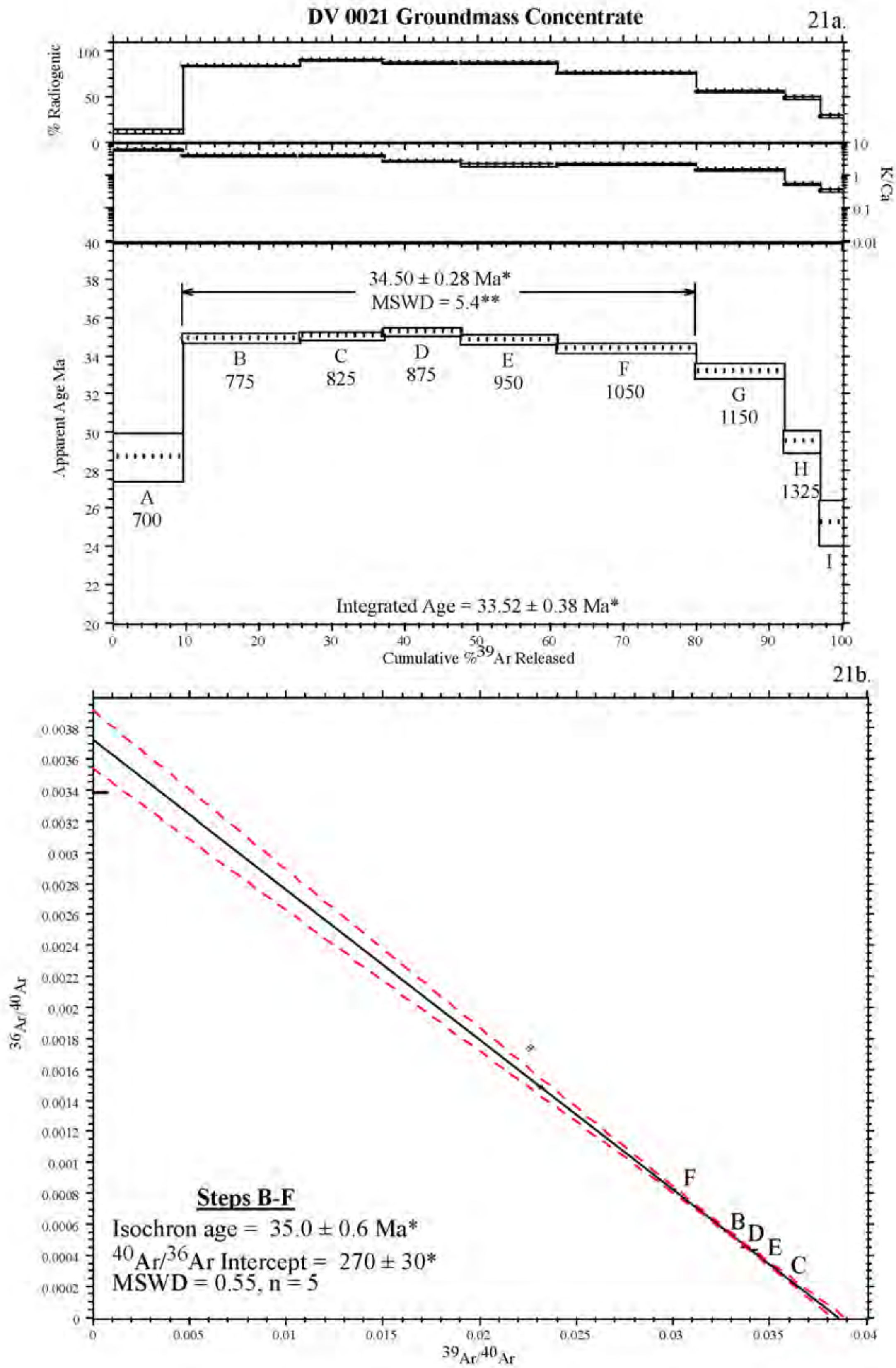


Figure 21. Age spectrum (21a) and isochron (21b) for sample DV 0021 groundmass concentrate. *2σ **outside 95% confidence interval

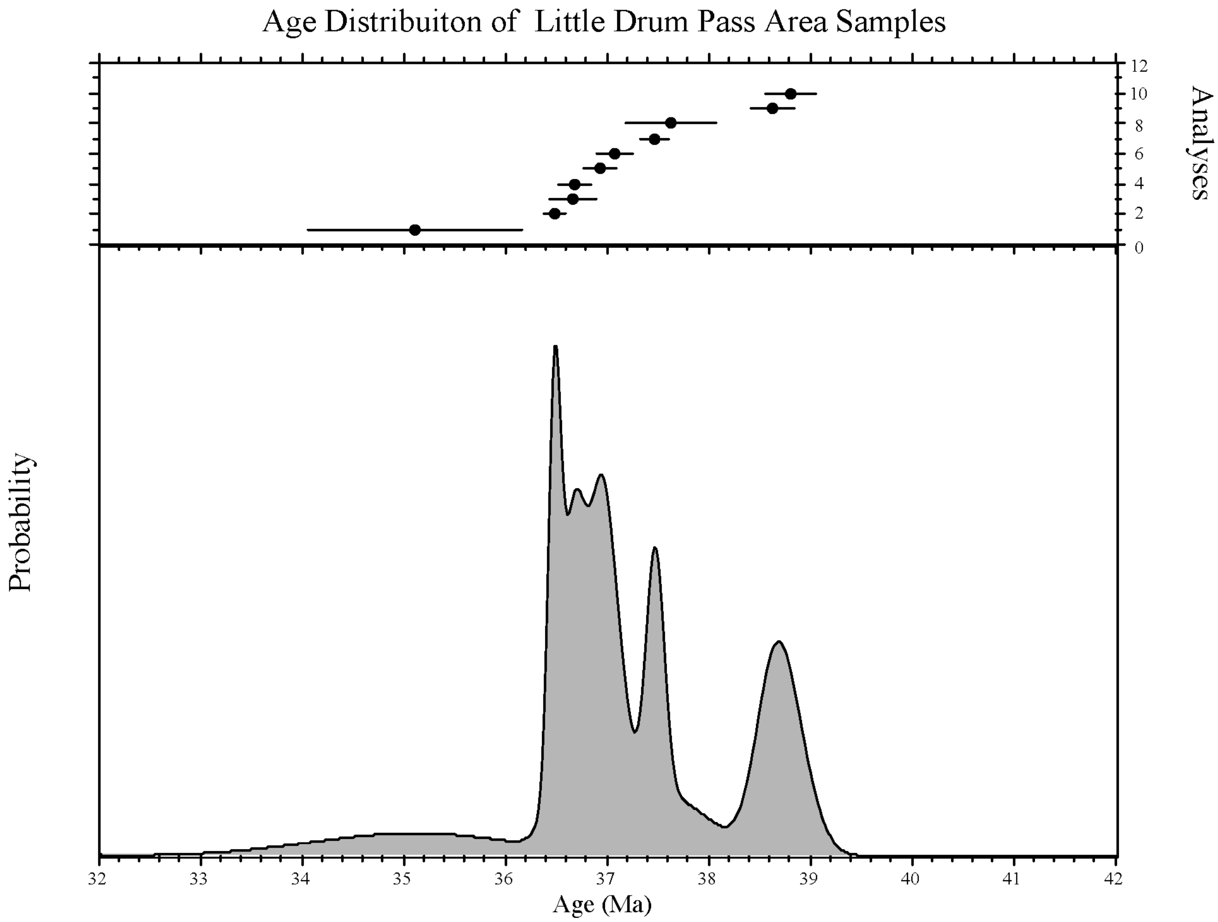


Figure 22. Age probability distribution diagram of the apparent ages assigned to the Little Drum Pass samples.

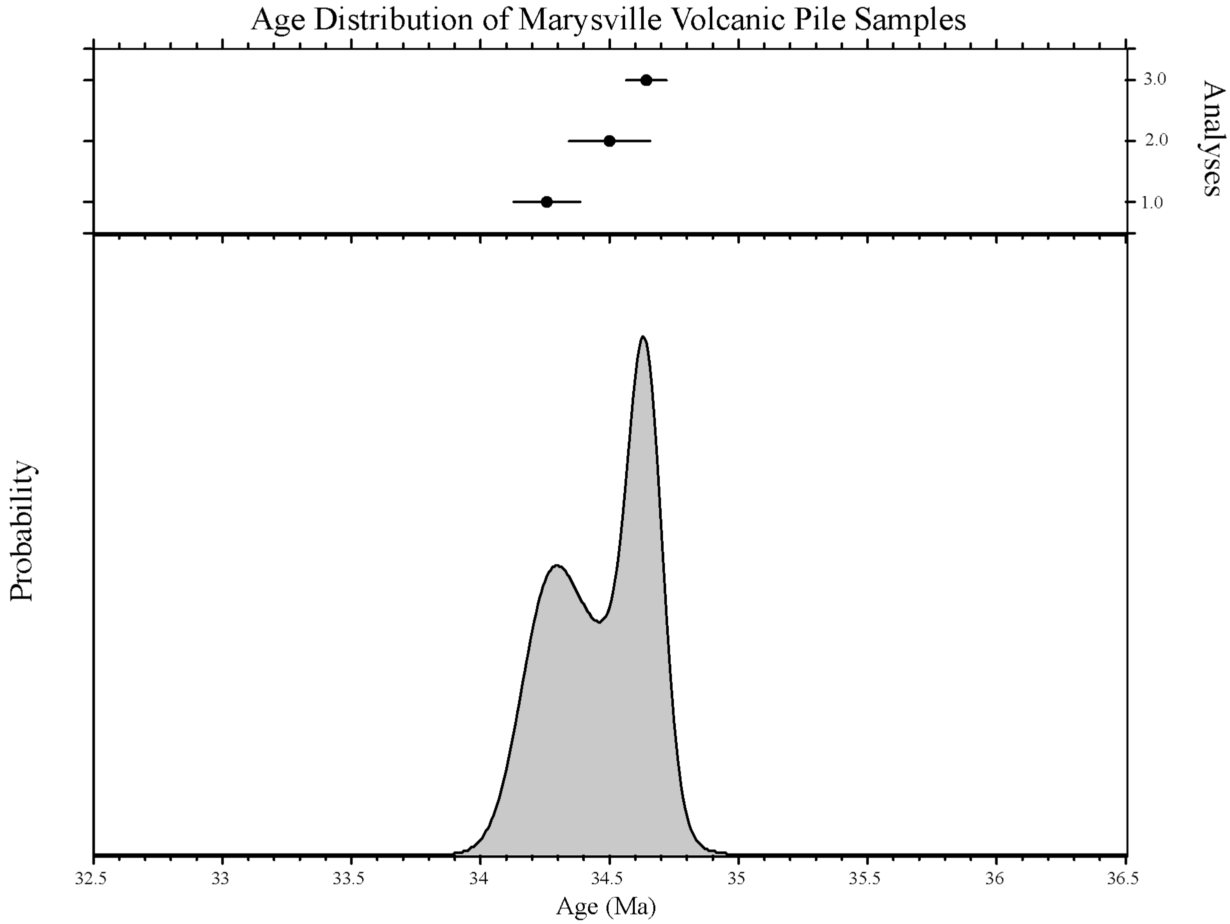


Figure 23. Age probability distribution diagram of the apparent ages assigned to the Marysville volcanic pile samples.

New Mexico Bureau of Mines and Mineral Resources

Procedures of the New Mexico Geochronology Research Laboratory

For the Period June 1998 – present

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$^{40}Ar/^{39}Ar$ and K-Ar dating

Often, large bulk samples (either minerals or whole rocks) are required for K-Ar dating and even small amounts of xenocrystic, authigenic, or other non-ideal behavior can lead to inaccuracy. The K-Ar technique is susceptible to sample inhomogeneity as separate aliquots are required for the potassium and argon determinations. The need to determine absolute quantities (i.e. moles of $^{40}Ar^*$ and ^{40}K) limits the precision of the K-Ar method to approximately 1% and also, the technique provides limited potential to evaluate underlying assumptions. In the $^{40}Ar/^{39}Ar$ variant of the K-Ar technique, a sample is irradiated with fast neutrons thereby converting ^{39}K to ^{39}Ar through a (n,p) reaction. Following irradiation, the sample is either fused or incrementally heated and the gas analyzed in the same manner as in the conventional K-Ar procedure, with one exception, no argon spike need be added.

Some of the advantages of the $^{40}Ar/^{39}Ar$ method over the conventional K-Ar technique are:

1. A single analysis is conducted on one aliquot of sample thereby reducing the sample size and eliminating sample inhomogeneity.
2. Analytical error incurred in determining absolute abundances is reduced by measuring only isotopic ratios. This also eliminates the need to know the exact weight of the sample.
3. The addition of an argon spike is not necessary.
4. The sample does not need to be completely fused, but rather can be incrementally heated. The $^{40}Ar/^{39}Ar$ ratio (age) can be measured for each fraction of argon released and this allows for the generation of an age spectrum.

The age of a sample as determined with the $^{40}Ar/^{39}Ar$ method requires comparison of the measured $^{40}Ar/^{39}Ar$ ratio with that of a standard of known age. Also, several isotopes of other elements (Ca, K, Cl, Ar) produce argon during the irradiation procedure and must be corrected for. Far more in-depth details of the determination of an apparent age via the $^{40}Ar/^{39}Ar$ method are given in Dalrymple et al. (1981) and McDougall and Harrison (1988).

Analytical techniques

Sample Preparation and irradiation details

Mineral separates are obtained in various fashions depending upon the mineral of interest, rock type and grain size. In almost all cases the sample is crushed in a jaw crusher and ground in a disc grinder and then sized. The size fraction used generally corresponds to the largest size possible which will permit obtaining a pure mineral separate. Following sizing, the sample is washed and dried. For plutonic and metamorphic rocks and lavas, crystals are separated using standard heavy liquid, Franz magnetic and hand-picking techniques. For volcanic sanidine and plagioclase, the sized sample is reacted with 15% HF acid to remove glass and/or matrix and then thoroughly washed prior to heavy liquid and magnetic separation. For groundmass concentrates, rock fragments are selected which do not contain any visible phenocrysts.

The NMGRL uses either the Ford reactor at the University of Michigan or the Nuclear Science Center reactor at Texas A&M University. At the Ford reactor, the L67 position is used (unless otherwise noted) and the D-3 position is always used at the Texas A&M reactor. All of the Michigan irradiations are carried out underwater without any shielding for thermal neutrons, whereas the Texas irradiations are in a dry location which is shielded with B and Cd. Depending upon the reactor used, the mineral separates are loaded into either holes drilled into Al discs or into 6 mm I.D. quartz tubes. Various Al discs are used. For Michigan, either six hole or twelve hole, 1 cm diameter discs are used and all holes are of equal size. Samples are placed in the 0, 120 and 240° locations and standards in the 60, 180 and 300° locations for the six hole disc. For the twelve hole disc, samples are located at 30, 60, 120, 150, 210, 240, 300, and 330° and standards at 0, 90, 180 and 270 degrees. If samples are loaded into the quartz tubes, they are wrapped in Cu foil with standards interleaved at ~0.5 cm intervals. For Texas, 2.4 cm diameter discs contain either sixteen or six sample holes with smaller holes used to hold the standards. For the six hole disc, sample locations are 30, 90, 150, 210, 270 and 330° and standards are at 0, 60, 120, 180, 240 and 300°. Samples are located at 18, 36, 54, 72, 108, 126, 144, 162, 198, 216, 234, 252, 288, 306, 324, 342 degrees and standards at 0, 90, 180 and 270 degrees in the sixteen hole disc. Following sample loading into the discs, the discs are stacked, screwed together and sealed in vacuo in either quartz (Michigan) or Pyrex (Texas) tubes.

Extraction Line and Mass Spectrometer details

The NMGRL argon extraction line has both a double vacuum Mo resistance furnace and a CO_2 laser to heat samples. The Mo furnace crucible is heated with a W heating element and the temperature is monitored with a W-Re thermocouple placed in a hole drilled into the bottom of the crucible. A one inch long Mo liner is placed in the bottom of the crucible to collect the melted samples. The furnace temperature is calibrated by either/or melting Cu foil or with an additional thermocouple inserted in the top of the furnace down to the liner. The CO_2 laser is a Synrad 10W laser equipped with a He-Ne pointing laser. The laser chamber is constructed from a 3 3/8" stainless steel conflat and the window material is ZnS. The extraction line is a two stage design. The first stage is equipped with a SAES GP-50 getter, whereas the second stage houses two SAES GP-50 getters and a tungsten filament. The first stage getter is operated at 450°C as is one of the second stage getters. The other second stage getter is operated at room temperature and the tungsten filament is operated at ~2000°C. Gases evolved from samples heated in the furnace are reacted with the first stage getter during heating. Following heating, the gas is expanded into the second stage for two minutes and then isolated from the first stage. During second stage cleaning, the first stage and furnace are pumped out. After gettering in the second stage, the gas is expanded into the mass spectrometer. Gases evolved from samples heated in the laser are expanded through a cold finger operated at -140°C and directly into the second stage. Following cleanup, the gas in the second stage and laser chamber is expanded into the mass spectrometer for analysis.

The NMGRL employs a MAP-215-50 mass spectrometer which is operated in static mode. The mass spectrometer is operated with a resolution ranging between 450 to 600 at mass 40 and isotopes are detected on a Johnston electron multiplier operated at ~2.1 kV with an overall gain of about 10,000 over the Faraday collector. Final isotopic intensities are determined by linear regression to time zero of the peak height versus time following gas introduction for each mass. Each mass intensity is corrected for mass spectrometer baseline and background and the extraction system blank.

Blanks for the furnace are generally determined at the beginning of a run while the furnace is cold and then between heating steps while the furnace is cooling. Typically, a blank is run every three to six heating steps. Periodic furnace hot blank analysis reveals that the cold blank is equivalent to the hot blank for temperatures less than about 1300°C. Laser system blanks are generally determined between every four analyses. Mass discrimination is measured using atmospheric argon which has been dried using a Ti-sublimation pump. Typically, 10 to 15 replicate air analyses are measured to determine a mean mass discrimination value. Air pipette analyses are generally conducted 2-3 times per month, but more often when samples sensitive to the mass discrimination value are analyzed. Correction factors for interfering nuclear reactions on K and Ca are determined using K-glass and CaF_2, respectively. Typically, 3-5 individual pieces of the salt or glass are fused with the CO_2 laser and the correction factors are calculated from the weighted mean of the individual determinations.

Data acquisition, presentation and age calculation

Samples are either step-heated or fused in a single increment (total fusion). Bulk samples are often step-heated and the data are generally displayed on an age spectrum or isochron diagram. Single crystals are often analyzed by the total fusion method and the results are typically displayed on probability distribution diagrams or isochron diagrams.

The Age Spectrum Diagram

Age spectra plot apparent age of each incrementally heated gas fraction versus the cumulative % $^{39}Ar_K$ released, with steps increasing in temperature from left to right. Each apparent age is calculated assuming that the trapped argon (argon not produced by *in situ* decay of ^{40}K) has the modern day atmospheric $^{40}Ar/^{36}Ar$ value of 295.5. Additional parameters for each heating step are often plotted versus the cumulative %$^{39}Ar_K$ released. These auxiliary parameters can aid age spectra interpretation and may include radiogenic yield (percent of ^{40}Ar which is not atmospheric), K/Ca (determined from measured Ca-derived ^{37}Ar and K-derived ^{39}Ar) and/or K/Cl (determined from measured Cl-derived ^{38}Ar and K-derived ^{39}Ar). Incremental heating analysis is often effective at revealing complex argon systematics related to excess argon, alteration, contamination, ^{39}Ar recoil, argon loss, etc. Often low-temperature heating steps have low radiogenic yields and apparent ages with relatively high errors due mainly to loosely held, non-radiogenic argon residing on grain surfaces or along grain boundaries. An entirely or partially flat spectrum, in which apparent ages are the same within analytical error, may indicate that the sample is homogeneous with respect to K and Ar and has had a simple thermal and geological history. A drawback to the age spectrum technique is encountered when hydrous minerals such as micas and amphiboles are analyzed. These minerals are not stable in the ultra-high vacuum extraction system and thus step-heating can homogenize important details of the true ^{40}Ar distribution. In other words, a flat age spectrum may result even if a hydrous sample has a complex argon distribution.

The Isochron Diagram

Argon data can be plotted on isotope correlation diagrams to help assess the isotopic composition of Ar trapped at the time of argon closure, thereby testing the assumption that trapped argon isotopes have the composition of modern atmosphere which is implicit in age spectra. To construct an "inverse isochron" the $^{36}Ar/^{40}Ar$ ratio is plotted versus the $^{39}Ar/^{40}Ar$ ratio. A best fit line can be calculated for the data array which yields the value for the trapped argon (Y-axis intercept) and the $^{40}Ar^*/^{39}Ar_K$ value (age) from the X-axis intercept. Isochron analysis is most useful for step-heated or total fusion data which have a significant spread in radiogenic yield. For young or low K samples, the calculated apparent age can be very sensitive to the composition of the trapped argon and therefore isochron analysis should be preformed routinely on these samples (cf. Heizler and Harrison, 1988). For very old (>Mesozoic) samples or relatively old sanidines (>mid-Cenozoic) the data are often highly radiogenic and cluster near the X-axis thereby making isochron analysis of little value.

The Probability Distribution Diagram

The probability distribution diagram, which is sometimes referred to as an ideogram, is a plot of apparent age versus the summation of the normal distribution of each individual analysis (Deino and Potts, 1992). This diagram is most effective at displaying single crystal laser fusion data to assess the distribution of the population. The K/Ca, radiogenic yield, and the moles of ^{39}Ar for each analysis are also often displayed for each sample as this allows for visual ease in identifying apparent age correlations between, for instance, plagioclase contamination, signal size and/or radiogenic concentrations. The error (1σ) for each age analysis is generally shown by the horizontal lines in the moles of ^{39}Ar section. Solid symbols represent the analyses used for the weighted mean age calculation and the generation of the solid line on the ideogram, whereas open symbols represent data omitted from the age calculation. If shown, a dashed line represents the probability distribution of all of the displayed data. The diagram is most effective for displaying the form of the age distribution (i.e. gaussian, skewed, etc.) and for identifying xenocrystic or other grains which fall outside of the main population.

Error Calculations

For step-heated samples, a plateau for the age spectrum is defined by the steps indicated. The plateau age is calculated by weighting each step on the plateau by the inverse of the variance and the error is calculated by either the method of Samson and Alexander (1987) or Taylor (1982). A mean sum weighted deviates (MSWD) value is determined by dividing the Chi-squared value by n-1 degrees of freedom for the plateau ages. If the MSWD value is outside the 95% confidence window (cf. Mahon, 1996; Table 1), the plateau or preferred age error is multiplied by the square root of the MSWD.

For single crystal fusion data, a weighted mean is calculated using the inverse of the variance to weight each age determination (Taylor, 1982). Errors are calculated as described for the plateau ages above.

Isochron ages, $^{40}Ar/^{36}Ar_i$ values and MSWD values are calculated from the regression results obtained by the York (1969) method.

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