Timing and Effect of Detachment-Related Potassium Metasomatism on $^{40}Ar/^{39}Ar$ Ages from the Windous Butte Formation, Grant Range, Nevada

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By William E. Brooks *and* Lawrence W. Snee

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CONTENTS

FIGURES

TABLES

TIMING AND EFFECT OF DETACHMENT-RELATED POTASSIUM METASOMATISM ON $^{40}Ar/^{39}Ar$ AGES FROM THE WINDOUS BUTTE FORMATION GRANT RANGE, NEVADA

By William E. Brooks *and* Lawrence W. Snee

ABSTRACT

Interpretation of K-Ar and $^{40}Ar/^{39}Ar$ dates from highly altered, potassium-metasomatized rocks at detachment faults in the Southwestern United States is difficult. The effects of added potassium, indicated by rock analyses with excessive K_2O, and elevated temperature, indicated by reset K-Ar and fission-track dates from upper- and lower-plate rocks at detachment faults, are implicit thermal and chemical problems in the interpretation of potassium-dependent dates.

In order to resolve these problems, comparative study of volcanic rocks that (1) are well-defined regionally and structurally, (2) have well-constrained regional chemistry and geochronology, and (3) have correlative metasomatized and unaltered sections must be made. The Windous Butte ash-flow tuff is one of several potassium-metasomatized volcanic units at Ragged Ridge, in the upper plate of a complicated detachment fault zone in the northern Grant Range. It is a calc-alkalic, rhyolitic to dacitic ash-flow tuff, and its Oligocene age is well constrained at 31.4–31.2 Ma.

At Ragged Ridge, which is 3–4 km from the detachment zone, the Windous Butte is potassium metasomatized (>9.0 weight percent K_2O and <1.0 weight percent Na_2O). At Stone Cabin Ridge, 7 km southeast of Ragged Ridge, the Windous Butte is unaltered (4–5 weight percent K_2O and 2–3 weight percent Na_2O).

In order to constrain timing of the alteration and determine the effect of K-metasomatism on potassium-dependent mineral dates, feldspar and biotite separates from two sites at Ragged Ridge and two sites at Stone Cabin Ridge were dated by the $^{40}Ar/^{39}Ar$ thermal release method. X-ray diffraction (XRD) analyses indicate that adularized sanidine is present in Ragged Ridge separates and only sanidine is present in Stone Cabin Ridge separates. Sanidine spectra from Stone Cabin Ridge are not disturbed and have plateau dates of 31.3±0.1 Ma and 31.2±0.1 Ma. Spectra for adularized sanidine from Ragged Ridge show apparent argon loss with stairstep patterns that indicate growth of adularia as late as ~20 Ma. Biotite dates from Ragged Ridge (two dates of 31.5±0.1 Ma) and Stone Cabin Ridge (31.7±0.1 Ma and 31.5±0.1 Ma) are slightly disturbed, but plateau dates are concordant. This indicates that temperatures associated with the alteration did not exceed 280°C. Disturbed spectra from adularized sanidine from potassium-metasomatized rocks at Ragged Ridge are interpreted to indicate that alteration occurred at ~20 Ma in response to detachment and associated hydrothermal circulation of potassium-rich brines.

Results of this study are applicable to the interpretation of $^{40}Ar/^{39}Ar$ dates from incipiently to pervasively potassium metasomatized upper-plate volcanic rocks at three detachment faults in Arizona.

INTRODUCTION

Potassium metasomatism is a widespread geochemical phenomenon that has affected Tertiary volcanic rock chemistry at detachment faults, in calderas, in fossil geothermal sites, and in lacustrine environments in New Mexico, Arizona, California, Utah, Colorado, and Nevada. Metasomatism is generally described as the transformation of one mineral or rock into another of different chemical composition (Lindgren, 1912). Potassium metasomatism, which may be incipient to pervasive, is indicated by rock analyses with excessive K_2O content, anomalously low Na_2O content, and absence of high-potassium minerals such as leucite, analcite, or nepheline.

Interpretation of K-Ar and fission-track dates from potassium-metasomatized rocks in the detachment setting is equivocal because added potassium and elevated temperature affect these geochronologic methods. Chemical and $^{40}Ar/^{39}Ar$ studies of potassium-metasomatized and unaltered ash-flow tuff from the Windous Butte Formation, in the northern Grant Range, Nevada, are herein compared.

The regionally extensive, well-described, ash-flow tuff of the Windous Butte Formation, which is potassium metasomatized near a detachment at Ragged Ridge and unaltered at Stone Cabin Ridge, is an ideal volcanic unit with which to examine the effects of potassium metasomatism on $^{40}Ar/^{39}Ar$ data. Results of this study document the chemical and thermal effects associated with detachment-related potassium metasomatism on potassium-dependent geochronologic methods in the Grant Range and are applicable to other detachment settings.

PREVIOUS WORK

Rock chemistry of volcanic and, to a lesser extent, sedimentary rocks from the upper plate of numerous detachment faults at core complexes in the Southwestern United States has been affected by potassium metasomatism (Chapin and Glazner, 1983; Lindley and others, 1983; Brooks, 1986; Chapin and Lindley, 1986; Brooks, 1988; Roddy and others, 1988; Spencer and others, 1989; Hollocher and others, 1994). Chemical effects of potassium metasomatism are not restricted to the detachment setting; this type of alteration, which is economically significant in the caldera setting (Scherkenbach and Noble, 1984; Sander and Einaudi, 1990), is apparent in analyses of volcanic rocks from calderas (Ratté and Steven, 1967; Bethke and others, 1985; Shawe and Lepry, 1985; Sawyer and others, 1989), from silicic tuffs deposited in lacustrine environments (Sheppard and Gude, 1965, 1973; Chapin and Lindley, 1986), and from fossil geothermal activity (Nusbaum and Grant, 1987). Areas that have been affected by detachment-related potassium metasomatism in Arizona are readily distinguished on a potassium aeroradioactivity map (Pitkin and others, 1994). These maps may serve as part of an exploration strategy by defining areas of detachment-related hydrothermal alteration with potential for associated mineral occurrences. The distribution of potassium-metasomatized rocks in the upper plate of detachment faults and development of sedimentary basins (Brown and Schmidt, 1991) in association with core complexes in extensional terrane suggests that peculiar hydrothermal regimes were generated at or near detachment-core complex localities (Kerrich and others, 1986).

GEOCHRONOLOGIC PROBLEMS OF POTASSIUM-METASOMATIZED VOLCANIC ROCKS

Our interpretation of $^{40}Ar/^{39}Ar$ mineral dates and spectra from potassium-metasomatized and unaltered ash-flow tuff of the Windous Butte Formation from the Grant Range, Nevada (fig. 1), is an important step in dating detachment-related metasomatism and documenting the thermal and chemical effects associated with detachment faulting. The $^{40}Ar/^{39}Ar$ thermal release method is a powerful dating tool that also provides information on the thermal history of the mineral separate. Because of this thermal sensitivity, this method has been used in structural studies, such as direct dating of mylonite (West and Lux, 1993).

The effects of potassium metasomatism include (1) rock analyses with suspiciously high K_2O, and (2) discordant and reset K-Ar, fission-track, and whole-rock dates in response to elevated temperatures associated with circulating potassium-rich fluids. Armstrong (1970) recognized this problem and advised exclusion of a 26.2-Ma (K-Ar method, biotite) date from a compilation of Needles Range Formation dates because the sample showed the effects of potassium metasomatism ("* * * matrix and plagioclase having been converted to potassium feldspar, the biotite being enriched in potassium." Armstrong, 1970, p. 218). He interpreted the date to indicate the time of metasomatism (see sample 81, table 3, Armstrong, 1970) and not the time of eruption. Armstrong's study strongly indicates cautious and critical interpretation of K-Ar dates from metasomatized volcanic rock as indicative of time of emplacement.

Megascopically, potassium metasomatism of upper-plate volcanic rocks may be indicated by a brick-red color of mafic volcanic rocks (silicic volcanic rocks rarely show anomalous color), by oxidation of some mafic minerals, by alteration of feldspars to clay, and by the presence of barite and calcite veinlets. Microscopically, potassium metasomatism is indicated by patchy growth of adularia on plagioclase or sanidine and by spotty growth of calcite and adularia in the groundmass.

The chemical effects of potassium metasomatism, which may be incipient to pervasive, are indicated by anomalously high K_2O content (as much as 12–13 weight percent), anomalously low Na_2O content (<1.0 weight percent), and a $K_2O:Na_2O>2$ (this ratio may be as much as 38 in the Harcuvar Mountains; see table 1) in intermediate to silicic volcanic rocks. These same rocks would normally be expected to contain 3–5 weight percent K_2O, 3–5 weight percent Na_2O, and $K_2O:Na_2O<2$. Alone, the high potassium content of the analysis might indicate a primary alkalic rock; however, likely phases for the excess potassium, such as leucite, analcite, and nepheline, are not present. TiO_2, rare earth elements (REE), Nb, Zr, Y, Th, and U are not changed during metasomatism at the Socorro, N. Mex., potassium anomaly (Lindley and others, 1983; Chapin and Lindley, 1986). In pervasively metasomatized volcanic rock at the Picacho Peak detachment fault, Zr, Rb, and As concentrations decrease, as does K_2O, with greater distance from the surface trace of the detachment; these same rocks are incipiently metasomatized some 4 km from the detachment (Brooks, 1985, 1987).

Until now, the thermal and chemical effects of detachment-related potassium metasomatism on K-Ar mineral and whole-rock dates from metasomatized volcanic rocks in the

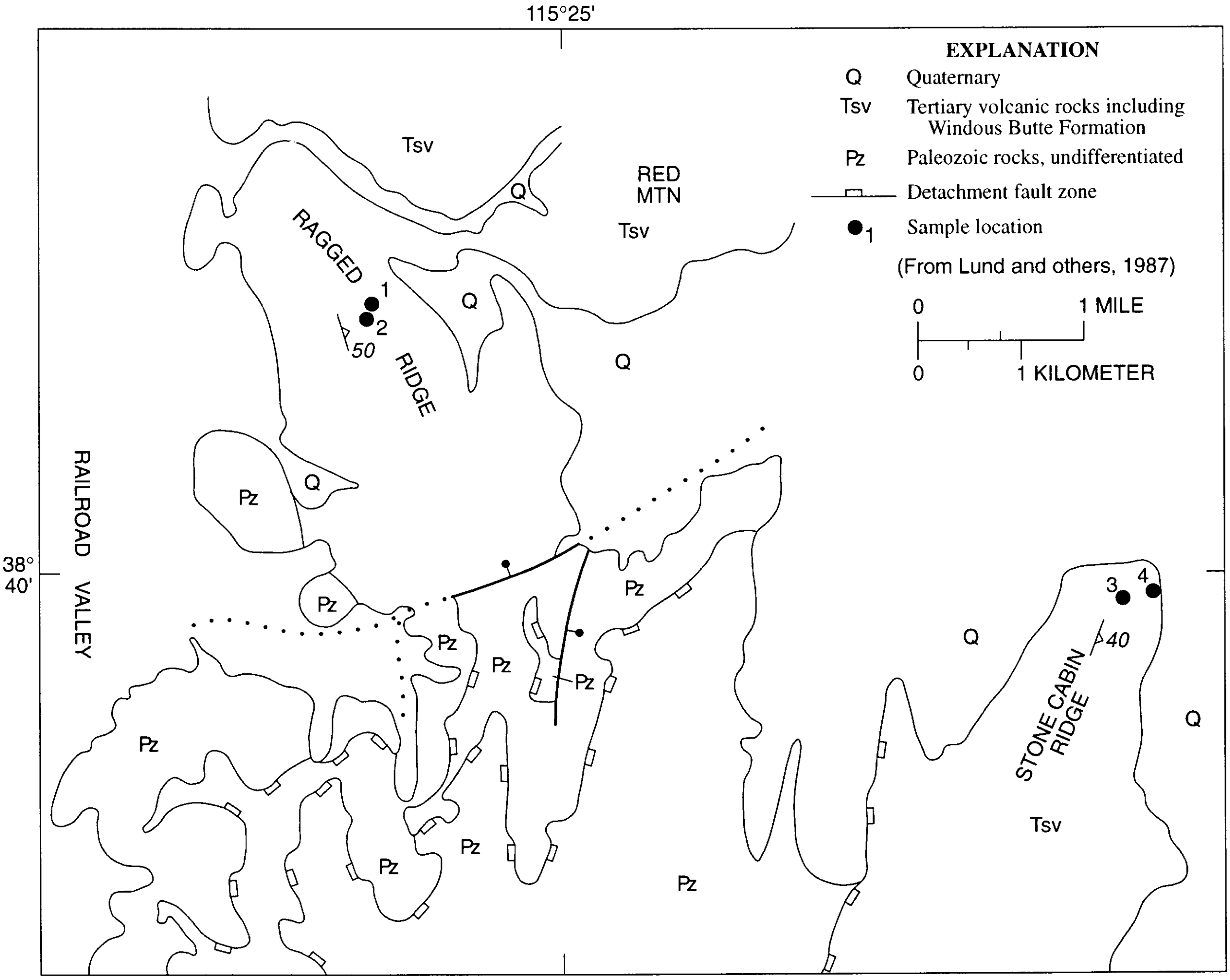


Figure 1. Location map of Grant Range area, Nevada.

upper plates of detachment faults were suspect. This resulted in broadly bracketed ages of volcanic rocks and timing of detachment-related metasomatism (Brooks, 1986; Spencer and others, 1989). For example, at Picacho Peak, Arizona, alteration of the volcanic rocks was considered (Shafiqullah and others, 1976), but effects of the metasomatism on K-Ar dates were poorly understood. Therefore, dates from those rocks were interpreted to indicate the age of the volcanism, and chemical analyses were interpreted to indicate primary alkalic magmatic composition (Shafiqullah and others, 1976). The use of potassium content of unaltered volcanic rocks was critically tested as a valid mechanism (Carr and others, 1979) for reconstruction of Tertiary subduction geometry (Lipman and others, 1972). However, analyses of altered rocks at Picacho Peak were wrongly included in Tertiary subduction modeling by Rowell and Edgar (1983).

Detachment faults are commonly associated with metamorphic core complexes in Oligocene-Miocene extensional-terrane that extends from Mexico, where a "detachment" setting was first described (Lindgren, 1888), through southwestern Arizona (Rehrig and others, 1980; Rehrig and Reynolds, 1980), into Nevada (Snoke and Lush, 1984; Fryxell, 1988; Lund and others, 1991), and Canada (Axen and others, 1993). K-Ar and fission-track dates from lower-plate rocks at detachment faults at several "Precambrian-appearing" core complexes in Arizona are mid-Tertiary. These data are interpreted to indicate a profound, regional, mid-Tertiary thermal and chemical disturbance (Davis, 1977; Rehrig and Reynolds, 1980). K-Ar dating of detachment faults and mylonites in the Whipple Mountains, California, and in the Buckskin Mountains, Arizona, indicated that lower-plate ages decrease toward the detachment and indicated a thermal event associated with detachment (Martin and others, 1980). On the basis of K-Ar studies in the Whipple Mountains, Davis and others (1982) interpret 15.9 Ma as the upper limit for detachment faulting. In the Grant Range, a Miocene thermal event has similarly affected and reset K-Ar dates from the lower-plate Cretaceous Troy Granite, which has a U-Pb

Table 1. Compilation of chemical analyses of volcanic rocks from the upper plate of detachment faults at Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona.

[$FeTO_3$ indicates total iron reported as Fe_2O_3. --, not reported. ^{V}, vitrophyre; ^{K}, potassium metasomatized. PP-2, uncorrected for volatiles (Brooks, 1986), is a recollection of UAKA 75-29 (Shafiqullah and others, 1976). PP-9, uncorrected for volatiles (Brooks, unpub. data), is a recollection of UAKA 73-141 (Shafiqullah and others, 1976). HM-1 uncorrected (Brooks, 1988). E-191B and E-191D recalculated (Brooks, 1984). E-210 uncorrected (Brooks, 1984). TG-8 uncorrected (Brooks, unpub. data) is a recollection of K-Ar no. 8 (Weaver, 1982)]

Locality	Picacho Peak		Harcuvar Mountains				Trigo Mountains
Field no.	PP-2^K	PP-9	HM-1^K	E-191B^V	E-191D^K	E-210	TG-8^K
Rock type	Andesite	Dacite	Ash-flow tuff	Ash-flow tuff	Ash-flow tuff	Dacite	Ash-flow tuff
Latitude	32°39'53"N.	32°32'57"N.	34°04'44"N.	34°00'56"N.	34°01'40"N.	34°13'39"N.	33°02'15"N.
Longitude	111°23'24"W.	111°27'53"W.	113°14'39"W.	113°06'55"W.	113°07'50"W.	113°10'48"W.	114°30'40"W.
SiO_2	56.6	64.2	63.0	70.0	68.6	67.5	68.7
Al_2O_3	14.5	15.5	9.3	16.0	14.8	14.2	13.4
$FeTO_3$	7.3	4.6	1.3	2.9	--	3.03	1.72
Fe_2O_3	--	--	--	--	2.6	--	--
FeO	--	--	--	--	0.1	--	--
MgO	0.6	1.72	0.3	0.8	0.3	0.91	0.72
CaO	3.5	3.47	9.6	2.4	0.6	3.47	1.22
Na_2O	0.8	3.80	0.2	5.0	0.4	3.64	1.49
K_2O	11.0	4.43	7.6	2.3	12.0	4.26	7.25
TiO_2	1.1	0.69	0.1	0.4	0.5	0.39	0.22
P_2O_5	0.9	0.45	0.1	0.1	0.1	0.19	0.05
MnO	0.3	0.08	0.1	0.1	--	0.05	<0.02
LOI 900°C	2.5	0.68	8.0	6.1	--	1.80	4.75
H_2O^+	--	--	--	--	0.7	--	--
H_2O^-	--	--	--	--	0.1	--	--
$K_2O:Na_2O$	13.7	1.2	38	0.46	30.0	1.2	4.9

date of 86.5 Ma (zircon) (D. Walker, University of Kansas, unpub. data) and a Rb/Sr isochron of 70.2 Ma (Fryxell, 1984), as well as K-Ar dates of 22.5 Ma (biotite) and 24.7 Ma (muscovite) (Armstrong, 1970). These reset ages are herein interpreted to indicate reheating of the Troy Granite, which is not metasomatized (table 2), during the Miocene at approximately the same time that the dates from the ash-flow tuff of the Windous Butte Formation were similarly disturbed. Reset K-Ar dates at detachment faults in the Colorado River region, California, Arizona, and Nevada, indicated that the detachment mechanism affected the K-Ar isotopic system in both upper-plate and lower-plate rocks; the degree of resetting increases toward the detachment fault (Martin and others, 1981). In the Harcuvar Mountains, Arizona (fig. 2), this detachment-related thermal and chemical disturbance is indicated in upper-plate ash-flow tuff by discordant K-Ar (23.9 Ma, biotite) and fission-track (18.6 Ma, zircon) ages (Brooks and Marvin, 1985) and a whole-rock K-Ar date of 17.3 Ma (Scarborough and Wilt, 1979) (table 3). Normally, dates from quenched volcanic rock, such as ash-flow tuff, should be concordant. In the absence of unaltered correlative rock in the Harcuvar Mountains and the known resetting of K-Ar ages near other detachment faults (Martin and others, 1981), the K-Ar mineral age should be assumed to indicate a minimum age of the volcanic rocks.

Table 2. Chemical analyses of the Troy granite, Grant Range, east-central Nevada.

[Major oxides (weight percent, uncorrected for volalites) and trace elements (ppm) determined by ICP methods at ACT LABS, Wheat Ridge, Colo. LOI, loss on ignition at 925°C]

Locality	Troy Granite	
Field no.	95B5	91KL53
Latitude	38°21'00"N.	38°20'44"N.
Longitude	115°35'15"W.	115°35'15"W.
SiO_2	71.4	70.89
Al_2O_3	14.63	15.47
Fe_2O_3	1.7	1.72
MgO	0.39	0.43
CaO	1.9	2.24
Na_2O	3.69	3.73
K_2O	3.49	3.32
TiO_2	0.21	0.21
P_2O_5	0.1	0.01
MnO	0.03	0.03
LOI	0.83	1.12
Total	98.36	99.24
Ba	1,317	1,318
Sr	717	778
Y	7	6
Sc	2	2
Zr	119	137

Table 3. Published ages of potassium-metasomatized upper-plate volcanic rocks at detachment faults at Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona.

Date	Mineral	Method	Reference
		Picacho Peak	
20.7 Ma	Whole rock	K-Ar	Shafiqullah and others (1976), sample no. UAKA 75-29
16.6 Ma	Zircon	Fission-track	Brooks (1986)
		Harcuvar Mountains	
23.9 Ma	Biotite	K-Ar	Brooks and Marvin (1985)
18.6 Ma	Zircon	Fission-track	Brooks and Marvin (1985)
18.3 Ma	Apatite	Fission-track	Brooks and Marvin (1985)
17.3 Ma	Whole rock	K-Ar	Scarborough and Wilt (1979)
		Trigo Mountains	
24.9 Ma	Biotite	K-Ar	Weaver (1982)

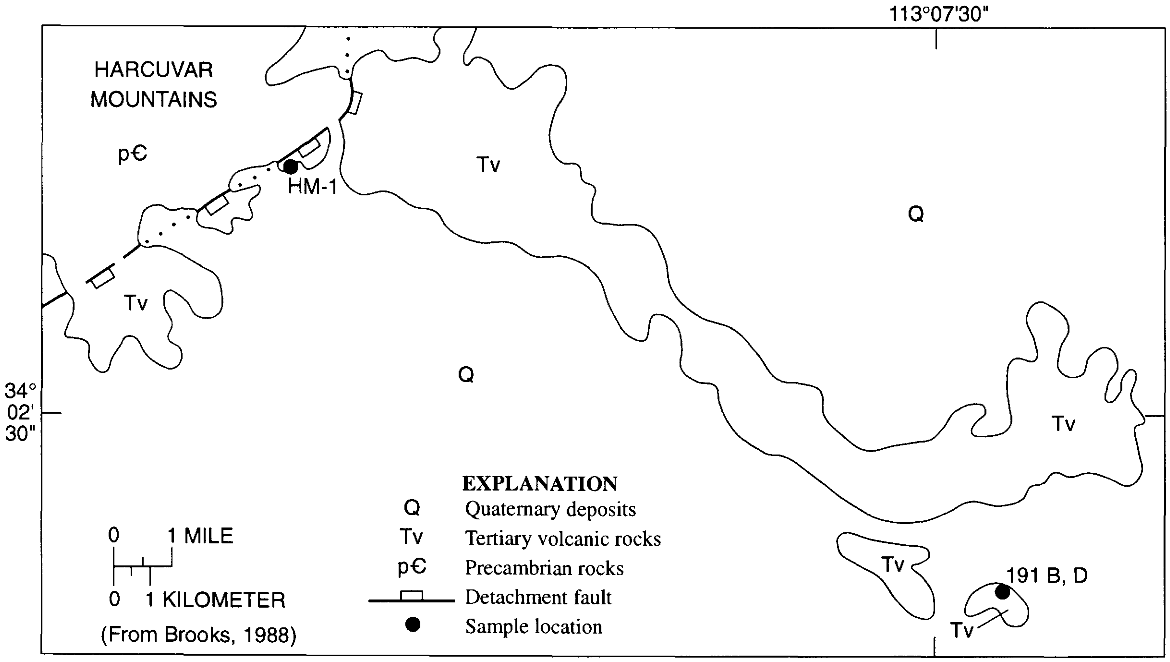


Figure 2. Location map of Harcuvar Mountains area, Arizona.

REGIONAL SETTING OF THE WINDOUS BUTTE FORMATION

The Windous Butte Formation, in the northern Grant Range, is an ideal volcanic unit with which to test the effects of potassium metasomatism on dates from correlative altered and unaltered rock. Field, analytical, and geochronologic data on the Windous Butte (Cook, 1965; Scott, 1965) are all well constrained. The Windous Butte is a widespread (17,000 km^2, Best and others, 1989), Oligocene (30.4 Ma, K-Ar method, Armstrong, 1970; 31 Ma, K-Ar method, Grommé and others, 1972; 31.4–31.2 Ma, $^{40}Ar/^{39}Ar$ method, A. Deino, Human Origins Lab, oral commun., 1993), calc-alkaline, dacitic to rhyolitic, biotite-sanidine (± smoky quartz) (Phillips, 1989) ash-flow tuff that erupted from the central Nevada caldera complex (Ekren and others, 1971). In the Grant Range, alteration of the Windous Butte and other volcanic units at Ragged Ridge was first recognized and called incipient hydrothermal alteration by Scott (1965). These volcanic units were reinterpreted by Brooks and others (1994) to have been altered by detachment-related potassium metasomatism.

Ash-flow tuff of the Windous Butte Formation and several other metasomatized volcanic units dip 50°–80° at Ragged Ridge, in the northern Grant Range

Table 4. Chemical analyses of ash-flow tuff from the Windous Butte Formation.

[Major oxides (weight percent, uncorrected for volatiles) determined by X-ray spectroscopy—analysts J.S. Mee and D.F. Siems. $FeTO_3$ indicates total iron reported as Fe_2O_3. LOI, loss on ignition at 925°C. Rb, Sr, Y, Zr, Nb, and Ba analyses (parts per million) determined on an energy dispersive analyzer, ^{109}Cd source and ^{95}Am source (Ba only) by K. Woodburne. Error is 10 percent of ppm listed or ±6 (Rb), ±5 (Sr), ±4 (Y), ±3 (Zr), ±3 (Nb), and ±10 (Ba), whichever is greater. ^{V}, indicates vitrophyre; ^{K}, potassium metasomatized]

Locality	Ragged Ridge		Stone Cabin Ridge	
Lab no.	D-503374	D-503375	D-503376	D-503377
Field no.	$91B1^K$	$91B2^K$	$91B3^V$	91B4
Latitude	38°41′23″N.	38°41′19″N.	38°39′54″N.	38°39′55″N.
Longitude	115°26′21″W.	115°26′25″W.	115°21′13″W.	115°21′0″W.
SiO_2	70.9	70.7	71.9	71.6
Al_2O_3	12.7	13.4	13.4	13.5
$FeTO_3$	1.69	1.97	1.30	2.18
MgO	0.32	0.32	0.24	0.43
CaO	1.10	0.45	1.62	1.77
Na_2O	0.82	0.80	3.12	2.26
K_2O	9.25	9.84	4.65	5.62
TiO_2	0.23	0.28	0.16	0.29
P_2O_5	0.07	0.08	0.05	0.08
MnO	0.04	0.02	0.05	0.03
LOI	1.87	1.34	2.47	1.51
Rb	260	273	202	178
Sr	139	111	222	306
Y	19	11	17	16
Zr	98	109	89	117
Nb	9	10	12	12
Ba	724	720	378	940
$K_2O:Na_2O$	11.3	12.3	1.5	2.5

approximately 4 km from a complicated west-dipping detachment fault zone (Lund and Beard, 1987; Lund and others, 1987; Lund and others, 1991; Lund and Beard, 1992; Lund and others, 1993) At Stone Cabin Ridge, about 10 km southeast of Ragged Ridge, the Windous Butte dips 25°–40° E. and is unaltered.

At Ragged Ridge, potassium metasomatism is indicated by K_2O content of 9.2–9.8 weight percent and Na_2O content of 0.8 weight percent (table 4). K_2O content of 4.6–5.6 weight percent and Na_2O content of 2.2–3.1 weight percent at Stone Cabin Ridge (table 4) are comparable to average regional (unaltered) Windous Butte K_2O content of 4.9 weight percent and average Na_2O content of 3.1 weight percent for 30 analyses compiled by Phillips (1989).

GEOCHEMICAL DATA—ANALYTICAL METHODS

In order to determine the effect of potassium metasomatism on mineral dates and constrain timing of this alteration, rock samples from two altered sites at Ragged Ridge and two unaltered sites at Stone Cabin Ridge were analyzed by several methods. These sites were chosen and resampled for this study based on K_2O and Na_2O data for the respective sites presented in Scott (1965). Feldspar and biotite separates from volcanic rocks at these four sites were dated by the $^{40}Ar/^{39}Ar$ thermal release method.

Major oxide analyses in table 4 were obtained by X-ray fluorescence techniques in the analytical laboratories of the U.S. Geological Survey (USGS) in Denver, Colo.; analytical methods, accuracy, and precision are described by Taggart and others (1987). Trace-element content (table 4) was determined by energy-dispersive X-ray spectroscopy (Elsass and duBray, 1982) using ^{109}Cd and ^{241}Am sources; accuracy and precision of these analyses are described by Sawyer and Sargent (1989). Major-oxide and trace-element analyses in table 2 were obtained by combined INAA (instrumental neutron activation analysis) and ICP (inductively coupled plasma mass spectrometry) methods.[1] Description of analytical techniques is available upon request. Microprobe analyses (table 5) and beam scans (fig. 3) were performed on a JEOL 8900 electron microprobe at USGS laboratories in Denver, Colo. Boron analyses (table 6) were obtained by dc-arc emission spectrometry in the analytical laboratories of the USGS in Menlo Park, Calif. This method is described by Golightly and others (1987).

[1] Analyses performed by ACTLABS, 11485 W. I-70 Frontage Road N., Wheat Ridge, CO 80033.

Table 5. Electron microprobe analyses of adularized sanidine from potassium-metasomatized sample 91B1 from Ragged Ridge, Grant Range, Nevada.

[See figure 3. Sample location coordinates shown in table 4. Analyses shown below in weight percent]

Element	Adularized sanidine (yellow-red on figure 3*B*)			Average of 8 adularia analyses (Deer, Howie, and Zussman, 1971)	Sanidine (yellow-blue on figure 3*B*)		Average of 7 sanidine analyses (Deer, Howie, and Zussman, 1971)
Na_2O	0.09	0.98	0.13	1.29	2.93	2.99	3.7
SiO_2	65.23	64.76	65.16	64.53	66.00	65.75	64.86
FeO	0.0	0.27	0.04	0.25	0.06	0.06	tr
Al_2O_3	18.34	17.99	18.18	18.99	18.83	18.68	19.19
MgO	0.0	0.0	0.0	0.11	0.0	0.0	tr
K_2O	16.72	14.84	16.40	14.50	12.36	12.37	10.6
CaO	0.0	0.20	0.0	0.22	0.13	0.14	0.6
TiO_2	0.0	0.01	0.0	0.0	0.01	0.01	tr

$^{40}Ar/^{39}Ar$ AGE SPECTRUM DATA—SAMPLE PREPARATION AND ANALYTICAL METHODS

Feldspar and biotite separates from metasomatized volcanic rocks at Ragged Ridge and unaltered rocks at Stone Cabin Ridge were obtained from 4–5 kg of crushed and sieved rock sample using magnetic, heavy-liquid, and hand-picking (biotite) techniques. After repeated, dilute heavy-liquid treatment to remove plagioclase and quartz from the potassium feldspar concentrates, the potassium feldspar concentrate was analyzed on a Philips PW 1840 X-ray diffractometer in USGS laboratories in Denver, Colo., to determine structural state and contamination. Interpretation of X-ray diffraction peaks indicated that the potassium feldspar concentrate from Ragged Ridge contained inseparable adularia and sanidine as adularized sanidine (micrometer-sized adularia incipiently replacing sanidine) and minor quartz. Diffraction peaks indicated that the potassium feldspar concentrate from Stone Cabin Ridge contained only sanidine. Samples from the Arizona localities received similar laboratory preparation and XRD identification in order to obtain and identify a feldspar (adularized plagioclase) concentrate for analysis.

In studies of timing of hydrothermal activity in the Bodie mining district, California, Silberman and Chesterman (1988) used K-Ar analyses of centimeter-sized adularia. However, the micrometer sized adularia common to metasomatized volcanic rocks at the Socorro anomaly (Chapin and Lindley, 1986), and at detachment faults elsewhere, is difficult to separate due to the alteration of groundmass and feldspars.

Mineral separates were analyzed using the $^{40}Ar/^{39}Ar$ age spectrum technique, a variant of the conventional K/Ar method. Age spectrum diagrams for samples analyzed in this study are shown in figures 4 and 5, and abbreviated $^{40}Ar/^{39}Ar$ data and production ratios are listed in tables 7 and 8, respectively. A summary of the dates is given in table 9.

Table 6. Low-level boron analyses of upper-plate volcanic rocks from detachment faults at the Grant Range, Nevada, and Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona.

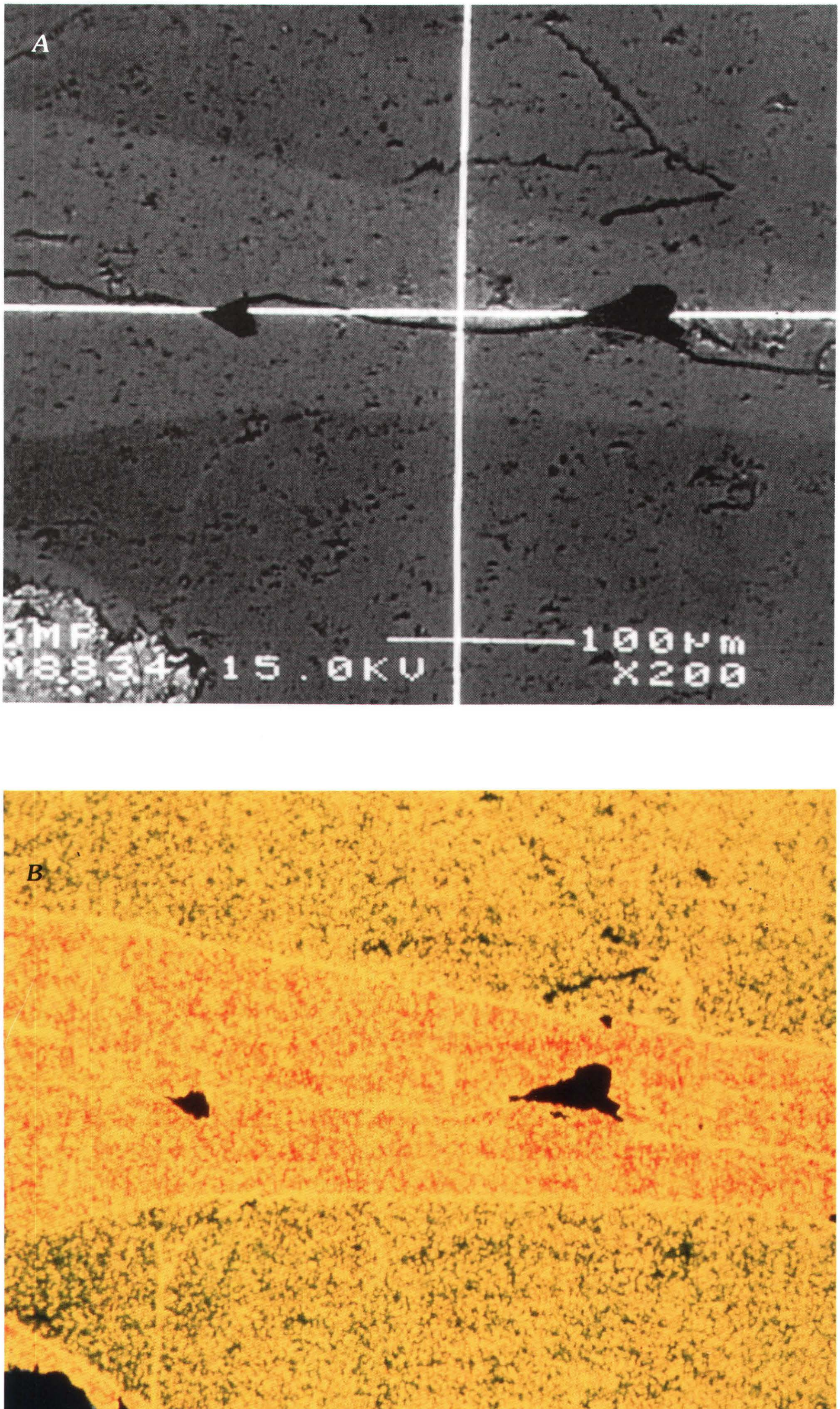
[Determined by X-ray spectroscopy—T. Fries, analyst, USGS, Menlo Park, Calif. ^{V}, vitrophyre; ^{K}, potassium metasomatized]

Location	Sample no.	B (ppm)[1]
Grant Range, Nevada		
Ragged Ridge	$91B1^{K}$	37
	$91B2^{K}$	44
Stone Cabin Ridge	$91B3^{V}$	28
	91B4	16
Picacho Peak, Arizona	$PP\text{-}2^{K}$	57
Harcuvar Mountains, Arizona	$HM\text{-}1^{K}$	26
	$E\text{-}191B^{V}$	28
	$E\text{-}191D^{K}$	16
Trigo Mountains, Arizona	$TG\text{-}8^{K}$	12

[1]Crustal boron average 5 ppm (mafic) to 10 ppm (silicic) (Turekian and Wedepohl, 1961).

A mineral separate of unknown age and a mineral standard of known age were irradiated at the USGS TRIGA reactor in Denver, Colo., following techniques described by Dalrymple and others (1981) to produce ^{39}Ar from ^{39}K by neutron bombardment. After irradiation, the $^{40}Ar_{Radiogenic}/^{39}Ar_{Potassium}$ ratios of sample and standard were determined. Standard techniques were employed to produce $^{40}Ar/^{39}Ar$ spectra as described by Shubat and Snee (1992), Snee (1982), and Snee and others (1988).

The isotopic composition of argon was measured at the USGS in Denver, Colo., using a MAP215 series rare-gas mass spectrometer made by Mass Analyzer Products Limited. Abundances of five argon isotopes (^{40}Ar, ^{39}Ar, ^{38}Ar, ^{37}Ar, and ^{36}Ar) were measured in each sample. Argon was released from the samples in 6–18 temperature steps; abbreviated results are listed in table 7. Radiogenic ^{40}Ar ($^{40}Ar_R$) is total ^{40}Ar derived from natural radioactive decay of ^{40}K after all corrections from non-decay-derived ^{40}Ar, including


A
100µm
15.0KV
X200
B

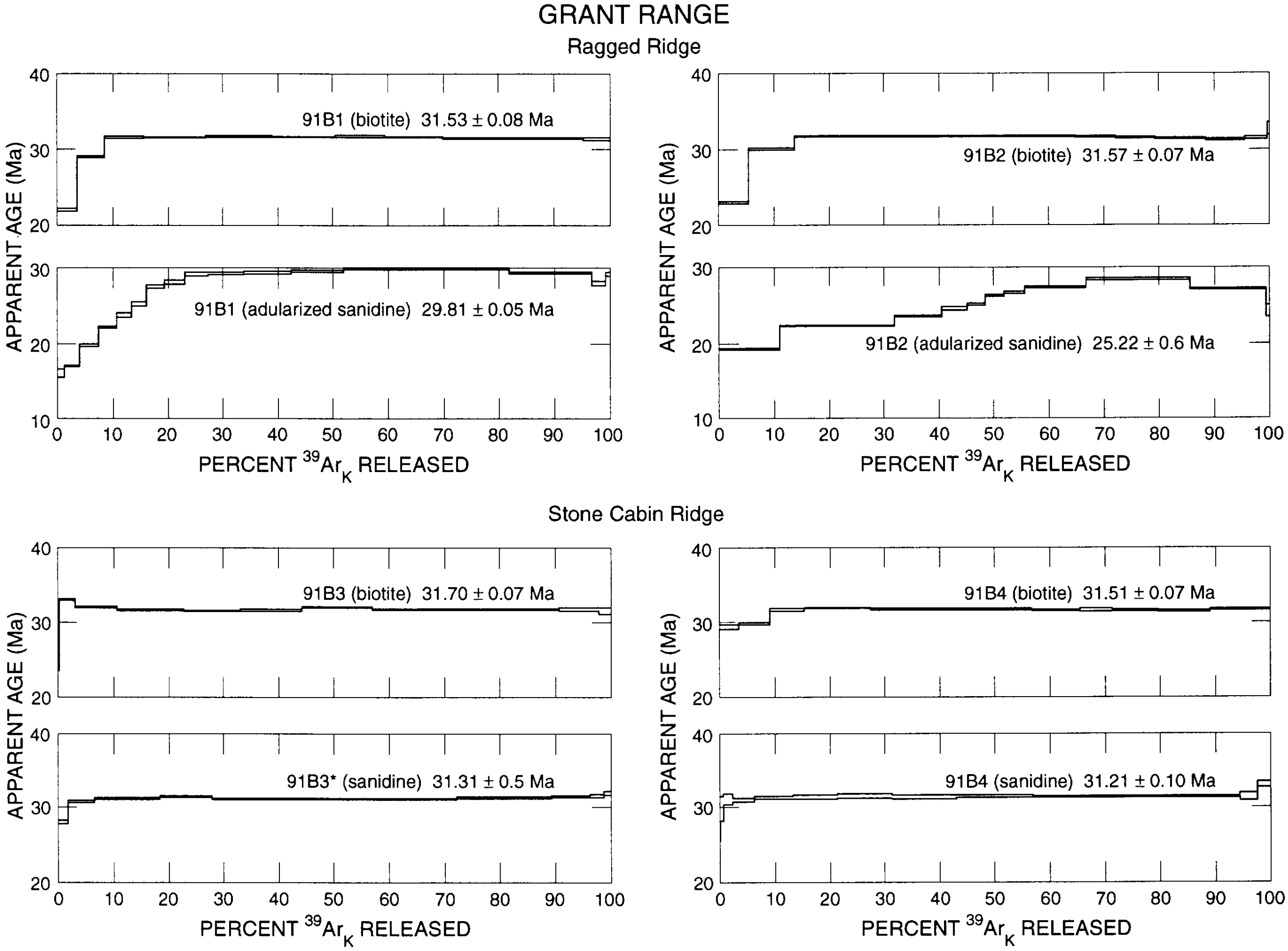


Figure 4. $^{40}Ar/^{39}Ar$ age spectrum diagrams from the Grant Range, east-central Nevada. Definition of $^{39}Ar_K$ is discussed in the text.

Figure 3 (facing page). *A*, Electron microprobe photomicrograph of adularized and cracked sanidine from 91B1, Ragged Ridge locality (sample coordinates are shown in table 4). Sanidine composition (12.36–12.37 weight percent K_2O and 2.93–2.99 weight percent Na_2O) is indicated by dark background, and adularia composition (14.8–16.72 weight percent K_2O and 0.09–0.98 weight percent Na_2O) is indicated by light zone along crack near horizontal cross hair. Analyses are given in table 5. *B*, Electron microprobe beam scan of same area shown in *A* showing potassium sites. Adularized sanidine zone (along crack) is yellow-red and has high K_2O and low Na_2O. Sanidine composition is indicated by the yellow-blue zone, which has normal K_2O and Na_2O content. Analyses are given in table 5.

atmospheric ^{40}Ar and ^{40}K-derived ^{40}Ar, have been made. K-derived ^{39}Ar ($^{39}Ar_K$) is total ^{39}Ar derived from the epithermal neutron-induced reaction $^{39}K(n,p)^{39}Ar$ after corrections for non-^{39}K-derived ^{39}Ar, including ^{42}Ca-derived ^{39}Ar, are made. F is the quantity resulting from the division of radiogenic ^{40}Ar by the amount of K-derived ^{39}Ar. Quantities for radiogenic ^{40}Ar and K-derived ^{39}Ar are given in volts of signal measured on a Faraday detector by a digital voltmeter. These quantities can be converted to moles, using the mass spectrometer sensitivity at time of measurement of 9.736×10^{-13} moles argon per volt of signal. The detection limit for argon at the time of this experiment was 2×10^{-17} moles. The measured $^{40}Ar/^{39}Ar$ ratio used for mass discrimination correction is 299.5.

Samples were irradiated in multiple irradiation packages for times ranging from 20 to 100 hours at 1 megawatt in the USGS TRIGA reactor in Denver. The J-value for each sample was determined from adjacent standards; errors in the calculated J-value were determined experimentally by calculating the reproducibility of multiple monitors. Corrections for the irradiation-produced, interfering isotopes of argon were made by measuring production ratios for the interfering isotopes of argon produced in pure K_2SO_4 and CaF_2 irradiated simultaneously with the samples of this study. Those production ratios, as determined from four measurements of each salt, are given in table 8.

Corrections were made for additional interfering isotopes of argon produced from irradiation of chlorine using the method described by Roddick (1983). Measured quantities of ^{37}Ar and ^{39}Ar were corrected for radioactive decay, and the $^{39}Ar/^{37}Ar$ ratios were corrected for this decay as well as for interfering argon isotopes. By multiplying the $^{39}Ar/^{37}Ar$ ratios by 0.5, the relative approximate K/Ca distribution of the samples may be obtained. Error estimates for apparent ages of individual temperature steps were assigned by using the equations of Dalrymple and others (1981); however, the equations were modified to allow the option of choosing the larger of separately derived errors in the F-value—either a calculated error or an experimental error determined from the reproducibility of identical samples. Age plateaus were determined by comparing contiguous gas fractions using the critical test of Dalrymple and Lanphere (1969), and the error was determined using the equations of Dalrymple and others (1981).

INTERPRETATION OF GRANT RANGE $^{40}Ar/^{39}Ar$ DATA

Age spectra for the feldspar and biotite separates from the ash-flow tuff of the Windous Butte Formation are summarized in figure 4 and table 7. Biotite spectra from Ragged Ridge (potassium metasomatized) and Stone Cabin Ridge (unaltered) are slightly disturbed, and dates range from 31.68±0.01 Ma to 31.47±0.1 Ma. These dates are comparable

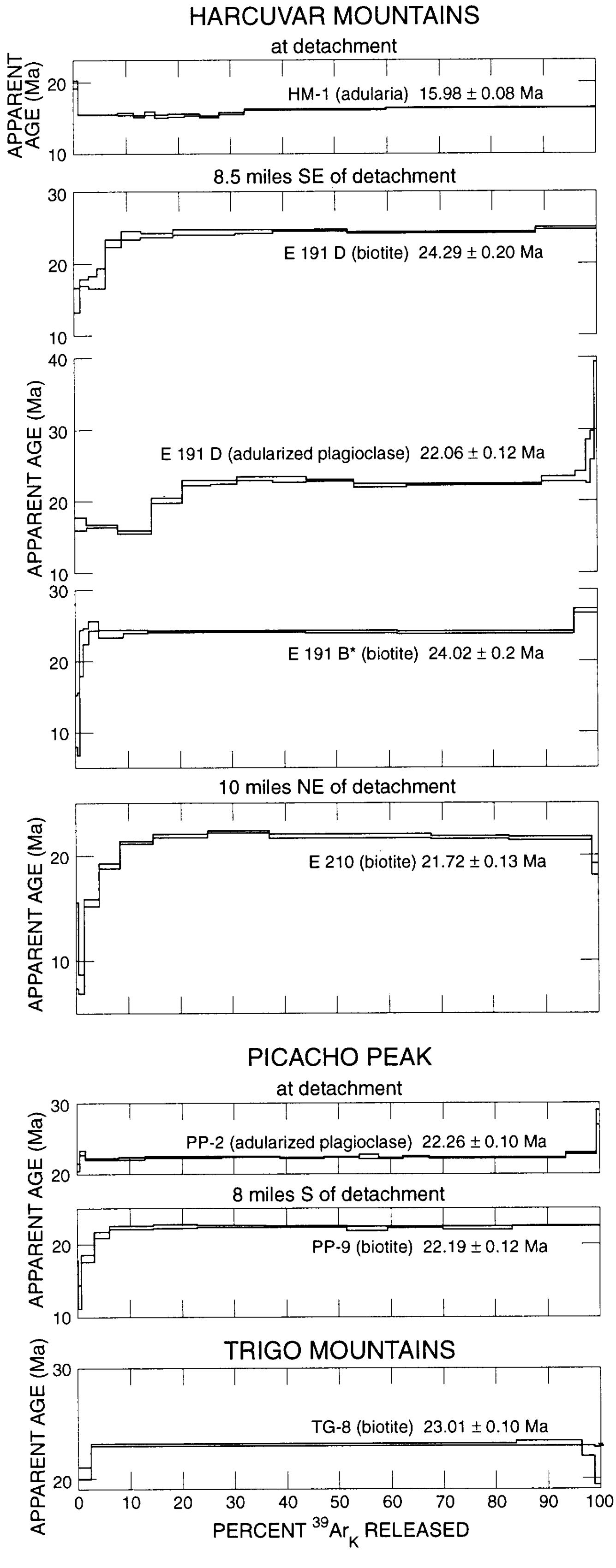


Figure 5. $^{40}Ar/^{39}Ar$ age spectrum diagrams from Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona. Definition of $^{39}Ar_K$ is discussed in the text.

to the regional age of 31.4–31.2 Ma ($^{40}Ar/^{39}Ar$ method, A. Deino, Human Origins Lab, oral commun., 1993). Biotite dates from Ragged Ridge (31.5±0.1 Ma, 31.5±0.1 Ma) and Stone Cabin Ridge (31.7±0.1 Ma, 31.5±0.1 Ma) are all slightly disturbed, but plateau, or preferred, dates are concordant and indicate that temperatures associated with potassium metasomatism did not exceed 280°C. Some argon loss is indicated. Age-spectra and locality references for each of the samples analyzed by the $^{40}Ar/^{39}Ar$ thermal release method from the Grant Range, Nevada, and Arizona localities are compiled in table 7.

Sanidine spectra from Stone Cabin Ridge are not disturbed and have plateau dates of 31.3±0.1 and 31.2±0.1 Ma and are comparable with the regional age of 31.4–31.2 Ma ($^{40}Ar/^{39}Ar$ method, A. Deino, Human Origins Lab, oral commun., 1993). Spectra for adularized sanidine from Ragged Ridge show apparent argon loss with stairstep patterns that indicate growth of adularia as late as ~20 Ma. The disturbed spectra from adularized sanidine from Ragged Ridge indicate that potassium metasomatism occurred sometime after 31 Ma and continued until ~20 Ma. This alteration is interpreted to be related to detachment and associated circulation of potassium-rich fluids.

This time period, 31 to 20 Ma, brackets detachment faulting in the Grant Range. It is significant that this is also the same time frame during which a thermal event affected the Cretaceous Troy Granite, which has a Rb/Sr isochron of 70.2 Ma (Fryxell, 1984) in the southern Grant Range. Biotite and muscovite from this Cretaceous pluton gave reset early Miocene K-Ar ages of 22.5 Ma and 24.7 Ma, respectively (Armstrong, 1970).

ADULARIZED SANIDINE

The difficulties of separating micrometer-sized adularia for dating and the knowledge that sanidine and plagioclase had been incipiently altered to adularia required use of the electron microprobe in order to determine the effect of this alteration on mineral chemistry. By using a beam scan, sites with excess potassium were defined. Lindley and others (1983) showed that metasomatic feldspar (adularia) has a composition of 90–100 percent orthoclase (Or) and a structural state approximating orthoclase, which is anomalous as a primary mineral in volcanic rocks.

For our study, several feldspar phenocrysts were analyzed on the microprobe, all of which had sanidine composition. However, one grain showed a crack and a subtle shade of dark gray along the crack (fig. 3*A*). Subsequent analysis of the dark- and light-gray zones showed distinctive adularia (dark gray) and sanidine compositions (light gray) (fig. 3*A* and table 5). A beam scan of the same area for potassium showed the potassium concentration to be higher along the crack (indicative of adularia composition) than away from the crack (sanidine composition). A beam scan for sodium showed the sodium concentration to be lower along the crack (indicative of adularia composition) and higher away from the crack (sanidine composition).

The adularia is present in metasomatized rocks as micrometer-sized crystals (Chapin and Lindley, 1986) in the groundmass and as incipient alteration of feldspar. Because the sanidine grain is not jacketed by adularia, which would be indicated by step-like exterior-to-interior-of-grain adularization, we infer that the potassium-rich zone along the crack indicates preferential movement of potassium-rich fluids along a preexisting microfracture in the mineral grain.

CONCLUSIONS FROM THE GRANT RANGE STUDY

Listed below are conclusions that resulted from this study of the potassium metasomatized Windous Butte Formation in the Grant Range. These conclusions are significant to interpretation of dates from detachments in Arizona and will be referred to, by number, in the later discussion of Arizona localities.

1. Potassium metasomatism, for which evidence was considered to be sparse in the northern Basin and Range (Glazner and Bartley, 1990), is now documented in the Grant Range (Brooks and others, 1994; this study) and elsewhere (Brooks and others, 1995a, 1995b; Brooks, Thorman, Snee, and others, 1995) in the northern Basin and Range.
2. Biotite dates are unaffected by potassium metasomatism 4 km from the detachment zone near Ragged Ridge. Therefore, temperatures of the hydrothermal fluids, 4 km from the surface trace of the detachment zone, were less than 280°C, the resetting temperature of biotite.
3. Sanidine dates from metasomatized rock near the detachment at Ragged Ridge are disturbed. The hydrothermal fluids that contributed excess potassium to the Ragged Ridge rocks moved along a detachment that was opened sometime after 31 Ma (age of the Windous Butte) and was closed to those fluids at about 20 Ma.
4. Biotite dates from the Cretaceous Troy Granite, southern Grant Range, are reset to 23–25 Ma. Parallel resetting of this lower-plate Cretaceous granite and Oligocene volcanic rocks, in the upper plate, to late Oligocene-early Miocene indicates that the thermal regime associated with mylonitization and the migration of hydrothermal fluids was sufficient enough at depth during the late Oligocene-early Miocene to reset biotite (>280°C) and muscovite in the Cretaceous Troy Granite (Armstrong, 1970). The potassium-rich hydrothermal fluids rose, cooled somewhat, but were still hot enough to reset and alter the sanidine in permeable upper-plate Oligocene volcanic rocks near the detachment at Ragged Ridge. Temperatures associated with mylonitization might range from 300°–700°C (Naruk, 1984).

Table 7. Abbreviated $^{40}Ar/^{39}Ar$ age-spectrum data for volcanic rocks from the upper plate of detachment faults in the Grant Range, Nevada, and Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona.

[See text for explanation of $^{40}Ar_R$, $^{39}Ar_K$, and F. Leaders (--) indicate quantity not calculated (^{37}Ar below dectection limit)]

Temperature, (°C)	$^{40}Ar_R$	$^{39}Ar_K$	F	$^{39}Ar/^{37}Ar$	$^{40}Ar_R$ (percent)	$^{39}Ar_K$ (percent)	Apparent age and error (Ma)
				RAGGED RIDGE, GRANT RANGE, NEVADA			
Sample 91B1/62/DD37; potassium-metasomatized Windous Butte Formation; 50.7 mg biotite; measured $^{40}Ar/^{36}Ar$ = 298.9; plateau date = 31.53±0.08 Ma; J-value = 0.00781±0.1 percent (1 σ); lat 38°41′23″N., long 115°26′21″W.							
600	0.44038	0.27969	1.575	28.91	42.3	3.7	22.05±0.16
700	0.73951	0.35597	2.077	20.16	46.7	4.7	29.03±0.09
750	1.19876	0.52979	2.263	70.58	79.8	7.1	31.60±0.13
800	1.90434	0.84282	2.259	68.60	88.4	11.2	31.56±0.06
850	2.06510	0.91010	2.269	159.76	91.7	12.1	31.69±0.07
900	1.93042	0.85494	2.258	100.04	89.1	11.4	31.54±0.07
950	1.51533	0.66904	2.265	44.61	84.6	8.9	31.63±0.15
1,000	1.77537	0.78561	2.260	88.32	80.6	10.5	31.56±0.05
1,050	2.42733	1.08034	2.247	53.34	79.3	14.4	31.38±0.05
1,100	1.82916	0.81312	2.250	19.70	78.4	10.8	31.42±0.06
1,300	0.88147	0.39311	2.242	12.45	77.3	5.2	31.32±0.11
TOTAL GAS			2.223				31.06±0.08
Sample 91B1/63/DD37; potassium-metasomatized Windous Butte Formation; 57.8 mg adularized sanidine; measured $^{40}Ar/^{36}Ar$ = 298.9, preferred date = 29.81±0.05 Ma; J-value = 0.007687±0.1 percent (1 σ); lat 38°41′23″N., long 115°26′21″W.							
450	0.00271	0.00587	0.461	25.91	2.5	0.1	6.38±5.54
500	0.22043	0.15559	1.417	--	54.7	1.4	19.54±0.31
550	0.45421	0.30765	1.476	39.60	86.4	2.7	20.36±0.05
600	0.63684	0.39266	1.622	26.25	89.4	3.4	22.35±0.12
650	0.63560	0.36206	1.755	--	68.3	3.2	24.18±0.09
700	0.56274	0.30598	1.839	25.92	85.2	2.7	25.33±0.17
750	0.58293	0.30382	1.919	109.67	91.5	2.7	26.41±0.19
800	0.74352	0.36409	2.042	--	94.4	3.2	28.10±0.11
850	0.90320	0.43536	2.075	--	93.8	3.8	28.54±0.20
900	1.00881	0.47253	2.135	69.77	94.2	4.1	29.37±0.14
950	1.60938	0.75210	2.140	77.98	95.2	6.6	29.43±0.07
1,000	2.09067	0.97562	2.143	98.39	95.6	8.5	29.47±0.07
1,050	2.32708	1.08102	2.153	136.67	95.8	9.5	29.61±0.07
1,100	3.13352	1.44521	2.168	66.73	95.4	12.6	29.82±0.05
1,150	4.26258	1.96648	2.168	141.00	93.4	17.2	29.81±0.05
1,200	3.61250	1.69106	2.136	211.80	91.4	14.8	29.38±0.05
1,250	0.59186	0.28735	2.060	44.10	81.0	2.5	28.34±0.19
1,400	0.27842	0.13098	2.126	15.91	79.0	1.1	29.24±0.21
TOTAL GAS			2.069				28.46±0.10
Sample 91B2/65/DD37; potassium-metasomatized Windous Butte Formation; 56.4 mg biotite; measured $^{40}Ar/^{36}Ar$ = 298.9; plateau date = 31.57±0.07 Ma; J-value = 0.007825±0.1 percent (1 σ); lat 38°41′23″N., long 115°26′25″W.							
600	0.77343	0.46947	1.647	36.71	41.8	5.6	23.11±0.15
700	1.45779	0.68043	2.142	56.87	58.0	8.1	29.99±0.05
750	2.81130	1.24584	2.257	97.38	82.6	14.8	31.58±0.05
800	2.26853	1.00583	2.256	167.13	88.3	12.0	31.57±0.07
850	2.64267	1.17118	2.256	--	91.1	14.0	31.57±0.08
900	1.91054	0.84717	2.255	195.39	89.9	10.1	31.56±0.08
950	1.39486	0.62018	2.249	73.93	82.2	7.4	31.47±0.07
1,000	1.33743	0.59609	2.244	78.37	78.7	7.1	31.40±0.07
1,050	1.73083	0.77400	2.236	55.36	82.0	9.2	31.29±0.07
1,100	1.33653	0.60066	2.225	17.43	80.8	7.2	31.14±0.10
1,150	0.75150	0.33662	2.232	8.91	80.4	4.0	31.24±0.11
1,300	0.10178	0.04388	2.320	4.41	62.5	0.5	32.45±0.79
TOTAL GAS			2.207				30.89±0.08

Table 7. Abbreviated $^{40}Ar/^{39}Ar$ age-spectrum data for volcanic rocks from the upper plate of detachment faults in the Grant Range, Nevada, and Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona—*Continued.*

Temperature, (°C)	$^{40}Ar_R$	$^{39}Ar_K$	F	$^{39}Ar/^{37}Ar$	$^{40}Ar_R$ (percent)	$^{39}Ar_K$ (percent)	Apparent age and error (Ma)
Sample 91B2/72/DD37; potassium-metasomatized Windous Butte Formation; 69.6 mg adularized sanidine; measured $^{40}Ar/^{36}Ar$ = 298.9; preferred date = 25.22±0.06 Ma; J-value = 0.007792±0.1 percent (1 σ); lat 38°41′23″N., long 115°26′25″W.							
650	1.43579	1.01356	1.417	166.18	86.9	11.0	19.80±0.03
750	3.10552	1.91115	1.625	175.16	92.5	20.8	22.70±0.04
800	1.35437	0.79309	1.708	223.34	96.3	8.6	23.85±0.06
850	0.75949	0.42671	1.780	188.06	96.3	4.6	24.85±0.14
900	0.53851	0.29613	1.819	227.55	93.9	3.2	25.38±0.14
950	0.60390	0.31827	1.897	167.32	95.0	3.5	26.48±0.07
1,000	0.66278	0.34490	1.922	219.53	95.4	3.7	26.81±0.09
1,100	2.02647	1.02676	1.974	182.81	96.6	11.2	27.53±0.04
1,200	3.54389	1.73457	2.043	181.13	95.9	18.8	28.49±0.06
1,300	2.48629	1.27482	1.950	186.52	94.8	13.9	27.21±0.04
1,400	0.10871	0.06203	1.753	66.06	79.2	0.7	24.47±0.77
TOTAL GAS			1.807				25.22±0.06
STONE CABIN RIDGE, GRANT RANGE, NEVADA							
Sample 91B3/64/DD37; Windous Butte Formation; 54.8 mg biotite; measured $^{40}Ar/^{36}Ar$ = 298.9; plateau date = 31.70±0.07 Ma; J-value = 0.007821±0.1 percent (1 σ); lat 38°39′54″N., long 115°21′13″W.							
600	0.04982	0.02671	1.865	11.36	13.9	0.3	26.12±2.57
700	0.53263	0.22544	2.363	18.08	37.3	2.7	33.03±0.11
750	1.47713	0.64620	2.286	43.89	78.2	7.6	31.97±0.08
800	2.31769	1.02646	2.258	79.12	89.8	12.1	31.58±0.07
850	1.97175	0.87527	2.253	64.19	92.3	10.3	31.51±0.05
900	2.14499	0.95137	2.255	57.17	91.5	11.2	31.53±0.09
950	2.46710	1.07949	2.285	11.86	87.6	12.7	31.96±0.06
1,000	3.07340	1.35733	2.264	30.55	79.1	16.0	31.67±0.05
1,050	3.44321	1.51827	2.268	39.47	73.6	17.9	31.72±0.05
1,100	1.38257	0.60967	2.268	13.05	77.8	7.2	31.72±0.12
1,300	0.37554	0.16638	2.257	3.69	79.4	2.0	31.57±0.23
TOTAL GAS			2.268				31.71±0.08
Sample 91B3/71/DD37; Windous Butte Formation; 65.8 mg sanidine; measured $^{40}Ar/^{36}Ar$ = 298.9; plateau date = 31.31±0.05 Ma; J-value = 0.007775±0.1 percent (1 σ); lat 38°39′54″N., long 115°21′13″W.							
700	0.46627	0.23048	2.023	14.08	43.8	1.8	28.15±0.22
800	1.30936	0.58904	2.223	37.71	91.6	4.7	30.91±0.15
900	3.34175	1.48151	2.256	42.68	96.7	11.8	31.36±0.08
950	2.70743	1.19143	2.272	26.82	97.9	9.5	31.59±0.05
1,000	3.29465	1.46407	2.250	62.53	98.2	11.7	31.29±0.05
1,050	4.28674	1.90274	2.253	148.70	98.3	15.2	31.33±0.05
1,100	4.92618	2.19139	2.248	102.08	98.4	17.5	31.26±0.05
1,150	4.84085	2.14713	2.255	90.58	98.5	17.1	31.35±0.05
1,200	1.97691	0.87449	2.261	68.81	97.9	7.0	31.43±0.07
1,250	0.70446	0.31063	2.268	32.66	96.4	2.5	31.53±0.15
1,400	0.32332	0.14159	2.283	19386.07	90.3	1.1	31.75±0.12
TOTAL GAS			2.250				31.28±0.06

Table 7. Abbreviated $^{40}Ar/^{39}Ar$ age-spectrum data for volcanic rocks from the upper plate of detachment faults in the Grant Range, Nevada, and Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona—*Continued.*

Temperature, (°C)	$^{40}Ar_R$	$^{39}Ar_K$	F	$^{39}Ar/^{37}Ar$	$^{40}Ar_R$ (percent)	$^{39}Ar_K$ (percent)	Apparent age and error (Ma)
Sample 91B4/63/DD37; Windous Butte Formation; 56.5 mg biotite; measured $^{40}Ar/^{36}Ar$ = 298.9; plateau date = 31.51±0.07 Ma; J-value = 0.007815±0.1 percent (1 σ); lat 38°39′55″N., long 115°21′0″W.							
600	0.53754	0.25577	2.102	17.23	52.5	3.5	29.39±0.28
700	0.88183	0.41496	2.125	12.30	65.0	5.7	29.71±0.07
750	1.05621	0.46700	2.262	27.60	89.4	6.4	31.61±0.16
800	1.90004	0.87785	2.275	79.31	94.1	12.0	31.79±0.09
850	2.63622	1.16567	2.262	42.88	96.5	15.9	31.61±0.07
900	2.23572	0.98929	2.260	--	96.6	13.5	31.58±0.07
950	1.43974	0.63905	2.253	39.85	92.6	8.7	31.49±0.05
1,000	0.97410	0.43206	2.255	31.83	86.6	5.9	31.51±0.14
1,050	1.37826	0.61268	2.250	22.32	85.1	8.4	31.44±0.05
1,100	1.54470	0.68845	2.244	12.71	84.4	9.4	31.36±0.07
1,300	1.78155	0.79068	2.253	10.97	87.3	10.8	31.49±0.05
TOTAL GAS			2.245				31.37±0.08
Sample 91B4/69/DD37; Windous Butte Formation; 66 mg sanidine; measured $^{40}Ar/^{36}Ar$ = 298.9; plateau date = 31.21±0.10 Ma; J-value = 0.007766±0.1 percent (1 σ); lat 38°39′55″N., long 115°21′0″W.							
500	0.02736	0.01276	2.145	--	21.0	0.2	29.80±4.30
600	0.06070	0.02835	2.141	--	64.6	0.5	29.75±1.60
700	0.22217	0.09964	2.230	--	34.4	1.7	30.97±0.69
800	0.50963	0.22929	2.223	12.15	91.2	3.9	30.87±0.21
900	0.91368	0.40771	2.241	14.76	94.1	7.0	31.13±0.11
950	1.06648	0.47452	2.247	--	95.7	8.1	31.22±0.13
1,000	1.30884	0.58137	2.251	30.28	97.2	10.0	31.27±0.12
1,050	1.53061	0.68170	2.245	49.75	97.3	11.7	31.19±0.14
1,100	1.81365	0.80667	2.248	45.48	97.2	13.8	31.23±0.09
1,150	2.89460	1.28960	2.245	--	96.8	22.1	31.18±0.05
1,200	1.99318	0.88679	2.248	40.49	96.3	15.2	31.22±0.05
1,250	0.40892	0.18187	2.248	8.40	92.1	3.1	31.23±0.45
1,450	0.35240	0.14882	2.388	0.45	97.1	2.6	32.87±0.35
TOTAL GAS			2.248				31.22±0.14
PICACHO PEAK, ARIZONA							
Sample PP-2/42/DD13; potassium-metasomatized andesite; 136.2 mg adularized plagioclase; measured $^{40}Ar/^{36}Ar$ = 298.9; preferred date = 22.26±0.10 Ma; J-value = 0.007524±0.25 percent (1 σ); lat 32°39′53″N., long 111°23′24″W.							
400	0.13982	0.09002	1.553	9095.67	5.5	0.6	20.96±0.52
500	0.28441	0.16657	1.707	--	25.2	1.1	23.03±0.30
600	1.53336	0.93440	1.641	--	76.4	6.2	22.14±0.08
650	1.29348	0.78590	1.646	--	88.5	5.2	22.20±0.11
700	3.64654	2.20744	1.652	--	90.5	14.5	22.28±0.06
750	2.83129	1.70814	1.658	--	95.2	11.2	22.36±0.08
800	2.09397	1.27242	1.646	--	93.9	8.4	22.20±0.08
850	1.71430	1.03682	1.653	--	92.9	6.8	22.30±0.06
900	0.88056	0.53039	1.660	--	91.0	3.5	22.40±0.29
950	1.16209	0.70893	1.639	--	88.2	4.7	22.11±0.08
1,000	1.27171	0.76662	1.659	--	87.6	5.0	22.38±0.10
1,050	1.50092	0.91167	1.646	--	86.1	6.0	22.21±0.07
1,100	1.92686	1.16858	1.649	--	81.8	7.7	22.24±0.08
1,150	3.11582	1.88844	1.650	--	71.2	12.4	22.26±0.06
1,200	1.53890	0.90997	1.691	--	64.8	6.0	22.81±0.07
1,250	0.15316	0.07422	2.064	3021.76	65.4	0.5	27.79±1.09
1,450	0.07752	0.02797	2.772	1143.43	64.7	0.2	37.24±1.71
TOTAL GAS			1.657				22.35±0.09

Table 7. Abbreviated $^{40}Ar/^{39}Ar$ age-spectrum data for volcanic rocks from the upper plate of detachment faults in the Grant Range, Nevada, and Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona—*Continued.*

Temperature, (°C)	$^{40}Ar_R$	$^{39}Ar_K$	F	$^{39}Ar/^{37}Ar$	$^{40}Ar_R$ (percent)	$^{39}Ar_K$ (percent)	Apparent age and error (Ma)
Sample PP-9/37/DD13; dacite; 64.6 mg biotite; measured $^{40}Ar/^{36}Ar$ = 298.9; preferred date = 22.19±0.12 Ma; J-value = 0.007462±0.25 percent (1 σ); lat 32°32′57″N., long 111°27′53″W.							
500	0.01390	0.01009	1.377	551.63	2.1	0.2	18.44±0.79
600	0.03401	0.03579	0.950	--	13.4	0.7	12.75±1.62
700	0.15643	0.11560	1.353	--	27.9	2.4	18.12±0.50
750	0.22180	0.13886	1.597	31220.12	47.1	2.9	21.38±0.41
800	0.67592	0.40353	1.675	--	71.3	8.4	22.41±0.14
850	0.68370	0.40633	1.683	--	83.4	8.4	22.51±0.20
900	1.04850	0.62288	1.683	--	86.1	12.9	22.52±0.11
950	1.26258	0.75331	1.676	--	85.8	15.6	22.42±0.09
1,000	0.61484	0.37353	1.646	--	77.7	7.7	22.02±0.22
1,050	0.85563	0.51424	1.664	--	76.8	10.7	22.26±0.08
1,100	1.05661	0.64038	1.650	--	79.0	13.3	22.08±0.09
1,250	1.35655	0.81332	1.668	--	81.4	16.8	22.31±0.08
TOTAL GAS			1.653				22.12±0.15
HARCUVAR MOUNTAINS, ARIZONA							
Sample HM-1/41/DD13; potassium-metasomatized ash-flow tuff; 86.2 mg adularia; measured $^{40}Ar/^{36}Ar$ = 298.9; (no plateau) total gas date = 15.98±0.08 Ma; J-value = 0.007482±0.25 percent (1 σ); lat 34°04′44″N., long 113°14′39″W.							
500	0.14146	0.09619	1.471	3252.26	10.6	0.9	19.74±0.52
700	0.97816	0.85044	1.150	--	34.5	7.6	15.46±0.07
750	0.40599	0.35245	1.152	--	51.1	3.1	15.48±0.19
800	0.26355	0.23266	1.133	--	51.2	2.1	15.23±0.18
850	0.26045	0.22377	1.164	--	54.5	2.0	15.64±0.26
900	0.32729	0.28869	1.134	--	55.4	2.6	15.24±0.22
1,000	0.38714	0.33734	1.148	--	64.3	3.0	15.42±0.15
1,050	0.44891	0.39953	1.124	--	67.7	3.6	15.10±0.14
1,100	0.64052	0.55343	1.157	--	68.0	4.9	15.55±0.16
1,200	3.63211	3.03100	1.198	--	50.5	27.0	16.10±0.06
1,450	5.46525	4.50706	1.213	--	40.3	40.2	16.29±0.05
TOTAL GAS			1.190				15.98±0.08
Sample E-191D/38/DD13; potassium-metasomatized ash-flow tuff; 45.8 mg biotite; measured $^{40}Ar/^{36}Ar$ = 298.9; plateau date = 24.29±0.20 Ma; J-value = 0.007473±0.25 percent (1 σ); lat 34°01′40″N., long 113°07′50″W.							
500	0.03796	0.03416	1.111	--	3.4	1.1	14.92±1.75
600	0.07078	0.05440	1.301	--	19.8	1.7	17.46±0.46
650	0.06517	0.05004	1.302	2879.79	25.2	1.6	17.47±0.92
700	0.06797	0.05077	1.339	2219.44	21.5	1.6	17.96±1.42
750	0.16404	0.09622	1.705	--	34.8	3.0	22.84±0.54
800	0.21386	0.11972	1.786	24724.77	54.8	3.7	23.92±0.52
850	0.35225	0.19723	1.786	--	67.9	6.2	23.92±0.27
900	0.33721	0.18604	1.813	--	65.6	5.8	24.27±0.31
950	0.35930	0.19835	1.812	--	59.0	6.2	24.26±0.30
1,000	0.41758	0.22942	1.820	--	67.9	7.2	24.37±0.19
1,050	0.83776	0.45721	1.832	--	80.7	14.3	24.53±0.10
1,150	2.09008	1.15681	1.807	--	84.9	36.2	24.19±0.08
1,300	0.68164	0.36924	1.846	--	79.3	11.5	24.72±0.17
TOTAL GAS			1.780				23.84±0.24

Table 7. Abbreviated $^{40}Ar/^{39}Ar$ age-spectrum data for volcanic rocks from the upper plate of detachment faults in the Grant Range, Nevada, and Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona—*Continued.*

Temperature, (°C)	$^{40}Ar_R$	$^{39}Ar_K$	F	$^{39}Ar/^{37}Ar$	$^{40}Ar_R$ (percent)	$^{39}Ar_K$ (percent)	Apparent age and error (Ma)
Sample E-191D/40/DD13; potassium-metasomatized ash-flow tuff; 64.6 mg adularized plagioclase; measured $^{40}Ar/^{36}Ar$ = 298.9; plateau date = 22.06±0.12 Ma; J-value = 0.007515±0.25 percent (1 σ); lat 34°01′40″N., long 113°07′50″W.							
600	0.08924	0.07144	1.249	--	25.5	2.1	16.86±0.96
700	0.24587	0.20064	1.225	14406.51	34.3	5.9	16.54±0.20
750	0.25461	0.21945	1.160	11846.66	30.4	6.5	15.66±0.21
800	0.30008	0.20104	1.493	174648.08	55.2	6.0	20.12±0.34
850	0.30395	0.18161	1.674	--	69.9	5.4	22.55±0.42
900	0.28863	0.17120	1.686	56704.03	71.7	5.1	22.71±0.34
950	0.39459	0.22955	1.719	528585.96	74.1	6.8	23.16±0.27
1,000	0.37341	0.21825	1.711	2902.80	72.5	6.5	23.05±0.40
1,050	0.52139	0.30718	1.697	85524.14	73.9	9.1	22.87±0.11
1,100	0.55186	0.33800	1.633	--	76.0	10.0	22.00±0.15
1,150	1.43298	0.87430	1.639	--	68.1	25.9	22.08±0.09
1,200	0.36431	0.21510	1.694	--	55.4	6.4	22.82±0.34
1,250	0.12734	0.07402	1.720	1691.16	40.3	2.2	23.17±0.71
1,300	0.04776	0.02554	1.870	1048.04	29.4	0.8	25.18±3.07
1,350	0.05295	0.02597	2.039	--	37.3	0.8	27.44±2.01
1,450	0.05760	0.02093	2.752	2888.10	50.5	0.6	36.93±2.14
TOTAL GAS			1.602				21.59±0.28
Sample E-191B/36/DD13; ash-flow tuff vitrophyre; 43.6 mg biotite; measured $^{40}Ar/^{36}Ar$ = 299.6; plateau date = 24.02±0.20 Ma; J-value = 0.007425±0.25 percent (1 σ); lat 34°00′56″N., long 113°06′55″W.							
500	0.01587	0.01819	0.872	--	5.4	0.5	11.64±3.62
600	0.01313	0.01564	0.840	--	8.3	0.5	11.21±4.41
700	0.02718	0.01708	1.591	736.67	11.7	0.5	21.19±3.24
750	0.06091	0.03447	1.767	--	21.3	1.0	23.52±1.12
800	0.11774	0.06278	1.875	10090.38	60.1	1.9	24.95±0.69
850	0.28257	0.15775	1.791	--	76.6	4.7	23.84±0.51
900	0.28481	0.15697	1.814	14600.85	80.6	4.7	24.14±0.28
950	0.82579	0.45632	1.810	--	84.9	13.6	24.08±0.11
1,000	1.01218	0.55843	1.813	--	84.6	16.7	24.12±0.09
1,050	1.05034	0.58082	1.808	--	82.3	17.4	24.06±0.12
1,100	1.25013	0.69534	1.798	--	81.4	20.8	23.92±0.11
1,150	0.79491	0.44175	1.799	--	79.9	13.2	23.94±0.15
1,300	0.30529	0.15208	2.007	12055.71	75.4	4.5	26.69±0.33
TOTAL GAS			1.805				24.01±0.26
Sample E-210/35/DD13; dacite; 70.7 mg biotite; measured $^{40}Ar/^{36}Ar$ = 298.9; plateau date = 21.72±0.13 Ma; J-value = 0.007477±0.25 percent (1 σ); lat 34°13′39″N., long 113°10′48″W.							
500	0.02199	0.02591	0.849	1077.34	5.5	0.5	11.41±4.05
600	0.04146	0.07215	0.575	3027.37	9.9	1.3	7.73±0.91
700	0.18122	0.15681	1.156	--	29.7	2.8	15.52±0.33
750	0.30166	0.21345	1.413	8046.79	39.6	3.8	18.96±0.23
800	0.54833	0.34727	1.579	15527.20	66.3	6.2	21.17±0.09
850	0.94890	0.58355	1.626	--	79.3	10.5	21.80±0.14
900	1.08934	0.65877	1.654	--	83.8	11.8	22.17±0.10
950	1.40794	0.86778	1.622	--	84.6	15.6	21.75±0.17
1,000	1.40286	0.86403	1.624	--	83.4	15.5	21.77±0.15
1,050	1.33292	0.82564	1.614	--	86.1	14.8	21.65±0.13
1,250	1.43141	0.89220	1.604	--	79.9	16.0	21.51±0.13
1,450	0.08560	0.06180	1.385	914.34	42.0	1.1	18.59±0.52
TOTAL GAS			1.579				21.17±0.21

Table 7. Abbreviated $^{40}Ar/^{39}Ar$ age-spectrum data for volcanic rocks from the upper plate of detachment faults in the Grant Range, Nevada, and Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona—*Continued.*

Temperature, (°C)	$^{40}Ar_R$	$^{39}Ar_K$	F	$^{39}Ar/^{37}Ar$	$^{40}Ar_R$ (percent)	$^{39}Ar_K$ (percent)	Apparent age and error (Ma)
TRIGO MOUNTAINS, ARIZONA							
Sample TG-8/39/DD13; potassium-metasomatized ash-flow tuff; 60.5 mg biotite; measured $^{40}Ar/^{36}Ar$ = 298.9; plateau date = 23.01±0.10 Ma; J-value = 0.007535±0.25 percent (1 σ); lat 33°02′15″N., long 114°30′40″W.							
750	0.17077	0.11285	1.513	24359.07	28.0	2.4	20.45±0.55
1,025	2.14488	1.25936	1.703	--	81.0	26.8	23.00±0.09
1,125	4.35601	2.55881	1.702	--	80.7	54.6	22.99±0.07
1,175	1.00778	0.58955	1.709	--	78.9	12.6	23.09±0.15
1,250	0.19108	0.11582	1.650	6816.02	56.5	2.5	22.29±0.60
1,450	0.08422	0.05433	1.550	3168.34	47.5	1.2	20.95±1.81
TOTAL GAS			1.696				22.91±0.13

Table 8. Production ratios for interfering isotopes of argon produced during irradiation.

[DD13 and DD37 indicate reactor run numbers]

	$(^{36}Ar/^{37}Ar)_{Ca}$	$(^{39}Ar/^{37}Ar)_{Ca}$	$(^{38}Ar/^{37}Ar)_{Ca}$	$(^{40}Ar/^{39}Ar)_K$	$(^{37}Ar/^{39}Ar)_K$	$(^{38}Ar/^{39}Ar)_K$
DD13	2.69×10^{-4}	7.08×10^{-4}	2.90×10^{-5}	8.76×10^{-3}	1.39×10^{-4}	1.30×10^{-2}
DD37	2.80×10^{-4}	6.94×10^{-4}	3.67×10^{-5}	8.99×10^{-3}	1.49×10^{-4}	1.31×10^{-2}
Approximate errors	$\pm0.01\times10^{-4}$	$\pm0.03\times10^{-4}$	$\pm0.18\times10^{-5}$	$\pm0.4\times10^{-3}$	$\pm0.6\times10^{-4}$	$\pm0.01\times10^{-2}$

Table 9. Summary of $^{40}Ar/^{39}Ar$ age spectrum data for volcanic rocks from the Grant Range, Nevada, and Picacho Peak, Harcuvar Mountains, and Trigo Mountains, Arizona.

[aft, ash-flow tuff; and, andesite; dac, dacite; bio, biotite; san, sanidine; ad, adularia; ad-san, adularized sanidine; ad-plag, adularized plagioclase. Tp, plateau date. Tpf, preferred date for disturbed spectrum. Np, no plateau. ^{V}, vitrophyre; ^{K}, potassium metasomatized. All analyses performed at U.S. Geological Survey, Denver. Chemical analyses available in tables 1 and 2; published ages for Arizona localities are in table 4]

Sample no.	Rock	Mineral	Apparent age (Ma) and error (1 σ)	Character of spectrum
Windous Butte Formation, Ragged Ridge, Grant Range, Nevada				
$91B1^K$	aft	bio	31.53±0.08	Tp; 91.5% of total $^{39}Ar_K$
		ad-san	29.81±0.05	Tpf; 29.8% of total $^{39}Ar_K$
$91B2^K$	aft	bio	31.57±0.07	Tp; 85.8% of total $^{39}Ar_K$
		ad-san	25.22±0.6	Tpf; 30.0% of total $^{39}Ar_K$
Windous Butte Formation, Stone Cabin Ridge, Grant Range, Nevada				
$91B3^V$	aft	bio	31.70±0.07	Tp; 87.4% of total $^{39}Ar_K$
		san	31.31±0.5	Tp; 61.5% of total $^{39}Ar_K$
91B4	aft	bio	31.51±0.07	Tp; 72.5% of total $^{39}Ar_K$
		san	31.21±0.10	Tp; 81.0% of total $^{39}Ar_K$
Picacho Peak, Arizona				
PP-2	and	ad-plag	22.26±0.10	Tpf; 91.6% of total $^{39}Ar_K$
PP-9	dac	bio	22.19±0.12	Tpf; 93.8% of total $^{39}Ar_K$
Harcuvar Mountains, Arizona				
$HM\text{-}1^K$	aft	ad	15.98±0.08	Np
$E\text{-}191D^K$	aft	bio	24.29±0.2	Tp; 69.6% of total $^{39}Ar_K$
		ad-plag	22.06±0.12	Tpf; 35.9% of total $^{39}Ar_K$
$E\text{-}191B^V$	aft	bio	24.02±0.2	Tp; 91.0% of total $^{39}Ar_K$
E-210	dac	bio	21.72±0.13	Tp; 90.5% of total $^{39}Ar_K$
Trigo Mountains, Arizona				
$TG\text{-}8^K$	aft	bio	23.01±0.10	Tp; 94.0% of total $^{39}Ar_K$

INTERPRETATION OF $^{40}Ar/^{39}Ar$ DATA FROM THREE DETACHMENTS IN ARIZONA

Interpretation of K-Ar and fission-track dates from potassium-metasomatized rocks along detachment faults in Arizona was problematic because of the known effects of added potassium and elevated temperatures (Armstrong, 1970; Martin and others, 1981). Also, absolute dating of volcanism at localities in Arizona by K-Ar or $^{40}Ar/^{39}Ar$ methods is hindered by the absence of unaltered correlative rock. Therefore, conclusions from the Grant Range study can be applied to the interpretation of these dates. Feldspar descriptions below are based on petrography and X-ray diffraction analysis of the separate.

PICACHO PEAK

On the basis of >11 weight percent K_2O content of the andesites at Picacho Peak, alteration was suspected (fig. 6, table 1), but Shafiqullah and others (1976) nonetheless concluded that the analyses were indicative of primary alkalic composition. They interpreted the uniformity of hornblende (22.2 Ma) and whole-rock dates (22.3 Ma) to preclude alteration of the rocks at a time significantly later than eruption.

In contrast, we interpret the uncomplicated spectrum of adularia from PP-2 (figs. 5, 6) to indicate introduction of adularia and pervasive hydrothermal replacement of plagioclase by adularia during detachment (Rehrig and Reynolds, 1980). On the basis of conclusion number 3 from the Grant Range study and proximity (1–2 km) of this sample (PP-2) to the surface trace of the detachment fault, we interpret our date of 22.26 Ma as the time when the detachment was finally closed to circulation of hydrothermal fluids. Because correlative, unaltered samples of the andesite at Picacho Peak are not known, volcanism cannot be directly dated, but it is inferred to be older than 22 Ma. Duration of detachment cannot be bracketed.

The spectrum from biotite (PP-9) from a dacite dome in the Samaniego Hills, 8 km south of Picacho Peak (fig. 6), gave an uncomplicated date of 22.19 Ma (fig. 5). Due to erosion and faulting, the dacite has an unknown structural and stratigraphic relationship to the andesite and the date of 22.19 Ma only confirms local early Miocene dacitic volcanism in the area.

HARCUVAR MOUNTAINS

Potassium metasomatism of an unnamed ash-flow tuff, first dated at 17.3 Ma (Scarborough and Wilt, 1979) and later at 18.3–23.9 Ma (table 3; see also Brooks and Marvin, 1985), was initially recognized in the Harcuvar Mountains, Arizona (fig. 2), by Brooks (1984, 1988). Mapping and subdivision of the volcanic units in the eastern Harcuvar Mountains was done by Reynolds and Spencer (1984), and further studies by Roddy and others (1988) described detachment, associated mineralization, and the thermal regime (>300°C) during detachment.

We interpret the uncomplicated spectrum from adularia from pervasively potassium metasomatized (K_2O:Na_2O = 38, table 1) ash-flow tuff sample HM-1 (fig. 5) to indicate a minimum age of the metasomatism (15.98 Ma). And, on the basis of conclusion number 3 from the Grant Range work, we infer that this adularia date indicates the end of detachment-related metasomatism and closure of the hydrothermal system in the Harcuvar Mountains. This sample was obtained <3 m above the surface trace of the detachment (Brooks, 1988).

An uncomplicated spectrum from biotite from unaltered basal vitrophyre sample E191B (fig. 5), collected approximately 10 km southeast of the detachment, indicates the age of the base of the ash-flow tuff to be 24.02 Ma. Interpretation of this date as the age of eruption of the ash-flow tuff is supported by lack of potassium metasomatism of this sample (table 1) and distance (10 km) from the Harcuvar detachment. This is corroborated by Grant Range conclusion number 2. Therefore, detachment in the Harcuvar Mountains is interpreted to have taken place after emplacement of the ash-flow tuff (24 Ma) and terminated at ~16 Ma, the minimum age of the adularia introduced during detachment.

Biotite and adularized plagioclase from potassium-metasomatized sample E191D (12 weight percent K_2O, table 1), which is stratigraphically higher than E191B, provide more information about detachment in the Harcuvar Mountains. The biotite separate gave a date of 24.29 Ma (fig. 5, table 7) with no plateau—somewhat older than the 24.02 Ma date from the vitrophyre. This supports the interpretation that the date of 24 Ma is reliable as the age of the unit. This interpretation is also supported by conclusion number 2 of the Grant Range study. The adularia spectrum from sample E191D (fig. 5), however, is disturbed and has a rough plateau date of 22.06 Ma. Thus, we interpret that incipient adularization of the plagioclase began sometime after 24.29 Ma and continued until 16–18 Ma. Metasomatism of the volcanic units above the vitrophyre indicates a more permeable nature of the non-vitrophyric units.

The spectrum from biotite from sample E210, from an unaltered dacite flow 16 km northeast of the detachment, gave a plateau date of 21.72 Ma (fig. 5, table 7). The distance of this outcrop from the detachment and lack of alteration (conclusion 2 from the Grant Range) indicates that this date is reliable as the age of the dacite flow. This date confirms early Miocene volcanism in the area that was younger than ash-flow-producing volcanism. This flow is unaffected by thermal regimes that occurred during the detachment.

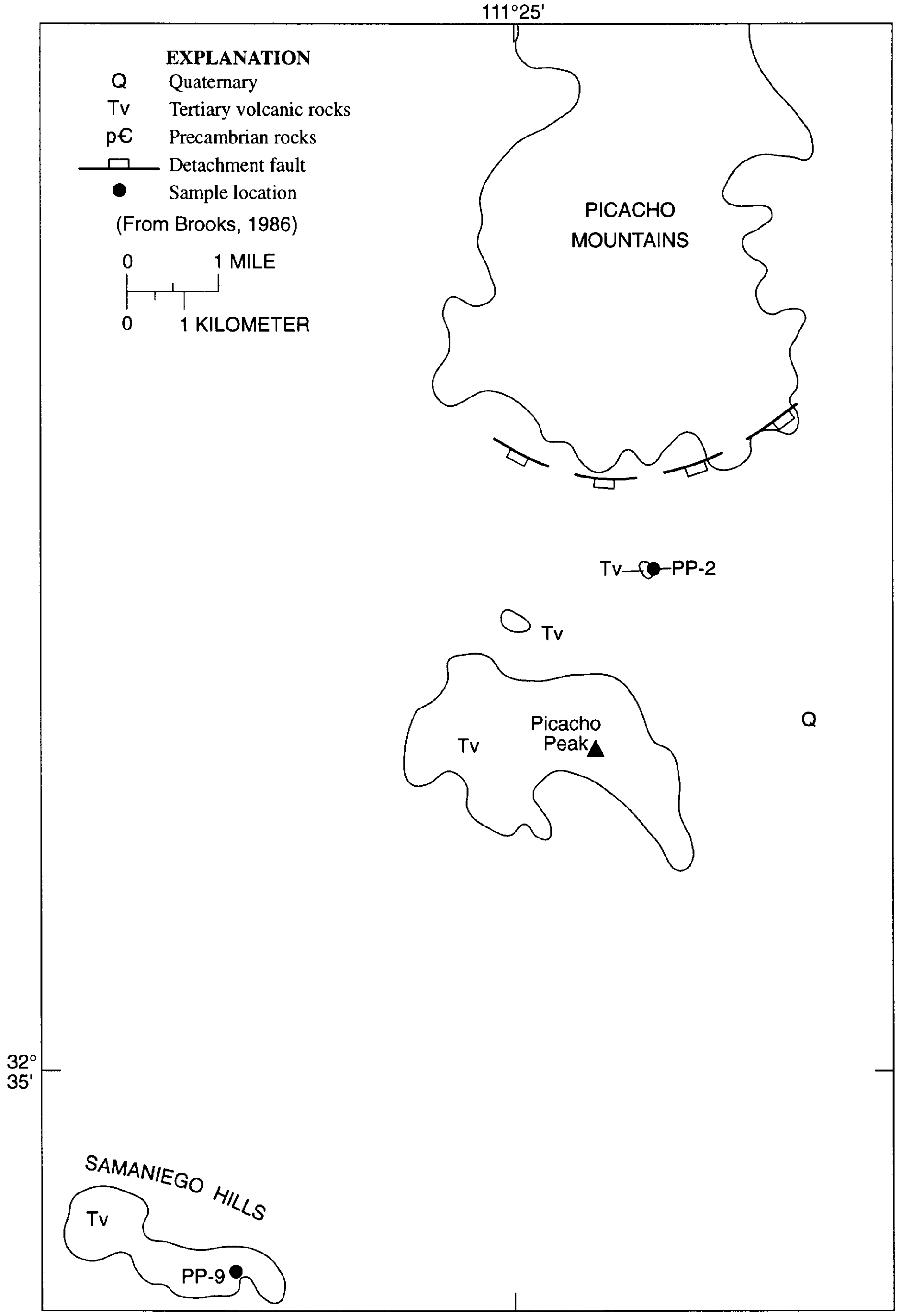


Figure 6. Location map of Picacho Peak area, Arizona.

TRIGO MOUNTAINS

Detachment faulting and associated mineralization were identified in the Trigo Mountains of southwest Arizona (fig. 7) by Garner and others (1982), and volcanic rocks in the area were dated (K-Ar method) by Weaver (1982). Due to this structural setting, we suspected and confirmed potassium metasomatism of these rocks (table 1).

A biotite separate from potassium-metasomatized ash-flow tuff (7.25 weight percent K_2O, table 1) in the Trigo Mountains gave an uncomplicated spectrum with an age of 23.01 Ma (sample TG-8, fig. 5). The K-Ar date on biotite from this location is 24.9 Ma (Weaver, 1982). Due to incipient potassium metasomatism (K_2O:Na_2O = 4.9, table 1), which resulted in marginal alteration, an adularia separate could not be obtained. Therefore, the $^{40}Ar/^{39}Ar$ biotite date of 23.0 Ma indicates early Miocene ash-flow volcanism, refinement of a K-Ar date and, in the absence of dates from correlative rock, indicates that detachment-related metasomatism in the Trigo Mountains occurred after 23 Ma.

DISCUSSION OF MODELS FOR DETACHMENT-RELATED POTASSIUM ENRICHMENT

Although the chemical effects of potassium metasomatism on volcanic rocks from calderas, at fossil geothermal sites, in lacustrine settings, and at detachments are analytically similar, no universal model satisfactorily explains the origin of the potassium-bearing fluids. Any model for detachment-related potassium metasomatism must also explain the thermal phenomenon of reset dates at detachments.

Chapin and Lindley (1986) propose a basin-brine model to explain the excess potassium in volcanic rocks at the Socorro, N. Mex., potassium anomaly. Based on their oxygen isotope studies, they conclude that potassium metasomatism can originate from (1) equilibration with waters enriched in heavy oxygen at temperatures of 250°–350°C, or (2) reaction with meteoric waters at temperatures of 30°–80°C. Their conclusions are based on geologic evidence from saline-lake environments, and they prefer a low-temperature regime (30°–80°C) and propose application of this model to potassium metasomatism in the detachment setting. We disagree with application of this brine model to the detachment setting because temperatures indicated by Chapin and Lindley (1986) are insufficient to reset dates that are well documented at several detachments (Martin and others, 1981; Brooks, 1986).

The structural setting of the Socorro potassium anomaly includes cauldrons, rift terrane, and early-rift clastic to playa deposits (Chapin and Lindley, 1986); however, it lacks a detachment fault. Therefore, the structural setting of the Socorro potassium anomaly is distinct and different than the structural setting of the Grant Range (Lund and Beard, 1987; Lund and others, 1987; Lund and others, 1991; Lund and Beard, 1992; Lund and others, 1993), Picacho Peak (Briscoe, 1967; Rehrig and Reynolds, 1980), the Harcuvar Mountains (Reynolds and Spencer, 1984), and the Trigo Mountains (Weaver, 1982), where a complicated regional detachment was mapped.

Tuffs that have undergone potassium metasomatism (12–16 weight percent K_2O) in the lacustrine environment also have elevated boron (0.58–0.97 B_2O_3) (Sheppard and Gude, 1965). Boron enrichment commonly takes place in closed basins under arid conditions (Christ, 1969; Orris, 1992). Boron enrichment might be useful in evaluation of the low-temperature brine model as applied to potassium-metasomatized volcanic rocks of the Grant Range. Therefore, metasomatized rocks from Ragged Ridge and unaltered rocks from Stone Cabin Ridge were analyzed for boron. Potassium-metasomatized ash-flow tuff of the Windous Butte Formation at Ragged Ridge has boron content that is higher (37–44 ppm) than unmetasomatized rock at Stone Cabin Ridge (16–28 ppm) (table 6). However, the somewhat elevated boron content, which might be interpreted to support the Chapin and Lindley (1986) brine model, can also be explained by (1) direct addition of boron, which is common in hydrothermal fluids (CRC Handbook of Chemistry and Physics, 1985), or (2) boron that is admixed from the upper meteoric reservoir (Kerrich and Rehrig, 1987) as the hydrothermal fluids moved up the detachment pathway and intersected a closed lacustrine basin.

Evidence for hydrothermal alteration, with a meteoric component, of upper-plate volcanic rocks at detachments is compelling. At Picacho Peak, Kerrich and Rehrig (1987) and Kerrich (1988) use oxygen isotopes and concluded that two fluid reservoirs were involved in alteration of the lower- and upper-plate rocks. Their studies show an upward transition from high to low temperatures and from ductile creep to brittle fracturing. They also describe hydraulic breccias and an interface of deep fluids with a shallow surface reservoir. The brine model of Chapin and Lindley (1986) does not account for those features nor does it explain the Miocene thermal regime that reset the Cretaceous Troy Granite and the Oligocene Windous Butte Formation in the Grant Range to late Oligocene or early Miocene ages. Because the biotite from the granite was reset, we infer that temperatures at depth must have exceeded 280°C (the resetting temperature of biotite). The 31-Ma ash-flow tuff of the Windous Butte Formation at Ragged Ridge has sanidine that was adularized from 31–20 Ma by fluids that were cooler than 280°C (biotite dates from adularized Ragged Ridge samples were not reset). This parallel resetting can be accomplished by a circulating, upward-cooling, hydrothermal system, but not by a low-temperature (30°–80°C) lacustrine brine system.

A regional hydrothermal model (Bartley and Glazner, 1985; Glazner and Bartley, 1989) best explains detachment-related potassium metasomatism at locations in the Mojave Desert, California, and provides a mechanism for reset K-Ar (Martin and others, 1980), fission-track (Brooks, 1986), and $^{40}Ar/^{39}Ar$ dates (this study). Such a system also provides an appropriate means of transferring Au, As, Zr, and other types of mineralization (Brooks, 1985; Rehrig and Kerrich, 1986), such as argentiferous galena and sphalerite (Naruk, 1984). The hydrothermal model does not imply a pluton beneath each detachment.

The brine model of Chapin and Lindley (1986), which conflicts with the hydrothermal model, is not valid in the Mojave, California, study areas because (1) lacustrine sedimentary rocks of the proper age are missing, and (2) the brine model does not account for upward-terminating, jasper-filled breccia zones that served as conduits for the potassium-rich fluids (Glazner and Bartley, 1989). Similarly, temperatures of the brine model (30°–80°C) of Chapin and Lindley (1986)

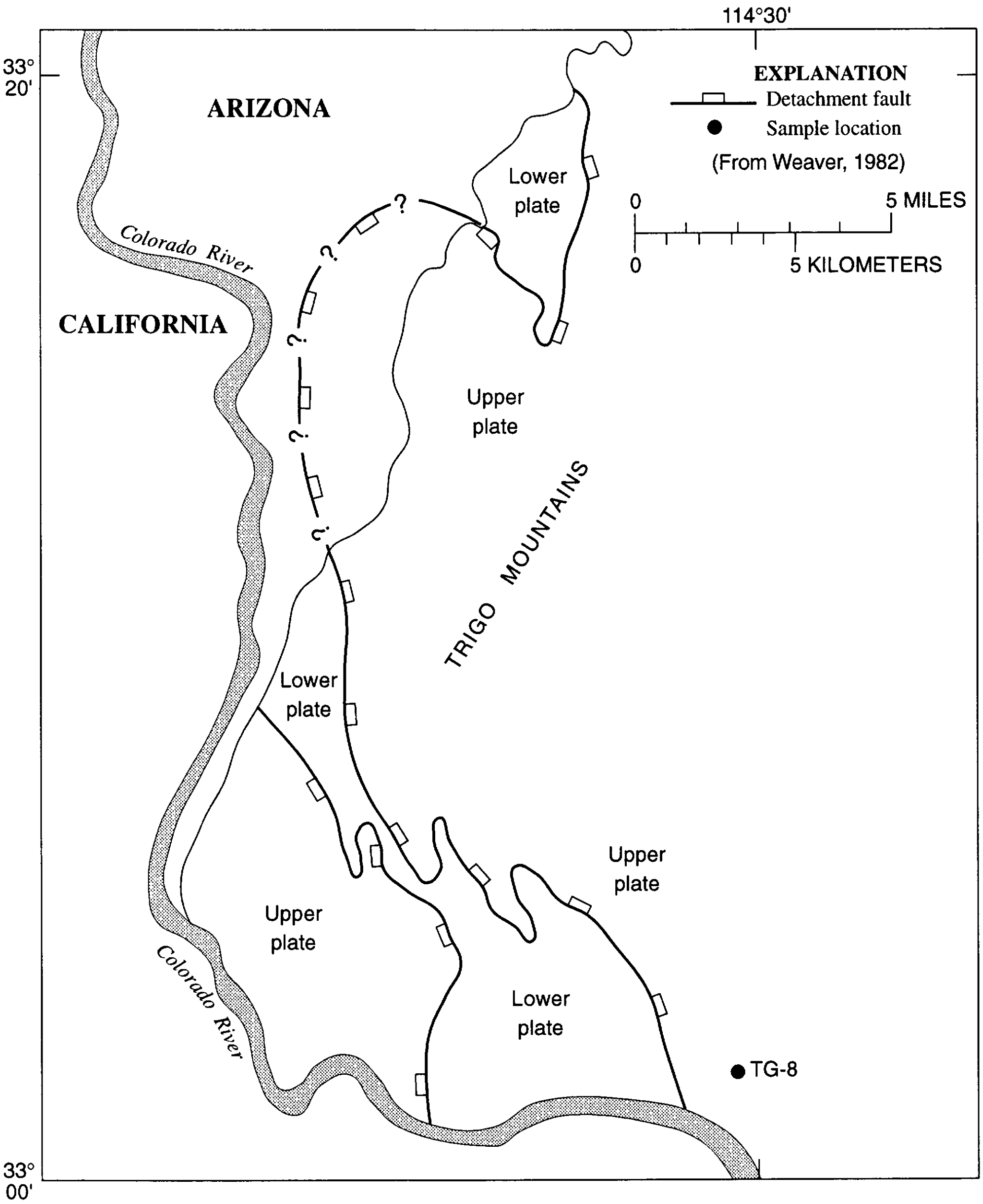


Figure 7. Location map of Trigo Mountains area, Arizona.

are inadequate to explain the well-documented and widespread reset biotite K-Ar dates at detachments. Temperatures in excess of 280°C are needed. However, resetting of dates would occur in response to the estimated 300°–700°C temperatures of mylonitization at the Swansea and Copper Penny, Arizona, detachments (Naruk, 1984).

Further support of a hydrothermal model is based on fluid-inclusion studies by Beane and others (1986) on mineralized detachments. Their work indicates homogenization temperatures of 150°–225°C and 200°–325°C for two mineral assemblages; these temperatures are hotter than temperatures used in definition of the brine model. Similarly, for the Harcuvar Mountains and the Picacho Peak localities, Rehrig and Kerrich (1986) cite geochemical and oxygen-isotopic evidence that indicates a magmatic-metamorphic signature for fluids responsible for the metasomatic alteration with temperatures of 300°–350°C. Similarly, ore mineralogy and fluid-inclusion studies support a primary hydrothermal source for the mineralizing event at the detachement-related Bannock propect in California (Saunders, 1996).

At the Harcuvar Mountains detachment, hydrothermal evidence also includes the presence of psilomelane, a potassium-rich type of manganese generally derived from thermal waters from depth (Hewett and others, 1963); this mineral is reported at the Harris claims near the detachment (Farnham and Stewart, 1958; Keith and others, 1983). This implies middle Tertiary (Keith and others, 1983) hydrothermal mineralization coeval with potassium-rich hydrothermal fluids that caused potassium metasomatism.

A fossil geothermal system is the mechanism for alkali (potassium) metasomatism of the Wah Wah Springs tuff in southwestern Utah (Nusbaum and Grant, 1987). Oxygen isotope and chemical studies show that metasomatism at Creede resulted from interaction of the intracaldera tuffs with deeply circulating ground water that resulted in alteration of phenocrystic and groundmass feldspars to more Or-rich compositions (Bethke and others, 1985).

Fluid-inclusion studies of a currently active meteoric-hydrothermal system in the Grant Canyon and Bacon Flat oil fields, west of the Grant Range, indicate homogenization temperatures of 117°C and 121°C, respectively (Hulen and others, 1991, 1994). On the basis of comparison with other geothermal systems in the Basin and Range, these workers conclude that the Grant Canyon–Bacon Flat system is probably no older than 2.5 Ma.

CONCLUSIONS

Evidence for potassium metasomatism in the northern Basin and Range is now documented in the Grant Range. Our work shows that $^{40}Ar/^{39}Ar$ dates on biotite from potassium-metasomatized Windous Butte Formation at Ragged Ridge, 4 km from the surface trace of the detachment in the Grant Range, are concordant with regional Windous Butte Formation dates. Biotite dates from metasomatized rocks at this distance or greater are insensitive to the thermal effects of metasomatism and are, therefore, reliable indicators of the age of volcanism. The temperatures of hydrothermal fluids that contributed excess potassium (as adularia) did not exceed the resetting temperature of biotite (280°C). However, independent evidence (Armstrong, 1970) of reset-to-Miocene ages from the Cretaceous Troy granite suggests that these temperatures were greater at depth.

Effects of potassium metasomatism on feldspars range from incipient to pervasive. At Ragged Ridge, northern Grant Range, the sanidine dates from metasomatized rock near the detachment are disturbed, and XRD studies show that the sanidine has been adularized. Adularization took place in response to detachment-related potassium metasomatism some time after 31 Ma (the age of the Windous Butte Formation) and terminated at about 20 Ma. We infer that the detachment fault zone that contributed the potassium-rich fluids was closed to circulation in the early Miocene (20 Ma). Our chemical and geochronological studies of correlative potassium-metasomatized and unaltered rocks in the Grant Range are fundamental to comparative study of the effects of metasomatism on potassium-dependent dating methods. Application of conclusions from this study permits more accurate understanding of isotopic dating of metasomatism and metasomatized rocks elsewhere in the Basin and Range.

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REFERENCES CITED

Armstrong, R.L., 1970, Geochronology of Tertiary igneous rocks, eastern Basin and Range Province, western Utah, eastern Nevada, and vicinity, U.S.A.: Geochimica et Cosmochimica Acta, v. 34, p. 203–232.

Axen, G.J., Taylor, W.J., and Bartley, J.M., 1993, Space-time patterns and tetonic controls of Tertiary extension and magmatism in the Great Basin of the Western United States: Geological Society of America Bulletin, v. 105, p. 56–76.

Bartley, J.M., and Glazner, A.F., 1985, Hydrothermal systems and Tertiary low-angle normal faulting in the Southwestern United States: Geology, v. 13, p. 562–564.

Beane, R.E., Wilkins, J., and Heidrick, T.L., 1986, A geochemical model for gold mineralization in the detachment fault environment, *in* Beatty, B., and Wilkinson, P.A.K., eds., Frontiers in Geology and Ore Deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 232.

Best, M.G., Christiansen, E.H., Deino, A.L., Grommé, C.S., Edwin, H.M., and Noble, D.C., 1989, Excursion 3A—Eocene through Miocene volcanism in the Great Basin of the Western United States: New Mexico Bureau of Mines and Mineral Resources Memoir 47, p. 91–133.

Bethke, P.M., Rye, R.O., and Barton, P.B., 1985, Pre-ore potassium metasomatism, Creede mining district, Colorado [abs.]: *in* Hausen, D.M., and Kopp, O.C., eds., Mineralogy—Applications to the Minerals Industry, Proceedings of the Paul F. Kerr Memorial Symposium, New York, Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 241.

Briscoe, J.A., 1967, The general geology of the Picacho Peak area: Tucson, University of Arizona, M.S. thesis, 52 p.

Brooks, W.E., 1984, Volcanic stratigraphy of part of McLendon volcano, Anderson mine area, Yavapai County, Arizona: U.S. Geological Survey Open-File Report 84-350, 42 p.

———1985, Analyses of upper-plate volcanic rocks at Picacho Peak, Pinal County, Arizona: U.S. Geological Survey Open-File Report 85-0740, 5 p.

———1986, Distribution of anomalously high K_2O volcanic rocks in Arizona: Metasomatism at the Picacho Peak detachment fault: Geology, v. 14, p. 339–342.

———1987, Spatial relationship of K_2O metasomatism and base metals to the Picacho Peak detachment fault, Pinal County, Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 7, p. 602.

———1988, Recognition and geologic implications of potassium metasomatism in upper-plate volcanic rocks at the detachment fault at the Harcuvar Mountains, Yavapai County, Arizona: U.S. Geological Survey Open-File Report 88-0017, 9 p.

Brooks, W.E., and Marvin, R.F., 1985, Discordant isotopic ages and potassium metasomatism in volcanic rocks from Yavapai

County, Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 17, no. 6, p. 344.

Brooks, W.E., Snee, L.W., and Scott, R.B., 1994, Timing and effect of detachment-related potassium metasomatism on $^{40}Ar/^{39}Ar$ dates from the Windous Butte ash-flow tuff, Grant Range, east-central Nevada [abs]: Geological Society of America Abstracts with Programs, v. 26, no. 2, p. 41.

Brooks, W.E., Thorman, C.H., and Snee, L.W., 1995a, The $^{40}Ar/^{39}Ar$ ages and tectonic setting of the middle Eocene northeast Nevada volcanic field: Journal of Geophysical Research, v. 100, no. B7, p. 10403–10416.

Brooks, W.E., Thorman, C.H., and Snee, L.W., 1995b, Correction to "The $^{40}Ar/^{39}Ar$ ages and tectonic setting of the middle Eocene northeast Nevada volcanic field:" Journal of Geophysical Research, v. 100, no. B8, p. 15545–15548.

Brooks, W.E., Thorman, C.H., Snee, L.W., Nutt, C.J., Potter, C.J., and Dubiel, R.F., 1995 Summary of chemical analyses for volcanic rocks from the central part of the northeast Nevada volcanic field, chap. K *of* Cook, H.E., and Potter, C.J., project coordinators, Evolution of Sedimentary Basins—Eastern Great Basin: U.S. Geological Survey Bulletin 1988, p. K1–K33.

Brown, C.L., and Schmidt, J.G., 1991, Horse Camp Formation, record of Miocene-Pliocene extensional basin development, northern Grant Range, Nevada, *in* Flanigan, D.M.H., Hansen, M., and Flanigan, T.E., eds., Geology of White River Valley, the Grant Range, Eastern Railroad Valley and Western Egan Range, Nevada: 1991 Field Trip Guidebook, Reno, Nevada Petroleum Society, p. 7–13.

Carr, M.J., Rose, W.I., and Mayfield, D.G., 1979, Potassium content of lavas and depth to the seismic zone in Central America: Journal of Volcanology and Geothermal Research, v. 5, p. 387–401.

Chapin, C.E., and Glazner, A.F., 1983, Widespread K_2O metasomatism of Cenozoic volcanic and sedimentary rocks in the Southwestern United States [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 282.

Chapin, C.E., and Lindley, J.I., 1986, Potassium metasomatism of igneous and sedimentary rocks in detachment terranes and other sedimentary basins; economic implications, *in* Beatty, B., and Wilkinson, P.A.K., eds., Frontiers in Geology and Ore Deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 118–126.

Christ, C.L., 1969, Boron, *in* Wedepohl, K.H., ed. Handbook of Geochemistry, New York, McGraw Hill, p. 5-A-1.

Cook, E.F., 1965, Stratigraphy of Tertiary volcanic rocks in eastern Nevada: Nevada Bureau of Mines, Report II, 61 p.

CRC Handbook of Chemistry and Physics, 1985, Boron, *in* Weast, R.C., ed., CRC Handbook of Chemistry and Physics, Boca Raton, Fla., CRC Press, p. B10.

Dalrymple, G.B., Alexander, E.C.J., Lanphere, M.A., and Kraker, G.P., 1981, Irradiation of samples for $^{40}Ar/^{39}Ar$ dating using the Geological Survey TRIGA reactor: U.S. Geological Survey Professional Paper 1176, 55 p.

Dalrymple, G.B., and Lanphere, M.A., 1969, Potassium-Argon Dating: San Francisco, W.H. Freeman, 251 p.

Davis, G.A., Anderson, J.L., Martin, D.L., Krummenacher, D., Frost, E.G., and Armstrong, R.L., 1982, Geologic and geochronologic relations in the lower plate of the Whipple detachment fault, Whipple Mountains, southeastern California: A progress report, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada: Anderson-Hamilton Volume, in conjunction with a Symposium and Field Trip for the Geological Society of America, San Francisco, Cordilleran Publishers, p. 409–432.

Davis, G.H., 1977, Characteristics of metamorphic core complexes, southern Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 9, no. 7, p. 944.

Deer, W.A., Howie, R.A., and Zussman, J., 1971, Rock-Forming Minerals, v. 4, Framework Silicates: London, Longman Group, 435 p.

Ekren, E.B., Anderson, R.E., Rogers, C.L., Noble, D.C., 1971, Geology of northern Nellis Air Force Base Bombing and Gunnery Range, Nye County, Nevada: U.S. Geological Survey Professional Paper 651, 91 p.

Elsass, F., and duBray, E.A., 1982, Energy-dispersive X-ray fluorescence spectrometry with the Kevex 7000 system: Saudi Arabian Ministry of Mineral Resources Open File Report USGS-OF-02-52, 53 p.

Farnham, L.L., and Stewart, L.A., 1958, Manganese deposits of western Arizona: U.S. Bureau of Mines Information Circular 7843, 65 p.

Fryxell, J.E., 1984, Structural development of the west-central Grant Range, Nye County, Nevada: Chapel Hill, University of North Carolina, Ph.D. dissertation, 139 p.

———1988, Geologic map and descriptions of stratigraphy and structure of the west-central Grant Range, Nye County, Nevada: Geological Society of America, Map and Chart Series MCH064, map scale 1:24,000, 8 cross sections, 16 p.

Garner, W.E., Frost, E.G., Tanges, S.E., and Germinario, M.P., 1982, Mid-Tertiary detachment faulting and mineralization in the Trigo Mountains, Yuma County, Arizona, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada: Anderson-Hamilton Volume, in conjunction with a Symposium and Field Trip for the Geological Society of America, San Francisco, Cordilleran Publishers, p. 158–173.

Glazner, A.F., and Bartley, J.M., 1989, Source of potassium in potassium-metasomatized, extended Tertiary rocks of the Mojave Desert, *in* Continental Magmatism Abstracts, International Association of Volcanology and Chemistry of the Earth's Interior, General Assembly, Santa Fe, New Mexico, June 25–July 1, 1989 [abs.]: New Mexico Bureau of Mines and Mineral Resources, Bulletin 131, p. 109.

———1990, Contrasting Cenozoic tectonomagmatic histories of the northern and southern Basin and Range [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 25.

Golightly, D.W., Dorrzapf, A.F., Mays, R.E., Fries, T.L., and Conklin, N.M., 1987, Analysis of geologic materials by X-ray fluor escence spectrometry, *in* Baedecker, P.A., ed., Methods for Geochemical Analysis: U.S. Geological Survey Bulletin 1770, p. A1–A13.

Grommé, C.S., McKee, E.H., and Blake, M.C., 1972, Paleomagnetic correlations and potassium-argon dating of middle Tertiary ash-flow sheets in the eastern Great Basin, Nevada and Utah: Geological Society of America Bulletin, v. 83, p. 1619–1638.

Hewett, D.F., Fleischer, M., and Conklin, N., 1963, Deposits of the manganese oxides, supplement: Economic Geology, v. 58, no. 1, p. 1–51.

Hollocher, K., Spencer, J., and Ruiz, J., 1994, Compositional changes in an ash-flow cooling unit during K metasomatism, west-central Arizona: Economic Geology, v. 89, p. 877–888.

Hulen, J.B., Bortz, L.C., and Bereskin, S.R., 1991, Geothermal processes in evolution of the Grant Canyon and Bacon Flat oil reservoirs, Railroad Valley, Nye County, Nevada, *in* Flanigan, D.M.H., Hansen, M., and Flanigan, T.E., eds., Geology of White River Valley, the Grant Range, Eastern Railroad Valley, and Western Egan Range, Nevada: 1991 Field Trip Guidebook, Reno, Nevada Petroleum Society, p. 47–54.

Hulen, J.B., Goff, F., Ross, J.R., Bortz, L.C., and Bereskin, S.R., 1994, Geology and geothermal origin of Grant Canyon and Bacon Flat oil fields, Railroad Valley, Nevada: American Association of Petroleum Geologists, v. 78, no. 4, p. 596–623.

Keith, S.B., Schnabel, L., DeWitt, E., Gest, D.E., and Wilt, J., 1983, Map, description, and bibliography of the mineralized areas of the Basin and Range Province in Arizona: U.S. Geological Survey Open-File Report 84-0086, 129 p.

Kerrich, R., 1988, Detachment zones of Cordilleran metamorphic core complexes: Thermal, fluid, and metasomatic regimes: Geologische Rundschau, v. 77, no. 1, p. 157–182.

Kerrich, R., and Rehrig, W., 1987, Fluid motion associated with Tertiary mylonitization and detachment faulting: $^{18}O/^{16}O$ evidence from the Picacho metamorphic core complex, Arizona: Geology, v. 15, p. 58–62.

Kerrich, R., Rehrig, W., Arima, M., and McLarty, E., 1986, Southwest metamorphic core complexes—Upper plate Tertiary potassic mafic volcanics and their hydrothermal metasomatism [abs]: Geological Society of America Abstracts with Programs, v. 18, no. 2., p. 124.

Lindgren, W., 1888, Notes on the geology of Baja California, Mexico: Proceedings of the California Academy of Sciences, v. 1, p. 173–196.

———1912, The nature of replacement: Economic Geology, v. 7, no. 6, p. 521–535.

Lindley, J.I., Dinkleman, J.F., Glazner, A.F., and Osburn, G.R., 1983, Chemical and mineralogic variations associated with potassium metasomatism of Tertiary volcanic rocks from the Rio Grande rift and Mohave Desert [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 282.

Lipman, P.W., Protska, H.J., and Christiansen, R.L., 1972, Cenozoic volcanism and plate-tectonic evolution of the Western United States, I, early and middle Cenozoic: Philosophical Transactions of the Royal Society of London, ser. A, v. 271, p. 271–248.

Lund, K., and Beard, L.S., 1987, Heterogeneous extensional geometries in the northern Grant Range, east-central Nevada [abs.]: Geological Society of America Abstracts with Programs, v. 19, p. 751.

———1992, Extensional geometry in the northern Grant Range, east-central Nevada: Implications for oil deposits in Railroad Valley, *in* Thorman, C.H., ed., Application of Structural Geology to Mineral and Energy Resources of the Central and Western United States: U.S. Geological Survey Bulletin 2012, p. I1–I9.

Lund, K., Beard, L.S., and Perry, W.J., 1991, Structures of the northern Grant Range and Railroad Valley, Nye County, Nevada: Implications for oil occurrences, *in* Flanigan, D.M.H., Hansen, M., and Flanigan, T.E., eds., Geology of White River Valley, the Grant Range, Eastern Railroad Valley and Western Egan Range, Nevada: 1991 Field Trip Guidebook, Reno, Nevada Petroleum Society, p. 1.

———1993, Relation between extensional geometry of the northern Grant Range and oil occurrences in Railroad Valley, east-central Nevada: American Association of Petroleum Geologists Bulletin, v. 77, no. 6, p. 945–962.

Lund, K., Nash, J.T., Beard, L.S., and Blank, H.R., 1987, Mineral resources of the Blue Eagle Wilderness Study Area, Nye County, Nevada: U.S. Geological Survey Bulletin 1731, p. D1–D19.

Martin, D.L., Barry, W.L., Krummenacher, D., and Frost, E.G., 1980, K-Ar dating of mylonitization and detachment faulting in the Whipple Mountains, San Bernardino County, California, and the Buckskin Mountains, Yuma County, Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 12, no. 3, p. 118.

Martin, D.L., Krummenacher, D., and Frost, E.G., 1981, Regional resetting of the K-Ar isotopic system by mid-Tertiary detachment faulting in the Colorado River region, California, Arizona, and Nevada [abs.]: Geological Society of America Abstracts with Programs, v. 13, no. 7, p. 504.

Naruk, S.J., 1984, A model for detachment fault gold mineralization [abs.]: Geological Society of America Abstracts with Programs, v. 16, no. 6, p. 607.

Nusbaum, R.L., and Grant, S.K., 1987, Alkali metasomatism and fossil geothermal activity: Wah Wah Springs tuff, Utah: The Rocky Mountain Geologist, v. 24, no. 1, p. 26–29.

Orris, G.J., 1992, Industrial mineral deposit models—Descriptive models for three lacustrine deposit types: U.S. Geological Survey Open-File Report 92-593, 14 p.

Phillips, L.V., 1989, The petrology and magmatic evolution of the large-volume ash-flow tuffs of the central Nevada caldera complex, Nye County, Nevada: Athens, University of Georgia, Ph.D. dissertation, 285 p.

Pitkin, J.A., Conway, C.M., and Haxel, G.B., 1994, Thorium, uranium, and potassium aeroradioactivity maps of Arizona—Geologic interpretation and metallogenic significance, *in* Carter, L.M.H., and others, eds., USGS Research on Mineral Resources—1994, Part A—Program and Abstracts [abs.]: U.S. Geological Survey Circular 1103-A, p. 75–76.

Ratté, J.C., and Steven, T.A., 1967, Ash flows and related volcanic rocks associated with the Creede caldera, San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 524–H, p. H1–H58.

Rehrig, W.A., and Kerrich, R., 1986, Tectonic-economic significance of isotopic and geochemical data from detachment zones of metamorphic complexes, Southwestern United States [abs.]: Geological Society of America Abstracts with Programs, v. 18, no. 2, p. 174.

Rehrig, W.A., and Reynolds, S.J., 1980, Geologic and geochronologic reconnaissance of a northwest-trending zone of metamorphic core complexes in southern and western Arizona: Geological Society of America Memoir 153, p. 131–157.

Rehrig, W.A., Shafiqullah, M., and Damon, P.E., 1980, Geochronology, geology, and listric normal faulting of the Vulture Mountains, Maricopa County, Arizona: Arizona Geological Society Digest, v. 12, p. 89–110.

Reynolds, S.J., and Spencer, J.E., 1984, Geologic map of the Aguila Ridge and Bullard Peak area, eastern Harcuvar Mountains, west-central Arizona: Arizona Bureau of Geology and Mineral Technology, Open-File Report 84-4, scale 1:24,000.

Roddick, J.S., 1983, High-precision intercalibration of $^{40}Ar/^{39}Ar$ standards: Geochimica et Cosmochimica Acta, v. 47, p. 887–898.

Roddy, M.S., Reynolds, S.J., Smith, B.M., Ruiz, J., 1988, K-metasomatism and detachment-related mineralization, Harcuvar Mountains, Arizona: Geological Society of America Bulletin, v. 100, p. 1627–1639.

Rowell, W.F., and Edgar, A.D., 1983, Cenozoic potassium-rich mafic volcanism in the Western U.S.A.: Its relationship to deep subduction: Journal of Geology, v. 91, p. 338–341.

Sander, M.V., and Einaudi, M.T., 1990, Epithermal deposition of gold during transition from propylitic to potassic alteration at Round Mountain, Nevada: Economic Geology, v. 85, p. 285–311.

Saunders, F., 1996, Bannock prospect, San Bernardino County California, *in* Rehrig, W.A., ed., Tertiary Extension and Mineral Deposit, Southwestern U.S., I. Low-Angle Tectonic Features of the Southwestern United States and their Influence on Mineral Resources: Guide book Prepared for the Society of Economic Geologists Field Conferences, Guide book Series, V.25, p.115-126.

Sawyer, D.A., and Sargent, K.A., 1989, Petrologic evolution of divergent peralkaline magmas from the Silent Canyon caldera complex, southwestern Nevada volcanic field: Journal of Geophysical Research, v. 94, p. 6021–6040.

Sawyer, D.A., Sweetkind, D., Rye, R.O., Siems, D.F., Reynolds, R.L., Rasenbaum, J.G., Lipman, P.W., Boylan, J.A., Barton, P.B., Bethke, P.M., and Curtin, G.C., 1989, Potassium metasomatism in the Creede mining district, San Juan volcanic field, Colorado [abs.], *in* Continental Magmatism Abstracts, International Association of Volcanology and Chemistry of the Earth's Interior, General Assembly, Santa Fe, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 131, p. 234.

Scarborough, R.B., and Wilt, J.C., 1979, A study of the uranium favorability of Cenozoic sedimentary rocks, Basin and Range Province, Arizona: U.S. Geological Survey Open-File Report 79-1429, 101 p.

Scherkenbach, D.A., and Noble, D.C., 1984, Potassium and rubidium metasomatism at the Julcani district, Peru: Economic Geology, v. 79, p. 565–572.

Scott, R.B., 1965, The Tertiary geology and ignimbrite petrology of the Grant Range, east-central Nevada: Houston, Rice University, Ph.D. dissertation, 116 p.

Shafiqullah, M., Lynch, D.J., and Damon, P.E., 1976, Geology, geochronology and geochemistry of the Picacho Peak area, Pinal County, Arizona: Arizona Geological Society Digest, v. 10, p. 305–324.

Shawe, D.R., and Lepry, L.B., 1985, Analytical data for rock samples from the Round Mountain and Manhattan quadrangles, Nye County, Arizona: U.S. Geological Survey Open-File Report 85-0538, 38 p.

Sheppard, R.A., and Gude, A.J., 1965, Potash feldspar of possible economic value in the Barstow Formation, San Bernardino County, California: U.S. Geological Survey Circular 500, 7 p.

———1973, Zeolites and associated authigenic silicate minerals in tuffaceous rocks of the Big Sandy Formation, Mohave County, Arizona: U.S. Geological Survey Professional Paper 830, 36 p.

Shubat, M.A., and Snee, L.W., 1992, High-precision $^{40}Ar/^{39}Ar$ geochronology, volcanic stratigraphy, and mineral deposits of Keg Mountain, west-central Utah, *in* Thorman, C.H., ed., Application of Structural Geology to Mineral and Energy Resources of the Central and Western United States: U.S. Geological Survey Bulletin 2012, p. G1–G16.

Silberman, M.L., and Chesterman, C.W., 1988, Hydrothermal adularia in the Bodie mining district, Mono County, California: Mode of occurrence, structure, and chemistry, *in* Modreski, P.J., ed., Mineralogy of Precious Metal Deposits: Colorado Chapter, Friends of Mineralogy, Symposium Volume, p. 40–52.

Snee, L.W., 1982, Emplacement and cooling of the Pioneer batholith, southwestern Montana: Columbus, Ohio State University, Ph.D. dissertation, 320 p.

Snee, L.W., Sutter, J.F., and Kelley, W.C., 1988, Thermochronology of economic mineral deposits: Dating the stages of mineralization at Panasqueira, Portugal, by high-precision $^{40}Ar/^{39}Ar$ age spectrum techniques on muscovite: Economic Geology, v. 83, p. 335–354.

Snoke, A.W., and Lush, A.P., 1984, Polyphase Mesozoic-Cenozoic deformational history of the northern Ruby Mountains and East Humboldt Range, Nevada, *in* Lintz, J., Jr., ed., Western Geological Excursions: Geological Society of America Annual Meeting, v.4, p. 232–303.

Spencer, J.E., Shafiqullah, M., Miller, R.J., and Pickthorn, L.G., 1989, K-Ar geochronology of Miocene extension, volcanism, and potassium metasomatism in the Buckskin and Rawhide Mountains, *in* Spencer, J.E., and Reynolds, S.J., eds., Geology and mineral resources of the Buckskin and Rawhide Mountains, west-central Arizona: Arizona Geological Survey Bulletin 198, p. 184–189.

Taggart, J.E., Lindsay, J.R., Scott, B.A., Vivit, D.V., Bartel, A.J., and Stewart, K.C., 1987, Analysis of geologic materials by X-ray fluorescence spectrometry, *in* Baedecker, P.A., ed., Methods for Geochemical Analysis: U.S. Geological Survey Bulletin 1770, p. E1–E9.

Turekian, K.K., and Wedepohl, K.H., 1961, Distribution of elements in some major units of the Earth's crust: Geological Society of America Bulletin, v. 72, p. 175–192.

Weaver, B.F., 1982, Reconnaissance geology and K-Ar geochronology of the Trigo Mountains detachment terrane, Yuma County Arizona: San Diego, San Diego State University, M.S. thesis, 61 p.

West, D.P., and Lux, D.R., 1993, Direct dating of mylonitization by the $^{40}Ar/^{39}Ar$ method, an example from the Norumbega fault zone, Maine [abs.]: American Geophysical Union Abstracts with Programs, v. 74, no. 16, p. 122.

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