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$^{40}Ar/^{39}Ar$ chronology of the Leucite Hills, Wyoming: eruption rates, erosion rates, and an evolving temperature structure of the underlying mantle

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Abstract

The lamproite lavas of the Leucite Hills, Wyoming comprise an isolated volcanic field of mesas and buttes, which erupted onto a thick sequence of K/T shales and sandstones. Volcanic activity spanned the interval from 3.0 to 0.89 Ma, during which time < 0.7 km^3 of magma were erupted. Approximately 84% of the magma was erupted within a 10–90 ky interval (between 0.94 and 0.89 Ma), with an average eruption rate of ~ 5 m^3/km^2/yr (more than an order of magnitude lower than the 'background trickle' eruption rate at continental arcs). The eruption rate prior to this burst of activity, between 3.0 and 0.94 Ma, was two orders of magnitude lower at ~ 0.02 m^3/km^2/yr. There is a strong correlation ($r^2 = 0.99$) between the height of the volcanic mesas (the volcanic cap protects the underlying sediment from erosion) and their eruption age, providing an average sediment erosion rate of 0.113 ± 0.002 mm/yr over the last 2.5 million years. Recent seismic studies indicate that the Leucite Hills volcanic field overlies an abrupt transition in lithospheric structure between the Archean craton to the north (with fast upper mantle seismic velocities) and the Colorado Plateau to the south (with a low-velocity zone similar to that beneath East Pacific Rise spreading ridge). The trigger for the Leucite Hills magmatism may be related, therefore, to the recent emplacement of asthenospheric mantle immediately to the south and not necessarily to the more distant Yellowstone hotspot to the north.

Keywords: lamproite; geochronology; eruptions; rates; erosion rates; volcanoes

1. Introduction

The lamproite lavas of the Leucite Hills, Wyoming, with their extreme compositions and distinctive mineralogy, have attracted significant attention since their initial discovery by S.F. Emmons, while undertaking a survey of the 40th parallel in the western United States. More than a century ago, Kemp [1] and Cross [2] published the first whole rock analyses of the Leucite Hills lavas and recognized them as among the most potassium-rich on Earth (≤ 13 wt% K_2O; [3]). They classified three types, all characterized by phenocrysts of phlogopite: orendite, wyomingite and madupite. According to Cross [2], the wyo-

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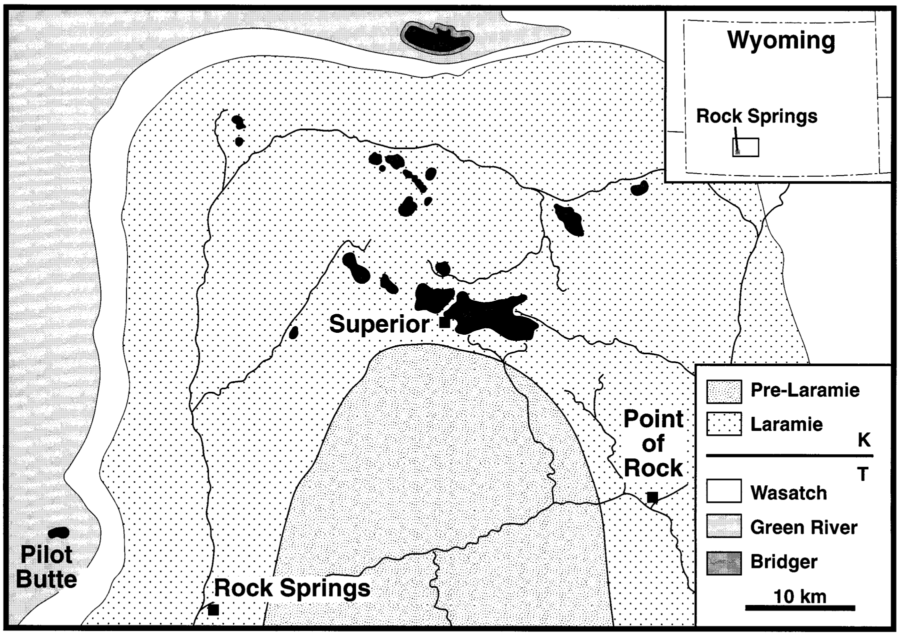

Fig. 1. Geological map of the Leucite Hills, Wyoming (after Kemp and Knight [15]). Inset shows location of mapped region in the state of Wyoming. Black shading denotes volcanic mesas, buttes, dikes and plugs.

mingite and orendite lavas represent the same magma type and are moderately siliceous (50–56 wt%), magnesian (<11 wt%), and strikingly poor in Na_2O (can be <1 wt%). In contrast, the madupite lavas are silica-poor (43–46 wt%), though equally impoverished in soda.

The source for lamproites is generally envisioned to be a lherzolitic-harzburgitic mantle, previously depleted of a basalt fraction, which has subsequently been enriched in phlogopite-bearing veins [4–6]. The age of the metasomatic event that introduced a vein component to the Archean mantle beneath the Leucite Hills is broadly constrained by the Nd isotopic composition of the lavas, from which model ages of >1.2 Ga have been derived [7,8]. The metasomatism may have been caused by ancient subduction along the margin of the Wyoming craton, which is consistent with the general occurrence of lamproite magmatism along mobile belts surrounding Archean cratons with thick, lithospheric keels [4].

Despite the fact that so much has been written about the Leucite Hills over the last century (see references in Mitchell and Bergman [4]), there are several features that attracted our attention and led to the present study. The first is the contrast between the ancient age of the Leucite Hills mantle source and the relatively young age of its volcanism. A second feature is the isolation of the Leucite Hills volcanic field, where the closest contemporaneous volcanism is $\sim$300 km away. In other words, if the veined, mantle source for the Leucite Hills has been in existence for more than 1.2 Gy, what caused it to melt only within the last few million years? Other questions relate to the duration of volcanism: has there been a steady trickle of small eruptions spanning several million years or does the Leucite Hills represent a brief burst of activity of <100 ky duration? The answer to this question relates to the time scale over which the temperature structure of the upper mantle has evolved beneath the western United States [9–12].

To address these issues, detailed geochronology is required to constrain both the timing and duration of volcanism. In this study, we use the laser-heated $^{40}Ar/^{39}Ar$ technique to date 12 separate volcanic centers in the Leucite Hills and to

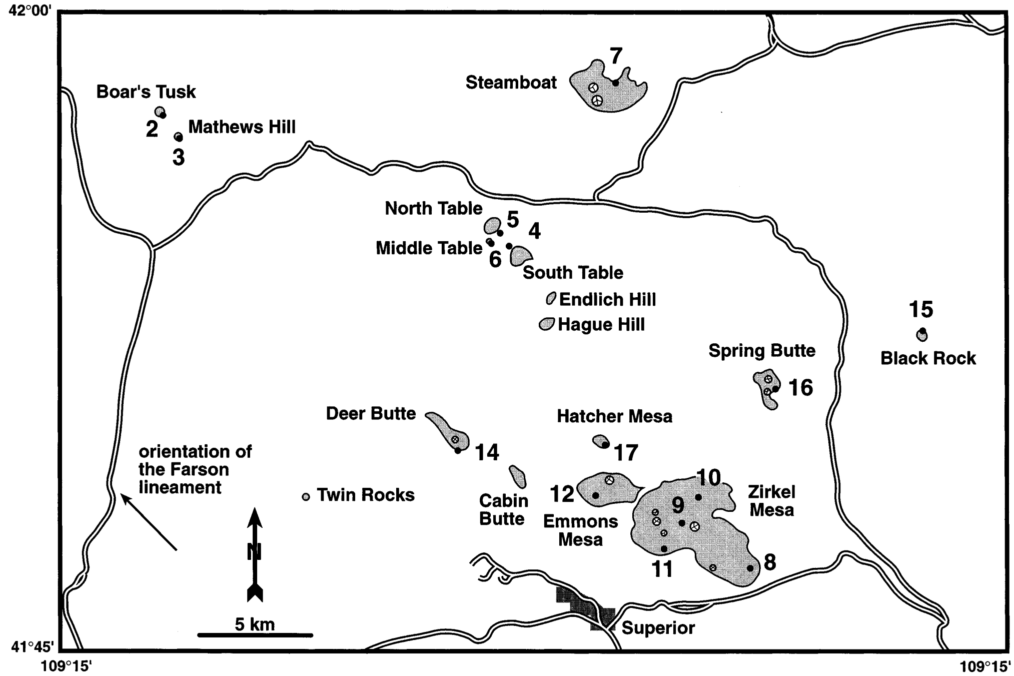

Fig. 2. Detailed map of the Leucite Hills volcanic field (excluding Pilot Butte) indicating sample locations. The orientation of the Farson lineament is given, but is best viewed on a landsat image.

expand on previously published K–Ar dates on five vents [4,13,14]. We use these results, combined with field constraints on the volume of the Leucite Hills lavas (<0.7 km^3), to derive an eruption rate and to constrain the erosion rate of the sedimentary landscape upon which the Leucite Hills lavas were erupted.

2. Geologic setting

The Leucite Hills volcanic field is located in southwestern Wyoming (Fig. 1), along the northeastern margin of the Rock Springs anticline, a Laramide structure within the Green River Basin. The Rock Springs uplift has been greatly reduced by erosion, exposing a thick sequence of early Cretaceous and late Tertiary shales and sandstones upon which the Leucite Hills lavas were erupted [15]. The Leucite Hills are underlain by the Archean Wyoming craton, an agglomeration of back-arc basins, island arcs and micro-continental fragments intruded by Archean granites and largely stable since ~2.6–2.7 Ga [16]. The volcanic field lies ~100 km north of the Cheyenne belt, which separates the Wyoming craton from the Colorado Plateau, and is interpreted as a Proterozoic suture developed at a paleo-Benioff zone [17]. A major tectonic lineament trends N40W (the Farson lineament [18]) and parallels the axis of the Rock Springs anticline. Many of the volcanic vents and dikes within the Leucite Hills (including the alignment of cones on Zirkel and Emmons mesas) are aligned parallel to this trend (Fig. 2).

3. Volume of erupted magma

The Leucite Hills are comprised of 14 lava-capped buttes and mesas, half of which feature small (<115 m height) cinder and lava cones, along with eight additional exposures of volcanic necks, dikes and plugs (Fig. 2). The volcanic field extends over a distance of 50 km from east to west (Black Rock to Pilot Butte) and 40 km from north to south (Steamboat Mountain to Zirkel Mesa), encompassing a region of ~ 2000 km^2 (Fig. 2). As described by Kemp and Knight [15], Ogden [19] and Mitchell and Bergman [4], and corroborated by our own field observations, the entire Leucite Hills volcanic field is comprised of < 50 individual lava flows. The flows vary in thickness from as thin as 20 cm to as thick as 15–21 m, and are of limited aerial extent (e.g., 5.8×10^3 m^2 at Cabin Butte to 5.6×10^6 m^2 at Zirkel Mesa; [19]). The average volume for an individual flow is ~ 0.01 km^3 and never exceeds 0.05 km^3 [4,19]. Our calculations, summarized in Table 1, indicate a total volume for all lava flows of < 0.53 km^3, whereas the 14 cinder cones and four lava cones contribute < 0.05 km^3. The volcanic necks, dikes and plugs (Boar's Tusk, Matthews Hill, Twin Rocks, Iddings Butte and dike, Wortman dike, Weed Butte, Hallock Butte, Endlich Hill, and Hague Hill) contribute < 0.004 km^3. Thus the total uncorrected volume for all flows, cones, necks, dikes and plugs is ~ 0.58 km^3. For comparison, Schulz and Cross [20] obtained a similar volume for the total erupted material at the Leucite Hills of ~ 0.5 km^3. More than 99% of the volume is comprised of wyomingite/orendite, whereas $< 1\%$ is madupite.

To derive a volume of erupted magma (or dense rock equivalent), a correction is required for the vesicularity of the lava flows (15–40% [19]) and the extent of their erosion, which Ogden [19] estimates to be $\leq 50\%$. In our opinion, 50% is an overestimate given the young age of the Leucite Hills lavas (1–3 Ma) and the fact that the easily eroded cinder cones on Zirkel Mesa, Spring Butte, Emmons Mesa and Deer Butte are all largely intact after 1 Ma. Although Cross [2] initially speculated that the entire Leucite Hills may once have been a continuous shield, both Kemp and Knight [15] and Ogden [19] demonstrated from field relations that this cannot be the case. Moreover, the difference in the eruption age and composition of lavas between different vents further argues for isolated, small volume eruptions of the lamproite lavas. As a consequence, we assume a maximum extent of erosion of 20% for those lavas that are ≤ 1 Ma, and apply the 50% correction only to flows > 1 Ma, leading to a final volume estimate of ~ 0.66 km^3, a maximal value by every line of reasoning. This volume is two orders of magnitude less than the 25–50 km^3 estimated by Mitchell and Bergman [4].

Table 1
Calculated volume of lava erupted at individual vents

Vent	Area (km^2)	Thickness (km)	Volume (km^3)	Volume of cones (km^3)
Spring Butte	1.653	0.030	0.0496	0.0033
Deer Butte	1.670	0.015	0.0251	0.0028
Zirkel Mesa	14.422	0.023	0.3317	0.0361
Steamboat Mtn	4.018	0.017	0.0683	0.0044
Middle Table			0.0011	
Boar's Tusk			0.0031	
North Table	0.360	0.015	0.0054	
South Table	0.100	0.015	0.0015	
Hatcher Mesa	0.120	0.015	0.0018	
Pilot Butte	0.070	0.030	0.0021	
Emmons Mesa	1.960	0.015	0.0294	0.0028
Black Rock	0.053	0.030	0.0016	
Cabin Butte	0.068	0.030	0.0020	
Badgers Teeth			0.0001	
Matthews Hill			0.0001	
Buttes			0.0003	
Total volume			0.5232	0.0494

4. $^{40}Ar/^{39}Ar$ chronology

4.1. Methods

Samples were taken from 12 isolated volcanic mesas, buttes and necks (Black Rock, Boar's Tusk, Deer Butte, Emmons Mesa, Hatcher Mesa, Middle Table Mountain, North Table Mountain, South Table Mountain, Spring Butte, Steamboat Mountain, Pilot Butte, and Zirkel Mesa; Fig. 1) for $^{40}Ar/^{39}Ar$ dating. The samples were crushed and the sieve fraction (84–140 μm) was separated and washed in deionized water; phlogopite crystals were then handpicked for all samples except Pilot Butte (a madupite with phlogopite as poikolitic grains that could not be easily separated) and Hatcher Mesa (with phlogopite phenocrysts that were too fine grained for easy separation). Approximately 2 mg of phlogopite, as well as a single whole-rock grain of ~ 10 mg, were packaged in duplicate for each of the 10 samples (only whole-rock grains were loaded for the Pilot Butte and Hatcher Mesa samples) in pure Al foil. The foil packets were placed in evacuated quartz tubes and irradiated in the Phoenix Ford Nuclear Reactor at the University of Michigan. Neutron flux variation (J) was measured using the standard mineral Fish Canyon Tuff biotite (split 3) and the age used for this standard was calibrated earlier using standard hornblende MMhb-1. The error weighted mean of five analyses vs. an age of 520.4 Ma for MMhb-1 was 27.99 ± 0.04 Ma (2σ). This value is extremely close to the age of 28.02 Ma found for Fish Canyon Tuff sanidine by Renne et al. [21] who adjusted the age of this standard so that a suite of ages would be compatible with astronomically derived time scales. All age estimates include uncertainties in the value of J.

Subsequent to irradiation, the sample packets were opened and the whole-rock grains and phlogopite separates were placed into 2 mm diameter wells in a copper disk and step-heated at increasing levels of laser power. The details of the Ar isotope analyses are similar to those reported in Hall and Farrell [22]. All analyses were corrected for fusion-system blank levels at the five Ar mass positions; blanks were run every three to five analyses. Blank levels were approximately 1×10^{-13} ml STP at mass 36 and 3×10^{-11} ml STP at mass 40.

4.2. Results

Total gas, plateau, and isochron ages are reported for each sample (phlogopite and whole-rock) in Table 2. Plateau age spectra and isochron diagrams for each sample are available via the electronic data repository. A phlogopite age for Emmons Mesa is not reported because the phlogopite separate was contaminated during sample preparation. Splits from the highly altered Black Rock sample (phlogopite and whole-rock) were run in duplicate. Although the plateau ages are generally more precise than the isochron ages, there is excellent agreement between the total gas, plateau, and isochron ages obtained from phlogopite separates and those from whole-rock grains for six samples: Spring Butte, Deer Butte, Zirkel Mesa, Steamboat Mountain, Middle Table Mountain, and Boar's Tusk. In three cases (North Table, South Table, and Black Rock) the ages determined from the phlogopite separates are consistently older than those obtained from the whole-rock grains. The reason for the discrepancy may reside in the partial alteration of groundmass leucite to analcime (observed with electron microprobe analyses), which was likely caused by interaction with Na-rich groundwater after their eruption. One of the whole-rock analyses of Ogden [19] for Black Rock (BR-1 with 5.2% Na_2O and 3.3% K_2O) reflects this Na exchange for K. The analcime contains 1–2 wt% K_2O and therefore may be the cause of the younger ages obtained on the altered whole-rock samples. As a consequence, the phlogopite ages are considered more accurate than the whole-rock grains in these samples, because the phlogopite phenocrysts display little evidence of alteration or problems with excess argon. Examination of Table 2 indicates that for all samples but one, the initial $^{40}Ar/^{36}Ar$ ratios derived from the isochron diagrams are within 2σ error of the atmospheric value; the single exception is the Middle Table phlogopite, which is slightly deviant. This general lack of excess argon in our samples is probably caused by

Table 2
$^{40}Ar/^{39}Ar$ ages (± 2σ) from individual vents

Vent	Material dated	Total gas age (Ma)	Plateau age (Ma)	Plateau MSWD	Plateau % ^{39}Ar	Isochron age (Ma)	MSWD	$(^{40}Ar/^{36}Ar)_i$	Points fitted
Spring Butte	phlog	0.90 ± 0.04	0.89 ± 0.04	1.86	100	0.68 ± 0.34	1.73	302.3 ± 10.5	A
Spring Butte	wr	0.81 ± 0.03	0.89 ± 0.02	0.55	67	0.90 ± 0.04	0.63	295.4 ± 3.8	P
Deer Butte	phlog	0.93 ± 0.02	0.91 ± 0.03	2.11	52	0.88 ± 0.07	1.80	297.9 ± 5.0	A
Deer Butte	wr	0.96 ± 0.03	0.96 ± 0.03	1.6	100	0.96 ± 0.06	1.76	295.4 ± 4.4	A
Zirkel Mesa	phlog	0.96 ± 0.05	0.95 ± 0.05	1.39	99	0.87 ± 0.13	1.70	298.3 ± 3.8	A
Zirkel Mesa	wr	0.95 ± 0.02	n/a			1.10 ± 0.11	7.03	292.4 ± 2.6	A
Steamboat Mtn	phlog	1.82 ± 0.04	1.78 ± 0.04	1.21	88	1.80 ± 0.09	2.49	294.9 ± 2.6	A
Steamboat Mtn	wr	1.70 ± 0.03	1.77 ± 0.02	0.98	69	1.85 ± 0.07	0.82	291.9 ± 4.0	P
Middle Table	phlog	2.05 ± 0.03	2.03 ± 0.03	1.07	80	1.79 ± 0.13	1.03	310.3 ± 7.6	A
Middle Table	wr	2.05 ± 0.03	2.02 ± 0.04	1.93	65	2.03 ± 0.08	5.62	301.9 ± 11.0	A
Boar's Tusk	phlog	2.23 ± 0.03	2.23 ± 0.04	1.57	100	2.24 ± 0.25	1.74	294.7 ± 7.5	A
Boar's Tusk	wr	2.56 ± 0.09	2.19 ± 0.04	0.99	90	2.26 ± 0.16	1.03	293.5 ± 5.1	P
North Table	phlog	1.43 ± 0.05	1.47 ± 0.06	1.45	93	1.51 ± 0.24	2.40	293.2 ± 8.7	A
North Table	wr	1.24 ± 0.01	n/a			1.24 ± 0.04	11.60	295.2 ± 4.8	A
South Table	phlog	2.55 ± 0.06	2.53 ± 0.06	1.34	100	2.45 ± 0.12	1.22	298.8 ± 4.4	A
South Table	wr	1.81 ± 0.04	n/a			n/a			
Emmons Mesa	wr	0.94 ± 0.03	0.96 ± 0.03	1.97	72	0.99 ± 0.05	2.18	294.2 ± 4.0	P
Hatcher Mesa	wr	0.97 ± 0.03	0.92 ± 0.02	0.86	81	0.89 ± 0.07	0.81	300.9 ± 9.2	P
Pilot Butte	wr	3.00 ± 0.03	n/a			n/a			
Black Rock	phlog-1	1.35 ± 0.07	1.34 ± 0.06	0.77	100	1.37 ± 0.14	0.92	294.2 ± 4.3	A
Black Rock	phlog-2	1.30 ± 0.06	1.33 ± 0.06	1.08	100				
Black Rock	wr-1	0.80 ± 0.02	0.80 ± 0.02	1.65	100	0.78 ± 0.03	1.81	296.4 ± 2.3	A
Black Rock	wr-2	0.79 ± 0.02	0.78 ± 0.02	1.7	95				

All correlation diagrams with MSDW > 2 are considered errorchrons. Fits denoted P were fitted to the plateau points, A were fitted to all points (except Deer Butte phlogopite which had one outlier removed). Plateau ages are error weighted averages with scatter included in the error estimate.

the high temperature of the eruptions (≥ 1100°C) and the fluidity of the magma, both facilitating rapid equilibration with the atmosphere. The large error in the Spring Butte phlogopite isochron age (0.68 ± 0.34 Ma) does not reflect a problem with excess argon, but rather the fact that for this sample, there was not a sufficient spread in the $^{39}Ar/^{40}Ar$ ratio to allow precise determination of the initial $^{40}Ar/^{36}Ar$ ratio from the isochron. Therefore, for the Spring Butte sample, the plateau phlogopite age is considered more accurate.

Alteration of the leucite was evaluated for all 12 samples, and is only found in samples from Black Rock, North Table, and South Table. In contrast, the pristine nature of groundmass leucite in the Emmons Mesa and Hatcher Mesa lavas (and its absence in the Pilot Butte lava) lends confidence to the total gas, plateau and isochron ages obtained on their whole-rock grains (Table 2). Nonetheless, because phlogopite separates were not available as a check on the whole-rock ages, and because groundmass alteration of leucite can lead to apparent ages that are too young, the dates for Emmons Mesa and Hatcher Mesa should be considered minimum values.

4.3. Comparison with the geomagnetic time scale

The accuracy of the $^{40}Ar/^{39}Ar$ eruption ages for all 12 samples listed in Table 2 can be evaluated, in part, by comparison with the paleomagnetic data of Sheriff and Shive [23] on the same lavas. Interestingly, 10 of the 12 lavas are reversely magnetized, and only Pilot Butte and Black Rock record normal polarities. In all cases but one, the combined paleomagnetic and $^{40}Ar/^{39}Ar$ results are compatible with the astronomically calibrated, geomagnetic time scale of Shackleton et al. [24] and Hilgen [25,26]. The exception is the Black Rock sample, for which an accurate date on the phlogopite separate appears to have been obtained (an isochron age of 1.37 ± 0.14 Ma, and four plateau ages of 1.35 ± 0.07, 1.30 ± 0.06, 1.34 ± 0.06; 1.33 ± 0.06 Ma; Table 2), despite the whole-rock alteration. The Black Rock sample thus appears to have erupted well within the Matayuma Reversal and yet records normal polarity. Recent work by Singer et al. [27] documents at least five geomagnetic events (although not all may be complete polarity reversals) between 1.18 and 0.78 Ma (the end of the Matuyam Reversed Chron). The authors point out that within this 400 ky interval, there were at least seven and possibly more than 11 attempts by the geodynamo to reverse, providing evidence that the geodynamo may be active at a frequency far higher than previously recognized. Within this context, it is possible that the Black Rock lava was erupted within a previously unrecognized normal-polarity subchron within the Matayuma Reversed Chron at ~1.37 ± 0.14 Ma. Alternatively, the carrier of the normal magnetization may have crystallized at the same time the groundmass alteration occurred and not necessarily at the time of eruption. Further work is needed to resolve this issue.

4.3. Comparison with previous results

Previously published eruption ages for the Leucite Hills lavas are restricted to those obtained by the K/Ar technique. Our $^{40}Ar/^{39}Ar$ ages for Zirkel Mesa (Table 2) compare favorably to those obtained on phlogopite separates by Bradley ([13] 1.25 Ma) and McDowell ([14] 1.1 ± 0.4 Ma). However, a comparison of our $^{40}Ar/^{39}Ar$ ages with the K/Ar ages (on phlogopite separates) reported by Mitchell and Bergman [4] reveals a systematic discrepancy, with the K/Ar ages consistently older (Spring Butte: 2.2 ± 0.1 Ma; Zirkel Mesa: 1.6 ± 0.1 Ma; Emmons Mesa: 1.4 ± 0.1 Ma; Steamboat Mountain: 2.4 ± 0.1 Ma; Boar's Tusk: 3.1 ± 0.1 Ma). Because details of the K/Ar age analyses are not given by Mitchell and Bergman [4], the reasons for the discrepancy are not known.

5. Erosion rate and faulting of the sedimentary landscape

The Leucite Hills lamproite lavas erupted over a 2 My interval onto an eroding landscape. Because the volcanic cap protects the underlying sediment from erosion, there is a strong correlation between the thickness of sediments beneath the volcanic mesas (relative to the baseline elevation) and the age of the overlying lava, which can be used to estimate the sediment erosion rate (Fig. 3). For example, the difference in elevation between South Table (~287 m) and North Table (~165 m) is not caused by faulting, as first surmised by Cross [2] and later disproved by Kemp and Knight [15], but rather reflects the difference in their eruption ages (2.53 vs. 1.47 Ma, respectively), and hence the level of the eroding land surface at the time of eruption.

Of the 12 samples for which $^{40}Ar/^{39}Ar$ ages were obtained, two are volcanic necks or plugs (Boar's Tusk and Middle Table Mountain). For the remaining nine samples the thickness of the underlying sediment is compiled in Table 3. Because the lavas were erupted along the slope of the Rock Springs anticline (Fig. 2), there is a

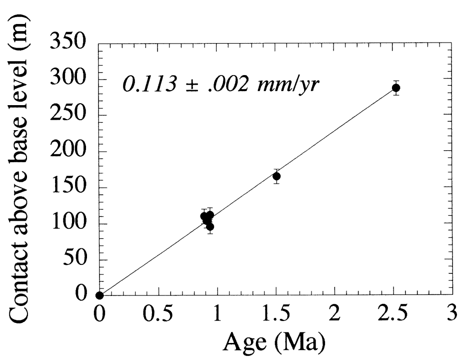

Fig. 3. Plot of sediment thickness beneath seven volcanic mesas (relative to the baseline elevation) vs. eruption age of the overlying lava. The seven samples used to obtain the slope (average erosion rate) are South Table, North Table, Emmons Mesa, Zirkel Mesa, Hatcher Mesa, Spring Butte, and Deer Butte.

Table 3
Thickness of sediment underneath volcanic mesas and buttes

Vent	Thickness[a] (m)
Spring Butte	110
Deer Butte	104
Zirkel Mesa	96
Steamboat Mtn	314
North Table	165
South Table	287
Emmons Mesa	112
Hatcher Mesa	104
Pilot Butte	127
Black Rock	73

[a]Estimated error is ±10 m.

gradual change in the baseline elevation for the various vents. Excluding Steamboat Mountain and Pilot Butte (discussed below), Deer Butte has the highest baseline at ~2550 m, whereas Black Rock has the lowest with a baseline at ~2050 m. If Black Rock is excluded (discussed below), there is a strong correlation ($r^2 = 0.99$) between the height of the volcanic mesas (relative to the surrounding baseline elevation) and the eruption age of the lavas, as shown in Fig. 3. The fitted line was forced to pass through the origin; namely, the base level of the sedimentary surface is presently zero meters. The resultant slope (based on seven samples) is 0.113 ± 0.002 mm/yr, which is the average erosion rate along the axis of the Rock Springs anticline over the last 2.5 My. This rate is within the range (0.07 to 0.20 mm/yr) calculated for the Sierra Nevada Range in California over the last 15–30 My on the basis of apatite fission track studies [28]. In general, however, the Green River sediments are far less consolidated than the crystalline, Sierran batholith, thus the comparable erosion rates reflect the greater uplift rate for the Sierra Nevada than the Leucite Hills region. Interestingly, the erosion rate is only ~0.04 mm/yr at Pilot Butte, which sits well off to the west from the main axis of the Rock Springs uplift (Fig. 1) and only ~0.05 mm/yr at Black Rock, which at its lower elevation may be receiving some sediment from the eroding crest of the Rock Springs dome.

Steamboat Mountain is another significant outlier that falls well outside the correlated trend in Fig. 3. It appears that either Steamboat Mountain rests on sediments that are ~130 m too thick, or the erosion rate near Steamboat Mountain is ~0.176 mm/yr (almost twice the value derived from Fig. 3). The first scenario is far more likely, given the abrupt escarpment (oriented N40W, parallel to the Farson lineament) upon which Steamboat Mountain rests, and which probably formed from uplift along a fault. There is a dike at the base of the Steamboat Mountain escarpment (identified by Ogden [19]), also trending N40W and offset by ~1 m, indicating that faulting was active after volcanism began. The magnitude of the upthrow on the escarpment (~130 m) suggests that movement on the fault pre-dates the eruption of Steamboat Mountain at 1.78 Ma.

6. An exceptionally low eruption rate

Volcanic activity in the Leucite Hills spanned the interval from 3.0 to 0.89 Ma, during which time <0.66 km^3 of magma were erupted. A plot of erupted volume vs. age (Fig. 4) shows that 98% of the Leucite Hills lavas erupted between 1.78 and 0.89 Ma. However, approximately 84% of that volume erupted within a 50,000 (±40,000) yr interval, which marked the end of volcanic activity at the Leucite Hills. These calculations of erupted volume with time are based on

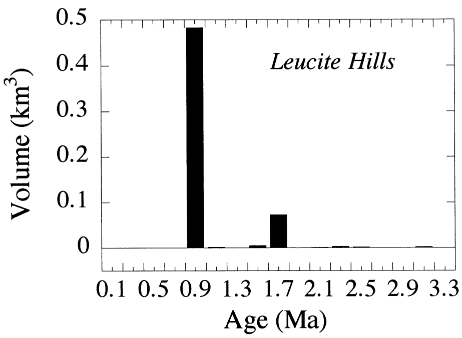

Fig. 4. A histogram of erupted volume of lava vs. age for the Leucite Hills volcanic field. The graph illustrates that ~84% of the magma was erupted within a 50,000 (±40,000) yr interval at ~0.9 Ma.

plateau $^{40}Ar/^{39}Ar$ ages with the highest reproducibility and smallest uncertainties (Spring Butte, Zirkel Mesa, Steamboat Mountain; Table 2).

The area over which the Leucite Hills volcanic field occurs, including Pilot Butte, spans 2000 km^2. Given a total erupted volume of < 0.65 km^3, the eruptive flux between 3.0 and 0.89 Ma was < 0.15 $m^3/km^2/yr$. This is an exceptionally low rate and is ~ 4 orders of magnitude lower than the eruption rate at slow spreading, mid-ocean ridges [29]. The eruption rate during the 50,000 yr burst of activity between 0.94 and 0.89 Ma is higher at ~ 5 $m^3/km^2/yr$, but is still more than an order of magnitude lower than the 'background trickle' eruption rate at continental arcs [30].

The extremely low eruption rate at the Leucite Hills, combined with the absence of other lavas of less extreme composition, suggests that the wyomingite/orendite lavas ($> 99\%$ of the erupted magma) primarily represent melting of a vein component, without substantial involvement of the host matrix. Although lamproite compositions may range widely because of variable involvement of peridotitic wall rock with the vein component during partial melting [5,6,31], vein-derived melting has been invoked to explain the siliceous, extremely potassic, and relatively MgO-poor (< 10 wt%) lamproites that predominate at the Leucite Hills [32]. A refractory host mantle beneath the Leucite Hills is consistent with the Archean age of the Wyoming lithosphere.

7. The thermal history of the upper mantle beneath the Leucite Hills

The occurrence of mantle xenoliths in some of the wyomingite/orendite flows (e.g., Hatcher Mesa [33]) indicates that the Leucite Hills lavas are di-

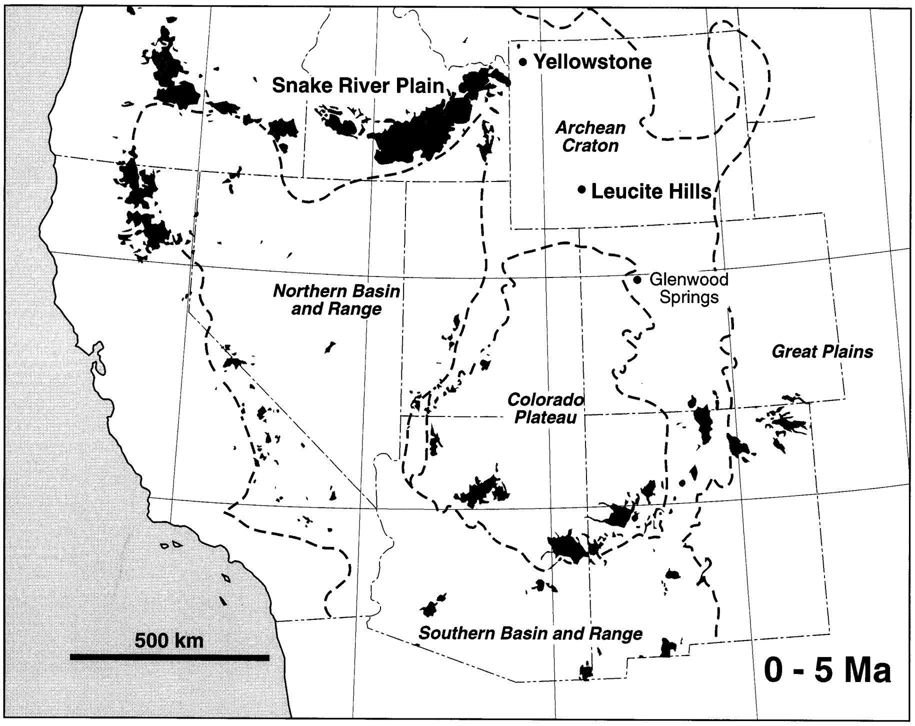

Fig. 5. A map of mafic volcanism throughout the western United States between 0 and 5 Ma (after Luedke and Smith [34]), indicating the isolation of the Leucite Hills volcanic field, as well as its location relative to the Yellowstone hot spot, the northern boundary of the Colorado Plateau, and the Quaternary volcanism near Glenwood Springs, Colorado [36].

rect melts of the mantle that ascended rapidly to the surface. Their small volume precludes any long-term storage in the crust as they would rapidly freeze. It is likely, therefore, that the time of eruption is closely linked to the time of melt generation. Experimental studies indicate that the Leucite Hills lavas were both hydrous (>3 wt% H_2O) and hot ($\sim 1100 \pm 50$°C) at the time of eruption [34], requiring mantle temperatures of 1100°C or hotter. If the mantle source for the Leucite Hills existed for more than 1.2 Gy, then the recent volcanism implies that it was only until 3 Ma that this mantle was heated to sufficiently high temperatures to allow partial fusion of the vein component. Moreover, the distribution of erupted volume with time suggests that the mantle continued to warm until 0.9 Ma, when the final 84% of the Leucite Hills volcanic field was erupted.

The isolation of the Leucite Hills with respect to contemporaneous mafic volcanism is striking (Fig. 5) [35]. The closest, contemporaneous eruptions include the voluminous ($>10^3$ km^3) rhyolite at Yellowstone, $\sim$300 km to the north-west and the extremely sparse (<0.3 km^3) alkali basalts erupted near Glenwood Springs, $\sim$300 km to the south-east [36]. The question arises as to what caused the mantle source of the Leucite Hills to finally undergo partial melting after more than 1.2 billion years. Previous workers [4] have proposed that the proximity of the Leucite Hills to the Yellowstone hot spot, albeit $\sim$300 km distant, suggests a linkage. More specifically, Mitchell and Bergman [4] point to the close temporal coincidence between the age of the Leucite Hills volcanism (1–2 Ma) and the time that the fringe of the Yellowstone-Snake River Plain hot spot track (200–300 km off axis) passed by the Rock Springs region. A variance on this model is not unlike that of Ebinger and Sleep [37] where they propose a single, large plume beneath east Africa, which flowed laterally and ponded into pre-existing zones of lithospheric thinning, thus explaining the distribution and timing of volcanism in east Africa. It is perhaps possible that the Yellowstone plume has behaved in a similar manner.

The results of recent seismic studies (e.g., [9,10,12]) indicate that the close proximity of the Leucite Hills to the uplifted Colorado Plateau provides an additional perspective as to what triggered the Leucite Hills volcanism. The 1995 Deep Probe seismic study of Henstock et al. [12] follows the 110th meridian (which runs $\sim$60 km west of the Leucite Hills) from the border with Canada to that with Mexico. Their results indicate an abrupt change in the lithospheric structure in the vicinity of the Cheyenne belt ($\sim$100 km from the Leucite Hills), with a well developed low-velocity zone beneath the Colorado Plateau, which is similar to that observed for the East Pacific Rise spreading system in the Gulf of California [12,38]. In contrast, the upper-mantle seismic profile for the Archean Wyoming province is comparable to that for the average Canadian shield with fast velocities >8 km/s [12,39]. Humphreys and Dueker [9] argue that such abrupt lateral gradients in seismic velocities likely reflect differences in mantle temperature of $\geq$200 degrees and strongly suggest the presence of partial melt. If they are correct, then the trigger for the Leucite Hills volcanism may be more directly related to the emplacement of hot mantle beneath the Colorado Plateau $\sim$100 km to the south and not to the more distant Yellowstone hotspot to the north.

Humphreys and Dueker [9] emphasize the youthfulness of the high lateral gradients seen in the upper mantle seismic structure in various regions of the western United States. They argue that if these lateral gradients reflect temperature gradients of $\sim$200 degrees, then these are expected to diffuse on time scales of less than a few tens of millions of years. Our ^{40}Ar/^{39}Ar age results from the Leucite Hills volcanic field support the view that the low-velocity zone beneath the Colorado Plateau is both a youthful and dynamic feature.***[CL]***

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