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Preliminary Report on $^{40}Ar/^{39}Ar$ Incremental Heating Experiments on Feldspar Samples from the Felsite Unit, Geysers Geothermal Field, California

by

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Introduction

This is a progress report on some preliminary $^{40}Ar/^{39}Ar$ incremental heating experiments on feldspar separates from four samples of the felsite unit, a complex silicic batholith that intrudes the overlying Franciscan Complex (Late Jurassic to Late Cretaceous) and underlies the Geysers Geothermal Field, northern California (Schriener and Suemnicht, 1981; Thompson, 1989, 1991). The felsite unit is only found in the subsurface but it appears to be an elongate body whose axis trends northwest-southeast and whose surface is shallowest in the southeast part of the field (Figure 1). It ranges in composition from granite to granodiorite (Schriener & Suemnicht, 1981; Thompson, 1991).

The apparent coincidence of the heat flow anomaly within the Geysers field (Walters and Combs, 1989) with the distribution of felsite within and below the zone of steam production suggests that the felsite unit may be the primary source of heat. Presently available K-Ar ages (0.9 Ma to 2.7 Ma) suggest, however, that the felsite unit may be too old to be the primary source of heat for the present thermal activity. Resolution of this apparent paradox should be of interest for the purposes of both exploration and field management. If the felsite unit is young ($<$ 1 Ma), for example, then it should be hot wherever it is found. If the felsite unit is old ($>$ 1 Ma), on the other hand, then it may be relatively cold outside of the region of present production. The felsite unit also may be a complex body emplaced over a significant interval of time with both older and younger parts. Regardless of its age, the felsite unit appears to play an important role in the geothermal field and its intrusion and thermal history is of interest.

The age of the felsite unit is not known. Schriener and Sueminicht (1981) reported K-Ar ages of 1.6 ± 0.4 Ma on sanidine, 2.7 ± 0.3 Ma on biotite, and 2.5 ± 0.4 Ma on whole rock felsite. The samples for their study came from cutting recovered from wells that penetrate the felsite unit in the subsurface. Thompson (1991) mentions unpublished age measurements, presumably K-Ar, of as young as

0.9 Ma. McLaughlin and others (1983) reported a K-Ar age of 0.69 ± 0.03 Ma on adularia separated from veins that intrude Franciscan rocks above, and presumably associated with, the felsite unit. The details of these limited age studies have not been published and it is, therefore, difficult to evaluate their significance.

The K-Ar method is remarkably reliable in simple systems, e.g., volcanic rocks. In more complex systems, however, it is subject to errors from Ar loss due to thermal events and alteration, and (rarely) from excess ^{40}Ar due to contamination, incomplete degassing, and elevated ^{40}Ar partial pressures (Dalrymple and Lanphere, 1969). The felsite unit has been subjected to elevated temperatures, fluid and gas flow, and alteration over an extended period of time. It is, therefore, a complex system and K-Ar ages are probably of limited, if any, value. The discordance in its reported ages suggests that the felsite unit is not an undisturbed system and, therefore, cannot be reliably dated by conventional K-Ar methods. Also unknown is the degree to which the dated cuttings samples might be contaminated with material from the older Franciscan rocks.

In the $^{40}Ar/^{39}Ar$ method the sample is irradiated with fast neutrons, along with a *monitor mineral* of known age, to induce the reaction $^{39}K(n,p)^{39}Ar$. The age of the sample is then calculated from the $^{40}Ar/^{39}Ar$ ratio after determining the fraction of ^{39}K converted to ^{39}Ar (expressed by the neutron conversion efficiency factor, J) by analyzing the monitor mineral. Appropriate corrections for interfering Ar isotopes produced from K and Ca, and for contaminating atmospheric Ar must also be applied in the age calculations. The $^{40}Ar/^{39}Ar$ method can be used in two different ways. If all of the Ar is released by fusing the sample in a single heating, the result is a *total fusion age*, which is analogous to, and interpreted the same as, a conventional K-Ar age. If the argon is released from the sample in steps by incrementally heating the sample to progressively higher temperatures, the result is a series of ages known as an *age spectrum*.

The $^{40}Ar/^{39}Ar$ age spectrum method has the advantage of providing information about the degree to which the system has been disturbed or contaminated. In many instances it is possible to determine a crystallization age for a sample that has lost a significant fraction of its radiogenic ^{40}Ar due to thermal or chemical (alteration) disturbance. In others it is possible to determine a minimum crystallization age for a disturbed sample. Regardless of the degree of disturbance or contamination, the method nearly always gives information about the reliability of the sample as a geochronometer and so the apparent ages measured in this way are easily evaluated. In some instances, information about the thermal history of the sample can be extracted from age spectra. For a recent and thorough description of $^{40}Ar/^{39}Ar$ methods, see McDougall and Harrison (1988).

The purposes of this preliminary study were three. The first and most important goal was to determine if $^{40}Ar/^{39}Ar$ age spectrum analyses of sufficient precision could be made on feldspars from the felsite unit. The ability to measure precise $^{40}Ar/^{39}Ar$ age spectra on small samples of very young rocks is a relatively recent development, and it was felt from the outset that there was no point in undertaking a detailed geochronological study of the Geysers subsurface rocks if precise and detailed age spectra could not be obtained on these samples. The second goal was to determine a reliable, if only preliminary, minimum age for the felsite unit. The third goal, assuming success for the first goal, was to use the information obtained from the preliminary results to design a sensible $^{40}Ar/^{39}Ar$ research program with the goal of determining the age and (perhaps) some information about the thermal history of the felsite unit.

The preliminary experiments reported here have resulted in precise $^{40}Ar/^{39}Ar$ age spectra on feldspar separated from four samples of the felsite unit, thereby fulfilling the first goal, and a reliable minimum age of 1.3-1.4 Ma for the parts of the felsite unit sampled, thereby fulfilling the second. An analysis of the age spectrum data to determine what, if any, thermal history information might be extracted from these four samples or from future analyses of other samples has not commenced. These preliminary data indicate that a more comprehensive $^{40}Ar/^{39}Ar$ study of the felsite unit, and perhaps of selected samples from the overlying Franciscan Complex, will be productive.

Sample Descriptions and Locations

The samples studied were from cores taken from the felsite unit below the first steam entry and, for two of the cores, within the geothermal reservoir (Figure 1, Table 1; Gunderson, 1990,1991). The wells have not been logged and so the temperatures at the sample depths are not known with certainty, but data from surrounding wells indicates that the temperatures should be in the range 243-249 °C (R. P. Gunderson, personal communication, 1992).

Table 1. Location of cores from the felsite unit (Gunderson, 1990, 1991).

Well	Sample From	Core interval (drilled depth, ft.)	Core elev. (ft., MSL)	Felsite elev. (ft., MSL)
DV-2	steam entry	3,708-3,718	-665	-300
GDC-21	reservoir	5,864-5,868	-3,310	-1,500
LF-48	reservoir	8,089-8,096	-4,805	-3,000

The samples studied came from two core segments from DV-2 (DV-2B, DV-2E) and one each from GDC-21 and LF-48. The parts of the cores used for mineral separation and dating were selected to avoid the most highly altered parts of the core segments, which surround fractures. The samples have not yet been studied petrographically and the descriptions that follow are based on only a cursory thin section examination. All four of the samples appear to be approximately rhyolite to quartz monzonite in composition

Sample LF-48 is porphyritic with phenocrysts (2-3 mm) of quartz, K-feldspar, plagioclase, and rare biotite in an equigranular groundmass (avg. ~ 0.1 mm) of quartz, feldspar, and rare mafic minerals. Most of the groundmass feldspar is altered to clays(?) but many of the K-feldspar phenocrysts show relatively minor alteration.

Sample DV-2B and DV-2E are similar to LF-48 but more highly altered, except that the groundmass of DV-2B has a somewhat coarser grain size (0.2-0.3 mm). The groundmass in both of these samples is highly altered and recrystallized and contains abundant white mica and amphibole. Some of the K-feldspar phenocrysts are only slightly to moderately altered.

Sample GDC-21 contains rare phenocrysts of K-feldspar (2-3 mm). The rock has a poikilitic texture with crystals (1 mm) of quartz, K-feldspar, and rare plagioclase enclosing small crystals of plagioclase, biotite, and minor accessory minerals. Both the ground mass and phenocrystic K-feldspar is slightly altered but optically continuous.

Sample GDC-21 is by far the least altered of the samples, with DV-2B and DV-2E the most altered.

Analytical Methods

Selected sections of the four core pieces were crushed and sieved to 150-250 µm. Potassium-feldspar crystals (which, because of the sizing, were presumably phenocrysts), were separated from the sized fractions using heavy liquids. The feldspar was etched in 10% HF for 5-10 minutes to remove adhering alteration products and the feldspar was then cleaned ultrasonically and washed in distilled H_2O.

The feldspar samples were packaged in Al-foil envelopes, sealed in a quartz vial along with aliquants of 85G003 (sanidine from the Taylor Creek Rhyolite of Elston (1968), the neutron flux monitor mineral, 27.92 Ma), shielded with Cd foil, and irradiated in the core of the U.S. Geological Survey TRIGA reactor for 2 hours, where they received an integrated fast neutron flux of 1.2×10^{17} *nvt*. The reactor characteristics, corrections for interfering Ar isotopes produced from K and Ca, and irradiation procedures are described in detail by Dalrymple and others (1981). The monitor minerals were measured on a $^{40}Ar/^{39}Ar$ continuous laser system that incorporates a high-sensitivity MAP-216 rare-gas mass spectrometer optimized for Ar analyses (Dalrymple, 1989). The Geysers feldspar samples were measured on a similar system equipped with with a double-vacuum resistance furnace.

The *J*-value curve determined from measurements of the four packets of the monitor mineral (85G003) is shown in Figure 2. The figure shows the weighted mean values calculated from multiple analyses of crystals from each packet, where weighting is by the inverse of the estimated variance of each individual run (Taylor, 1982). A total of 26 analyses were made on the monitor mineral packets and the errors (σ_{best} of Taylor) of the weighted means range from 0.09% to 0.15%. The *J* values applied to each sample is found by interpolation of the curve in Figure 2. The errors in the *J* values applied to the age spectrum calculations for these samples is less than 0.5%.

Preliminary Results

The $^{40}Ar/^{39}Ar$ analytical data for the four samples are listed in Table 2 and the age spectra shown in Figure 3. The number of increments in the age spectra range from 16 for GDC-21 to 19 for DV-2B and DV-2E.

The age spectra indicate that the four samples have been disturbed by thermal events, alteration, or both. The first few gas increments of each of the spectra have high apparent ages. This is often caused by ^{39}Ar loss due to ^{39}Ar recoil from ^{40}K sites near the surfaces of mineral grains and the apparent ages calculated from such increments do not have any geologic age significance. Although the feldspar grains are too large for significant ^{39}Ar recoil effects, the alteration products visible in thin section are very fine-grained and recoil of ^{39}Ar from these phases is not unexpected.

The overall patterns of the age spectra are more-or-less typical of samples that have undergone thermal loss of Ar, with low apparent ages in the low-temperature steps increasing to higher apparent ages in the intermediate- and high-temperature steps. The decrease in apparent age for the high-temperature steps in samples DV-2B and DV-2E are consistent with ^{39}Ar recoil effects but such "humped" age spectra also occur in altered samples. The cause of the"saddle" in the age spectrum of GDC-21 is, at present, unknown. How much of the disturbance of the four age spectra is due to thermal causes and how much to alteration is not known but further analyses on a broader suite of samples plus a more detailed analysis of the present data may clarify this question. The feldspar from these samples is altered, however, and it is very likely that alteration effects are important. It also may be significant that the feldspar from GDC-21, which is the least altered of the four samples, has the highest intermediate- and high-temperature increment ages (see below).

It is virtually impossible for either thermal events or alteration to disturb an age spectrum in such a way that the apparent ages for the bulk of the intermediate- and high-temperature increments exceed the crystallization age of the sample, the increments at the extremes, i.e., near 100% ^{39}Ar released, excepted. A conservative interpretation, therefore, is that the intermediate- and high-temperature maxima in the age spectra are minimum ages. Accordingly, the results from sample GDC-21 suggest that the crystallization age of the part of the felsite unit sampled by the three cores is at least 1.3-1.4 Ma. The results also indicate that the interpretation of conventional K-Ar and total fusion $^{40}Ar/^{39}Ar$ ages from the felsite unit is equivocal and that if the crystallization age of the felsite unit can be determined, it will be by $^{40}Ar/^{39}Ar$ age spectrum methods.

Acknowledgments

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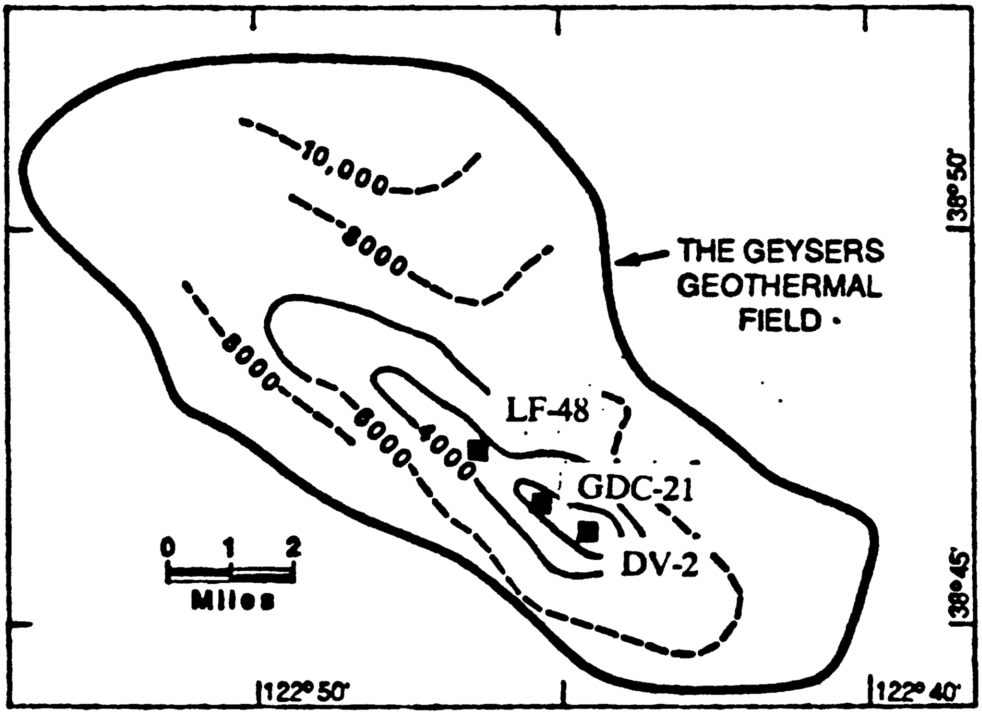

Figure 1. Location of core samples showing approximate boundary of geothermal reservoir and generalized top of the felsite unit. Contours in feet below sea level. From Thompson (1991) and Gunderson (1991).

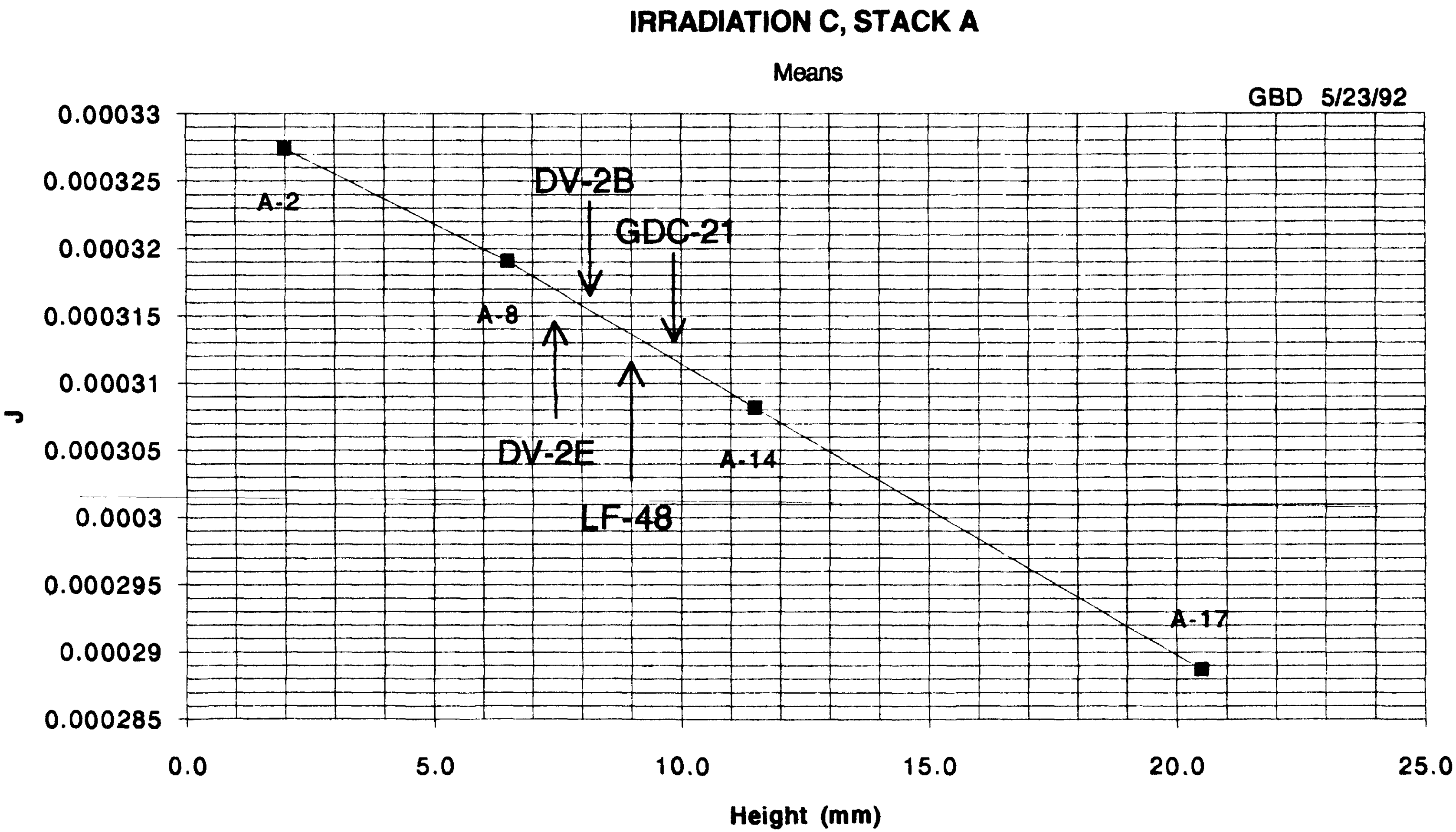

Figure 2. *J*-curves showing mean values (squares) for packets of the monitor mineral (85G003, 27.92 Ma) and the locations within the sample stack of the four Geysers K-feldspar samples.

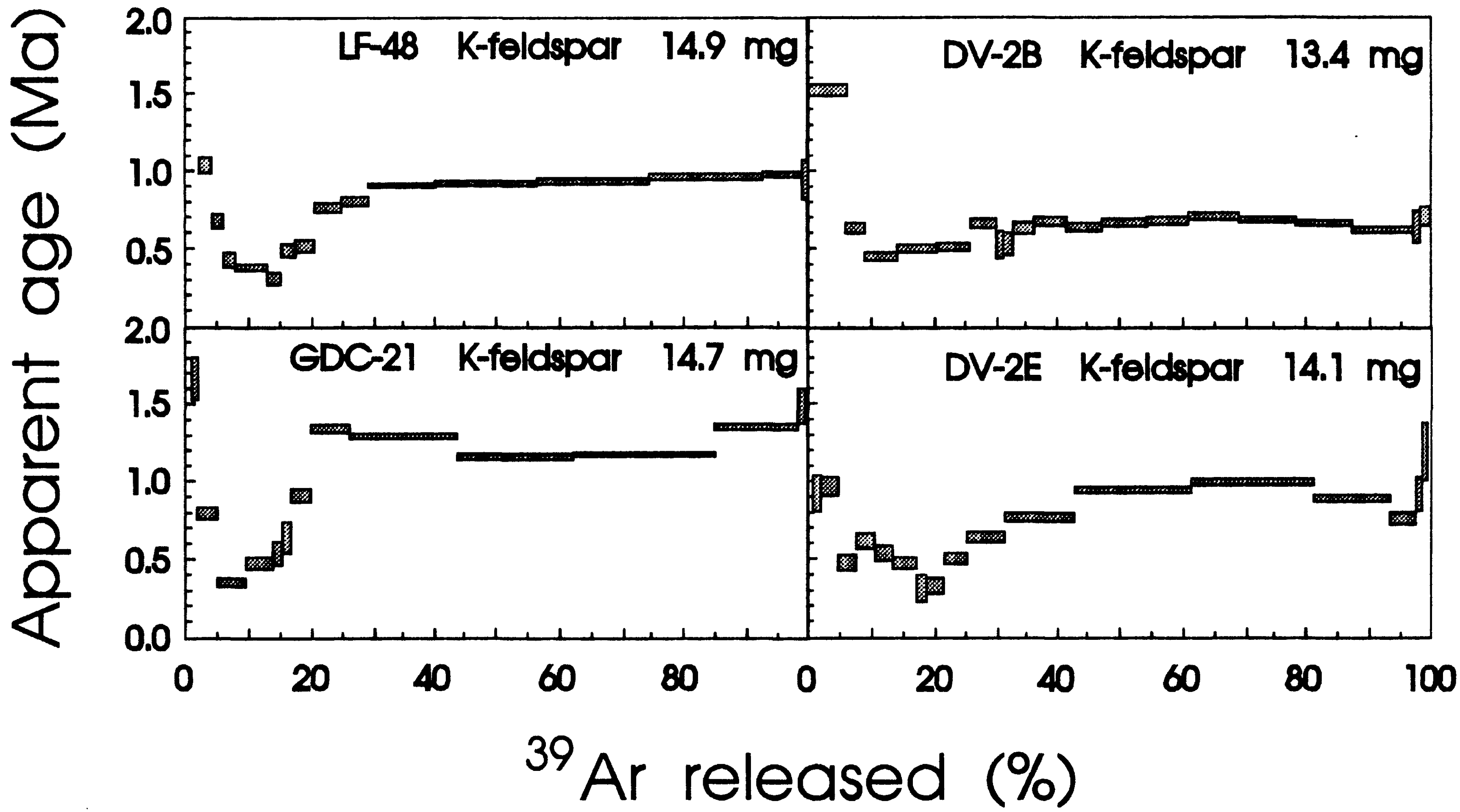

Figure 3. $^{40}Ar/^{39}Ar$ age spectra for four samples of potassium feldspar from core samples of the felsite unit, Geysers geothermal field. The thickness of the shaded bars is two standard deviations of precision of the calculated age

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Table 2 Analytical data for $^{40}Ar/^{39}Ar$ age spectrum data on K-feldspar from the felsite unit, Geysers Geothermal Field, California.

Temp. (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar^{a}$	$^{36}Ar/^{39}Ar$	$^{40}Ar_{rad}$ [b] (%)	$^{40}Ar_{K}$ [b] (%)	$^{36}Ar_{Ca}$ [b] (%)	K/Ca	^{39}Ar (%)	Age[c] (Ma)
DV-2B (J = 0.0003154) Total gas age = 0.684 ± 0.006 Ma									
450	15.714	0.000981	0.04416	16.9	0.0	0.0	499.6	5.9	1.513 ± 0.035
500	4.752	0.001782	0.012298	23.4	0.1	0.0	274.9	3.5	0.633 ± 0.031
550	3.442	0.001269	0.008949	23.0	0.1	0.0	386.0	4.9	0.451 ± 0.022
625	3.062	0.001583	0.007373	28.7	0.2	0.0	309.5	6.6	0.499 ± 0.017
700	2.568	0.003106	0.005650	34.8	0.2	0.0	157.8	5.3	0.508 ± 0.020
775	3.726	0.003351	0.008655	31.2	0.1	0.0	146.2	4.2	0.662 ± 0.026
850	3.035	0.002769	0.007121	30.5	0.2	0.0	176.9	1.2	0.527 ± 0.089
925	2.430	0.002424	0.005050	38.4	0.2	0.0	202.1	1.5	0.531 ± 0.068
1000	2.952	0.001881	0.006238	37.4	0.2	0.0	260.5	3.2	0.628 ± 0.034
1050	3.077	0.001650	0.006363	38.7	0.2	0.0	297.0	5.3	0.678 ± 0.021
1080	2.738	0.001335	0.005479	40.7	0.2	0.0	367.1	5.6	0.633 ± 0.019
1110	2.548	0.001005	0.004598	46.5	0.2	0.0	487.4	7.3	0.673 ± 0.015
1130	2.132	0.000732	0.003118	56.6	0.2	0.0	669.2	6.6	0.686 ± 0.016
1150	1.9957	0.000642	0.002486	62.9	0.3	0.0	763.8	7.8	0.714 ± 0.014
1175	1.9006	0.000473	0.002302	63.9	0.3	0.0	1035	9.6	0.691 ± 0.011
1200	2.503	0.000485	0.004454	47.2	0.2	0.0	1010	9.0	0.672 ± 0.012
1250	1.8699	0.000242	0.002579	59.0	0.3	0.0	2026	9.7	0.627 ± 0.011
1300	3.043	0.000609	0.006400	37.7	0.2	0.0	804.0	1.0	0.653 ± 0.103
1500	7.220	0.000852	0.02011	17.6	0.1	0.0	575.1	1.8	0.724 ± 0.059
DV-2E (J = 0.0003170) Total gas age = 0.894 ± 0.008 Ma									
500	97.26	0.003949	0.2907	11.7	0.0	0.0	124.1	0.7	6.487 ± 0.259
525	27.33	0.004393	0.08679	6.1	0.0	0.0	111.6	1.2	0.958 ± 0.116
575	19.542	0.002932	0.06018	9.0	0.0	0.0	167.1	2.8	1.003 ± 0.059
625	9.995	0.002603	0.03085	8.7	0.1	0.0	188.2	2.9	0.499 ± 0.048
675	11.208	0.002298	0.03409	10.1	0.0	0.0	213.2	2.9	0.646 ± 0.048
725	8.982	0.002066	0.02704	11.0	0.1	0.0	237.2	3.0	0.564 ± 0.046
800	7.563	0.001799	0.02263	11.5	0.1	0.0	272.4	3.9	0.498 ± 0.035
875	3.609	0.001562	0.010215	16.2	0.1	0.0	313.6	1.5	0.334 ± 0.082
950	5.744	0.002041	0.017347	10.7	0.1	0.0	240.1	2.6	0.351 ± 0.051
1000	7.842	0.002122	0.02339	11.8	0.1	0.0	230.9	3.8	0.529 ± 0.037
1050	8.042	0.001924	0.02324	14.5	0.1	0.0	254.6	6.3	0.669 ± 0.025

1100	6.917	0.002108	0.018667	20.2	0.1	0.0	232.5	11.1	0.798 ± 0.017
1150	5.767	0.002106	0.013683	29.8	0.1	0.0	232.7	18.6	0.982 ± 0.013
1180	4.390	0.001756	0.008696	41.4	0.1	0.0	279.0	19.7	1.038 ± 0.010
1210	4.548	0.001772	0.009851	35.9	0.1	0.0	276.5	12.4	0.933 ± 0.013
1250	4.505	0.002164	0.010485	31.1	0.1	0.0	226.4	3.9	0.802 ± 0.034
1325	6.716	0.005555	0.016981	25.2	0.1	0.0	88.21	1.2	0.968 ± 0.108
1450	15.413	0.003489	0.04482	14.0	0.0	0.0	140.4	0.7	1.237 ± 0.184
1550	11.195	0.02534	0.02377	37.2	0.0	0.0	19.34	0.8	2.382 ± 0.153
GDC-21 (J = 0.0003117) Total gas age = 1.169 ±0.008 Ma									
500	11.195	0.02534	0.02377	37.2	0.0	0.0	19.34	0.8	2.342 ± 0.150
550	7.297	0.017874	0.014572	40.9	0.1	0.0	27.41	0.9	1.679 ± 0.130
625	2.911	0.013899	0.004982	49.3	0.2	0.1	35.25	3.6	0.807 ± 0.033
700	1.5566	0.015966	0.003108	40.8	0.3	0.1	30.69	4.6	0.357 ± 0.026
775	1.6368	0.014544	0.002625	52.4	0.3	0.1	33.69	4.2	0.482 ± 0.029
850	1.9272	0.010351	0.003228	50.3	0.3	0.1	47.34	1.6	0.545 ± 0.074
925	2.324	0.008024	0.003941	49.7	0.2	0.1	61.07	1.3	0.649 ± 0.094
1000	2.705	0.006575	0.003586	60.7	0.2	0.0	74.53	3.3	0.922 ± 0.036
1050	3.255	0.005188	0.002843	74.0	0.2	0.0	94.45	6.1	1.354 ± 0.020
1100	2.789	0.003624	0.001536	83.6	0.2	0.1	135.2	17.5	1.310 ± 0.008
1130	2.378	0.002625	0.000920	88.4	0.2	0.1	186.6	18.7	1.181 ± 0.007
1160	2.352	0.002340	0.000722	90.7	0.2	0.1	209.4	22.6	1.199 ± 0.006
1200	2.765	0.004204	0.001058	88.5	0.2	0.1	116.6	13.2	1.376 ± 0.010
1250	4.659	0.03627	0.006625	57.9	0.1	0.1	13.51	1.1	1.517 ± 0.110
1400	21.49	0.05775	0.05489	24.5	0.0	0.0	8.48	0.3	2.962 ± 0.382
1550	199.28	0.03264	0.6291	6.7	0.0	0.0	15.01	0.1	7.509 ± 1.357
LF-48 (J = 0.0003136) Total gas age = 0.931 ± 0.006 Ma									
450	57.81	0.007400	0.15878	18.8	0.0	0.0	66.21	0.8	6.149 ± 0.152
500	19.898	0.006168	0.05232	22.3	0.0	0.0	79.45	1.3	2.506 ± 0.080
550	9.518	0.004224	0.02588	19.6	0.1	0.0	116.0	2.0	1.055 ± 0.048
625	3.521	0.003380	0.007755	34.8	0.1	0.0	145.0	2.0	0.692 ± 0.045
850	2.251	0.003195	0.004926	35.1	0.2	0.0	153.4	2.0	0.447 ± 0.045
700	2.004	0.003967	0.004361	35.4	0.3	0.0	123.5	5.1	0.402 ± 0.018
775	2.073	0.003969	0.005035	28.0	0.2	0.0	123.5	2.3	0.328 ± 0.040
925	2.011	0.003028	0.003771	44.4	0.3	0.0	161.8	2.4	0.504 ± 0.038
1000	2.091	0.003297	0.003871	45.1	0.2	0.0	148.6	2.8	0.533 ± 0.032
1050	3.059	0.002794	0.005680	45.0	0.2	0.0	175.4	4.4	0.778 ± 0.021
1080	3.007	0.002754	0.005269	48.1	0.2	0.0	177.9	4.5	0.818 ± 0.021
1110	2.682	0.002471	0.003537	60.8	0.2	0.0	198.3	10.7	0.923 ± 0.010
1130	2.269	0.001970	0.002027	73.4	0.2	0.0	248.7	16.5	0.942 ± 0.007

1150	2.077	0.001565	0.001298	81.3	0.2	0.0	313.1	17.6	0.955 ± 0.006
1175	2.086	0.001422	0.001113	84.0	0.2	0.0	344.6	18.7	0.991 ± 0.006
1200	2.287	0.002196	0.001725	77.5	0.2	0.0	223.1	6.0	1.003 ± 0.015
1250	3.652	0.008950	0.006526	47.1	0.1	0.0	54.75	0.7	0.972 ± 0.125
1400	19.460	0.009326	0.05667	13.9	0.0	0.0	52.54	0.2	1.532 ± 0.482

[a] Corrected for ^{37}Ar decay, half-life=35.1 days.

[b] Subscripts: rad, radiogenic; K, potassium-derived; Ca, calcium derived.

[c] Decay constants: $\lambda_\varepsilon = 0.581 \times 10^{-10} yr^{-1}$, $\lambda_\beta = 4.692 \times 10^{-10} yr^{-1}$. Errors assigned to individual ages are estimates of the standard deviation of analytical precision and do not include the error in J, which is 0.5%.
$(^{36}Ar/^{37}Ar)_{Ca} = 0.000269 \pm 2$, $(^{39}Ar/^{37}Ar)_{Ca} = 0.000670 \pm 5$, $(^{40}Ar/^{39}Ar)_K = 0.0051 \pm 4$.