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Rapid uplift and rotation of mylonitic rocks from beneath a detachment fault: Insights from potassium feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology, northern Snake Range, Nevada

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Abstract. The thermal histories of mylonitic rocks from the footwall of the northern Snake Range decollement (NSRD), Nevada, were calculated using multiple diffusion domain analyses of potassium feldspar Arrhenius data and $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra in order to characterize the cooling (exhumation) history of these mylonitic rocks and thereby constrain the origin and movement history of the NSRD. The calculated thermal histories, along with reported apatite fission track ages, indicate the three following episodes of rapid cooling (10–55°C/m.y.) related to extensional denudation: (1) middle Eocene (48–41 Ma), (2) late Oligocene (30–26 Ma), and (3) early Miocene (20–16 Ma). The first episode of rapid cooling may be related to the earliest period of normal faulting in east central Nevada and initiation of slip along the NSRD. The second episode signals a pulse of slip along the NSRD, and the third episode marks the cessation of lower plate mylonitic deformation and the onset of the major pulse of uplift and rotation of lower plate rocks from beneath the NSRD and/or younger east dipping normal faults. The thermal history data provide evidence for a temperature difference across the range within the same structural horizon; the northwestern flank of the range dropped below 300°C by 46 Ma and reached 115°C by 20 Ma, whereas lower plate rocks in the eastern parts of the range were at temperatures above 300°C until 19 Ma. If isotherms were subhorizontal, these relations suggest that either lower plate units had an eastward dip prior to the onset of Tertiary mylonitic deformation or that layering dipped eastward as a result of top-to-the-east shear within an east dipping shear zone. Either case results in differential cooling (uplift) of lower plate rocks from beneath the NSRD. A temperature-distance-age graph, constructed based upon the calculated thermal histories, shows differential uplift and rotation of moderately to steeply east dipping lower plate units from beneath the NSRD. Furthermore, this reconstruction shows that the dip of lower plate units increases and then decreases in time and space. This reconstruction implies that the NSRD initiated at moderate to steep angles that shallowed at depth, listric style, into a shallow dipping shear zone. These reconstructions provide a spectacular example of the rolling hinge/isostatic rebound model.

Introduction

Metamorphic core complex detachment faults have been the subject of much study over the last 15 years, and yet the origin

and movement histories of these faults and the mechanisms by which they translate midcrustal rocks to the surface are still topics of debate [cf. *Wernicke*, 1981, 1985; *Gans et al.*, 1985; *Davis*, 1983, 1987; *Davis et al.*, 1986; *Buck*, 1988; *Hamilton*, 1988; *Wernicke and Axen*, 1988; *Lister and Davis*, 1989]. Due to the lack of suitable offset markers across detachment faults that are also paleohorizontal indicators, questions remain as to whether these faults initiated and moved at low angles or whether they initiated at high angles and rotated to shallow dips during slip.

The northern Snake Range metamorphic core complex, Nevada (Figure 1), is at the center of this controversy. *Wernicke* [1981] first introduced the idea of a low-angle origin for detachment faults and cited the northern Snake Range decollement (NSRD) as a type example. Later geologic mapping and structural studies in the northern Snake Range by *Miller et al.* [1983] and *Gans and Miller* [1983] lead these workers to argue that the NSRD originated as a subhorizontal ductile-brittle transition zone, with little or no translation, between a brittlely extended upper plate and a ductilely thinned lower plate. This interpretation was disputed by *Bartley and Wernicke* [1984], who proposed, instead, that the NSRD originated as a low-angle normal fault with at least 60 km of displacement and brought footwall rocks up and out from beneath a thrust plate. New, high-resolution seismic reflection data and surface geology data lead *Gans et al.* [1985] to suggest that the NSRD exposed in the northern Snake Range originated as a near flat zone of decoupling, with of the order of 10 km of displacement, between brittle deformation above and ductile deformation below. To the west the NSRD was a brittle structure that merged with a high-angle, east dipping normal fault. Mesoscopic, microstructural, and petrofabric studies showed that lower plate mylonitic strain was complex, involving coaxial and noncoaxial components and was kinematically linked to the evolution of the NSRD [*Lee et al.*, 1987]. On the basis of these studies, *Lee et al.* [1987] concluded that the detachment fault/shear zone system originated as a high-angle fault that rooted into a moderately dipping shear zone, a conclusion similar to *Gans et al.* [1985]. Clearly, establishing the degree of footwall rotation within this metamorphic core complex in space and time is a critical element in distinguishing between these different models. Yet because footwall rocks beneath the NSRD are penetratively deformed, the magnitude of footwall rotation, and therefore the magnitude of rotation of the overlying detachment fault is difficult to assess.

One method that can establish the degree of footwall rotation involves characterizing the thermal history of lower plate mylonitic rocks. $^{40}\text{Ar}/^{39}\text{Ar}$ and fission track thermochronologic studies, in conjunction with other geologic data, provide evidence for a temperature difference across the footwall of detachment

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Figure 1. Index map of east central Nevada showing locations of the Deep Creek, Confusion, northern Snake, Schell Creek, Egan, and southern Snake ranges and the Kern Mountains. Inset shows location of Figure 3.

faults, which is interpreted to be the result of differential cooling (uplift) during protracted slip along a fault at a variety of angles [e.g., Foster *et al.*, 1990b; Gans *et al.*, 1990; Richard *et al.*, 1990; Lee and Sutter, 1991; Holm *et al.*, 1992; Dokka, 1993; John and Foster, 1993]. Assuming reasonable geothermal gradients, Richard *et al.* [1990] (Harquahala Mountains, Arizona) concluded that the detachment fault originated at 30–40°. John and Foster [1993] (Chemehuevi Mountains, California) argue for an initiation angle of (<30°) based on a variety of structural and thermochronologic data. In contrast, Gans *et al.* [1990] (Kern Mountains-Deep Creek Range, Nevada-Utah) argue that the detachment fault originated at ~60° based on the dip of footwall and hanging wall units, tilted dikes, and pronounced differences in cooling histories across the range. Similarly, thermochronologic and geobarometric data lead Holm *et al.* [1992] (Black Mountains, California) to conclude that the detachment fault initiated at a dip of 40–90° at depths of 5–10 km and 6–13° at deeper structural levels (an average dip of ~20°).

In the northern Snake Range, Lee and Sutter [1991] completed a $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronologic study of igneous and metamorphic white mica, biotite, and potassium feldspar from a broad sampling of footwall rocks, in part, to address this problem. Ages decreased west to east across the range parallel to the slip direction of the NSRD. Lee and Sutter [1991] interpreted these ages as reflecting differential uplift of footwall rocks from beneath the NSRD. They concluded that the west flank cooled before the east flank, that mylonitic deformation in lower plate rocks occurred between 37 Ma and ~24 Ma, and that thermal gradients were steep. They suggested that this differential cooling history was compatible with differential unroofing from beneath a moderate to high-angle detachment fault that rotated to shallow dips as it moved [Lee *et al.*, 1987] or with a rolling hinge/isostatic re-

bound model [e.g., Buck, 1988; Wernicke and Axen, 1988]. Yet because most of the age data were derived from white mica and many of the samples yielded disturbed age spectra, Lee and Sutter [1991] were unable to provide quantitative constraints on the cooling history of lower plate rocks, nor were they unequivocally able to establish an origin and movement history for the NSRD.

In this paper I build on this earlier database by constraining the quantitative thermal or cooling histories for lower plate rocks in the northern Snake Range using a powerful new thermochronometric technique, multiple diffusion domain analyses of potassium feldspar Arrhenius data and $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra [see Lovera *et al.*, 1989, 1991]. The thermal histories presented in this paper more tightly constrain the timing and temperature conditions of deformation related to ductile extension and provide convincing evidence for differential cooling, rotation, and rapid footwall uplift of lower plate rocks from beneath the NSRD. The thermal history data, in conjunction with the structural history and geometry of footwall deformation, provide constraints and insight on the geometric evolution of metamorphic core complex detachment faults.

Geology of the northern Snake Range

East central Nevada was the site of accumulation of up to 14 km of continental shelf sediments consisting of an upper Precambrian to Lower Cambrian sandstone and shale sequence and a Middle Cambrian to Permian predominantly carbonate sequence (Figure 2) [Stewart and Poole, 1974; Hose and Blake,

Figure 2. Simplified stratigraphic column of miogeoclinal rocks exposed in east central Nevada. Sources of data are Stewart and Poole [1974]; Hose and Blake [1976]; Gans and Miller [1983]; Rodgers [1987]. Stratigraphic locations of potassium feldspar samples are shown.

1976; *Gans and Miller*, 1983; *Rodgers*, 1987]. In the Jurassic and then in the Cretaceous, upper Precambrian and lower Paleozoic rocks located at deeper structural levels were metamorphosed, penetratively deformed, and intruded [*Miller et al.*, 1988], whereas upper Paleozoic sediments at supracrustal levels were gently folded and cut by minor displacement thrust faults [*Armstrong*, 1968, 1972; *Gans and Miller*, 1983; *Gans et al.*, 1987]. In the Tertiary, east central Nevada underwent approximately 250% extension in a WNW-ESE direction [*Gans and Miller*, 1983]. Supracrustal rocks were extended along one or more generations of high-angle normal faults that penetrated to depths of 6 to 10 km. Normal faults were active during a period of voluminous volcanism (40–33 Ma), although locally there is evidence for an earlier period of Tertiary faulting [*Gans et al.*, 1989, 1993]. Apatite fission track analyses indicate rapid cooling of footwall rocks beneath range-bounding faults, suggesting a period of normal faulting during the middle Miocene [*Gans et al.*, 1990, 1991; *Miller et al.*, 1989, 1993]. Locally, Quaternary alluvial fans are offset along range front faults, indicating that extension has continued either episodically or continuously to the present day. Midcrustal rocks experienced extreme lateral and thermal gradients in the Cenozoic [*Miller et al.*, 1988]. In the Egan, Schell Creek, Deep Creek Ranges, and the western part of the southern Snake Range, relatively low Tertiary thermal gradients led to preservation of Mesozoic metamorphic and deformational fabrics [*Rodgers*, 1987; *Miller et al.*, 1988], whereas in the Kern Mountains and eastern part of the southern Snake Range, and as inferred for the northern Snake Range, high thermal gradients were associated with ductile extensional fabrics and intrusion of Tertiary granites [*Miller et al.*, 1988; *Lee and Sutter*, 1991].

Lower plate rocks of the NSRD record all three metamorphic, deformational, and intrusive events described above. Evidence for the first metamorphic event is best preserved along the southern flank of the northern Snake Range where upper Precambrian and Lower Cambrian pelites are intruded and contact metamorphosed by a mid-Jurassic plutonic complex (Figure 3). The second metamorphic event occurred in the Late Cretaceous and affected a broad portion of the lower plate. Along the eastern flank of the range a series of mineral-in isograds in upper Precambrian pelitic units trend east-west and demonstrate an increase in metamorphic grade, both northward and with depth in the range [*Geving*, 1987; *Huggins*, 1990]. Geobarometry and geothermometry data from the late Precambrian metapelites at the deepest levels of exposure along the eastern flank of the range indicate pressures of 3.9–8.0 kbar and temperatures of 500–650°C [*Huggins*, 1990; *Lewis et al.*, 1992]. A strong Tertiary deformational and metamorphic event largely obliterates evidence for synmetamorphic deformational fabrics except in the northwestern part of the range where Tertiary strain decreases and dies out and Cretaceous penetrative deformational fabrics are well preserved [*Lee*, 1990; *Lee et al.*, 1995a].

U/Pb dating of metamorphic monazites from upper Precambrian schist units in the Smith Creek area, as well as detrital zircons and metamorphic monazites from Precambrian schists in Hampton Creek (Figure 3), yield a metamorphic age of 78 Ma [*Lee and Fischer*, 1985; *Huggins and Wright*, 1989; *Huggins*, 1990]. Abundant muscovite-bearing pegmatites in the Smith Creek area, inferred to be coeval with the peak

metamorphic event, are dated at 82 Ma (U/Pb on monazite) [*Huggins and Wright*, 1989; *Huggins*, 1990]. Hence, on the basis of the available data the Late Cretaceous metamorphism in the northern Snake Range occurred at ~78–82 Ma.

Lower to upper greenschist facies metamorphism of Tertiary age affected much of the lower plate, causing retrogression of older Late Cretaceous metamorphic assemblages. This metamorphic event was accompanied by ductile thinning and stretching of lower plate units, resulting in a subhorizontal, bedding parallel foliation and WNW-ESE trending mineral elongation lineation. Mesoscopic structures and finite strain measurements indicate a dramatic west-to-east increase in strain from a low on the west of 6:1 (X:Z) (where X>Y>Z are axes of the finite strain ellipsoid) to a high on the east of 600:1 (X:Z); on average, lower plate rocks were plastically extended ~300% [*Miller et al.*, 1983; *Lee et al.*, 1987]. Quartz microstructures and c-axis fabric patterns, along with finite strain measurements and mesoscopic structures, document a complex extensional strain history of early coaxial strain that is overprinted by deformation with an eastward increasing component of top-to-the-east noncoaxial strain. In the northern part of the range the mylonitic foliation, however, is not everywhere parallel to bedding and, as described above, actually dies out in the northwestern part of the range.

Metamorphic grade associated with the mylonitic fabric increases both with depth and from south to north along the east flank of the range. At high structural levels there was new growth of chlorite and white mica in pressure shadows of older porphyroblasts, and at deeper structural levels there was new growth of muscovite and biotite in pressure shadows. Quartz grains exhibit crystal-plastic textures, whereas feldspars exhibit brittle textures [*Lee et al.*, 1987]. These mineral assemblages, as well as comparison of quartz and feldspar textures to laboratory-derived constitutive laws for intracrystalline plastic flow [e.g., *Koch et al.*, 1989; *Tullis*, 1990, and references therein] (see, however, cautionary note by *Rutter and Brodie* [1991]), suggest that temperatures during mylonitic deformation were between 450°C and 300°C. Data presented here suggest that slip along the NSRD began as early as 48 Ma and continued episodically until ~16 Ma and that mylonitic extensional deformation in footwall rocks was ongoing prior to 37 Ma and had ceased by 19 Ma.

Analytical Methods

Potassium feldspar mineral separates were obtained by using Na-polytungstate heavy liquid and magnetic separatory methods and were handpicked to >99% purity. Samples were wrapped in Sn foil, placed in evacuated quartz vials with flux monitor Fe-mica (age = 307.3 Ma), and irradiated for 31 hours at the Ford Reactor, University of Michigan. Flux monitors were placed at ~1-cm intervals in each quartz vial to determine flux gradients. Samples were step heated in a Ta crucible within a double-vacuum resistance furnace, and temperatures were monitored with a tungsten-rhenium thermocouple to $\pm 5^\circ\text{C}$. Argon isotopes were analyzed using a Nuclide 4.5-60-RSS mass spectrometer. The extraction line blank was typically 10^{-14} mol ^{40}Ar .

Thermochronologic Results

Recently, *Lovera et al.* [1989, 1991] proposed, and laboratory experiments have confirmed [*Lovera et al.*, 1991, 1993; *Harrison*

Figure 3. Simplified geologic map of the northern Snake Range. Sources of mapping are Gans et al. [1995a, b], Lee and Gans [1995], Lee et al. [1995a, b], Miller and Gans [1995], Miller et al. [1995] and E.L. Miller, P.B. Gans, and J. Lee (unpublished mapping, 1994). Potassium feldspar sample localities are shown.

et al., 1991; *Fitz Gerald and Harrison*, 1993], that potassium feldspar is characterized by a discrete distribution of diffusion length scales rather than a single diffusion domain [Dodson, 1973]. An important consequence of this hypothesis is that a single potassium feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum can reveal a segment of the thermal history rather than the usually expected time-temperature datum because each discrete domain has a characteristic argon closure temperature. This hypothesis is based on the underlying assumption that diffusion in nature is replicated exactly by the heating experiments in the laboratory. The thermal degassing experiment of a potassium feldspar sample in the laboratory yields (1) an age spectrum, from which a thermal history is calculated, (2) an Arrhenius plot, from which the domain diffusion parameters (activation energy E and frequency factor D_0/r^2) are calculated, and (3) a $\log(r/r_0)$ plot, from which the domain distribution characteristics (number of domains, relative sizes r and volume fractions f) are calculated. Given estimates of the domain diffusion and distribution parameters, a thermal history can be derived by iteratively calculating a theoretical age spectrum until a close match with the laboratory-derived age spectrum is attained.

In this study, six potassium feldspars were analyzed in order to elucidate the Tertiary thermal history of lower plate rocks of the NSRD. Samples of a Late Cretaceous pegmatite and aplite dike swarm in the central part of the range were collected across the range along a transect subparallel to the lower plate mineral elongation lineation (Figure 3). The samples vary from undeformed pegmatites on the west flank of the range to highly strained pegmatites on the east flank. Results of isotopic analyses are listed in Table 1. Details of the calculations are given by *Lovera et al.* [1989, 1991]. Note that in the calculations below, small differences in activation energy between domains have not been taken into account, nor have errors associated with estimation of the activation energy (up to ± 3.1 kcal/mol) and $\log(D_0/r^2)$ (up to ± 0.81 s $^{-1}$) been propagated through these calculations. However, the effect of incorporating these errors results in a small error of $\pm 3^\circ\text{C}/\text{m.y.}$ in the calculated cooling rate for the largest domain and an uncertainty of $\sim 30^\circ\text{C}$ for the calculated temperatures (for example, the range in temperature at 20 Ma for sample KPA2 is 300–330°C) (Figure 10b). The effect of these errors on the calculated thermal histories is systematic and does not alter the form of the thermal histories (Figure 10).

KPA5, a sample from a small pegmatite and aplite body located on the western flank of the range in Eightmile Canyon (Figure 3), does not possess a penetrative fabric of Tertiary age, indicating that in this part of the range Tertiary strain decreases and dies out [Lee *et al.*, 1995a]. Sample KPA5 yields an age spectrum that, in general, rises monotonically from 27.4 Ma to 47.3 Ma (Figure 4a). The corresponding Arrhenius diagram is a plot of ^{39}Ar diffusion coefficients, calculated from the fractional loss data (assuming a plane slab geometry), against the reciprocal heating temperature (Figure 4b). A linear fit to steps 2–5 on the associated Arrhenius plot yields an activation energy E of 40.83 kcal/mol and a log frequency factor/effective domain size parameter [$\log(D_0/r^2)$] of 4.68 s $^{-1}$. The domain distribution characteristics are best displayed on a log of relative domain size [$\log(r/r_0)$] versus cumulative % ^{39}Ar released plot (Figure 4c). An excellent fit to the laboratory-derived results is obtained using six domains with domain distribution parameters listed in Figure 4c. The deviation at $\sim 65\%$ of gas released is a consequence of

the temperature cycling heating schedule used in the laboratory [cf. *Harrison et al.*, 1991]. The lack of any fit for the last 12% of gas released is the result of gas extraction at temperatures greater than the onset of incongruent melting of potassium feldspar ($\sim 1150^\circ\text{C}$), and hence no volume diffusion information is obtained [Lovera *et al.*, 1993]. Given the above estimates for domain diffusion and distribution parameters, a synthetic age spectrum can be calculated that closely fits the laboratory-derived spectrum by an iterative approach in which the thermal history is the only variable. This forward modeling approach, using the thermal history shown in Figure 4d, yields a synthetic age spectrum that closely fits the laboratory-derived spectrum (Figure 4a). The close fit to the laboratory-derived age spectrum suggests that the calculated thermal history closely approximates the actual cooling history in nature. In this sample the high-temperature portion of the cooling history is consistent with a coexisting muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 48.3 ± 0.3 Ma [Lee and Sutter, 1991] (Figure 4d). The thermal history is characterized by moderate to fast cooling rates of $\sim 20^\circ\text{C}/\text{m.y.}$ from 48 Ma until 46 Ma, followed by 16 m.y. of substantially slower cooling rates of $1\text{--}5^\circ\text{C}/\text{m.y.}$ At 30 Ma, cooling rates increase substantially to $10\text{--}22^\circ\text{C}/\text{m.y.}$ continuing until 26 Ma. The cooling history can be extrapolated, at a cooling rate of $\sim 5^\circ\text{C}/\text{Ma}$ (dashed portion of the cooling curve in Figure 4d), to 15.7 ± 1.8 Ma, an age calculated from apatite fission track data covering a broad portion of the lower plate [Miller *et al.*, 1989, 1993]. Track length distribution characteristics for these data indicate moderate cooling rates of $\sim 15^\circ\text{C}/\text{m.y.}$ through the apatite annealing zone ($120\text{--}60^\circ\text{C}$), followed by residence at low, near-surface temperatures [Miller *et al.*, 1989, 1993].

Sample KPA4 comes from a small pegmatite dike emplaced into the middle part of the Middle Cambrian Limestone (Figure 2) and is located ~ 6.2 km to the ESE of sample KPA5 (Figure 3). In this part of the range the dike and country rock have been moderately deformed by the Tertiary ductile strain event. Sample KPA4 yields an age spectrum with a large component of excess argon over the first 20% of gas released, followed by a monotonic rise from 20.8 Ma to 44.7 Ma, where it flattens for the last $\sim 30\%$ of gas released (Figure 5a). A linear fit to steps 2–5 on the associated Arrhenius plot yields an E of 50.39 kcal/mole and a $\log(D_0/r^2)$ of 6.86 s $^{-1}$ (Figure 5b). The domain distribution parameters listed in Figure 5c result in an excellent fit to the $\log(r/r_0)$ plot, with the exception of the last 18% of gas released above the incongruent melting temperature of potassium feldspar. The calculated thermal history, shown in Figure 5d, produces a good fit to the laboratory-derived age spectrum (Figure 5a). The thermal history for this sample shows moderate cooling rates of $10^\circ\text{C}/\text{m.y.}$ from 45 Ma until 41 Ma, followed by 20 m.y. of slow cooling at rates of $1\text{--}4^\circ\text{C}/\text{m.y.}$ At 20 Ma there is a marked increase in cooling rates to $40^\circ\text{C}/\text{m.y.}$ which can be extrapolated to the 15.7 ± 1.8 Ma apatite fission track age [Miller *et al.*, 1989, 1993].

Sample KPA2 comes from a small pegmatite dike emplaced into the late Precambrian Osceola Argillite (Figure 2) and is located in the central part of the range (Figure 3). The dike and country rock have been strongly deformed by the Tertiary ductile strain event. Sample KPA2 yields an age spectrum with a small component of excess argon over the first 5% of gas released, followed by a shallow rise in age from 15.7 Ma to 24.4 Ma over the next 75% of gas released and a rapid rise in age to 59.3 Ma

Table 1. Isotopic Analyses of Dated Samples

Temp., °C	$^{40}\text{Ar}/^{39}\text{Ar}^a$	$^{37}\text{Ar}/^{39}\text{Ar}^b$	$^{36}\text{Ar}/^{39}\text{Ar}^a$ $\times 10^{-3}$	$^{39}\text{Ar} \times 10^{-13}$ mol	% ^{39}Ar Released	$^{40}\text{Ar}^{*c}$, %	$^{40}\text{Ar}^*/^{39}\text{ArK}$	Age ± 1 standard deviation, Ma	Time, min	1000/°T, 1/°K	$\log D/r^2$, 1/s
KPA5 Potassium Feldspar ($J = 0.005022$; Weight = 0.1285 g)											
450	48.82	0.2837	108.5	0.230	0.357	33.4	16.75	145.7 ± 5.8	30	1.383	8.254
500	5.490	0.0384	3.750	0.862	1.69	74.8	4.368	39.1 ± 0.5	30	1.294	6.921
550	3.475	0.0193	1.405	2.10	4.95	84.1	3.044	27.4 ± 0.5	30	1.215	6.025
600	3.368	0.0152	0.8608	2.68	9.1	89.0	3.098	27.9 ± 0.3	30	1.145	5.594
630	3.332	0.0182	0.8017	2.02	12.2	88.5	3.080	27.7 ± 0.4	14	1.107	5.204
670	3.469	0.0198	0.6253	1.82	15.1	90.0	3.268	29.4 ± 0.4	15	1.060	5.172
700	3.404	0.0181	0.1217	1.75	17.8	93.8	3.352	30.1 ± 0.0	16	1.028	5.137
750	3.516	0.0268	0.6006	1.80	20.6	90.2	3.324	29.9 ± 0.2	15	0.978	5.029
800	3.497	0.0340	0.0000	1.83	23.4	99.0	3.623	32.5 ± 0.4	15	0.932	4.962
800	3.513	0.0315	0.0000	1.60	25.9	96.6	3.577	32.1 ± 0.1	20	0.932	5.097
800	3.572	0.0189	0.0000	1.47	28.1	96.1	3.629	32.6 ± 0.1	30	0.932	5.270
800	3.622	0.0430	0.0000	1.67	30.7	95.1	3.614	32.5 ± 0.0	60	0.932	5.476
750	4.011	-0.0073	0.0336	0.778	31.9	90.6	3.983	35.7 ± 0.0	150	0.978	6.180
700	5.796	0.0307	4.521	0.229	32.3	62.6	4.445	39.8 ± 4.2	844	1.028	7.449
800	3.880	0.0308	0.5882	1.18	34.1	89.3	3.691	33.1 ± 0.2	90	0.932	5.752
850	3.953	0.0322	0.2327	1.22	36.0	92.2	3.869	34.7 ± 0.1	30	0.890	5.236
900	3.940	0.0359	1.045	1.21	37.9	86.3	3.617	32.5 ± 0.5	15	0.853	4.917
950	3.940	0.0242	0.0000	1.42	40.1	99.2	4.118	36.9 ± 0.3	14	0.818	4.794
1000	4.085	0.0205	0.3741	1.91	43.1	93.3	3.959	35.5 ± 0.4	10	0.786	4.491
1000	4.176	0.0213	0.8438	2.54	47.0	91.1	3.911	35.1 ± 0.2	20	0.786	4.633
1000	4.310	0.0155	0.0000	2.43	50.8	99.8	4.426	39.7 ± 0.5	30	0.786	4.794
1000	4.437	0.0214	0.7277	2.95	55.3	92.7	4.206	37.7 ± 0.3	60	0.786	4.974
1000	4.615	0.0168	0.6642	3.43	60.7	93.6	4.403	39.5 ± 0.2	120	0.786	5.136
900	5.165	-0.0092	1.023	0.545	61.5	84.8	4.845	43.4 ± 0.8	149	0.853	6.006
800	11.78	0.1942	1.336	0.065	61.6	69.3	11.38	100.3 ± 0.6	1157	0.932	7.817
950	4.929	0.0141	1.069	0.959	63.1	87.7	4.597	41.2 ± 0.8	150	0.818	5.749
1030	4.865	0.0313	0.8081	1.12	64.8	89.8	4.611	41.3 ± 0.5	30	0.767	4.965
1050	4.922	0.0411	0.4175	0.753	66.0	89.9	4.784	42.8 ± 0.2	14	0.756	4.787
1075	5.040	0.0587	1.502	1.14	67.8	86.4	4.583	41.1 ± 0.9	15	0.742	4.618
1100	5.244	0.0498	1.881	1.14	69.5	84.9	4.674	41.9 ± 1.0	10	0.728	4.420
1100	5.152	0.0592	2.421	1.77	72.3	83.1	4.423	39.6 ± 0.5	20	0.728	4.496
1100	5.189	0.0515	1.464	1.97	75.3	88.8	4.743	42.5 ± 0.4	30	0.728	4.580
1100	5.265	0.0323	1.525	3.06	80.1	89.5	4.800	43.0 ± 0.6	60	0.728	4.618
1100	5.432	0.0392	1.786	3.31	85.2	88.5	4.890	43.8 ± 0.5	120	0.728	4.774
1100	6.964	0.0986	4.472	0.952	86.7	77.4	5.632	50.3 ± 1.1	1350	0.728	6.278
1200	6.130	0.0754	2.348	1.26	88.6	84.9	5.307	47.5 ± 0.5	15	0.679	4.144
1300	5.282	0.0148	1.439	5.26	96.8	90.7	4.840	43.3 ± 0.3	15	0.636	3.244

Table 1. (continued)

Temp., °C	$^{40}\text{Ar}/^{39}\text{Ar}^a$	$^{37}\text{Ar}/^{39}\text{Ar}^b$	$^{36}\text{Ar}/^{39}\text{Ar}^a$ $\times 10^{-3}$	$^{39}\text{Ar} \times 10^{-13}$ mol	% Ar Released	$^{40}\text{Ar}^{*c}$, %	$^{40}\text{Ar}^{*}/^{39}\text{ArK}$	Age $\pm$ standard deviation, Ma	Time, min	1000/ T , 1/ $^\circ\text{K}$	$\log D/t^2$, 1/s
1550	6.531	0.0246	4.139	2.06	100	79.3	5.293	47.3 $\pm$ 0.3	20	0.549	2.783
KPA4 Potassium Feldspar ($I = 0.005079$; Weight = 0.1076 g)											
450	225.3	0.8562	374.2	0.032	0.039	48.9	114.8	829 $\pm$ 55.9	30	1.383	10.18
500	12.01	0.0357	10.45	0.736	0.929	71.7	8.906	79.8 $\pm$ 3.4	30	1.294	7.424
550	5.448	0.0118	1.633	1.90	3.22	88.3	4.949	44.8 $\pm$ 0.7	30	1.215	6.380
600	3.712	0.0127	1.642	2.93	6.77	84.2	3.210	29.2 $\pm$ 0.4	30	1.145	5.811
630	3.133	0.0083	0.0000	2.60	9.91	96.6	3.139	28.5 $\pm$ 0.0	15	1.107	5.339
665	3.147	0.0175	0.0000	2.25	12.6	96.0	3.149	28.6 $\pm$ 0.0	15	1.066	5.270
700	3.052	0.0063	0.0000	2.30	15.4	97.6	3.108	28.3 $\pm$ 0.3	15	1.028	5.166
750	3.342	0.0166	0.3475	1.40	17.1	90.6	3.223	29.3 $\pm$ 0.2	14	0.978	5.289
800	3.128	0.0060	0.0000	2.34	19.9	98.5	3.208	29.2 $\pm$ 0.2	10	0.932	4.863
800	2.608	0.0355	1.037	2.47	22.9	83.8	2.287	20.8 $\pm$ 0.6	20	0.932	5.077
800	2.649	0.0213	0.8062	2.27	25.7	86.1	2.395	21.8 $\pm$ 0.2	30	0.932	5.236
800	2.710	0.0112	0.2848	2.79	29.0	92.6	2.609	23.8 $\pm$ 0.1	60	0.932	5.395
750	2.991	0.0221	1.198	1.38	30.7	81.7	2.621	23.9 $\pm$ 0.7	127	0.978	5.989
700	0.000	0.0000	0.0000	0.425	31.2	00.0	0.000	00.0 $\pm$ 0.0	860	1.028	7.314
800	2.913	0.0088	0.0000	1.94	33.5	97.3	2.984	27.1 $\pm$ 0.1	90	0.932	5.656
850	3.061	0.0188	0.7248	1.65	35.5	87.3	2.831	25.8 $\pm$ 0.3	25	0.890	5.141
900	3.140	0.0064	0.5635	1.44	37.3	88.3	2.957	26.9 $\pm$ 0.3	13	0.853	4.894
950	3.127	0.0045	0.0000	2.06	39.8	95.3	3.120	28.4 $\pm$ 0.0	15	0.818	4.776
1000	3.404	0.0203	0.2448	1.85	42.0	93.0	3.316	30.1 $\pm$ 0.1	10	0.786	4.620
1000	3.532	0.0092	0.2844	2.36	44.9	93.8	3.432	31.2 $\pm$ 0.1	20	0.786	4.789
1000	3.818	0.0268	0.8311	2.00	47.3	89.7	3.558	32.3 $\pm$ 0.6	30	0.786	5.011
1000	4.186	0.0047	0.7761	2.28	50.0	91.3	3.940	35.7 $\pm$ 0.5	60	0.786	5.231
1000	4.519	0.0079	0.6008	3.52	54.3	93.9	4.325	39.2 $\pm$ 0.2	120	0.786	5.314
900	5.022	0.0569	2.812	0.772	55.2	77.2	4.178	37.9 $\pm$ 0.7	145	0.853	6.034
800	7.834	0.1167	18.95	0.25	55.5	24.6	2.227	20.3 $\pm$ 6.8	850	0.932	7.287
950	4.770	0.0329	1.372	1.56	57.4	87.6	4.350	39.4 $\pm$ 0.4	150	0.818	5.731
1030	5.045	0.0234	1.548	1.26	58.9	90.2	4.572	41.4 $\pm$ 0.9	27	0.767	5.065
1050	4.958	0.0340	1.375	0.865	60.0	85.5	4.537	41.1 $\pm$ 0.6	14	0.756	4.934
1075	5.057	0.0373	1.312	1.19	61.4	87.7	4.655	42.2 $\pm$ 0.5	16	0.742	4.715
1100	5.004	0.0086	1.363	2.28	64.2	89.3	4.585	41.5 $\pm$ 0.2	10	0.728	4.299
1100	5.088	0.0241	1.538	1.33	65.8	86.9	4.618	41.8 $\pm$ 0.5	20	0.728	4.807
1100	5.208	0.0093	0.2507	1.83	68.0	95.3	5.117	46.3 $\pm$ 0.1	30	0.728	4.821
1100	5.357	0.0233	2.086	2.73	71.3	86.4	4.725	42.8 $\pm$ 0.4	60	0.728	4.911
1100	5.431	0.0087	1.610	4.54	76.8	89.8	4.939	44.7 $\pm$ 0.3	120	0.728	4.921
1100	5.631	0.0093	2.282	5.52	83.5	86.9	4.940	44.7 $\pm$ 0.3	784	0.728	5.534
1200	5.654	0.0184	0.9739	0.984	84.7	89.8	5.351	48.4 $\pm$ 0.5	17	0.679	4.527

Table 1. (continued)

Temp., °C	$^{40}\text{Ar}/^{39}\text{Ar}^a$	$^{37}\text{Ar}/^{39}\text{Ar}^b$	$^{36}\text{Ar}/^{39}\text{Ar}^a$ $\times 10^{-3}$	$^{39}\text{Ar} \times 10^{-13}$ mol	% ^{39}Ar Released	$^{40}\text{Ar}^{*c}$, %	$^{40}\text{Ar}^{*}/^{39}\text{Ar}^d$	Age ± 1 standard deviation, Ma	Time, min	1000/ $^{\circ}\text{T}$, 1/ $^{\circ}\text{K}$	$\log D/r^2$, 1/s
1300	5.340	0.0037	1.313	9.41	96.0	91.9	4.935	44.7 $\pm$ 0.2	15	0.636	3.215
1550	6.413	0.0170	4.958	3.25	100	75.8	4.932	44.6 $\pm$ 0.5	20	0.549	2.796
<i>KPA3 Potassium Feldspar ($J = 0.005051$; Weight = 0.14409 g)</i>											
450	184.4	0.6199	353.5	0.068	0.079	42.4	80.02	612.4 $\pm$ 54.1	30	1.383	9.562
500	6.324	0.0155	5.051	0.917	1.14	72.4	4.816	43.4 $\pm$ 1.7	30	1.294	7.245
550	2.711	0.0016	0.1631	2.94	4.55	94.1	2.646	24.0 $\pm$ 0.1	30	1.215	6.071
600	2.250	0.0110	0.0000	3.58	8.71	98.7	2.303	20.9 $\pm$ 0.1	30	1.145	5.618
630	2.157	0.0076	0.0000	2.84	12.0	96.2	2.177	19.7 $\pm$ 0.1	14	1.107	5.194
670	2.130	0.0070	0.0153	2.86	15.3	94.4	2.109	19.1 $\pm$ 0.0	15	1.060	5.100
700	2.149	0.0033	0.0007	3.97	19.9	95.8	2.132	19.3 $\pm$ 0.0	15	1.028	4.847
750	2.184	-0.0002	0.0000	2.45	22.8	98.4	2.269	20.6 $\pm$ 0.3	15	0.978	4.974
800	2.230	0.0109	0.4505	3.15	26.4	89.5	2.080	18.9 $\pm$ 0.3	10	0.932	4.627
800	2.164	0.0073	0.0000	3.36	30.3	95.5	2.151	19.5 $\pm$ 0.0	20	0.932	4.839
800	2.182	0.0002	0.0869	2.69	33.5	93.3	2.140	19.4 $\pm$ 0.0	30	0.932	5.061
800	2.232	0.0073	0.3741	2.67	36.6	89.8	2.105	19.1 $\pm$ 0.3	60	0.932	5.324
750	2.422	0.0191	0.1828	0.814	37.5	84.3	2.352	21.3 $\pm$ 0.1	150	0.978	6.214
700	5.694	0.0411	0.0000	0.148	37.7	120.7	9.312	82.9 $\pm$ 6.8	870	1.028	7.710
800	2.370	0.0063	0.0000	1.51	39.4	97.7	2.511	22.7 $\pm$ 0.3	90	0.932	5.706
850	2.475	-0.0045	0.0000	2.00	41.7	95.1	2.497	22.6 $\pm$ 0.1	30	0.890	5.085
900	2.597	0.0062	0.3224	2.22	44.3	91.0	2.485	22.5 $\pm$ 0.1	15	0.853	4.713
950	2.620	0.0145	0.9651	2.96	47.8	85.2	2.319	21.0 $\pm$ 0.2	15	0.818	4.558
1000	2.795	0.0070	0.8600	2.92	51.1	87.1	2.524	22.9 $\pm$ 0.4	10	0.786	4.358
1000	2.930	0.0076	0.8913	3.33	55.0	87.7	2.650	24.0 $\pm$ 0.5	20	0.786	4.571
1000	3.252	0.0093	1.607	3.71	59.3	82.8	2.761	25.0 $\pm$ 0.4	30	0.786	4.668
1000	3.476	0.0025	1.580	3.87	63.8	84.2	2.992	27.1 $\pm$ 0.5	60	0.786	4.851
1000	3.538	0.0117	1.365	3.00	67.3	85.7	3.119	28.2 $\pm$ 0.2	120	0.786	5.244
900	3.738	0.0228	1.343	0.384	67.7	73.6	3.326	30.1 $\pm$ 0.6	145	0.853	6.194
800	16.01	0.6615	35.58	0.045	67.8	24.4	5.526	49.7 $\pm$ 7.7	815	0.932	7.871
950	3.944	0.0270	1.518	0.748	68.6	80.1	3.480	31.4 $\pm$ 0.8	150	0.818	5.909
1030	3.834	0.0049	1.115	1.88	70.8	87.3	3.488	31.5 $\pm$ 0.3	30	0.767	4.789
1050	3.623	0.0092	0.9854	1.25	72.3	85.8	3.316	30.0 $\pm$ 0.2	14	0.756	4.608
1075	3.671	0.0048	0.2228	1.70	74.2	93.3	3.588	32.4 $\pm$ 0.1	15	0.742	4.477
1100	3.680	0.0257	0.0000	1.33	75.8	93.9	3.666	33.1 $\pm$ 0.0	10	0.728	4.379
1100	3.654	0.0048	0.0540	2.04	78.2	95.3	3.622	32.7 $\pm$ 0.1	20	0.728	4.457
1100	3.679	0.0106	0.5823	2.17	80.7	91.5	3.491	31.5 $\pm$ 0.4	30	0.728	4.558
1100	3.736	0.0106	1.197	2.63	83.7	87.4	3.366	30.4 $\pm$ 0.9	60	0.728	4.713
1100	3.830	0.0058	0.907	2.23	86.3	89.4	3.546	32.0 $\pm$ 0.2	120	0.728	5.009
1100	4.972	0.0129	5.246	0.573	87.0	62.0	3.406	30.8 $\pm$ 3.0	875	0.728	6.414

Table 1. (continued)

Temp., °C	$^{40}\text{Ar}/^{39}\text{Ar}^a$	$^{37}\text{Ar}/^{39}\text{Ar}^b$	$^{36}\text{Ar}/^{39}\text{Ar}^a$ $\times 10^{-3}$	$^{39}\text{Ar} \times 10^{13}$ mol	% ^{39}Ar Released	$^{40}\text{Ar}^{*c}$, %	$^{40}\text{Ar}^{*}/^{39}\text{Ar}^k$	Age ± 1 standard deviation, Ma	Time, min	1000/T, 1/°K	log D/r ² , 1/s
1200	4.686	0.0076	2.874	2.13	89.5	79.1	3.820	34.5 $\pm$ 0.7	15	0.679	4.023
1300	5.102	0.0029	4.859	1.22	90.9	68.2	3.650	33.0 $\pm$ 4.6	15	0.636	4.188
1550	18.25	0.0033	49.15	7.59	100	20.3	3.709	33.5 $\pm$ 0.3	21	0.549	2.972
KPA2 Potassium Feldspar ($J = 0.005068$; Weight = 0.11989 g)											
450	239.8	0.1019	505.6	0.384	0.409	37.7	90.43	680.6 $\pm$ 4.9	33	1.383	8.178
500	6.958	0.0808	14.58	0.632	1.08	37.1	2.637	23.9 $\pm$ 6.1	25	1.294	7.280
550	25.56	0.5274	155.4	1.68	2.87	00.0	0.000	00.0 $\pm$ 0.0	27	1.215	6.464
640	3.176	0.0342	4.875	4.71	7.88	53.3	1.721	15.7 $\pm$ 2.1	5	1.095	4.850
600	2.314	0.0095	0.8933	3.30	11.4	86.8	2.034	18.5 $\pm$ 0.9	30	1.145	5.530
650	2.310	0.0112	0.3868	3.76	15.4	93.3	2.180	19.8 $\pm$ 0.4	15	1.083	5.029
700	2.360	0.0131	1.192	4.01	19.6	83.5	1.992	18.1 $\pm$ 1.3	20	1.028	5.009
750	2.426	0.0214	1.024	2.15	21.9	85.2	2.107	19.2 $\pm$ 1.5	16	0.978	5.109
800	2.533	0.0026	0.2759	1.79	23.8	94.0	2.435	22.1 $\pm$ 0.7	10	0.932	4.943
800	2.530	0.0312	0.9506	2.27	26.2	86.8	2.234	20.3 $\pm$ 2.1	20	0.932	5.101
800	2.606	0.0244	1.809	2.30	28.7	77.6	2.056	18.7 $\pm$ 1.5	30	0.932	5.232
800	2.650	0.0184	1.170	2.73	31.6	85.2	2.289	20.8 $\pm$ 1.6	60	0.932	5.417
750	3.211	0.0261	5.172	1.96	33.7	51.1	1.667	15.2 $\pm$ 1.5	134	0.978	5.875
700	3.888	0.0156	5.007	2.44	36.3	60.9	2.392	21.7 $\pm$ 2.2	898	1.028	6.577
800	2.820	0.0191	1.961	3.04	39.5	78.0	2.225	20.2 $\pm$ 0.7	94	0.932	5.467
850	2.906	0.0215	1.797	2.30	42.0	80.0	2.359	21.4 $\pm$ 1.2	26	0.890	4.997
900	2.876	0.0186	1.213	2.95	45.1	86.0	2.502	22.7 $\pm$ 1.0	14	0.853	4.592
950	2.797	0.0204	0.9901	4.96	50.4	88.3	2.489	22.6 $\pm$ 1.1	14	0.818	4.327
1000	2.906	0.0183	1.037	4.11	54.7	88.2	2.584	23.5 $\pm$ 0.6	10	0.786	4.220
1000	3.019	0.0104	0.8555	4.60	59.6	90.4	2.750	25.0 $\pm$ 0.7	20	0.786	4.436
1000	3.231	0.0110	1.513	4.29	64.2	85.0	2.768	25.1 $\pm$ 0.6	30	0.786	4.539
1000	3.404	0.0080	1.396	3.65	68.1	86.7	2.975	27.0 $\pm$ 1.5	32	0.786	4.615
1000	3.512	0.0078	1.617	6.34	74.8	85.5	3.018	27.4 $\pm$ 0.3	120	0.786	4.874
900	5.840	0.0226	11.23	0.858	75.7	42.1	2.507	22.8 $\pm$ 3.7	145	0.853	5.764
800	11.69	0.0735	41.86	0.42	76.2	00.0	0.000	00.0 $\pm$ 0.0	828	0.932	6.818
950	4.296	0.0071	3.843	1.59	77.9	72.1	3.143	28.5 $\pm$ 0.7	140	0.818	5.447
1030	3.928	0.0169	4.156	1.89	79.9	67.4	2.684	24.4 $\pm$ 3.0	26	0.767	4.606
1050	4.126	0.0221	4.894	1.15	81.1	63.2	2.664	24.2 $\pm$ 3.6	13	0.756	4.488
1075	4.393	0.0130	2.267	1.43	82.6	83.1	3.707	33.6 $\pm$ 3.1	14	0.742	4.391
1100	4.706	0.0266	5.035	1.35	84.1	67.0	3.203	29.0 $\pm$ 1.2	10	0.728	4.233
1100	4.865	0.0225	3.228	1.72	85.9	79.1	3.896	35.3 $\pm$ 1.5	20	0.728	4.385
1100	5.195	0.0120	4.599	1.77	87.8	72.7	3.820	34.6 $\pm$ 2.2	30	0.728	4.492
1100	5.548	0.0270	5.561	2.23	90.1	69.5	3.890	35.2 $\pm$ 2.0	60	0.728	4.616
1100	6.122	0.0243	6.303	2.21	92.5	68.8	4.245	38.4 $\pm$ 1.5	120	0.728	4.814

Table 1. (continued)

Temp., °C	$^{40}\text{Ar}/^{39}\text{Ar}^a$	$^{37}\text{Ar}/^{39}\text{Ar}^b$	$^{36}\text{Ar}/^{39}\text{Ar}^a$ $\times 10^{-3}$	$^{39}\text{Ar} \times 10^{-13}$ mol	% ^{39}Ar Released	$^{40}\text{Ar}^{*c}$, %	$^{40}\text{Ar}^{*}/^{39}\text{Ar}^{\text{K}}$	Age ± 1 standard deviation, Ma	Time, min	1000/ $^{\circ}\text{T}$, 1/ $^{\circ}\text{K}$	$\log D/r^2$, 1/s
1100	7.422	0.0305	9.109	3.41	96.1	63.3	4.715	42.6 $\pm$ 1.7	860	0.728	5.286
1200	7.579	0.0371	3.276	0.951	97.1	85.8	6.596	59.3 $\pm$ 5.7	15	0.679	3.868
1300	5.555	-0.0189	5.327	0.597	97.7	69.2	3.963	35.9 $\pm$ 9.4	15	0.636	3.951
1550	66.56	0.0278	213.0	2.12	100	5.39	3.592	32.5 $\pm$ 2.3	15	0.549	3.534
KPA1 Potassium Feldspar ($J = 0.005090$; Weight = 0.1059 g)											
450	27.46	0.8857	58.14	0.152	0.127	35.1	10.33	92.5 $\pm$ 22.4	30	1.383	9.151
500	3.612	0.0673	4.574	1.81	1.63	59.5	2.284	20.5 $\pm$ 1.7	30	1.294	6.936
550	2.375	0.0199	0.9341	4.29	5.22	87.5	2.083	19.0 $\pm$ 0.2	30	1.215	5.969
600	2.199	0.0324	0.0000	4.48	8.96	100	2.211	20.2 $\pm$ 0.2	30	1.145	5.635
630	2.146	0.0309	0.8519	3.70	12.0	87.2	1.879	17.2 $\pm$ 0.9	15	1.107	5.247
670	3.636	0.0098	5.394	8.03	18.7	55.1	2.026	18.5 $\pm$ 0.3	15	1.060	4.744
700	2.298	0.0070	1.118	11.1	28.0	83.9	1.951	17.8 $\pm$ 0.3	15	1.028	4.420
750	2.206	0.0610	0.7782	4.34	31.7	86.3	1.964	17.9 $\pm$ 0.4	15	0.978	4.724
800	3.506	0.0574	4.822	3.47	34.6	57.6	2.068	18.9 $\pm$ 0.4	10	0.932	4.600
800	2.357	0.0603	0.945	4.72	38.5	85.3	2.065	18.9 $\pm$ 0.2	20	0.932	4.724
800	2.277	0.0594	0.7328	3.96	41.8	87.0	2.048	18.7 $\pm$ 0.2	30	0.932	4.935
800	2.382	0.0542	1.418	3.61	44.8	81.6	1.949	17.8 $\pm$ 0.2	60	0.932	5.244
750	2.530	0.0501	1.371	2.01	46.5	83.0	2.111	19.3 $\pm$ 0.7	135	0.978	5.826
700	2.614	0.0443	1.643	2.68	48.7	77.6	2.114	19.3 $\pm$ 0.4	908	1.028	6.512
800	2.451	0.0547	0.5391	2.36	50.7	88.4	2.279	20.8 $\pm$ 0.2	90	0.932	5.544
850	2.532	0.0480	0.7916	1.62	52.1	84.1	2.284	20.9 $\pm$ 0.4	25	0.890	5.138
900	2.565	0.0671	0.4005	1.84	53.6	89.2	2.435	22.2 $\pm$ 0.2	14	0.853	4.818
950	2.633	0.0453	0.1531	2.16	55.4	92.9	2.574	23.5 $\pm$ 0.1	14	0.818	4.735
1000	2.822	0.0306	0.7714	3.24	58.1	88.5	2.579	23.5 $\pm$ 0.4	10	0.786	4.396
1000	3.024	0.0238	0.3664	3.72	61.2	93.4	2.900	26.4 $\pm$ 0.1	20	0.786	4.552
1000	3.270	0.0239	0.7528	3.78	64.4	90.5	3.032	27.6 $\pm$ 0.4	30	0.786	4.718
1000	3.563	0.0252	0.9474	5.14	68.6	90.2	3.268	29.8 $\pm$ 0.3	60	0.786	4.839
1000	3.966	0.0283	1.053	5.55	73.3	90.5	3.640	33.1 $\pm$ 0.4	120	0.786	5.045
900	4.379	0.0820	2.121	0.759	73.9	78.4	3.741	34.0 $\pm$ 0.5	145	0.853	5.951
800	9.205	0.0854	19.25	0.34	74.2	34.8	3.506	31.9 $\pm$ 3.6	765	0.932	7.014
950	4.166	0.0271	0.9211	1.45	75.4	88.7	3.879	35.3 $\pm$ 0.3	150	0.818	5.662
1030	5.401	0.0671	3.511	1.10	76.3	80.2	4.351	39.5 $\pm$ 1.0	26	0.767	5.006
1050	5.547	0.0760	3.731	0.725	76.9	79.3	4.433	40.3 $\pm$ 3.0	13	0.756	4.870
1075	5.535	0.0749	2.706	1.32	78.0	82.0	4.724	42.9 $\pm$ 0.8	15	0.742	4.656
1100	6.144	0.1156	3.324	1.04	78.9	83.5	5.152	46.7 $\pm$ 1.3	10	0.728	4.563
1100	6.033	0.0688	1.971	1.79	80.4	89.9	5.439	49.3 $\pm$ 1.5	20	0.728	4.605
1100	5.729	0.0447	1.551	2.17	82.2	89.6	5.257	47.6 $\pm$ 0.2	30	0.728	4.660
1100	5.764	0.0341	1.747	3.14	84.8	89.3	5.233	47.4 $\pm$ 0.9	60	0.728	4.745

Table 1. (continued)

Temp., °C	$^{40}\text{Ar}/^{39}\text{Ar}^a$	$^{37}\text{Ar}/^{39}\text{Ar}^b$	$^{36}\text{Ar}/^{39}\text{Ar}^a$ $\times 10^{-3}$	$^{39}\text{Ar} \times 10^{-13}$ mol	% ^{39}Ar Released	$^{40}\text{Ar}^{*c}$, %	$^{40}\text{Ar}^{*}/^{39}\text{Ar}^k$	Age ± 1 standard deviation, Ma	Time, min	1000/ $^{\circ}\text{T}$, 1/ $^{\circ}\text{K}$	$\log D/r^2$, 1/s
KPA Potassium Feldspar ($J = 0.005048$; Weight = 0.11935 g)											
1100	5.893	0.0262	1.682	4.15	88.3	90.2	5.380	48.7 $\pm$ 0.4	120	0.728	4.835
1100	6.594	0.0129	2.386	9.33	96.1	88.6	5.873	53.1 $\pm$ 0.3	882	0.728	5.076
1200	7.276	0.0182	2.005	2.36	98.0	90.1	6.668	60.2 $\pm$ 0.3	15	0.679	3.503
1300	6.255	0.0288	3.967	1.37	99.2	78.3	5.068	45.9 $\pm$ 0.4	15	0.636	3.402
1550	28.27	0.0140	62.29	0.954	100	34.4	9.844	88.2 $\pm$ 1.2	20	0.549	2.873
450	295.2	0.1032	615.1	0.436	0.201	38.4	113.4	816.8 $\pm$ 15.7	30	1.383	8.752
500	27.37	0.0156	43.15	1.29	0.796	53.2	14.60	128.3 $\pm$ 5.2	30	1.294	7.586
550	11.79	0.0189	12.62	2.68	2.03	68.0	8.043	71.8 $\pm$ 2.8	24	1.215	6.719
640	10.72	0.0214	9.757	4.95	4.31	72.8	7.820	69.8 $\pm$ 1.4	5	1.095	5.421
600	-11.44	3.321	25.49	0.128	4.37	00.0	0.0000	00.0 $\pm$ 0.0	30	1.145	7.651
640	0.5200	0.1599	0.000	1.66	5.13	31.1	0.9117	08.3 $\pm$ 0.3	15	1.095	6.196
670	0.8290	0.0888	0.000	2.24	6.17	70.5	1.844	16.7 $\pm$ 2.3	15	1.060	5.992
700	2.745	0.0636	2.842	2.96	7.53	65.7	1.892	17.1 $\pm$ 0.3	15	1.028	5.787
750	4.285	0.0461	4.765	3.68	9.23	65.2	2.863	25.9 $\pm$ 0.9	15	0.978	5.604
800	3.405	0.0317	3.216	3.59	10.9	69.4	2.440	22.1 $\pm$ 0.3	10	0.932	5.361
800	2.158	0.0127	0.000	2.74	12.1	94.9	2.186	19.8 $\pm$ 0.3	20	0.932	5.720
800	2.150	0.0120	1.152	2.38	13.2	77.4	1.794	16.3 $\pm$ 0.6	31	0.932	5.930
800	2.230	0.0228	0.811	2.53	14.4	82.7	1.975	17.9 $\pm$ 0.7	60	0.932	6.152
750	2.486	0.0219	0.946	1.15	14.9	77.3	2.191	19.8 $\pm$ 0.4	150	0.978	6.867
700	2.878	0.0220	2.930	1.25	15.5	62.5	1.997	16.3 $\pm$ 1.7	929	1.028	7.605
800	2.544	0.0177	1.949	1.77	16.3	70.5	1.953	17.9 $\pm$ 0.7	90	0.932	6.421
850	2.985	0.0120	2.423	1.77	17.1	70.2	2.253	20.4 $\pm$ 1.1	30	0.890	5.924
900	3.432	0.0087	2.997	2.30	18.2	70.2	2.530	22.9 $\pm$ 1.2	14	0.853	5.455
950	3.614	0.0056	2.436	5.39	20.7	78.0	2.877	26.0 $\pm$ 0.5	16	0.818	5.101
1000	4.235	0.0058	3.262	6.28	23.6	75.7	3.254	29.4 $\pm$ 0.3	10	0.786	4.775
1000	4.132	0.0087	2.591	7.82	27.2	80.1	3.350	30.2 $\pm$ 0.2	20	0.786	4.921
1000	4.222	0.0029	1.929	7.92	30.8	85.1	3.636	32.8 $\pm$ 0.4	30	0.786	5.034
1000	4.246	0.0061	1.706	9.87	35.4	86.9	3.726	33.6 $\pm$ 0.4	60	0.786	5.182
1000	4.327	0.0060	1.541	11.2	40.5	88.4	3.855	34.8 $\pm$ 0.1	120	0.786	5.369
900	5.573	0.0219	5.865	1.40	41.2	65.3	3.824	34.5 $\pm$ 2.0	150	0.853	6.336
800	5.042	0.0012	3.781	1.69	42.0	74.0	3.908	35.2 $\pm$ 1.9	2231	0.932	7.418
950	4.421	0.0052	1.460	4.15	43.9	88.0	3.973	35.8 $\pm$ 0.5	210	0.818	5.990
1030	4.915	0.0069	1.868	3.23	45.4	86.3	4.346	39.2 $\pm$ 0.5	30	0.767	5.237
1050	5.001	0.0164	2.013	2.10	46.3	84.6	4.390	39.5 $\pm$ 0.5	14	0.756	5.081
1075	5.203	0.0112	1.992	4.05	48.2	86.7	4.598	41.4 $\pm$ 0.7	17	0.742	4.867
1100	5.348	0.0129	2.976	3.19	49.7	81.3	4.453	40.1 $\pm$ 0.8	10	0.728	4.725
1100	5.299	0.0114	2.307	5.19	52.0	85.6	4.601	41.4 $\pm$ 0.4	20	0.728	4.797

Table 1. (continued)

Temp., °C	$^{40}\text{Ar}/^{39}\text{Ar}^a$	$^{37}\text{Ar}/^{39}\text{Ar}^b$	$^{36}\text{Ar}/^{39}\text{Ar}^a$ $\times 10^{-3}$	$^{39}\text{Ar} \times 10^{-13}$ mol	% ^{39}Ar Released	$^{40}\text{Ar}^{*c}$, %	$^{40}\text{Ar}^{*}/^{39}\text{ArK}$	Age ± 1 standard deviation, Ma	Time, min	1000/ T , 1/°K	$\log D/r^2$, 1/s
1100	5.298	-0.0012	1.277	5.95	54.8	91.4	4.904	44.1 $\pm$ 0.3	30	0.728	4.893
1100	5.360	0.0092	1.603	8.34	58.6	90.1	4.870	43.8 $\pm$ 0.5	60	0.728	5.021
1100	5.493	0.0050	1.619	10.1	63.3	90.3	4.998	45.0 $\pm$ 0.2	120	0.728	5.146
1100	5.587	0.0088	1.746	24.2	74.4	90.2	5.055	45.5 $\pm$ 0.1	731	0.728	5.475
1200	6.085	0.0079	2.727	9.24	78.7	85.9	5.263	47.3 $\pm$ 0.3	15	0.679	4.086
1300	5.144	0.0044	1.714	38.5	96.4	89.7	4.621	41.6 $\pm$ 0.1	16	0.636	3.124
1550	4.459	0.0116	2.429	7.76	100	82.6	3.725	33.6 $\pm$ 0.3	20	0.549	2.746

Abbreviations are Temp., Temperature; ^{39}ArK , amount of ^{39}Ar produced from ^{39}K in the sample; D/r^2 , frequency factor; and I , irradiation parameter.

^aValues are corrected for mass discrimination, background, and line blank.

^bValues are corrected for ^{37}Ar decay.

^cValues include line blank.

over the last 20% of gas released (Figure 6a). A linear fit to the first 5 steps on the associated Arrhenius plot yields an E of 55.79 kcal/mol and a $\log (D_0/r_0^2)$ of 8.47 s^{-1} (Figure 6b). The domain distribution parameters listed in Figure 6c give an excellent fit to the $\log (r/r_0)$ plot, with the exception of the last 7% of gas released above the incongruent melting temperature of potassium feldspar. The calculated thermal history, shown in Figure 6d, produces an excellent fit to the laboratory-derived age spectrum (Figure 6a). The thermal history for this sample shows slow cooling rates of $0.5\text{--}5^\circ\text{C/m.y.}$ from 40 Ma to 21 Ma through a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age on metamorphic muscovite of 25.1 ± 0.2 Ma from nearby in the late Precambrian Osceola Argillite [Lee and Sutter, 1991]. At 21 Ma, cooling rates dramatically increase to 22°C/m.y. followed by a further increase to 55°C/m.y. at 18 Ma. These rapid cooling rates can be extrapolated to the 15.7 ± 1.8 Ma apatite fission track age.

Sample KPA3 comes from a larger pegmatite body that intrudes the Lower Cambrian Prospect Mountain Quartzite (Figure 2), located ~ 61 m (present-day distance) vertically above and ~ 2.8 km to the NE of sample KPA2 (Figure 3). The dike and country rock have been strongly deformed by the Tertiary ductile strain event. Sample KPA3 yields an age spectrum with a large component of excess argon over the first 23% of gas released, followed by a small plateau at 19 Ma for the next 14% of gas released (Figure 7a). This is followed by a moderately well-defined monotonic increase in age to 35 Ma. A linear fit to steps 2-5 on the associated Arrhenius plot yields an E of 48.67 kcal/mol and a $\log (D_0/r_0^2)$ of 6.65 s^{-1} (Figure 7b). The domain distribution parameters listed in Figure 7c give an excellent fit to the $\log (r/r_0)$ plot, with the exception of the last 12% of gas released above the incongruent melting temperature of potassium feldspar. The calculated thermal history, shown in Figure 7d, produces an excellent fit to the laboratory-derived age spectrum (Figure 7a). The thermal history for this sample shows slow cooling rates of $1\text{--}4^\circ\text{C/m.y.}$ from 36 Ma to 19 Ma through the $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age on metamorphic muscovite of 25.1 ± 0.2 Ma from nearby in the late Precambrian Osceola Argillite [Lee and Sutter, 1991]. At 19 Ma, cooling rates noticeably increase to 40°C/m.y. which can be extrapolated to the apatite fission track of 15.7 ± 1.8 Ma [Miller et al., 1989, 1993].

Sample KPA1 from the eastern part of the lower plate (Figure 3) possesses an age spectrum (Figure 8a) similar in age and overall shape to sample KPA2 but contains a plateau over the first $\sim 40\text{--}50\%$ of gas released, followed by a rapid rise in age and a more pronounced convex-up form. The shape of this age spectrum is similar to those generated by a "large-domain-trapped-argon-effect" documented by Foster et al. [1990a]. Foster et al. [1990a] found that potassium feldspar spectra that contain a plateau over the first $\sim 40\text{--}50\%$ of gas released, followed by a rapid rise in age, were the result of rapid cooling through $\sim 400^\circ\text{C}$ in the presence of nonatmospheric argon. They suggested that the ages obtained over the first $\sim 40\text{--}50\%$ of gas released were geologically reasonable, whereas incorporation of nonatmospheric argon into large domains led to ages older than the true age of the sample over the last $\sim 50\text{--}60\%$ of gas released. For sample KPA1 such an interpretation is supported by the thermal history calculations.

A linear fit to steps 2-7 on the associated Arrhenius plot for sample KPA1 yields an E of 42.32 kcal/mol and a $\log (D_0/r_0^2)$ of 5.06 s^{-1} (Figure 8b). The domain distribution parameters listed in

KPA5

Figure 4. (a) Age spectrum for potassium feldspar sample KPA5. The dashed curve is the calculated age spectrum using the domain diffusion, domain distribution, and cooling history parameters shown in Figures 4b-4d. (b) Arrhenius plot calculated assuming a plane slab diffusion geometry from measured ^{39}Ar loss during the thermal degassing experiment. The domain diffusion parameters activation energy E and frequency factor $\log(D_0/r_0^2)$ shown arise from fitting the initial linear data array. Inset shows the temperature cycling heating schedule used in the experiment. (c) Plot of $\log(r/r_0)$ versus cumulative % ^{39}Ar released (solid line) together with the theoretical fit (dashed line) using the domain distribution parameters shown. (d) Proposed cooling history for KPA5 that produces an excellent fit to the age spectrum in Figure 4a and also incorporates a coexisting $^{40}\text{Ar}/^{39}\text{Ar}$ white mica age [Lee and Sutter, 1991] and apatite fission track ages from a broad portion of lower plate rocks [Miller et al., 1989, 1993]. See text for details.

Figure 8c give an excellent fit to the $\log(r/r_0)$ plot, with the exception of the last 6% of gas released above the incongruent melting temperature of potassium feldspar. The calculated thermal history, shown in Figure 8d, produces an excellent fit to the laboratory-derived age spectrum over the first ~50-60% of gas released and minimizes the degree of misfit over the last ~40-50% of gas released (Figure 8a). The poor fit to the age spectrum over the last ~40% of gas released (i.e., >22.2 Ma) reflects incorporation of a nonatmospheric trapped argon component. Furthermore, the calculated cooling history for this part of the age spectrum is incompatible with the calculated cooling histories for samples KPA4, KPA3, and KPA2 (see discussion section below). Nevertheless, the excellent fit to the laboratory-derived age spectrum over the first ~40-50% of gas released (17.2-20.9

Ma) based on a derived cooling rate of 10-40°C/m.y., which is similar to the cooling rates for samples KPA4, KPA3, and KPA2 over the same time span, suggests that the calculated thermal history for this part of the age spectrum closely approximates the actual cooling history.

Sample KPA, which represents the easternmost exposure of lower plate rocks in the Smith Creek drainage (Figure 3), possesses a complex-shaped age spectrum characterized by excess argon in the low-temperature steps, a hump-shaped rise in ages over 80% of gas released and a drop in age over the last 20% gas released (Figure 9). The shape of this spectrum is almost identical to some of the spectra with a large-domain-trapped-argon-effect documented by Foster et al. [1990a]. This effect most likely explains why this sample could not be adequately modeled. The

KPA4

Figure 5. (a) Age spectrum, (b) Arrhenius plot, (c) $\log(r/r_0)$ versus cumulative % ^{39}Ar released plot, and (d) proposed cooling history for sample KPA4. All four graphs are the same as in Figure 4. See text for details.

minimum ages of 16.7 Ma at 6% of gas released and 16.3 Ma at 13% are interpreted as an upper limit on the time of rapid cooling for this sample.

Discussion

Cooling Histories

The calculated thermal histories presented here, along with reported apatite fission track ages [Miller *et al.*, 1989, 1993], record three periods of rapid cooling as follows: the first at 48-41 Ma, the second at 30-26 Ma, and the third at 20-16 Ma (Figure 10a). Although mechanisms such as fluid convection and lateral heat flow can cause crustal rocks to cool, the lack of evidence for pervasive hydrothermal alteration and Tertiary plutons within the northern Snake Range suggests that these rapid cooling rates largely reflect tectonic denudation resulting from motion along normal faults, including a large component of motion along the NSRD and/or younger, east dipping normal faults exposed along the eastern flank of the range. Samples KPA5 and KPA4, the two westernmost samples, which are from undeformed and moderately deformed pegmatites, respectively, exhibit a period of

moderate to rapid cooling (rates of 10-20°C/m.y.), the westernmost sample (KPA5) cooling first, during middle Eocene time. This period of rapid cooling may reflect extensional unroofing due to movement along pre-35 Ma north-south and east-west striking normal faults now exposed in the Schell Creek Range and western northern Snake Range [Gans, 1990; Gans *et al.*, 1993]. The kinematics, magnitude of extension, and absolute age of these faults are poorly known because of superimposed large-magnitude extension. Nevertheless, the geometry of these faults suggests that they probably soled at depth into the NSRD, implying that slip along the western exposures of the NSRD likely began as early as the middle Eocene. This interpretation is compatible with field observations that show major north-south striking normal faults and westernmost exposures of the NSRD are depositionally overlain by 35 Ma volcanic rocks [Gans *et al.*, 1993]. The time of onset of this period of extensional deformation, its duration, and its magnitude are unknown. Temperatures along the northwestern flank of the range (undeformed sample KPA5) dropped below 300°C, the minimum temperature at which "wet" quartz is likely to deform crystal plastically [Koch *et al.*, 1989], by ~46 Ma, whereas 6.2 km (present-day horizontal distance) to

KPA2

Figure 6. (a) Age spectrum, (b) Arrhenius plot, (c) $\log(r/r_0)$ versus cumulative % ^{39}Ar released plot, and (d) proposed cooling history for sample KPA2. All four graphs are the same as in Figure 4. The $^{40}\text{Ar}/^{39}\text{Ar}$ white mica age [Lee and Sutter, 1991] is from nearby. See text for details.

the southeast (moderately deformed sample KPA4), temperatures did not drop below 300 $^{\circ}\text{C}$ until 34.0 ± 7 -10 Ma (Figure 10). These relations suggest that ductile extensional fabrics exposed in lower plate rocks along the western part of the range are at least pre-late Oligocene.

Undeformed 36.9 ± 0.3 Ma muscovite-bearing rhyolite porphyry dikes exposed on the northwestern part of the range crosscut the weakly developed mylonitic fabric [Lee and Sutter, 1991]. Lee and Sutter concluded that the undeformed nature of these dikes was the result of the rheologic contrast between dikes and weakly deformed marbles. In addition, they noted that compositionally similar dikes to the east were involved in the mylonitic deformation where the strain is considerably higher; thus they inferred that the 36.9 Ma dikes were emplaced before the formation of the mylonitic foliation. However, in light of the thermal histories presented here a more reasonable interpretation is that these dikes were emplaced after the formation of the mylonitic fabric on the western flank of the range. If true, then the 36.9 Ma age provides a better lower age limit for mylonitic deformation on the western flank of the range than does the thermal history data. This interpretation does not rule out continued mylonitic extensional deformation to the east because

these rocks were still above 300 $^{\circ}\text{C}$ and probably deforming plastically. An upper age limit for mylonitic deformation is provided by the Late Cretaceous metamorphic event because textural relations show that the mylonitic fabrics overprint this metamorphic event.

An alternative interpretation for this period of rapid cooling involves refrigeration of the continental lithosphere as a consequence of replacing a hot asthenospheric wedge with a cold slab as subduction beneath the North American plate shifted from a normal to shallow angle during the Laramide orogeny [Dumitru *et al.*, 1991]. Simple one-dimensional modeling of the time lag between onset of shallow angle subduction and onset of cooling indicates that the thickness of the continental lithosphere above the cold slab and the time shallow angle subduction became established are the dominant factors [Dumitru, 1990]. Extrapolation of this model to east central Nevada suggests that cold slab induced cooling may have continued to as late as middle Eocene time [Dumitru *et al.*, 1991]. Because the two samples exhibit a differential cooling history over such a short distance and exhibit rapid cooling at a much later time (10-20 m.y.) than the Schell Creek Range [see Dumitru *et al.*, 1991], factors which are contrary to the uniform cooling histories predicted by the re-

KPA3

Figure 7. (a) Age spectrum, (b) Arrhenius plot, (c) $\log(r/r_0)$ versus cumulative % ^{39}Ar released plot, and (d) proposed cooling history for sample KPA3. All four graphs are the same as in Figure 4. The $^{40}\text{Ar}/^{39}\text{Ar}$ white mica age [Lee and Sutter, 1991] is from nearby. See text for details.

refrigeration model, the cold slab induced refrigeration hypothesis is an unlikely alternative. However, given the fact that many of the parameters needed for this model are poorly known [see discussion by Dumitru, 1990], it is not possible to fully assess the validity of this hypothesis.

The second period of rapid cooling is only observed in sample KPA5. This sample drops below 300°C by 46 Ma and follows with a 16-m.y. period of slow cooling. At 30 Ma, cooling rates increase markedly to $10\text{--}22^\circ\text{C/m.y.}$; temperatures drop below 165°C by 26 Ma. These relations imply that by 46 Ma lower plate rocks on the northwestern flank of the range resided within the brittle crust beneath the NSRD. As such, the rapid late Oligocene cooling rates for lower plate rocks on the northwestern flank of the range suggest a pulse of footwall uplift from beneath the NSRD. At the same time, however, along the central and eastern parts of the range, lower plate rocks were still at temperatures above 300°C (Figure 10) and based on textural arguments [Lee *et al.*, 1987], were still deforming by intracrystalline plastic flow. Ductile shear in a subhorizontal or shallow angle shear zone may explain why samples KPA4, KPA3, and KPA2 exhibit a period of slow cooling while the west flank experiences a pulse of rapid cooling.

The third period of rapid cooling is observed in the four moderately to strongly deformed samples KPA4, KPA3, KPA2, and KPA1. These samples show thermal histories characterized by slow cooling rates of $1\text{--}4^\circ\text{C/m.y.}$ from 41 Ma to ~ 20 Ma which are followed by markedly increased cooling rates of $22\text{--}55^\circ\text{C/m.y.}$ At ~ 19 Ma, temperatures drop below 300°C (Figure 10), thus providing a lower age limit on ductile extension for lower plate rocks since crystal-plastic deformation of quartz is not likely to occur at temperatures below $\sim 300^\circ\text{C}$. These data, along with kinematic data from lower plate rocks [Lee *et al.*, 1987], suggest that by ~ 19 Ma, lower plate rocks had been uplifted and translated within an east dipping, top-to-the-east shear zone such that they resided entirely within the brittle part of the crust and had been "transferred" into the footwall of the NSRD. Cooling rates of $\geq 40^\circ\text{C/m.y.}$ continue until 15.7 Ma, at which time cooling rates throughout the footwall uniformly decrease to $\sim 15^\circ\text{C/m.y.}$ as lower plate rocks pass through the annealing zone for apatite ($120\text{--}60^\circ\text{C}$). This period of cooling is followed by residence at low, near surface temperatures [Miller *et al.*, 1989, 1993]. The onset of rapid cooling at ~ 20 Ma suggests rapid footwall uplift from beneath the NSRD and/or younger, east dipping normal faults exposed along the eastern flank of the range.

Figure 8. (a) Age spectrum, (b) Arrhenius plot, (c) $\log(r/r_0)$ versus cumulative % ^{39}Ar released plot, and (d) proposed cooling history for sample KPA1. All four graphs are the same as in Figure 4. $^{40}\text{Ar}/^{39}\text{Ar}$ white mica age [Lee and Sutter, 1991] is from the same stratigraphic horizon nearby. See text for details.

(Figure 3). This period of rapid cooling is not observed along the northwest flank of the range (sample KPA5) (Figure 10), suggesting that these rocks had already moved from beneath the NSRD and now resided at higher structural levels within the crust.

These calculated thermal histories imply that extension within the northern Snake Range is episodic and long-lived (at least 32 m.y.). Episodic extension has also been documented in the Ruby Mountains-East Humbolt Range metamorphic core complex [McGrew and Snee, 1994] and Kern Mountains-Deep Creek Range [Gans *et al.*, 1991]. Furthermore, the thermal histories suggest that the NSRD is a composite of more than one fault. Along the western flank of the range, movement along the NSRD which began during the middle Eocene, experienced a pulse of movement during the late Oligocene and had ceased activity by the early Miocene. In contrast, the period of main activity along the NSRD now exposed along the eastern flank of the range did not begin until ~20 Ma. These relations imply either a prolonged movement history (up to 32 m.y.) along the NSRD punctuated by three major pulses of slip or three distinct episodes of slip separated by long periods of relative quiescence. The thermal history data do not allow movement along the NSRD to be distinguished from movement along younger normal faults exposed along the

eastern flank of the range. In light of this, it is possible that the period of rapid uplift during the youngest cooling event (20–16 Ma) could have occurred largely along the younger set of normal faults. Data presented here suggest that slip along the NSRD began as early as 48 Ma and continued episodically until ~16 Ma.

Previous work [i.e., Lee and Sutter, 1991] suggested that the 300% of ductile extension documented within lower plate rocks occurred between 37 Ma and ~24 Ma. The thermal history calculations, along with published muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ data and textural relations, suggest, instead, that mylonitic extensional deformation in footwall rocks was ongoing prior to 37 Ma and had ceased by 19 Ma. These data, however, preclude estimates of the magnitude of extension for any given time period.

The inferred period of middle Eocene extension is part of a growing body of evidence (see compilation by Hodges and Walker [1992]) suggesting Late Cretaceous to early Tertiary extension in the hinterland of the Sevier fold and thrust belt, and yet the cause of this period of extension is unknown. A number of workers [e.g., Coney and Harms, 1984; Wernicke *et al.*, 1987; Hodges and Walker, 1992] have introduced the idea that gravitational collapse of overthickened crust, formed as a result of shortening during the Late Cretaceous, is the driving mechanism

Figure 9. (a) Age spectrum for potassium feldspar sample KPA. The saddle-shaped age spectrum is indicative of excess argon and therefore can not be adequately modeled. (b) Arrhenius plot calculated assuming a plane slab diffusion geometry from measured ³⁹Ar loss during the thermal degassing experiment. Inset shows the temperature cycling heating schedule used in the experiment. (c) Plot of $\log(r/r_0)$ versus cumulative % ³⁹Ar released.

for this period of extensional deformation. However, fundamentally different tectonic processes would have caused the Oligocene and Miocene episodes of extension. The documented late Oligocene cooling event, inferred to signal footwall uplift from beneath the NSRD, is part of region-wide extensional event in east central Nevada (Figure 1) that spans the Oligocene but is diachronous [cf. *Gans et al.*, 1989, 1991]. The final period of rapid cooling documented along the eastern flank of the range is also part of an east central Nevada-wide (Figure 1) rapid cooling event of early to middle Miocene age documented by apatite fission track analyses [Miller et al., 1993]. Miller et al. [1993] interpret this rapid cooling event as indicating a large component of slip along range-bounding normal faults. Furthermore, they suggest that because this rapid cooling event is observed along strike in the Deep Creek, northern Snake, and southern Snake ranges and in the Kern Mountains, these ranges form a single coherent fault block beneath a >150-km long east dipping Miocene fault system, of which the easternmost exposure of the NSRD is a component.

Steep Geothermal Gradients?

Pre- to synextensional intrusion of plutons into the middle crust leading to high thermal gradients and thermal softening of the middle crust has been proposed as a mechanism for triggering ductile flow at depth and brittle failure of the upper crust [e.g.,

Gans et al., 1989], as well as a triggering mechanism for formation of metamorphic core complex detachment faults [e.g., *Parsons and Thompson*, 1993; *Lister and Baldwin*, 1993]. In these models, rapid cooling of midcrustal rocks should take place after pluton emplacement as a consequence of cooling in the contact aureole and magmatism-induced extensional unroofing. In the northern Snake Range, steep geothermal gradients (i.e., $\geq 40^\circ\text{C}/\text{km}$) were inferred because it was argued that lower plate units were at stratigraphic depths [Gans and Miller, 1983; Miller et al., 1983] and were above 300°C [Miller et al., 1983; Lee and Sutter, 1991] during the Tertiary. The steep geothermal gradients and localization of metamorphism and mylonitic deformation in the footwall of the NSRD during the Tertiary were inferred to be a consequence of heat input by intrusion of batholiths at depth [Miller et al., 1983; 1988; Gans et al., 1985, 1989; Lee et al., 1987; Lee and Sutter, 1991]. However, no plutons of demonstrable Tertiary age have been documented at present levels of exposure in the northern Snake Range. In contrast, many of the metamorphic core complexes of the western Cordillera such as the Whipple Mountains [Wright et al., 1986; Davis, 1988], Ruby Mountains-East Humboldt Range [Wright and Snoke, 1993; McGrew and Snee, 1994; Hurlow et al., 1991], South Mountains [Reynolds et al., 1986] and Kern Mountains [Miller et al., 1988; Gans et al., 1991], provide evidence for a close spatial and temporal relation between magmatism, elevated geothermal gradients, and mylonitic deformation.

Figure 10. (a) Calculated thermal histories (thick, solid lines) for potassium feldspar samples KPA5, KPA4, KPA3 and KPA2. Included are coexisting white mica $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages (dark shaded rectangles) [Lee and Sutter, 1991] and apatite fission track ages (light shaded box) that cover a broad portion of lower plate rocks [Miller et al., 1989, 1993]. Thin, solid lines are extrapolation of the calculated potassium feldspar thermal histories to apatite fission track data. Thin horizontal line at 300°C represents minimum temperature at which "wet" quartz is likely to deform crystalplastically [Koch et al., 1989]. (b) Range of calculated thermal histories based on a $\pm 15^\circ\text{C}$ error for potassium feldspar samples KPA5, KPA4, KPA3, and KPA2. See text for discussion.

In the northern Snake Range the hypothesis that plutons may be present just below the present levels of exposure can be tested by incorporating a "reheating" event or thermal pulse resulting from pluton emplacement into the calculated thermal histories. Figure 11 shows two thermal histories for sample KPA2, continuous cooling (as discussed above) and a reheating event. Timing of the reheating event is constrained by a voluminous outpouring of volcanic rocks in east central Nevada at 35 Ma [Gans et al., 1989] implying magma chambers at depth and an elevated thermal gradient in the lower and middle crust (Figure 11). In order to adequately model the KPA2 age spectrum, the calculated thermal history requires a dramatic drop in temperature (cooling rates of 20–40°C/m.y.) just prior to the onset of the reheating event (the preceding 2.5 m.y.), followed by a long period (~15 m.y.) of slow cooling, and ending with a period of rapid cooling that begins at 20 Ma. Calculated thermal history curves for samples KPA3 and KPA4 show a similar form when incorporating a reheating event at 35 Ma. Furthermore, similarly shaped cooling curves are obtained when a reheating event is chosen for any time between 40 Ma and 20 Ma. The rapid cooling event reflects the necessity to maintain a balance between a large amount of argon loss during reheating and closure to argon loss during rapid cooling in order to fit a theoretical age spectrum to the laboratory-derived one. Clearly, incorporation of a reheating event into the thermal histories results in a nonunique solution, implying no geologic significance.

In light of this modeling the hypothesis that steep geothermal gradients and localization of metamorphism and mylonitic deformation in the footwall of the NSRD during the Tertiary were consequences of heat input by intrusion of batholiths at depth appears unlikely. A more likely explanation is that the geothermal gradient was of the order of ~20–30°C/km, which is typical for the Basin and Range [Lachenbruch and Sass, 1978]. For lower plate rocks at temperatures above 300°C, such a geothermal gradient would place units along the eastern flank of the range at their estimated Late Cretaceous metamorphic depths during the early Tertiary. Therefore it seems reasonable to suggest that the middle Eocene extensional event may have, at least in part, uplifted lower plate rocks from these depths to a depth greater than stratigraphic (~10 km) but less than Late Cretaceous depth (up to 24 km) by 40 Ma. Since both the duration and magnitude of this extensional event are unknown, we can only speculate as to the depth of lower plate units at this time. Assuming the geothermal gradient of ~20–30°C/km was constant through time, then the depth of lower plate units along the eastern flank of the range would have been between ~12 km and ~18 km at 40 Ma. A geothermal gradient of ~20–30°C/km is consistent with the estimated ~30°C/km Tertiary geothermal gradient for stratigraphically equivalent but nonmylonitic footwall rocks in the Deep Creek Range (Figure 1) [Gans et al., 1991] but is less than the synextensional geothermal gradient of ~45°C/km that was obtained based on geothermometry and geobarometry data from

Figure 11. Calculated thermal history curves for sample KPA2 which produce theoretical age spectra that provide an excellent fit to the laboratory-derived age spectrum. Dashed curve shows continuous cooling (see Figure 6), and solid curve shows a reheating event at 35 Ma.

footwall mylonitic rocks in the Ruby Mountains-East Humbolt Range metamorphic core complex [Hurlow *et al.*, 1991].

Differential Uplift and Rotation: Implications for the Origin and Movement History of the NSRD

Lee and Sutter [1991] interpreted chrontours of metamorphic white mica K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ total ages that monotonically decrease from a high of ~60 Ma on the west flank to a low of ~20 Ma on the east flank as suggesting prolonged residence at higher temperatures in the east. They attributed this differential cooling to asymmetric unroofing from beneath a moderate to high-angle detachment fault/shear zone system that rotated as it moved or to a rolling hinge/isostatic rebound mechanism. However, because many of the total gas ages were derived from disturbed age spectra the significance of these ages was questionable and the uplift history could not be quantified in space and time. In contrast, the thermal history data presented here clearly suggest a prolonged period of differential unroofing that began at least as early as ~48 Ma on the west flank of the range and continued until ~16 Ma on the east flank. Furthermore, the thermal history data provide temporal and spatial resolution of the uplift history allowing a better understanding of the origin and geometry of the NSRD.

The thermal history data suggest that in the northern Snake Range mylonitic deformation was ongoing sometime prior to late Eocene time but had certainly ceased by 19 Ma. However, crystal-plastic deformation was not synchronous throughout the range. Temperatures along the northwestern flank of the range were below the minimum required for crystal-plastic deformation (300°C) by 46 Ma, indicating that by this time this part of the range was in the brittle part of the crust. In contrast, from west to east across the range, calculated thermal histories show that the lower plate did not drop below 300°C until 34.0 $\pm$ 7/-10 Ma (KPA4), 23.0 $\pm$ 10/-4 Ma (KPA3), and 19.3 $\pm$ 0.7/-0.3 Ma (KPA2). The thermal history data provide evidence for a temperature difference, within a given structural horizon, of 70-170°C across the range from at least middle Eocene time (Figures

10 and 12). Such relations indicate differential cooling (asymmetric unroofing) of lower plate rocks that dipped eastward prior to the onset of extension and/or as a result of top-to-the-east shear within an east dipping shear zone.

Using the cooling histories derived from the modeling, one can construct a graph of temperature versus cross-sectional distance as a function of age for each sample (Figure 12). Because two of the samples analyzed (KPA5 and KPA3) are from the same stratigraphic horizon and exhibit contrasting thermal histories (Figures 2 and 10), isochrons between these two samples are representative of the average disposition of layering in the footwall of the NSRD. However, if we interpolate the position of the Prospect Mountain quartzite between these two samples, it is obvious that lower plate units were not planar during their uplift history (Figure 12). This is true regardless of the geothermal gradient and/or exact timing of ductile extensional deformation. Lower plate units to the west of KPA4 dip moderately to steeply to the east (assuming a geothermal gradient of between 20° and 30°C/km), whereas units to the east dip shallowly to the east throughout most of the uplift history. As argued above, rocks along the west flank of the range were at temperatures below 300°C by ~46 Ma and were therefore in the brittle part of the crust within the footwall of the NSRD. In contrast, rocks along the east flank of the range were at temperatures above 300°C and were, arguably, within the ductile part of the crust within a shal-

Figure 12. Graph of temperature versus present-day cross-sectional distance (subparallel to the stretching lineation in mylonitic rocks) as a function of age for potassium feldspar samples KPA5, KPA4, KPA3, and KPA2, and apatite fission track data [Miller *et al.*, 1989, 1993]. This reconstruction assumes a geothermal gradient of 30°C/km and that all of the ductile extensional deformation in lower plate rocks occurred prior to 45 Ma. Representative isochrons are drawn for the Lower Cambrian Prospect Mountain quartzite which includes samples KPA5 and KPA3 and is interpolated below and above samples KPA4 and KPA2, respectively. These isochrons illustrate a temperature differential (70-170°C) across the range for a given structural horizon and that lower plate units are nonplanar. To the west of sample KPA4, units dip more steeply than units to the east. In addition, the dip of units to the west of sample KPA4 increases between 30 Ma and 25 Ma and then decreases between 19 Ma and 15.7 Ma. These relations hold, regardless of whether the geothermal gradient is as high as 40°C/km or as low as 20°C/km and regardless of the temporal partitioning of lower plate ductile strain. See text for discussion.

low dipping shear zone. Since the NSRD cuts structurally down section to the east, the dip of units between samples KPA5 and KPA4 represents a minimum dip for the NSRD. Clearly, the magnitude of this dip is a function of the geothermal gradient. The maximum dip of lower plate units occurs at 25 Ma (Figure 12), implying an eastward dip of 52° (geothermal gradient of $20^\circ\text{C}/\text{km}$) or 40° (geothermal gradient of $30^\circ\text{C}/\text{km}$). The dip of the NSRD therefore is moderately to steeply east dipping ($\geq 40^\circ$).

This reconstruction implies a detachment fault/shear zone geometry characterized by a moderately to steeply east dipping detachment fault to the west that shallows at a depth of ~ 9 km (geothermal gradient of $30^\circ\text{C}/\text{km}$) or a depth of ~ 13.5 km (geothermal gradient of $20^\circ\text{C}/\text{km}$), listric style, into a shallow, east dipping shear zone to the east (Figure 13a). Furthermore, the dip of lower plate units to the west of sample KPA4 increases between 30 Ma and 25 Ma (24° to 40° for a geothermal gradient of $30^\circ\text{C}/\text{km}$; 34° to 52° for a geothermal gradient of $20^\circ\text{C}/\text{km}$) and then decreases between 19 Ma and 16 Ma (Figures 12 and 13). These relations indicate that between 25 Ma and ~ 16 Ma, lower plate units rotated between 40° and 52° to a subhorizontal orientation during uplift from beneath the NSRD. Such relations hold regardless of whether the geothermal gradient is as high as $40^\circ\text{C}/\text{km}$ (although the degree of rotation is 32°) and regardless of the temporal partitioning of lower plate ductile strain. On the basis of these reconstructions the deepest levels of exposure of

lower plate rocks along the sampling transect, located in the central part of the range (sample KPA2) (Figure 3), were uplifted ~ 6.7 km (a geothermal gradient of $30^\circ\text{C}/\text{km}$) or ~ 10.2 km (a geothermal gradient of $20^\circ\text{C}/\text{km}$) between 19.0 and 15.7 Ma (Figure 12), implying a vertical uplift rate of 2.0 mm/yr or 3.1 mm/yr, respectively.

Implicit in the above discussion is that the geothermal gradient was temporally constant and that paleoisotherms were subhorizontal. One-dimensional and two-dimensional modeling of synextensional thermal histories [e.g., England and Jackson, 1987; Ruppel *et al.*, 1988] provides some insight into this problem. In the case of footwall rocks that have not undergone synextensional ductile thinning during uplift from beneath a low-angle detachment (e.g., Figures 12 and 13) these models predict that the cooling rate is on the same timescale as the rate of extension; that is, the geothermal gradient remains constant through time and paleoisotherms would remain undisturbed. In contrast, in the case of synextensional ductile deformation of lower plate rocks during a uniform pure shear extensional episode the models predict a period of isothermal uplift and postextension cooling. In this case, isotherms would collapse, resulting in an increase in the geothermal gradient until equilibration and isotherms probably would not remain horizontal. Neither of these two studies models the case of a moderate to high-angle fault. Because of this limitation, the

Figure 13. A schematic diagram illustrating the temporal and spatial evolution of the NSRD at (a) 30 Ma, (b) 25 Ma, (c) 19 Ma, and (d) 17 Ma. The geometric evolution of the NSRD based on the calculated cooling histories provides a spectacular example of the rolling hinge/isostatic rebound model [e.g., Buck, 1988; Wernicke and Axen, 1988]. These schematic diagrams assume a geothermal gradient of $30^\circ\text{C}/\text{km}$. The geometric evolution illustrated here holds, regardless of whether the geothermal gradient is as high as $40^\circ\text{C}/\text{km}$ or as low as $20^\circ\text{C}/\text{km}$ and regardless of the temporal partitioning of lower plate ductile strain, although the magnitude of dips may vary.

assumptions of a temporally constant geothermal gradient and subhorizontal isotherms can not be assessed with this data set.

The sequence of changing lower plate dips through time and space is a spectacular example of the rolling hinge/isostatic rebound model for detachment faults [Buck, 1988; Wernicke and Axen, 1988] (Figure 13). In this model, listric-shaped detachment faults flex and rotate from moderate or steep dips to shallow dips in response to denudation of the hanging wall and isostatic unloading of the footwall. This is accomplished by "a hinge," located at the junction between the steep and shallow portions of the detachment fault, that migrates in the direction of extension (Figure 13). This model provides for earlier cooling and uplift of lower plate rocks on the west flank of the range as compared with the east flank. Similar conclusions which support the rolling hinge/isostatic rebound model have resulted from thermochronologic studies in the Ruby Mountains-East Humboldt Range, Nevada [McGrew and Snee, 1994], in the Black Mountains, California [Holm, et al., 1992], and in the Newberry Mountains, California [Dokka, 1993].

On the basis of published surface geology and geophysical data, Wernicke [1981] and Bartley and Wernicke [1984] proposed a low-angle normal fault origin and movement history for the NSRD. However, on the basis of calculated thermal histories this study shows temporal and spatial variations in magnitude of lower plate dips, as well as a moderate to steep initial dip for the NSRD, which are incompatible with a low-angle normal fault origin for the NSRD. Lee and Sutter [1991], using conventional $^{40}\text{Ar}/^{39}\text{Ar}$ mica age spectra, along with structural and kinematic data, favored either differential unroofing from beneath a moderate to high-angle detachment fault that rotated to shallow dips as it moved or a rolling hinge/isostatic rebound model. The cooling histories in this study, calculated from Arrhenius data and $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra data, provide detail on the temporal and spatial variations in magnitude of lower plate dips that can not be provided by conventional $^{40}\text{Ar}/^{39}\text{Ar}$ mica age spectra. Therefore the conclusions presented here for the origin and movement history of the NSRD are far more quantitative than those based on the conventional $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra.

Conclusions

1. Calculated thermal histories of potassium feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra from lower plate rocks of the northern Snake Range décollement, Nevada, yield three episodes of rapid cooling (a) middle Eocene, (b) late Oligocene, and (c) early Miocene. The first episode probably indicates a period of extensional unroofing in the northern Snake Range and provides a minimum upper age for movement along the NSRD. The second episode indicates a pulse of slip along the NSRD exposed along the western flank of the range. The third and most significant episode is characterized by a period of large-magnitude uplift and rotation of lower plate rocks along the eastern flank of the range from beneath the NSRD and/or younger, east dipping normal faults. The different ages for slip along the NSRD along the western flank of the range as compared with the eastern flank suggest that the NSRD is a composite fault with a prolonged but probably episodic movement history.

2. Previous workers have inferred steep geothermal gradients (i.e. $\geq 40^\circ\text{C}/\text{km}$) in the lower plate of the NSRD, the consequence of heat input by intrusion of batholiths, because it had been ar-

gued that lower plate units were at stratigraphic depths and above 300°C during the early Tertiary. This hypothesis was tested by incorporating a thermal pulse in the cooling histories. The results require a rapid cooling event just before the thermal pulse in order to adequately fit the laboratory-derived age spectrum. This rapid cooling event appears to be a consequence of the modeling process and therefore has no geologic significance. A more likely explanation is that the geothermal gradient was of the order of $\sim 20\text{--}30^\circ\text{C}/\text{km}$ which would place lower plate rocks along the eastern flank of the range at their estimated Late Cretaceous metamorphic depths during the early Tertiary.

3. The thermal history data provide evidence for temperature differences ($170\text{--}70^\circ\text{C}$) within a given structural horizon of the footwall across the range. These differences are maintained from middle Eocene to middle Miocene, at which time the entire lower plate uniformly cooled through the apatite annealing zone. These relations provide evidence for differential cooling and unroofing of lower plate rocks from beneath the NSRD. Using the calculated thermal histories, a temperature versus cross-sectional distance as a function of age graph was constructed. This reconstruction shows differential uplift and rotation of moderately to steeply east dipping lower plate units from beneath the NSRD. Furthermore, the reconstructions show that the dip of lower plate units increases and then decreases in time and space. Assuming a geothermal gradient of $30^\circ\text{C}/\text{km}$, lower plate units rotated up to 40° as they were uplifted from beneath the NSRD. These reconstructions, along with published structural data from lower plate mylonitic rocks, show that the NSRD initiated at moderate to steep angles that shallowed at depth, listric style, into a shallow-dipping shear zone. As lower plate rocks were translated up and out from beneath the NSRD, the NSRD rolled over to shallow angles as an isostatic response to denudation of the hanging wall. These reconstructions provide a spectacular example of the rolling hinge/isostatic rebound model.

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