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$^{40}Ar/^{39}Ar$ Thermochronologic Data for Minerals from Plutons of the Variscan Sila Batholith, Southern Italy (Calabria)

by

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ABSTRACT

A Variscan plutonic complex, the Sila batholith, intrudes metamorphic rocks that are now part of the Sila Nappe, an Alpine structural element of the Calabrian-Peloritan segment of the Apennine-Maghrebide orogenic belt in southern Italy and Sicily. Plutons in the Sila batholith range in composition from biotite-hornblende tonalite to two-mica, Al_2SiO_5 (andalusite, cordierite, and sillimanite) granite which are syntectonic and post-tectonic, respectively, relative to Variscan orogenesis. This plutonic complex, together with its metamorphic country rocks and Mesozoic-Cenozoic sedimentary cover was tectonically transported from the southern margin of the Tethys to its present structural position during at least one stage of Alpine orogenesis with final emplacement of the Sila nappe in Miocene. Field relations suggest plutons exposed in the northern and eastern parts of the batholith (mainly post-tectonic, two-mica granitoids) were emplaced at a shallower level in the crust than plutons exposed in the southern and western parts of the batholith (mainly syntectonic, biotite-hornblende tonalites and granodiorites). Published petrochemical data indicate all plutons of the Sila batholith are part of a coherent, cogenetic igneous suite of probable lower crustal origin. Published geochronologic data show that various parent-daughter isotope systems in various minerals of the plutons were only slightly disturbed by Alpine orogenesis. $^{40}Ar/^{39}Ar$ thermochronologic analyses of the plutons in the Sila batholith using hornblende, muscovite, biotite, and microcline document a rather simple Variscan emplacement and cooling history (293-270 Ma) with virtually no evidence of later thermal disturbance, at least to the level of the argon closure temperature in microcline ($\sim$150-200°C). Not only do

these data document that lack of a significant Alpine overprint in the Sila batholith, but also suggest the Sila nappe was emplaced at a very high structural level during the closing of the Tethys.

INTRODUCTION

The Apennines of southern Italy and the Maghrebides of Sicily are two segments of a circum-Mediterranean, Alpine orogenic belt (Figure 1). The two segments consist of a series of nappes, probably derived in large part from the Mesozoic to Cenozoic, carbonate-rich cover sequence of the northern continental margin of Africa. Between the southern Apennines and the Maghrebides in the Calabria-Peloritani arc, a series of Variscan lithotectonic units dominated by nappes of Paleozoic (or older?) crystalline basement rocks, but with some units having oceanic affinities. This area is in many ways "exotic" to the Apennine-Maghrebide chain and as such has been the subject of many controversial tectonic interpretations for nearly a century. These include (a) a piece of autochthonous continental crust (Gorler and Giese, 1978; Zanettin, 1982); (b) a fragment of European Variscan basement imbricated with oceanic units and thrust over the northern margin of Africa (Ogniben, 1973; Bouillin, 1984); (c) an African promontory deformed and thrust onto Apennine structural units (Caire et at., 1960; DuBois, 1976); and (d) a fragment of an Europe-verging Eoalpine belt, consisting of structural units from both occanic and African continental crust, backthrust during final stages of formation of the Africa-verging, Apennine-Maghrebide chain (Alvarez, 1976; Amodio Morelli et al., 1976; Bonardi et al.,

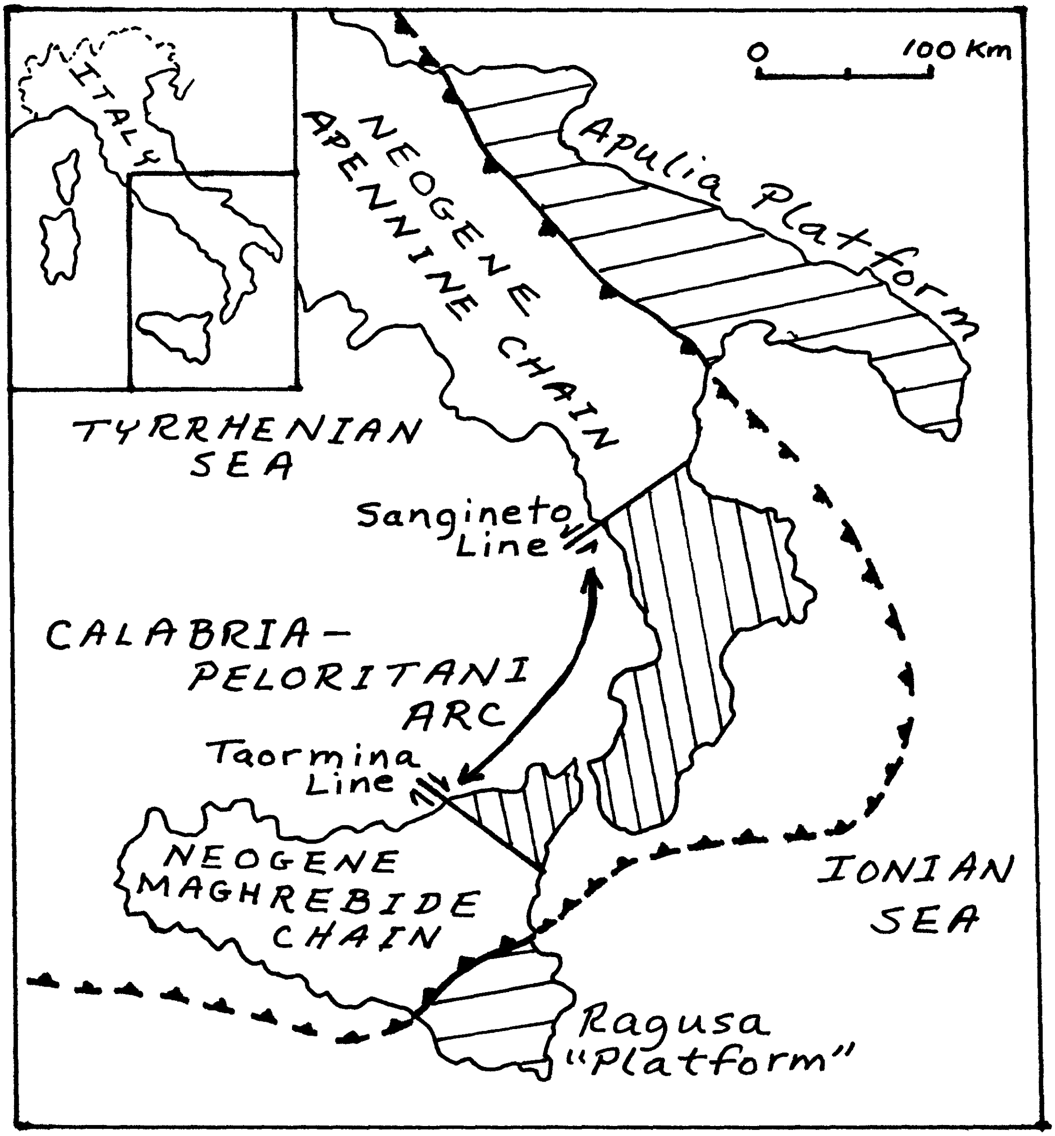

Figure 1. Tectonic sketch map of southern Italy. Simplified from Dietrich, et al. (1976).

1982; Scandone, 1982). These extremely diverse interpretations are difficult to evaluate mainly because neither the Variscan nor the Alpine history of this region is well understood. Therefore, we and our colleagues have embarked on a collaborative project to build on the existing structural, stratigraphic, petrologic, geochemical, and isotopic data bases with the express goal of a more definitive tectonic model for this part of the circum-Mediterranean, Alpine orogenic belt.

There are various provinces in the Calabria-Peloritani arc that hold the key to a more complete understanding of the importance and character of Variscan versus Alpine tectonism: the Catena Costiera, Sila, Serre, and Aspromonte in southern Italy and the Petoritani mountains in Sicily (Figure 2). The Sila massif, and in particular the emplacement and cooling history of Paleozoic plutons of the Sila batholith, is the subject of this report.

Plutons of the Sila batholith crop out in the Sila massif and form an igneous complex that is elongate from northwest to southeast (Figure 3). On the eastern side of the batholith, from Rossano in the north to Belvedere di Spinello in the south, the plutons are intruded into low-grade metasediments with stratigraphic ages of Cambrian to Ordovician (Bouillin et at., 1984). A well-developed contact aureole is developed in these low-grade rocks near the plutons and is characterized by hornfels that contain fibrolitic sillimanite, andalusite, cordierite, and biotite (Dubois, 1976; Gurrieri et at., 1979). On the east side of the batholith, the contact between the plutons and the country rocks appears to be subhorizontal with the plutons exposed in the steep valley walls and the country rocks on the intervening ridges (Barovero, 1988). Along the western side of the batholith, from Corigliano to the

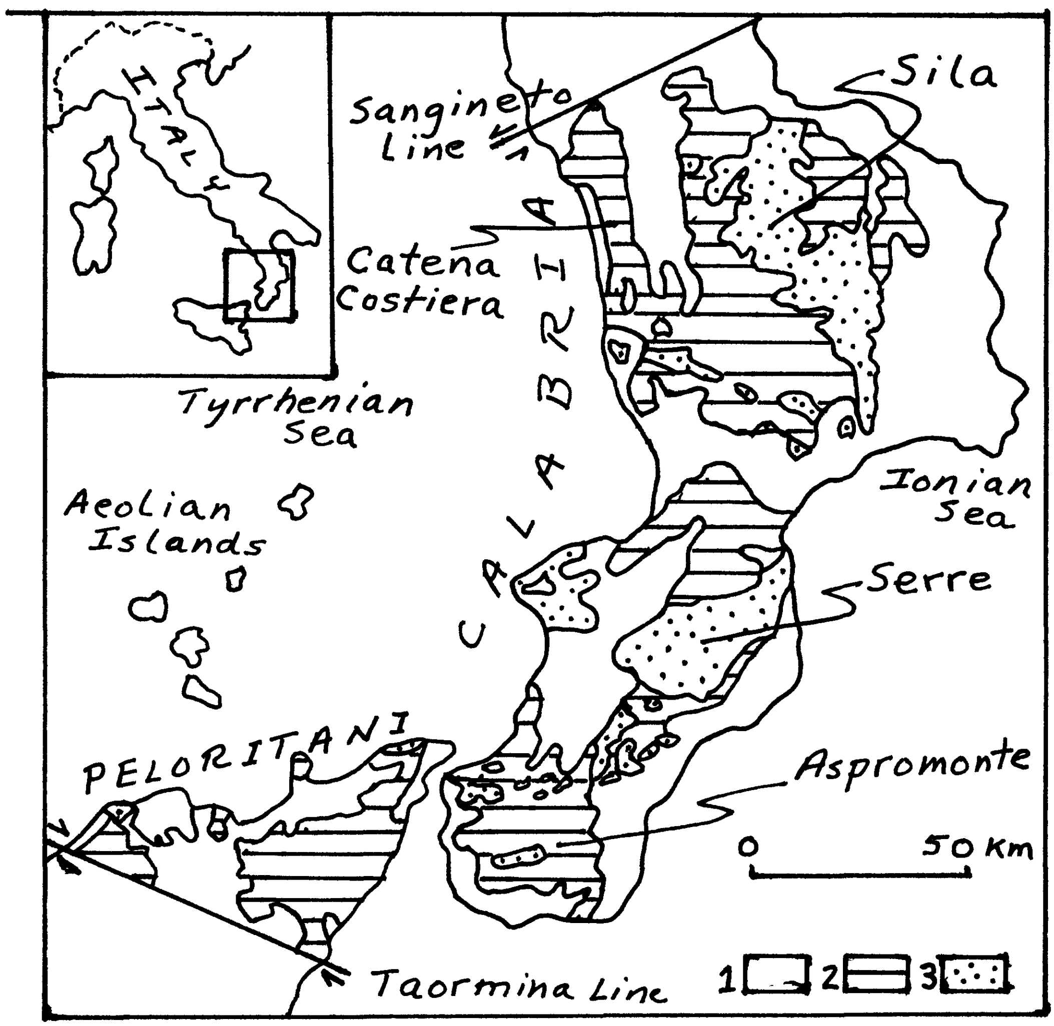

Figure 2. Geologic sketch map of the Calabria-Peloritani arc: 1) Tertiary and Quaternary sediments; 2) Pre-Alpine and Alpine metamorphic rocks; and 3) Paleozoic plutonic rocks. Simplified from Atzori, et al. (1981).

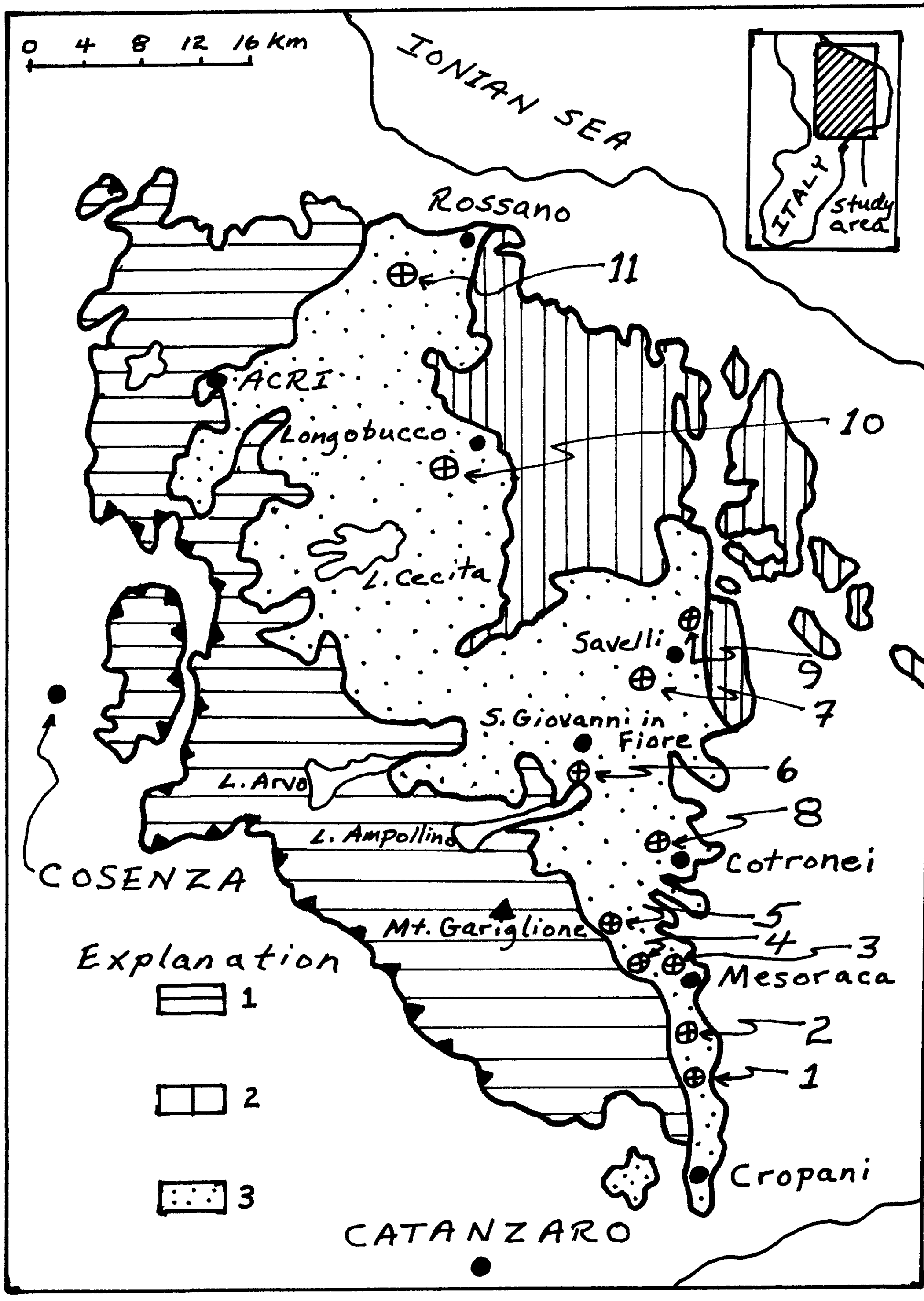

Figure 3. Sketch map of the Sila Tectonic Unit (nappe): 1) High-grade metamorphic rocks; 2) Low-grade metamorphic rocks and pre-tertiary sedimentary cover; and 3) Plutonic rocks of the Sila batholith. Simplified from Ayuso, et al. (1994). Numbers (1-11) refer to generalized locations of dated samples.

north to Sersale in the south, the plutons are intruded into amphibolite to granulite facies metamorphic rocks. Although no easily recognizable contact aureole is developed along the western margin of the batholith, the contact is very likely intrusive because over a distance of a few kilometers, the metamorphic rocks become richer in felsic dikes nearer the contact and create the appearance of a "layered migmatite". In addition, in the area of Mt. Gariglione, petrographic examination of metamorphic rocks (Valdemarin, 1989) reveal hornfelsic textures characterized by the recrystallization of biotite and by the presence of high-temperature, low-pressure minerals that on a regional scale define isograds parallel to the intrusive contacts.

The distribution and extent of the plutons in the Sila batholith, as well as their petrography and petrochemistry has been described recently by Messina and others (1991). The plutons range in composition from hornblende-biotite tonalites and granodiorites that are foliated and interpreted to be syntectonic to peraluminous, two-mica granites that are massive and interpreted to be post-tectonic relative to Variscan orogenesis. Published geochronologic data suggest the batholith has not been extensively retrograded during Alpine orogenesis and thus is likely to preserve much of its Variscan emplacement and cooling history (Borsi and Dubois, 1968).

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

Hornblende, muscovite, biotite, and microcline are all potentially valuable minerals for $^{40}Ar/^{39}Ar$ thermochronology. Each mineral has a characteristic and different closure temperature (CT) for diffusion of ^{40}Ar and thus when each is analyzed for age by the $^{40}Ar/^{39}Ar$ age spectrum or isochron method, a time of cooling to the characteristic closure temperatures can be calculated and a cooling history over the range of closure temperatures can be constructed. Hornblende (CT ~500°C), muscovite (CT ~350°C), and microline (CT ~150-200°C) are the most valuable minerals for $^{40}Ar/^{39}Ar$ thermochronology because their CTs generally change only as a function of cooling rate (faster rate of cooling results in a higher CT) and grain size (larger grain size results in higher CT). Biotite (CT ~280°C) is not nearly as valuable because its CT is also dependent on chemical composition (high Mg content results in higher CT), is far more susceptible to alteration and is often known to contain unresolvable, "extraneous) ^{40}Ar.

Obviously if all the above mentioned minerals crystallized above their characteristic closure temperatures (a certainty for magmatic minerals), the $^{40}Ar/^{39}Ar$ ages measured for each are times of cooling to closure temperature or "cooling ages". Cooling ages of minerals can be very good approximations of crystallization ages only when the time of cooling from crystallization temperature to closure temperature is short compared to the "cooling age". For example if we assume a hornblend-biotite granodiorite pluton was emplaced in the crust at a temperature of about 700°C, 295 million years ago and began cooling at a rate of 100°C/Ma, the hornblende (CT ~500°C) cooling age would be expected to be at least 293 Ma, a very good approximation of the emplacement and crystallization age of the pluton. Likewise if we assume a peraluminous, two-mica granite pluton was emplaced into the crust at a temperature of about 650°C, 295 million years ago and began cooling at a rate of 100°C/Ma, the muscovite (CT ~350°C) cooling age would be expected to be at least 292

Ma, still within 1% of the emplacement and crystallization age. Conversely, if the aforementioned hornblende-biotite granodiovite cooled only at an average rate of 10°C/Ma from emplacement to closure in hornblende, the $^{40}Ar/^{39}Ar$ cooling age would be expected to be about 275 Ma, and for the muscovite from the two-mica granite about 265 Ma, neither being a very good approximation of the emplacement age for the plutons.

The argon closure temperature for microcline under normal conditions is only about 150-200°C. This temperature is low enough that any Alpine metamorphic effects, except for brittle fracturing, would likely be reflected by Cenozoic cooling ages. Therefore, microcline $^{40}Ar/^{39}Ar$ thermochronology can be used as a rather sensitive indicator of the structural position of the Sila batholith and its country rocks during Alpine orogenesis.

Published geochronologic data from other portions of the Calabria-Peloritani arc indicate a variable degree of retrogression and reequilibration of minerals during post Variscan time (see Paglionico; 1985 for a review). Future studies in these other areas such as Serre, Aspromonte, and the Peloritiani mountains should delineate the post-Variscan tectonic history.

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Table 1: Location of samples collected for $^{40}Ar/^{39}Ar$ thermochronology of various plutons in the Sila batholith. Map No. refers to numbered general localities plotted on Figure 3.

Map No.	Sample No.	N. Latitude	E. Longitude
1	BD-347	39°01'19"	16°44'46"
2	BD-348	39°04'01"	16°47'04"
3	BD-356	39°05'39"	16°46'56"
4	BD-357	39°05'39"	16°43'53"
5	BD-358	39°08'11"	16°43'21"
6	BD-353	39°12'27"	16°40'21"
7	BD-366	39°18'25"	16°44'53"
8	BD-363	39°10'16"	16°47'53"
9	BD-364	39°18'38"	16°50'07"
10	BD-367	39°25'37"	16°36'21"
11	BD-369	39°34'01"	16°33'49"

Table 2: Summary of $^{40}Ar/^{39}Ar$ Ages for Minerals in Plutons of the Sila Batholith.

Sample No.	Mineral	Age(Ma)[1]
Syntectonic, main intrusions, hornblende ± biotite-bearing tonalite		
BD-347	Biotite	231 ± 1 (TG)
BD-348	Hornblende	293.4 ± 0.9 (P)
do	Biotite	218 ± 1 (TG)
BD-356	Biotite	260 ± 1 (TG)
BD-357	Biotite	234 ± 1 (TG)
BD-358	Hornblende	293.0 ± 1.0 (P)
do	Biotite	220 ± 1 (TG)
Decameter-sized inclusion of melatonalite in post-tectonic granodiorite		
BD-353	Hornblende	290.7 ± 0.9 (P)
DO	Biotite	277 ± 1 (TG)
Post-tectonic, main intrusions, hornblende ± biotite bearing granodiorite		
BD-366	Hornblende	291.5 ± 0.9 (P)
Main intrusions, two-mica ± cordierite ± Al-silicate monzogranite		
BD-363	Muscovite	289.4 ± 0.9 (P)
DO	Biotite	278 ± 1 (TG)
DO	Microcline	180, 270, 250 Min, Max, TG
Small intrusion, two-mica monzogranite		
BD-364	Muscovite	290.7 ± 0.9 (P)
do	Biotite	292 ± 1 (TG)
Main intrusions, two-mica ± cordierite ± Al-silicate monzogranite		
BD-367	Muscovite	291.4 ± 1.5 (P)
do	Microcline	complex age spectrum
Minor intrusions, lencomonzogranite		
BD-369	Muscovite	293.4 ± 0.9 (P)
do	Biotite	254 ± 1 (TG)

[1]Symbols next to ages are: TG = total gas age (integrated age from all temperature steps of age spectrum, essentially equivalent to a K/Ar age; P = plateau age, plateau criteria as described by Snee et al. (1988); Min = minimum age on age spectrum; Max = maximum high-temperature age on age spectrum. Errors on ages are 1σ analytical precision estimates only.

Table 3. $^{40}Ar/^{39}Ar$ age data for minerals from plutons of the Sila Batholith

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar x 10^{-12}$ (initial & radiogenic)	$^{39}Ar x 10^{-13}$ (K-derived)	$^{38}Ar x 10^{-14}$ (Cl-derived)	$^{37}Ar x 10^{-13}$ (Ca-derived)	$^{36}Ar x 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-347 biotite; syntectonic tonalite; J=0.006470; sample wt. = 0.1292 grams							
550	10.5	48.02	22.04	4.9	3	5.1	230.9±0.7
650	9.0	40.78	18.96	4.1	3	1.7	232.3±0.8
750	12.3	55.83	25.98	5.5	3	1.8	232.8±0.6
900	10.5	48.37	22.22	4.8	3	2.8	233.8±0.7
1000	3.3	15.44	6.94	1.5	3	1.6	235.5±0.7
1100	27.1	122.0	57.11	12.1	3	6.9	229.9±0.6
1250	23.3	104.6	49.07	10.3	3	5.8	229.5±1.4
1450	4.0	18.76	8.46	1.9	3	3.1	230.8±1.0
Total Gas	100.0	453.9	210.8	45.1	3	28.8	231.1

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-348 hornblende; syntectonic tonalite; J=0.006483; sample wt. = 0.3741 grams							
650	0.3	2.00	0.26	0.9	0.87	1.5	615+30
750	0.6	1.71	0.48	0.4	0.80	2.6	223±29
850	0.8	1.36	0.62	0.5	1.30	0.1	254±17
900	0.6	1.16	0.45	0.6	1.67	0.6	254±20
950	1.7	3.81	1.32	2.4	5.81	0.1	325.0±7.9
1000	43.8	88.64	34.01	71.4	169.2	2.3	293.9±0.8
1050	24.4	48.50	18.93	39.9	88.53	0.2	291.1±1.3
1100	7.2	14.43	5.56	11.7	27.36	0.4	292.5±1.9
1150	17.4	35.48	13.48	28.5	66.27	2.2	293.7±1.1
1250	3.3	7.34	2.54	5.5	12.63	2.9	290.4±3.3
Total Gas	100.0	204.4	77.66	161.7	374.4	12.9	293.7

Plateau age (1000-1250°C) = 293.4±0.9

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar x 10^{-12}$ (initial & radiogenic)	$^{39}Ar x 10^{-13}$ (K-derived)	$^{38}Ar x 10^{-14}$ (Cl-derived)	$^{37}Ar x 10^{-13}$ (Ca-derived)	$^{36}Ar x 1015^{-15}$ (initial)	Age[1,2] (Ma)
BD-348 biotite; syntectonic tonalite; J=0.006580; sample wt. = 0.1352 grams							
450	3.7	16.85	8.35	2.2	3	2.5	215.6±0.7
550	11.4	51.37	25.83	6.9	3	3.3	217.9±0.6
650	21.4	97.38	48.58	12.9	3	6.8	219.2±0.8
750	4.4	20.41	10.07	2.7	3	1.9	220.1±1.1
900	8.9	40.38	20.12	5.4	3	3.1	219.0±0.7
1000	22.2	100.7	50.43	13.3	3	8.5	217.5±0.9
1100	9.6	44.28	21.90	5.9	3	4.2	219.4±0.7
1250	14.9	67.38	33.96	8.9	3	2.6	219.0±0.6
1450	3.5	16.41	8.00	2.2	3	2.6	218.2±0.6
Total Gas	100.0	455.2	227.2	60.4	3	35.5	218.5

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar\times10^{-12}$ (initial & radiogenic)	$^{39}Ar\times10^{-13}$ (K-derived)	$^{38}Ar\times10^{-14}$ (Cl-derived)	$^{37}Ar\times10^{-13}$ (Ca-derived)	$^{36}Ar\times10^{-15}$ (initial)	Age[1,2] (Ma)
BD-356 biotite; syntectoic tonalite; J=0.006630; sample wt. = 0.1028 grams							
350	2.7	9.47	4.87	1.2	0.14	4.7	188.3±3.5
450	8.3	36.07	14.91	3.1	0.07	5.0	258.0±1.4
550	17.8	76.97	32.18	6.4	0.06	1.8	263.8±1.3
750	11.4	49.51	20.62	4.2	0.05	1.9	263.6±1.3
950	28.4	121.2	51.24	10.1	0.32	5.6	259.5±1.5
1150	29.1	124.8	52.41	10.5	0.62	4.6	261.8±1.3
1400	2.3	10.95	4.18	0.9	0.18	3.1	266.6±1.4
Total Gas	100.0	429.0	180.4	36.5	1.44	26.7	259.6

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-357 biotite; syntectonic tonalite; J=0.006843; sample wt. = 0.1138 grams							
550	9.5	38.80	19.74	6.0	0.30	7.6	215.2±0.5
700	17.7	76.32	36.90	11.1	3	3.3	235.9±0.5
900	16.3	70.68	34.08	10.2	0.15	2.3	237.2±0.6
1075	34.3	146.7	71.49	21.2	2.22	4.2	235.2±0.6
1250	19.4	83.14	40.44	11.9	1.38	2.1	235.8±0.6
1450	2.8	12.39	5.86	1.8	1.28	1.1	237.9±0.9
Total Gas	100.0	428.1	208.5	62.2	5.32	20.6	234.0

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar x 10^{-12}$ (initial & radiogenic)	$^{39}Ar x 10^{-13}$ (K-derived)	$^{38}Ar x 10^{-14}$ (Cl-derived)	$^{37}Ar x 10^{-13}$ (Ca-derived)	$^{36}Ar x 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-358 hornblende; syntectonic tonalite; J=0.006790; sample wt. = 0.5010 grams							
850	2.5	12.92	2.72	4.5	8.35	11.5	383.8±2.6
950	20.9	61.51	22.38	47.5	113.4	9.4	295.8±0.8
1000	37.1	105.8	39.69	84.7	201.3	8.0	293.9±1.0
1050	17.8	50.02	19.00	40.2	95.24	3.8	290.5±0.8
1100	8.0	22.72	8.58	18.4	44.33	1.6	292.4±1.2
1150	2.9	8.32	3.08	6.6	15.91	0.8	295.9±1.8
1450	10.8	30.62	11.52	24.7	59.06	1.9	294.4±1.0
Total Gas	100.0	291.9	107.0	226.6	537.6	37.1	296.0

Plateau age (950-1450°C) = 293.0±1.0

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-358 biotite; syntectonic tonalite; J=0.006843; samp~e wt. = 0.1160 grams							
550	6.0	21.36	12.34	3.8	0.19	7.8	181.4±0.5
700	14.5	59.06	30.08	8.9	0.24	7.1	219.8±0.5
900	16.1	65.69	33.47	9.7	0.13	3.2	224.3±0.5
1075	38.1	154.1	79.00	22.9	1.45	6.0	223.6±0.8
1250	22.9	92.15	47.54	13.7	2.16	3.7	222.2±0.8
1450	2.3	9.68	4.82	1.4	1.29	1.4	222.7±1.9
Total Gas	100.0	402.0	207.3	60.4	5.46	29.2	220.3

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-353 hornblende; decameter-sized inclusion of melatonalite in post-tectonic granodiorite; J=0.006843; sample wt. = 0.4957 grams							
650	0.3	2.62	0.29	0.6	0.92	6.8	244±23
850	0.6	1.90	0.57	0.4	1.31	2.6	229±28
950	0.7	2.69	0.75	0.9	2.77	3.3	263±20
1000	1.1	3.58	1.13	1.9	5.24	3.1	269.7±8.8
1050	12.6	33.87	12.81	24.1	69.00	3.8	290.8±0.7
1090	23.8	63.75	24.15	45.5	131.6	6.2	291.5±0.6
1125	15.3	40.32	15.48	29.2	83.18	3.7	288.5±0.7
1160	4.2	11.03	4.23	7.9	22.55	0.8	290.4±1.2
1450	41.4	108.2	42.00	79.9	226.2	3.9	290.1±0.9
Total Gas	100.0	268.0	101.4	190.4	542.8	34.3	289.4

Plateau age (1050-1450°C) =290.7±0.9

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-353 biotite; decameter-sized inclusion of melatonalite in post-tectonic granodiorite; J=0.006550; sample wt. = 0.1370 grams							
550	4.3	19.19	10.30	2.0	1.26	5.4	191.3±0.8
750	16.1	98.80	38.24	7.4	1.43	8.4	275.5±0.9
900	11.6	71.53	27.47	5.2	0.54	2.9	280.9±0.8
1050	19.1	119.2	45.20	8.8	3.48	4.8	284.2±0.9
1200	37.4	229.6	88.67	16.6	3.64	4.4	281.2±0.7
1450	11.5	71.06	27.33	5.1	2.51	1.1	282.5±0.7
Total Gas	100.0	609.4	237.2	45.1	12.86	27.0	277.2

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar x 10^{-12}$ (initial & radiogenic)	$^{39}Ar x 10^{-13}$ (K-derived)	$^{38}Ar x 10^{-14}$ (Cl-derived)	$^{37}Ar x 10^{-13}$ (Ca-derived)	$^{36}Ar x 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-366 hornblende; post-tectonic granodiorite; J=0.006843; sample wt. = 0.4837 grams							
700	0.8	2.96	0.44	0.9	1.10	7.1	228±25
800	0.6	1.09	0.35	0.2	0.81	1.1	250±40
900	1.2	1.80	0.63	0.9	5.96	0.6	291±22
950	2.0	3.16	1.12	2.7	14.57	0.7	300±24
980	10.5	15.22	5.75	16.6	51.80	1.3	293.3±2.2
1010	39.9	56.60	21.85	70.3	182.8	1.4	292.4±1.0
1040	14.6	20.67	7.97	26.0	63.94	1.5	288.8±1.0
1070	5.2	7.55	2.85	8.7	23.88	0.2	298.8±4.6
1150	16.2	23.01	8.84	28.4	72.52	0.8	292.9±1.1
1250	9.0	13.82	4.94	16.1	40.19	4.1	290.5±4.0
Total Gas	100.0	145.9	54.75	170.8	457.5	18.8	291.6

Plateau age (980-1250°C) = 292.5±0.9

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar x 10^{-12}$ (initial & radiogenic)	$^{39}Ar x 10^{-13}$ (K-derived)	$^{38}Ar x 10^{-14}$ (Cl-derived)	$^{37}Ar x 10^{-13}$ (Ca-derived)	$^{36}Ar x 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-363 muscovite; two-mica monzogranite; J=0.006843; sample wt. = 0.1142 grams							
450	0.9	2.51	0.97	0.50	0.03	1.7	240±14
550	1.2	3.48	1.29	0.07	0.03	3.3	274.3±8.1
650	1.7	5.60	1.88	0.11	0.03	3.3	281.8±4.2
750	4.2	12.12	4.56	0.07	0.04	1.6	290.4±1.1
850	6.1	17.57	6.69	3	0.05	1.7	290.1±1.4
900	13.9	39.77	15.29	0.03	0.08	3.1	289.1±0.8
950	24.1	68.36	26.40	3	0.16	4.5	289.0±1.3
1000	16.6	64.84	18.19	2.29	0.05	62.7	289.7±1.2
1050	18.6	52.88	20.41	0.10	0.05	3.7	288.8±0.8
1100	12.8	37.35	14.08	0.12	0.06	4.9	290.1±0.9
Total Gas	100.0	304.5	109.8	3.30	0.58	88.5	288.6

Plateau age (750-1100°C) = 289.4±0.9

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-363 biotite; 2-mica monzogranite; J=0.006785; sample wt. = 0.1115 grams							
450	25.0	118.8	44.34	9.2	0.21	47.3	268.3±1.5
550	20.7	107.5	36.77	7.9	0.08	47.9	286.8±1.9
750	9.4	54.88	16.66	4.3	0.05	44.1	283.9±1.7
950	11.5	60.30	20.49	4.5	0.10	34.4	277.2±1.5
1500	33.4	175.5	59.36	12.4	0.35	99.8	278.4±1.5
Total Gas	100.0	517.0	177.6	38.3	0.79	273.4	278.0

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-363 microcline; 2-mica monzogranite; J=0.006780; sample wt. = 0.1107 grams							
400	0.1	3.96	0.14	0.3	0.01	5.9	1292±41
450	0.1	4.81	0.25	0.1	0.01	1.1	1423±35
500	0.3	5.59	0.65	0.2	0.02	1.5	772±13
550	0.8	5.18	2.08	0.1	0.03	0.9	268.4±2.5
600	1.3	5.44	3.24	0.2	0.03	1.3	181.6±2.8
650	2.8	12.20	7.08	3	0.05	1.9	190.7±1.3
700	3.5	16.60	8.89	0.1	0.08	2.3	206.9±1.3
750	4.4	21.86	11.12	0.1	0.12	4.4	213.2±1.2
825	5.9	29.21	14.90	3	0.23	1.0	223.0±1.2
900	4.2	20.99	10.71	0.1	0.19	1.0	221.9±1.2
1000	5.6	28.73	14.16	0.1	0.17	2.4	226.9±1.2
1100	13.1	70.66	32.96	0.3	0.53	3.6	241.4±1.2
1200	45.9	274.2	115.6	1.6	0.57	19.6	263.6±1.3
1300	10.2	63.55	25.65	0.4	0.08	8.3	270.1±1.3
1375	1.9	14.80	4.71	0.5	0.06	1.2	268.9±1.8
Total Gas	100.0	577.8	252.2	4.1	2.19	67.4	252.1

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-364 muscovite; small pluton of two-mica, monzogranite; J=0.006843; sample wt. = 0.1468 grams							
450	2.2	11.23	4.41	0.61	3	4.7	256.8±2.5
550	4.1	21.40	8.35	0.10	3	1.5	286.0±0.8
750	5.4	28.66	11.10	3	3	1.5	289.4±1.0
900	25.8	135.9	52.57	3	3	5.7	290.5±0.9
1000	19.3	101.4	39.27	3	3	3.9	290.6±0.8
1100	11.0	58.00	22.40	3	3	2.5	290.9±0.7
1250	27.5	144.7	56.10	3	3	3.2	291.4±1.0
1450	4.6	25.16	9.46	0.12	3	3.4	290.6±0.9
Total Gas	100.0	526.5	203.6	0.80	3	26.4	289.8

Plateau age (750-1450°C) = 290.7±0.9

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar x 10^{-12}$ (initial & radiogenic)	$^{39}Ar x 10^{-13}$ (K-derived)	$^{38}Ar x 10^{-14}$ (Cl-derived)	$^{37}Ar x 10^{-13}$ (Ca-derived)	$^{36}Ar x 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-364 biotite; small pluton of two-mica monzogranite; J=0.006660; sample wt. = 0.1373 grams							
450	3.3	13.31	7.53	2.2	3	4.7	180.9±2.8
550	7.5	45.92	17.26	4.8	3	3.8	287.6±0.8
750	22.2	137.2	51.18	13.6	3	5.3	293.1±0.9
900	12.3	76.14	28.30	7.3	3	2.0	295.2±0.8
1000	11.7	74.81	27.12	7.0	3	2.6	301.4±0.7
1100	29.1	181.4	67.10	17.9	3	3.4	297.2±0.7
1250	12.3	76.42	28.43	7.4	3	2.7	294.3±0.8
1450	1.7	10.98	3.90	1.0	3	1.9	295.8±1.2
Total Gas	100.0	616.2	230.8	61.2	3	26.4	291.8

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar x 10^{-12}$ (initial & radiogenic)	$^{39}Ar x 10^{-13}$ (K-derived)	$^{38}Ar x 10^{-14}$ (Cl-derived)	$^{37}Ar x 10^{-13}$ (Ca-derived)	$^{36}Ar x 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-367 muscovite; two-mica granodiorite to monzogranite; J=0.006845; sample wt. = 0.1137 grams							
550	4.8	47.36	11.51	4.66	1.65	81.5	233.9±2.5
650	5.4	33.81	13.19	0.12	0.01	3.1	284.3±1.6
750	8.6	53.36	20.73	0.09	0.02	2.7	288.8±1.4
850	9.5	59.35	23.11	3	3	2.0	289.4±1.5
900	12.8	79.77	30.95	3	3	2.4	290.6±1.4
1000	26.9	168.9	65.22	3	0.06	6.4	291.3±1.4
1100	19.7	124.3	47.67	3	0.05	4.0	293.6±1.6
1200	9.3	57.69	22.60	3	0.07	2.6	286.9±5.0
1500	2.9	21.24	7.03	0.40	0.07	10.3	294.4±1.9
Total Gas	100.0	645.7	242.0	5.27	1.93	115.0	287.9

Plateau age (900-1100°C) =291.4±1.5

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
	BD-367 microcline; two-mica granodiorite to monzogranite; J=0.006820; sample wt. = 0.1183 grams						
550	1.5	4.09	5.52	0.4	3	8.4	35.7±1.1
600	2.6	2.92	9.46	3	3	2.3	28.8±0.9
650	2.3	3.99	8.34	3	3	1.3	52.3±0.7
700	1.9	6.50	6.93	3	3	1.2	105.8±1.0
750	1.6	7.94	5.84	3	3	1.0	154.4±1.4
800	1.5	8.89	5.55	3	3	0.5	183.7±1.2
850	1.7	10.04	6.00	3	3	1.0	189.6±1.2
900	1.9	11.28	6.79	3	3	1.2	187.9±1.3
950	2.2	13.29	8.05	3	3	1.0	188.5±0.7
1000	1.3	7.52	4.58	3	3	0.7	186.7±2.4
1050	3.9	21.42	13.84	3	3	1.8	176.8±1.2
1100	4.0	21.00	14.52	3	3	1.6	166.0±1.0
1150	5.4	25.56	19.47	0.2	3	2.8	149.9±0.6
1200	6.2	28.17	22.14	0.2	3	2.3	146.6±0.6
1250	9.8	40.29	35.05	0.3	3	3.2	133.1±0.4
1300	28.1	118.6	100.9	1.2	3	10.6	135.6±0.4
1350	21.8	111.7	78.38	0.8	3	7.7	164.1±0.7
1400	2.1	12.95	7.51	0.2	3	4.7	179.8±2.3
Total Gas	100.0	456.2	358.9	3.5	3	53.3	145.0

Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-369 muscovite; leucomonzogranite; J=0.006843; sample wt. = 0.1163 grams							
550	7.9	47.04	18.73	0.24	3	6.1	275.9±0.8
650	5.7	34.42	13.35	3	3	1.6	289.4±0.7
750	7.5	45.66	17.63	3	3	1.4	291.9±0.9
850	6.8	41.49	15.99	3	3	0.8	293.3±0.9
925	9.2	56.17	21.63	3	3	1.5	292.9±0.7
1000	7.0	42.92	16.49	3	3	1.0	293.9±0.7
1075	9.4	57.53	22.10	3	3	2.4	292.4±0.7
1450	46.7	288.9	110.4	3	3	11.8	293.9±0.7
Total Gas	100.0	614.1	236.3	0.24	3	26.6	291.8

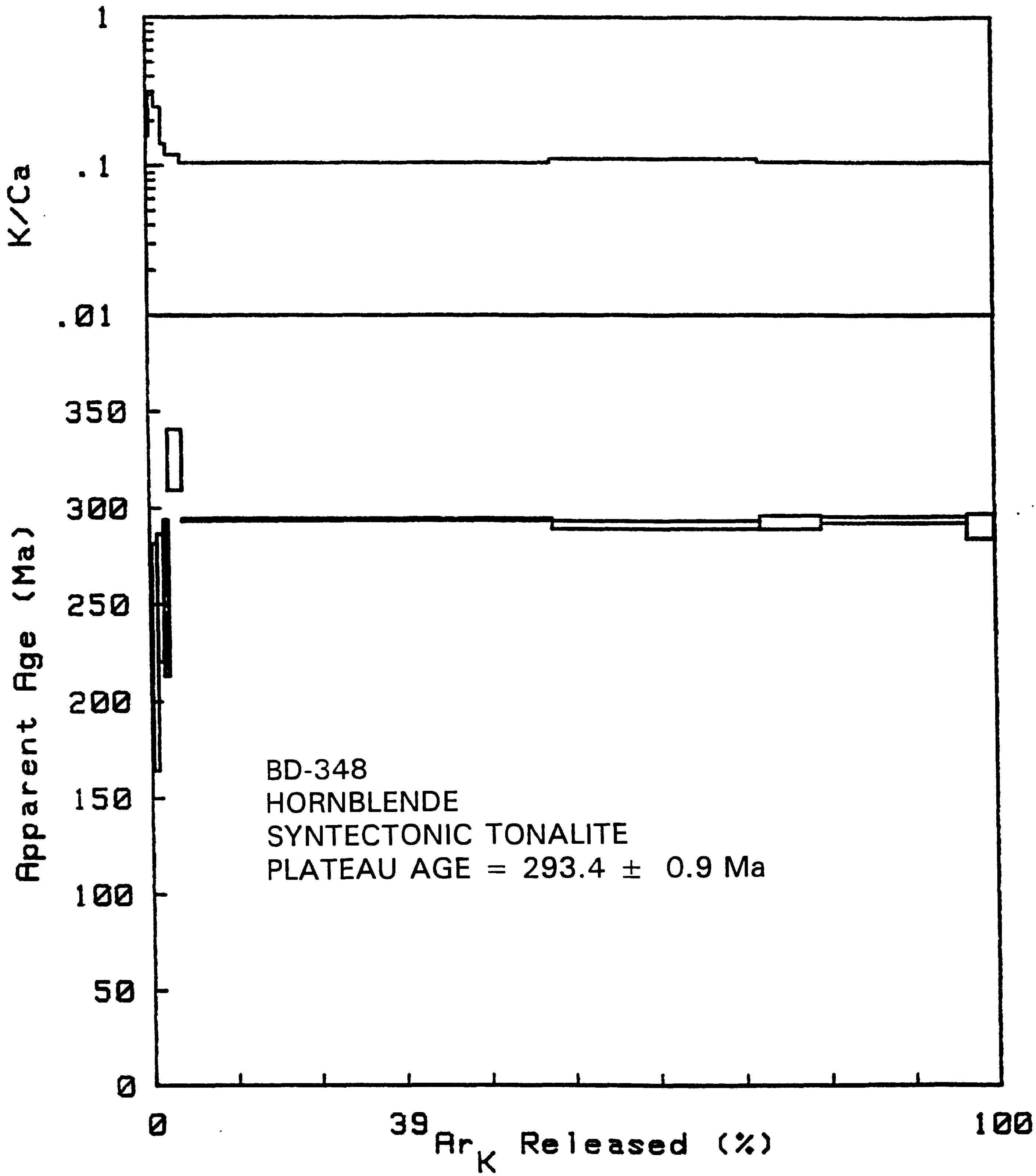
Plateau age (850-1450°C) =293.4±0.9

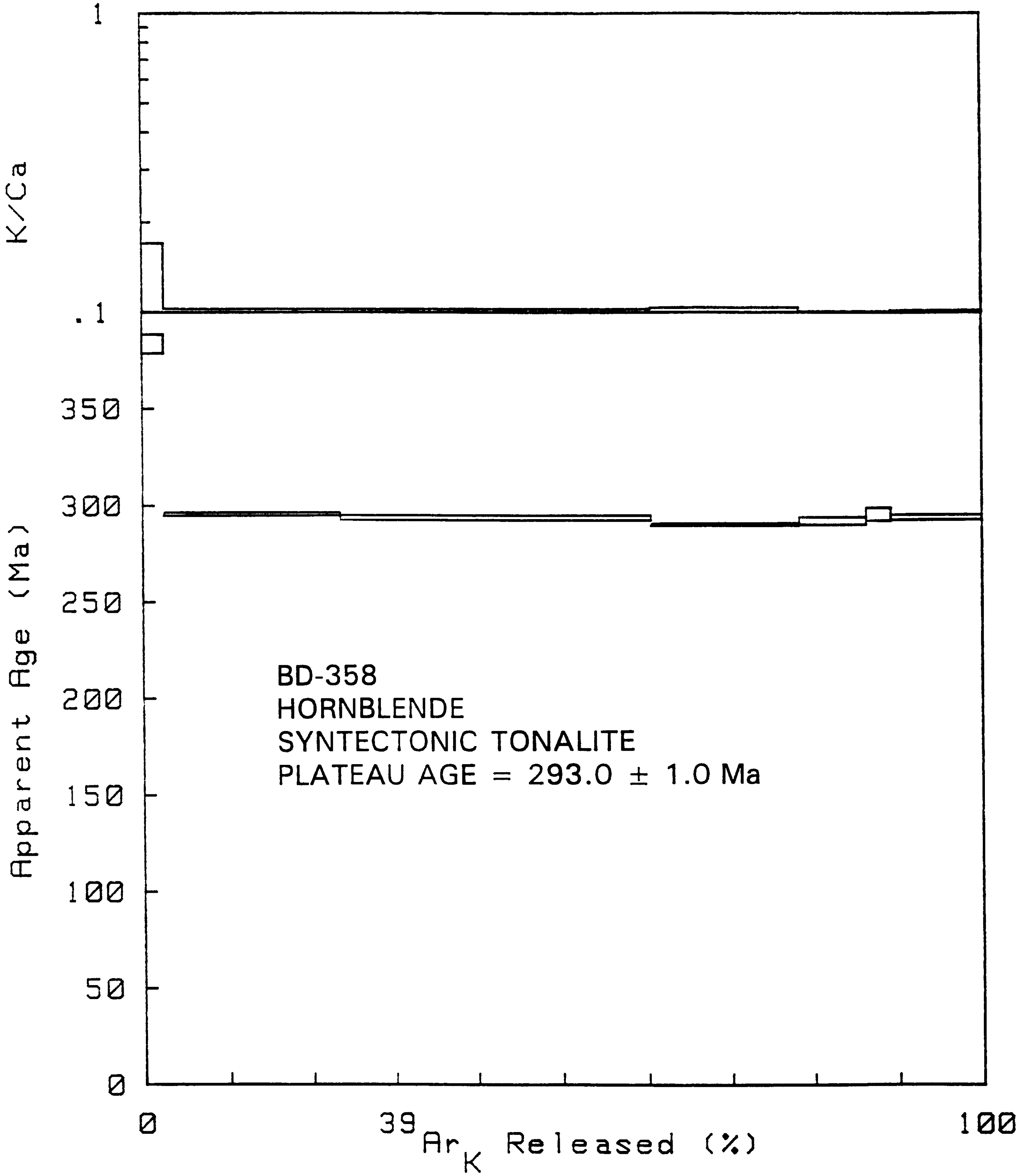
Temp (°C)	^{39}Ar (% of total)	$^{40}Ar \times 10^{-12}$ (initial & radiogenic)	$^{39}Ar \times 10^{-13}$ (K-derived)	$^{38}Ar \times 10^{-14}$ (Cl-derived)	$^{37}Ar \times 10^{-13}$ (Ca-derived)	$^{36}Ar \times 10^{-15}$ (initial)	Age[1,2] (Ma)
BD-369 biotite; leucomonzogranite; J=0.006430; sample wt. = 0.0963 grams							
450	16.5	38.05	21.06	3.0	0.62	18.4	171.3±0.5
550	29.5	96.28	37.56	5.1	2.97	13.2	264.8±1.2
650	9.2	30.53	11.71	1.5	0.50	4.8	267.5±0.9
750	6.4	20.96	8.11	1.0	3	4.4	261.3±0.7
850	5.0	16.63	6.37	0.8	1.03	4.1	260.8±1.0
950	16.2	55.27	20.69	2.6	3	8.6	273.8±0.8
1000	5.2	17.94	6.64	0.9	0.57	2.7	276.8±1.8
1050	3.3	11.31	4.17	0.5	0.48	2.0	275.6±0.9
1150	6.0	20.93	7.70	1.0	0.61	2.6	280.8±0.8
1300	2.7	9.64	3.46	0.4	0.64	1.6	283.4±2.1
Total Gas	100.0	317.5	127.5	16.8	7.43	62.5	253.5

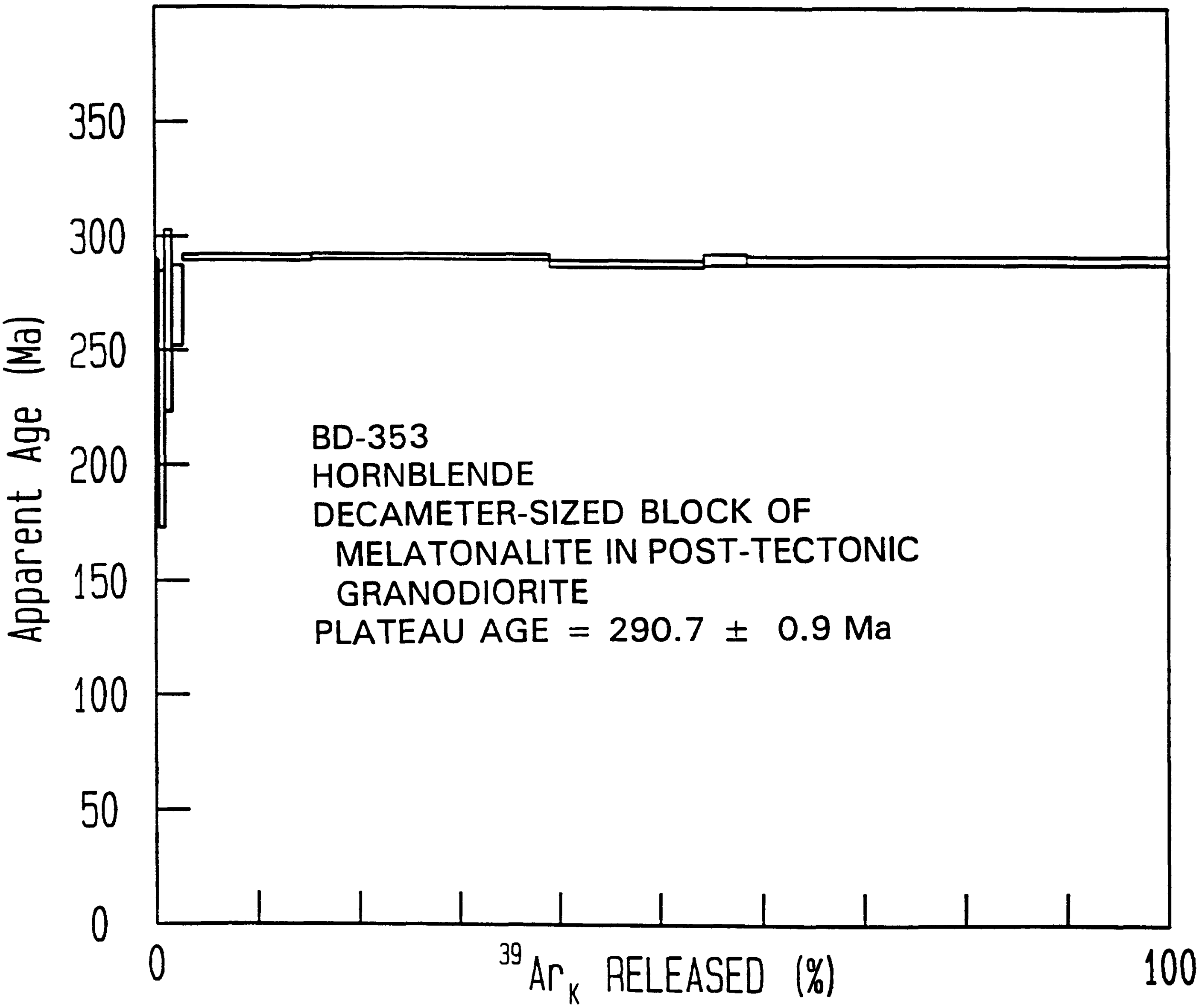
NOTE: All gas quantities are in moles. No blank corrections have been made.

1. Ages have been calculated assuming that the initial $^{40}Ar/^{36}Ar$=295.5 (present-day atmospheric argon).
2. 1-sigma precision estimates are for intra-irradiation package reproducibility.
3. Signal was below detection limit of mass spectrometer.

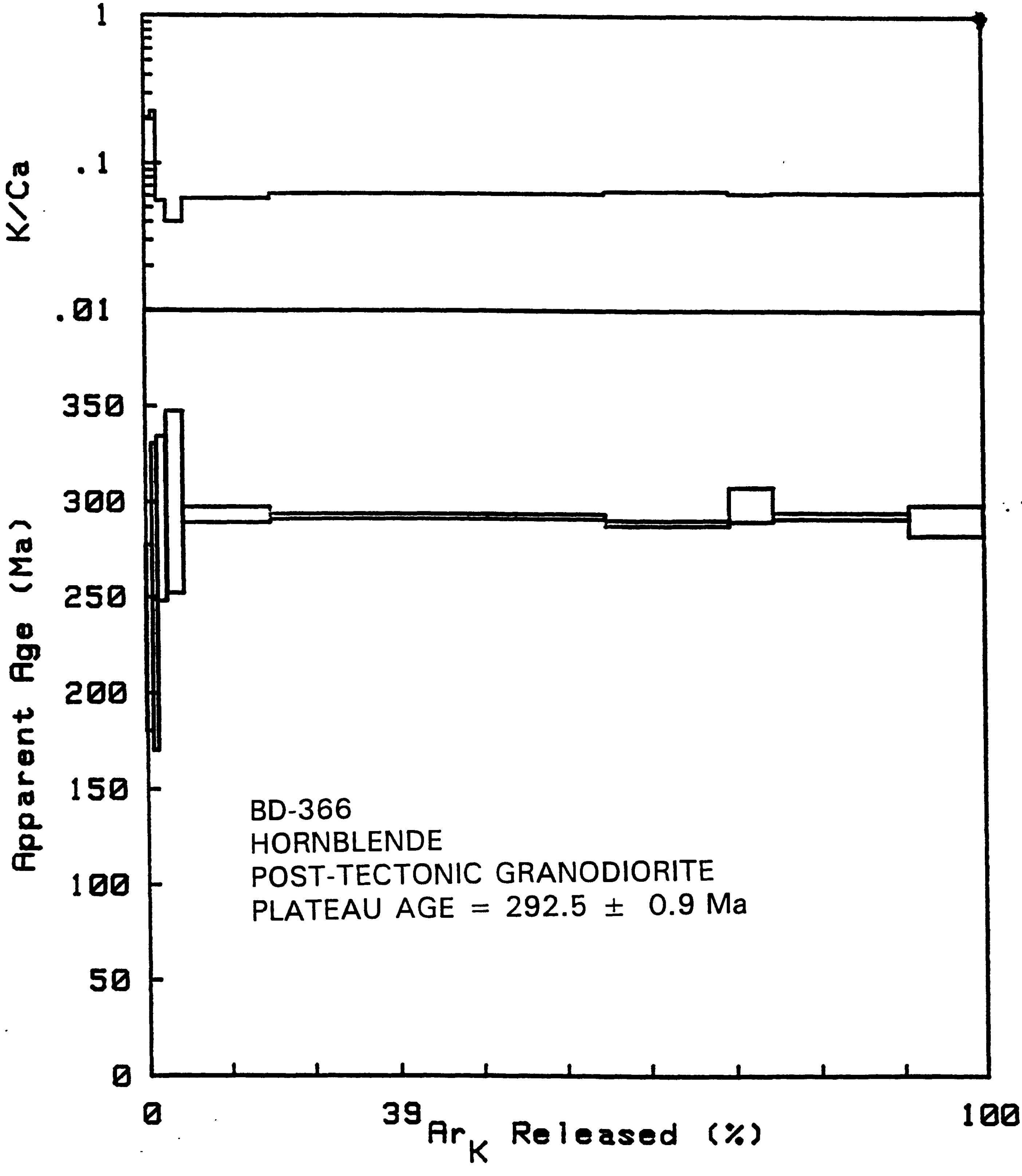
Monitor mineral used in this study was MMhb-1 (Minnesota hornblende) with an accepted age of 519.4 Ma (Alexander and others, 1978). J-value errors are estimated at 0.5%. Samples and monitors were irradiated in the Central Thimble facility of the U.S. Geological Survey, TRIGA Reactor (Dalrymple and others, 1981). Correction factors for interfering argon isotopes and decay rates for short-lived argon isotopes used in this study are those reported by Dalrymple and others (1981). The test for an "age plateau" in the age spectrum is that described by Snee and others (1988). The decay constant for ^{40}K and the isotopic composition of both K and Ar used in this study are those reported by Steiger and Jäger (1977).

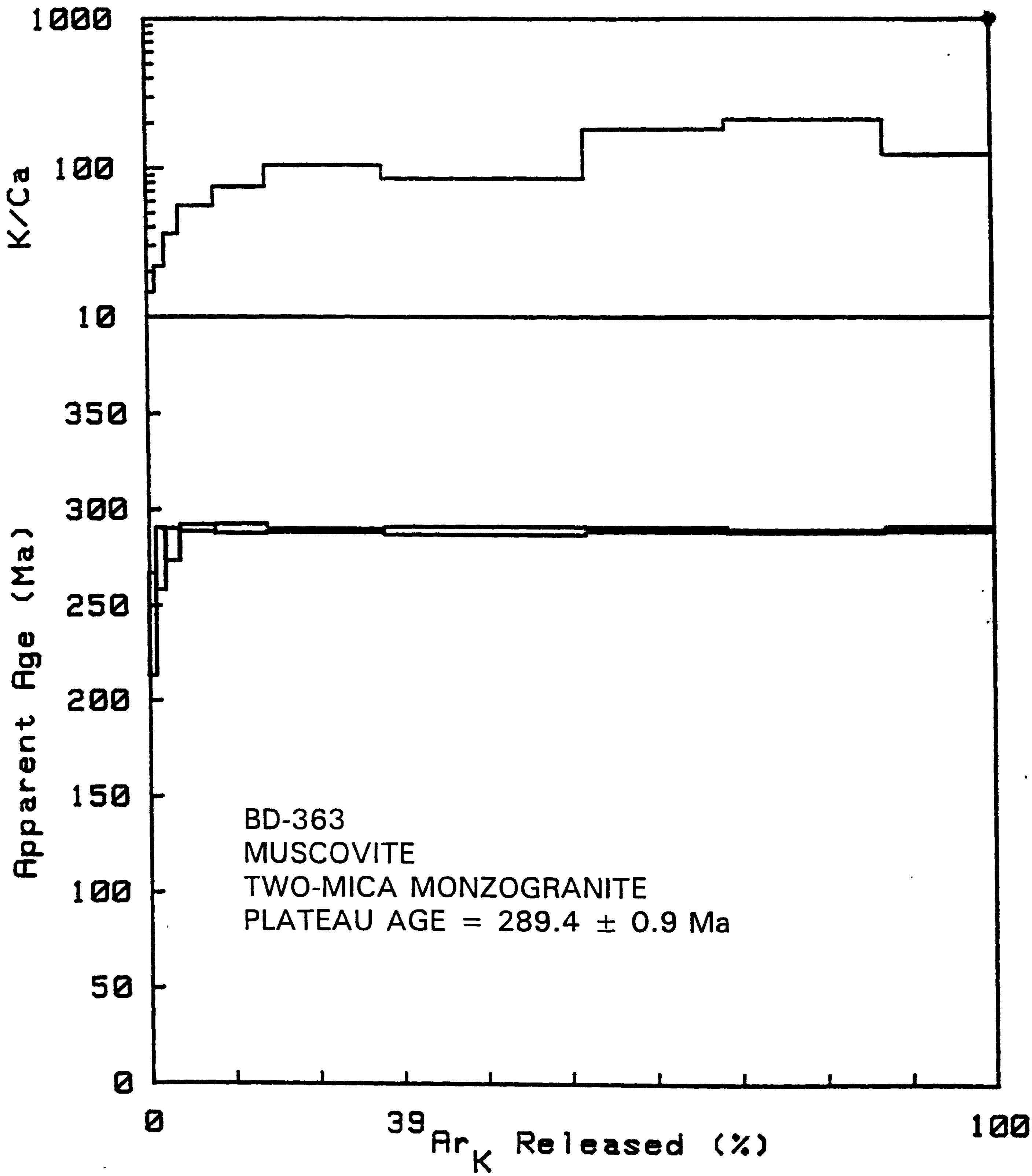

1
.1
.01
K/Ca
350
300
250
200
150
100
50
0
Apparent Age (Ma)
BD-348
HORNBLENDE
SYNTECTONIC TONALITE
PLATEAU AGE = 293.4 ± 0.9 Ma
0
100
39ArK Released (%)

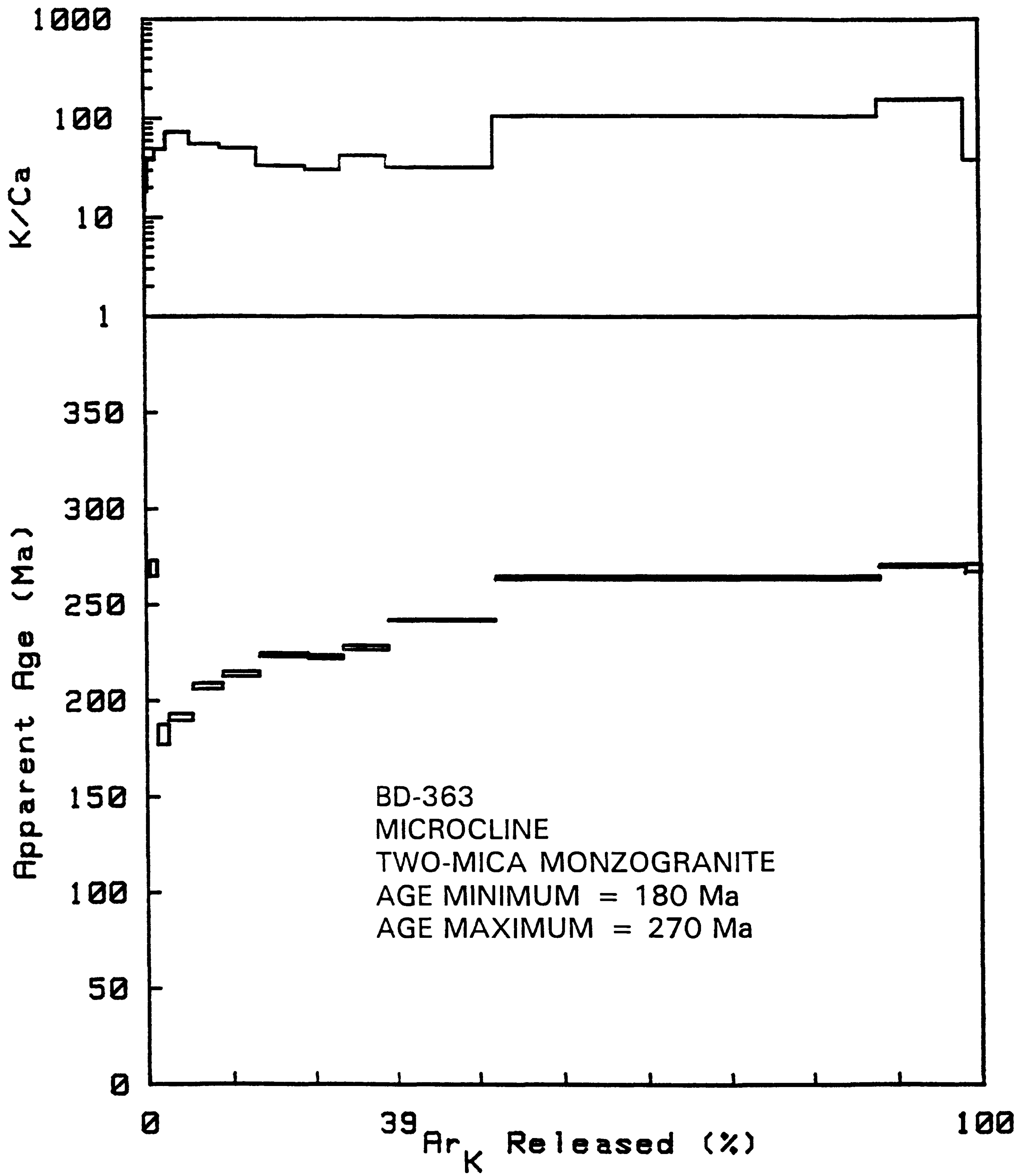

K/Ca
1
.1
Apparent Age (Ma)
350
300
250
200
150
100
50
0
BD-358
HORNBLENDE
SYNTECTONIC TONALITE
PLATEAU AGE = 293.0 ± 1.0 Ma
0
39ArK Released (%)
100

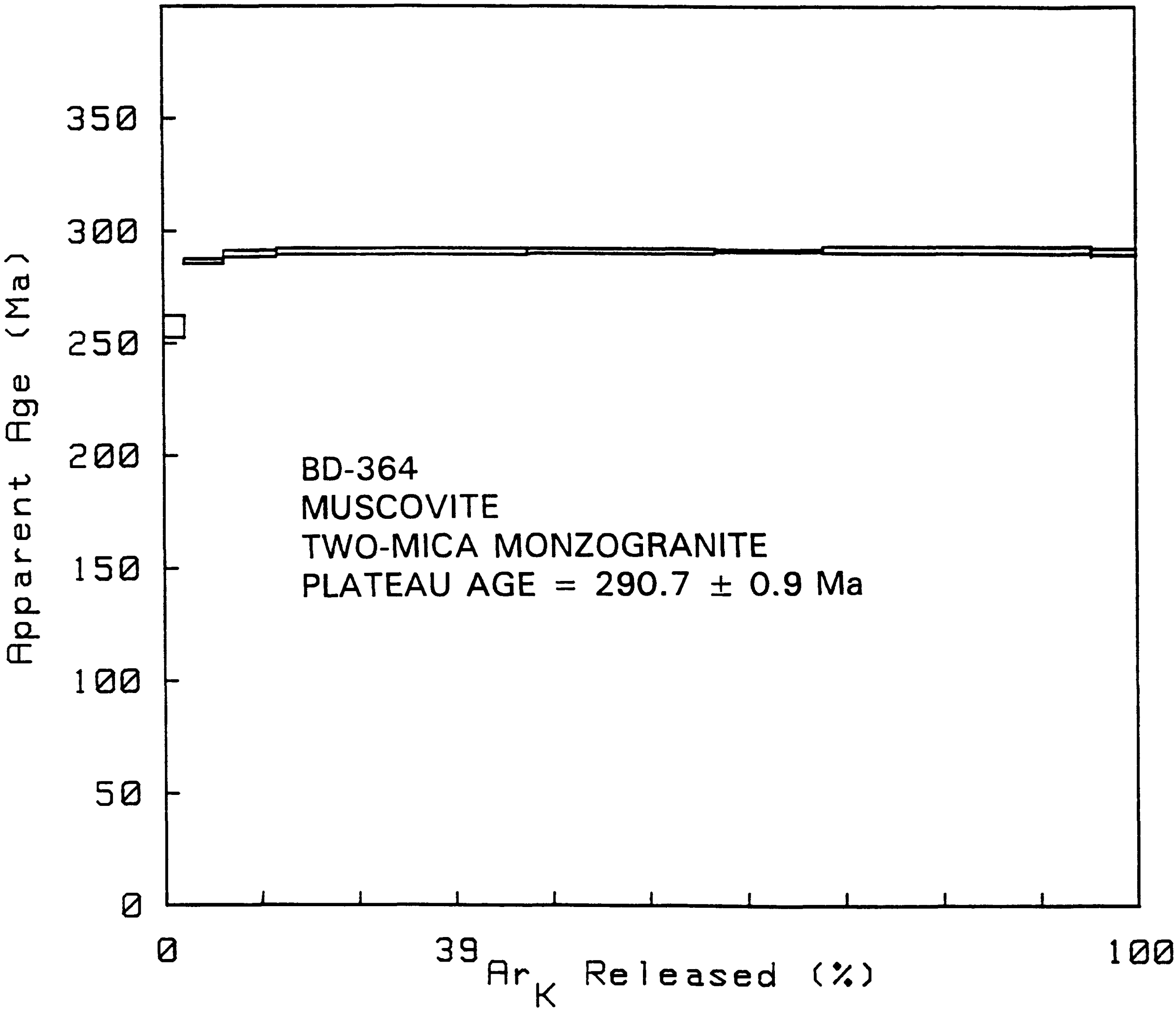


350
300
250
200
150
100
50
0
Apparent Age (Ma)
BD-353
HORNBLENDE
DECAMETER-SIZED BLOCK OF
MELATONALITE IN POST-TECTONIC
GRANODIORITE
PLATEAU AGE = 290.7 ± 0.9 Ma
0
39ArK RELEASED (%)
100

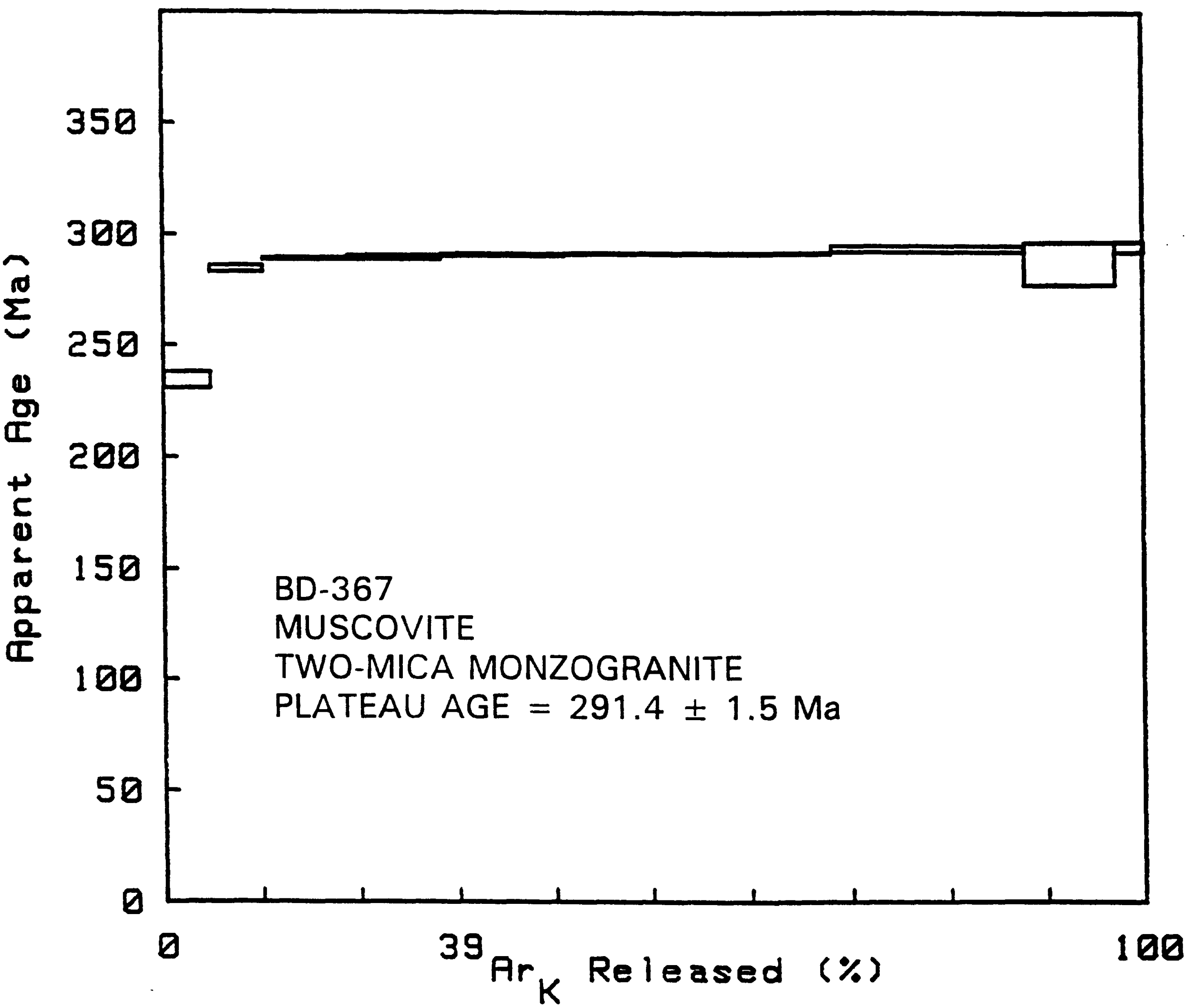

1
.1
.01
K/Ca
350
300
250
200
150
100
50
0
Apparent Age (Ma)
BD-366
HORNBLENDE
POST-TECTONIC GRANODIORITE
PLATEAU AGE = 292.5 ± 0.9 Ma
0
100
39ArK Released (%)


1000
100
10
K/Ca
350
300
250
200
150
100
50
0
Apparent Age (Ma)
BD-363
MUSCOVITE
TWO-MICA MONZOGRANITE
PLATEAU AGE = 289.4 ± 0.9 Ma
0
100
39ArK Released (%)

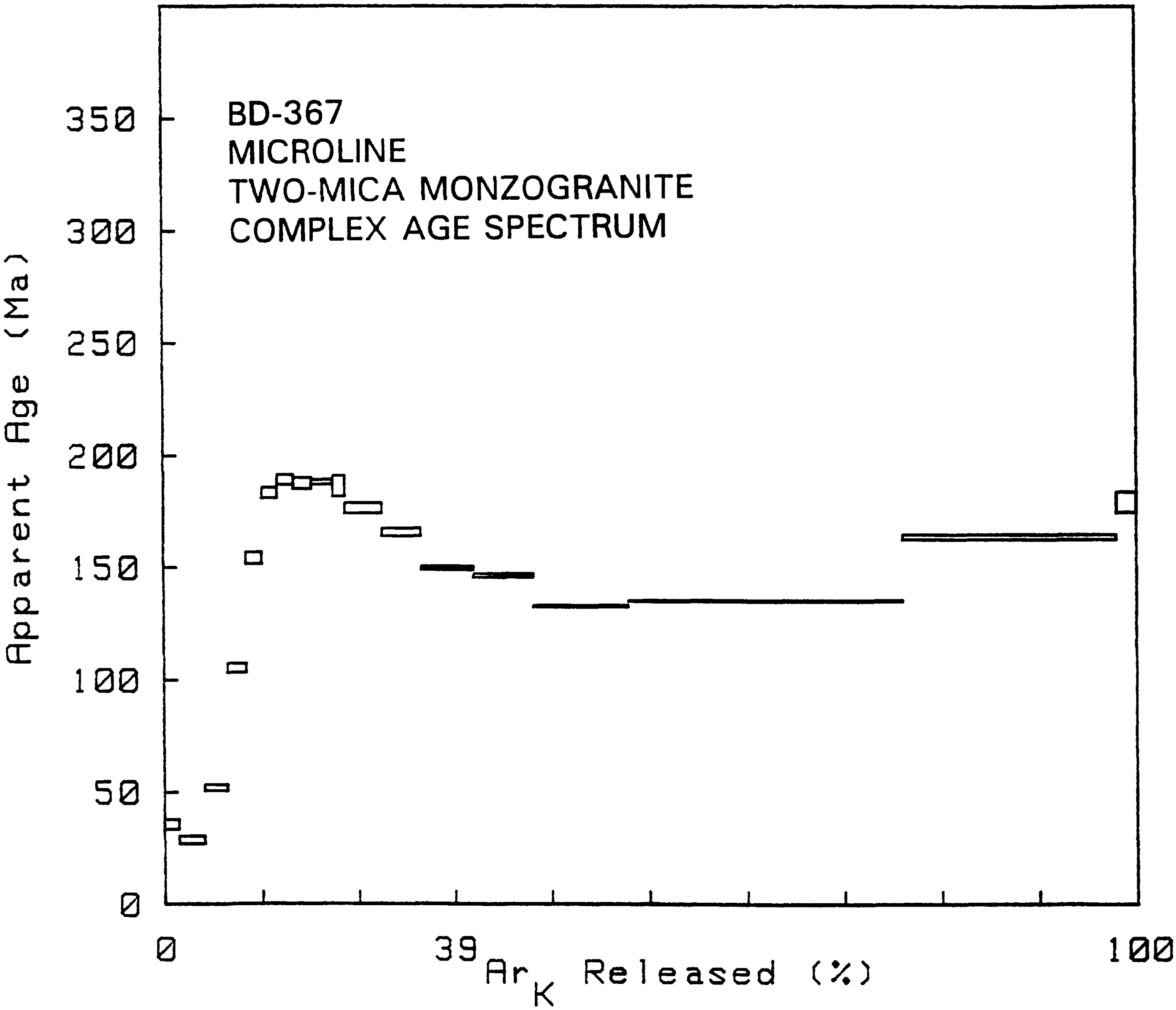

1000
100
10
1
K/Ca
350
300
250
200
150
100
50
0
Apparent Age (Ma)
BD-363
MICROCLINE
TWO-MICA MONZOGRANITE
AGE MINIMUM = 180 Ma
AGE MAXIMUM = 270 Ma
0
100
$^{39}Ar_K$ Released (%)

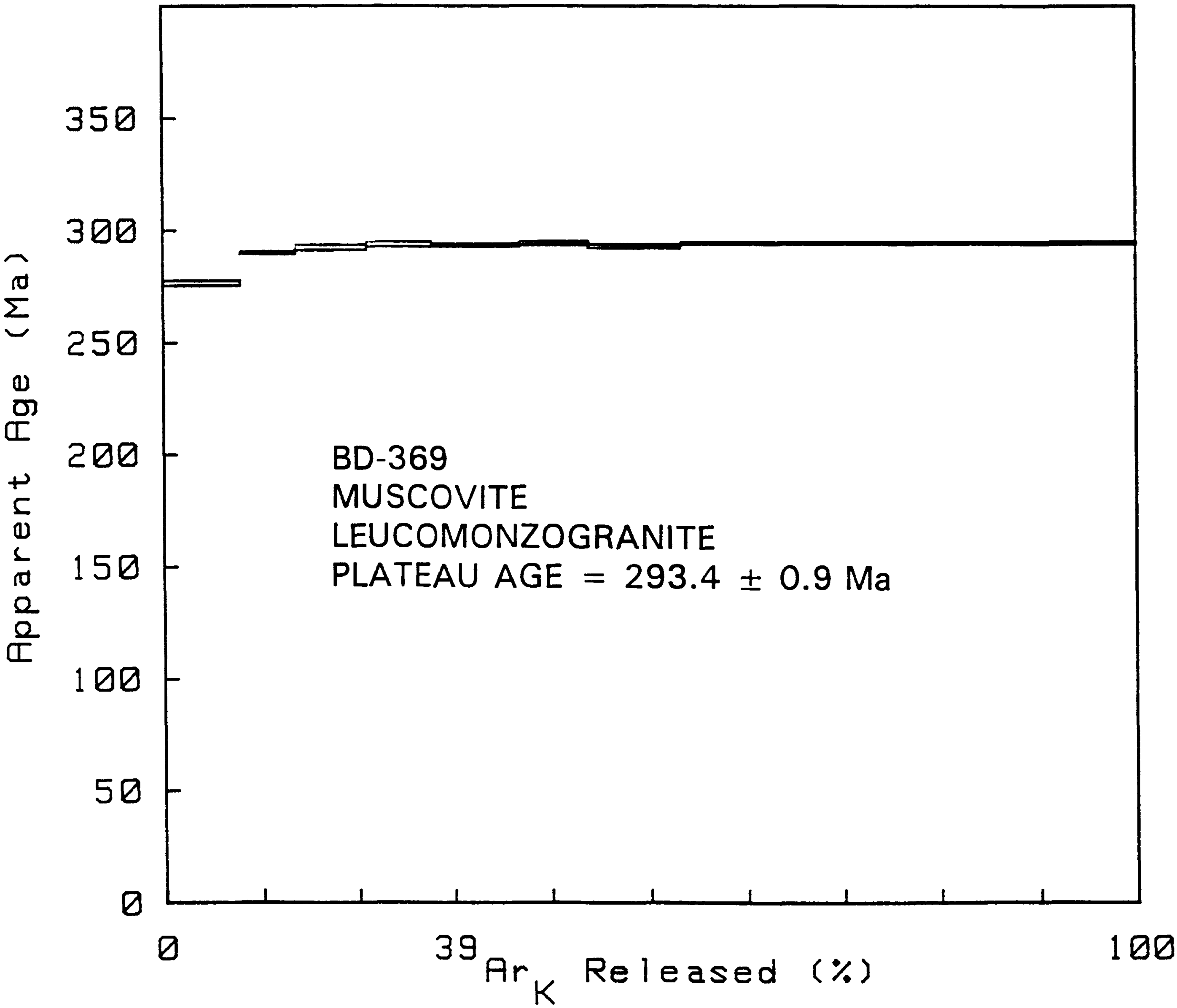


350
300
250
200
150
100
50
0
Apparent Age (Ma)
0
100
39ArK Released (%)
BD-364
MUSCOVITE
TWO-MICA MONZOGRANITE
PLATEAU AGE = 290.7 ± 0.9 Ma



350
300
250
200
150
100
50
0
Apparent Age (Ma)
0
100
39ArK Released (%)
BD-367
MUSCOVITE
TWO-MICA MONZOGRANITE
PLATEAU AGE = 291.4 ± 1.5 Ma


BD-367
MICROLINE
TWO-MICA MONZOGRANITE
COMPLEX AGE SPECTRUM
350
300
250
200
150
100
50
0
Apparent Age (Ma)
0
39
100
ArK Released (%)


Apparent Age (Ma)
350
300
250
200
150
100
50
0
BD-369
MUSCOVITE
LEUCOMONZOGRANITE
PLATEAU AGE = 293.4 ± 0.9 Ma
0
100
$^{39}Ar_K$ Released (%)