

# New ages for the climactic eruptions at Yellowstone: Single-crystal $^{40}\text{Ar}/^{39}\text{Ar}$ dating identifies contamination

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## ABSTRACT

Ash beds associated with the three climactic Yellowstone ignimbrites form important Quaternary chronostratigraphic markers over much of the continental United States. Previous K-Ar ages determined on crystal concentrates from these ashes varied by as much as 60–100 k.y. Laser-fusion  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of single sanidine grains from these units reveals a small number of grains with anomalously old ages. Eliminating these from the weighted averages results in highly precise refined ages of  $2.003 \pm 0.014$ ,  $1.293 \pm 0.012$ , and  $0.602 \pm 0.004$  Ma ( $2\sigma$  errors) for the Huckleberry Ridge Tuff, Mesa Falls Tuff, and member B of the Lava Creek Tuff, respectively. Individual single-grain ages that are slightly too old could result from incomplete degassing of xenocrysts in the magma. Electron-microprobe analyses of sanidine splits reveal no obvious xenocrystic compositions, suggesting another possibility—that phenocrysts from the crystallized rind of the magma chamber were re-entrained into the magma prior to eruption. Contamination and natural variation in phenocryst age may create larger uncertainty in bulk-crystal dating of young silicic volcanic rocks than incomplete extraction of Ar from sanidine.

## INTRODUCTION

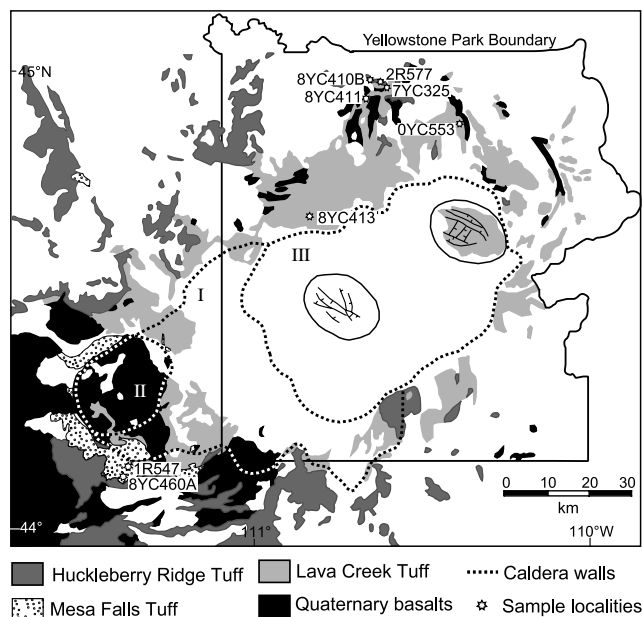
Voluminous silicic eruptions produce large ignimbrites and widespread fallout deposits. These pumice and ash layers provide instantaneous chronostratigraphic markers important in constraining the timing of glaciations and magnetic reversals and in correlating stratigraphy over large areas. For example, distal ashes from the three climactic caldera-forming eruptions of the Yellowstone Plateau, designated Pearlette types B, S, and O ashes (corresponding with the Huckleberry Ridge, Mesa Falls, and Lava Creek Tuffs; Izett, 1981), have been widely used in dating Quaternary landscapes, flora, and fauna throughout the central United States (Naeser et al., 1973), as well as glaciations in the Yellowstone area (Pierce, 1979; Richmond, 1986).

Contamination by older material is a major problem in the isotopic dating of both effusive and explosive young volcanic rocks, especially in distal ashes reworked by wind or water. An effective technique for identifying and correcting for contamination in age dating is the single-crystal  $^{40}\text{Ar}/^{39}\text{Ar}$  method. This high-precision technique allows the elimination of anomalously old ages, which is impossible in bulk-sample techniques (van den Bogaard et al., 1989; Spell and Harrison, 1993; van den Bogaard, 1995; Gansecki et al., 1996; Chen et al., 1996). One difficulty in conventional K-Ar dating is incomplete extraction of Ar from sanidine, which may produce apparent ages that are too young (e.g., Webb and McDougall, 1967; McDowell, 1983). The

$^{40}\text{Ar}/^{39}\text{Ar}$  method does not require complete extraction of radiogenic Ar for undisturbed samples, as it requires measuring only ratios and not a total amount of gas.

We report here refined ages for the three Yellowstone climactic eruptions based on single-crystal  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses. Although similar to previous age determinations of Obradovich (1992; Obradovich and Izett, 1991), our ages are better constrained due to a larger data set of single-crystal ages, coupled with statistical methods that account for anomalous grains in calculating a best estimate for the eruptive age.

**Figure 1. Simplified geologic map (modified from Christiansen, 1979) showing areal distribution of Huckleberry Ridge, Mesa Falls, and Lava Creek Tuffs, sample localities, and outlines of the two Yellowstone caldera resurgent domes. Roman numerals indicate successive calderas; III is Yellowstone caldera. Outline of Yellowstone National Park shown for reference.**



## GEOLOGIC BACKGROUND

All three massive, caldera-forming eruptions of the Yellowstone Plateau volcanic field produced sanidine-bearing, high-silica rhyolite deposited as ignimbrite, now largely welded and devitrified, and associated ash-fall tuff (Christiansen and Blank, 1972). The oldest of these units is the ~2500 km<sup>3</sup> Huckleberry Ridge Tuff, with associated ash fall that blanketed much of the continental United States. The near-source stratigraphy consists of a basal layer of bedded ash and pumice overlain by ignimbrite that welded as a compound cooling unit consisting of three members, designated A, B, and C (Christiansen, 1979, 1982). The compound cooling, lack of erosion between members, and similar transitional remanent magnetization for all three members (Reynolds, 1977) indicate short time spans between eruptions of the individual members.

Eruption of the ~280 km<sup>3</sup> Mesa Falls Tuff created the Henry's Fork caldera (II in Fig. 1), nested within the Huckleberry Ridge caldera (I in Fig. 1). The tuff consists of a thick basal layer of crystal-rich, bedded ash and pumice fall directly overlain by partially to densely welded ignimbrite (Christiansen, 1982).

Eruption of the ~1000 km<sup>3</sup> Lava Creek Tuff created the Yellowstone caldera (III in Fig. 1),

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now mostly filled by younger rhyolite lava flows. Two members, A and B, have been identified in the Lava Creek Tuff ignimbrite, with a slight break in welding and no erosion found between. Both members are normally magnetized and have similar natural remanent magnetization directions, suggesting rapid successive emplacement of both members (Reynolds, 1977). A basal ash-fall layer is present beneath member B where member A is not present. The two members are thought to have erupted from separate ring fracture zones, which collapsed to form the Yellowstone caldera and later were loci of resurgent doming (Fig. 1; Christiansen, 1979).

### PREVIOUS GEOCHRONOLOGY

The best ages for the Yellowstone units are principally conventional K-Ar analyses of sanidine and glass done by Obradovich (1992). Concern over incomplete extraction of Ar from sanidine led him to emphasize that the published ages may be underestimates and to place greater reliance on the older ages. Fission-track ages, determined on glass shards from distal ashes (Naeser et al., 1973; Ward et al., 1993), are useful in correlating the Yellowstone ash layers, but have a resolution too low to precisely date the eruptions.

Obradovich (1992) reported several ages for the Huckleberry Ridge Tuff, including (1) a weighted

mean of  $2.018 \pm 0.016$  Ma,<sup>1</sup> (2) a  $^{40}\text{Ar}/^{36}\text{Ar}$  vs.  $^{40}\text{K}/^{36}\text{Ar}$  isochron regression of all analyses that yielded  $1.99 \pm 0.02$  Ma, and (3) a preferred age of  $2.110 \pm 0.016$  Ma from a regression of only the oldest and more precise ages. The scatter in both regressions is large, with MSWDs (mean squared weighted deviations) of 10.8 and 4.46, respectively. Reconnaissance single-crystal  $^{40}\text{Ar}/^{39}\text{Ar}$  work by Obradovich and Izett (1991) yielded an average age of  $2.08 \pm 0.02$  Ma (11 grains). The errors given on these averages reflect analytical precision only, not variations between samples.

Bulk-crystal K-Ar dating of the Mesa Falls Tuff yielded an unweighted mean of  $1.27 \pm 0.02$  Ma and an isochron regression of  $1.25 \pm 0.01$  Ma (Obradovich, 1992). Obradovich and Izett (1991) obtained a  $^{40}\text{Ar}/^{39}\text{Ar}$  age of  $1.30 \pm 0.02$  Ma (two grains).

The Lava Creek Tuff was dated by Obradovich (1992) at  $0.617 \pm 0.008$  Ma, a weighted mean of 4 K-Ar analyses considered valid out of a total of 11. Sanidine  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of  $0.61 \pm 0.02$  Ma (two grains; Obradovich and Izett, 1991),  $0.66 \pm 0.02$ , and  $0.67 \pm 0.02$  Ma (Izett et al., 1992) were also obtained for Lava Creek Tuff tephra.

The problems encountered by Obradovich and coworkers dating the Yellowstone ignimbrites challenge workers in many young rhyolite provinces. Our work on the younger rhyolites at Yellowstone (Gansecki et al., 1996) showed that many of the problems may be related to the presence of sanidine xenocrysts that are chemically and visually nearly indistinguishable from phenocrysts. This realization led us to apply similar analytical and statistical techniques to the three caldera-forming eruptions.

### METHODS

We analyzed samples collected by R. L. Christiansen, W. Hildreth, and R. Reynolds from the three tuffs (Fig. 1). The two samples of the

<sup>1</sup>All K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  data in the text are quoted at  $2\sigma$  error.

TABLE 1.  $^{40}\text{Ar}/^{39}\text{Ar}$  ANALYTICAL DATA  
SORTED BY INCREASING APPARENT AGE MINUS  $1\sigma$  ERROR

K/Ca	%Ar*	Age (Ma)	Wtd Avg (Ma)	MSWD	K/Ca	%Ar*	Age (Ma)	Wtd Avg (Ma)	MSWD
		( $\pm 1\sigma$ )	( $\pm 1\sigma$ )				( $\pm 1\sigma$ )	( $\pm 1\sigma$ )	
<b>Huckleberry Ridge Tuff (8YC410B, 2R577)</b>					<b>Mesa Falls Tuff (cont.)</b>				
0.4	65.9	1.82 $\pm$ 0.33	—	—	26	97.3	1.32 $\pm$ 0.01	1.293 $\pm$ 0.006†	1.3290
1.1	93.3	1.97 $\pm$ 0.24	1.918 $\pm$ 0.071	0.1351	33	98.2	1.321 $\pm$ 0.002	1.317 $\pm$ 0.003	2.9109
24	10.0	1.85 $\pm$ 0.06	1.856 $\pm$ 0.020	0.1238	41	94.5	1.326 $\pm$ 0.002	1.321 $\pm$ 0.002	3.3432
23	87.3	1.86 $\pm$ 0.07	1.858 $\pm$ 0.013	0.0832	15	43.1	1.44 $\pm$ 0.03	1.322 $\pm$ 0.003§	4.0637
3.6	87.1	1.94 $\pm$ 0.13	1.866 $\pm$ 0.016	0.1524	<b>Lava Creek Tuff</b>				
2.6	70.6	2.02 $\pm$ 0.19	1.873 $\pm$ 0.020	0.2469	<b>Ash fall (0YC553)</b>				
20	93.9	1.94 $\pm$ 0.06	1.895 $\pm$ 0.020	0.3461	0.6	46.4	0.639 $\pm$ 0.083	—	—
19	90.5	1.95 $\pm$ 0.07	1.905 $\pm$ 0.019	0.3694	20	56.5	0.585 $\pm$ 0.025	0.590 $\pm$ 0.015	0.3881
20	92.4	1.95 $\pm$ 0.05	1.917 $\pm$ 0.016	0.3969	20	87.5	0.622 $\pm$ 0.018	0.610 $\pm$ 0.013	0.7831
22	7.3	2.01 $\pm$ 0.11	1.922 $\pm$ 0.017	0.4276	26	49.8	0.641 $\pm$ 0.033	0.615 $\pm$ 0.012	0.7651
47	17.9	1.95 $\pm$ 0.04	1.930 $\pm$ 0.014	0.4195	26	91.7	0.669 $\pm$ 0.021	0.630 $\pm$ 0.015†	1.7520
23	92.2	1.98 $\pm$ 0.06	1.936 $\pm$ 0.013	0.4372	13	85.7	0.689 $\pm$ 0.018	0.647 $\pm$ 0.016§	2.9325
25	76.4	2.00 $\pm$ 0.08	1.940 $\pm$ 0.013	0.4513	<b>Member A (8YC413)</b>				
23	91.2	1.95 $\pm$ 0.02	1.945 $\pm$ 0.009	0.4273	31	32.6	0.655 $\pm$ 0.055	—	—
27	94.1	1.97 $\pm$ 0.03	1.949 $\pm$ 0.008	0.4386	42	78.8	0.631 $\pm$ 0.022	0.634 $\pm$ 0.008	0.1641
21	90.8	1.97 $\pm$ 0.03	1.952 $\pm$ 0.008	0.4366	37	87.6	0.629 $\pm$ 0.013	0.631 $\pm$ 0.004	0.1061
23	93.1	1.99 $\pm$ 0.04	1.955 $\pm$ 0.008	0.4604	38	81.5	0.635 $\pm$ 0.018	0.632 $\pm$ 0.003	0.0857
22	85.3	2.01 $\pm$ 0.04	1.959 $\pm$ 0.008	0.5354	36	71.7	0.644 $\pm$ 0.019	0.634 $\pm$ 0.003	0.1480
84	91.9	2.07 $\pm$ 0.09	1.961 $\pm$ 0.008	0.5885	41	92.8	0.645 $\pm$ 0.011	0.638 $\pm$ 0.003†	0.2416
22	78.9	2.02 $\pm$ 0.03	1.968 $\pm$ 0.009	0.7391	24	62.8	1.04 $\pm$ 0.04	0.649 $\pm$ 0.027§	16.568
24	91.6	2.02 $\pm$ 0.03	1.973 $\pm$ 0.009	0.8396	<b>Member B (8YC411, 7YC325)</b>				
28	90.1	2.04 $\pm$ 0.05	1.975 $\pm$ 0.009	0.8824	18	63.2	0.557 $\pm$ 0.066	—	—
21	94.9	2.01 $\pm$ 0.01	1.991 $\pm$ 0.007	1.1343	19	27.6	0.551 $\pm$ 0.056	0.554 $\pm$ 0.003	0.0048
29	86.4	2.06 $\pm$ 0.06	1.992 $\pm$ 0.007	1.1409	28	71.2	0.559 $\pm$ 0.035	0.557 $\pm$ 0.002	0.0073
36	94.3	2.04 $\pm$ 0.03	1.995 $\pm$ 0.007	1.1931	27	52.4	0.580 $\pm$ 0.041	0.564 $\pm$ 0.006	0.0793
33	98.0	2.04 $\pm$ 0.02	1.999 $\pm$ 0.007	1.3300	25	91.8	0.599 $\pm$ 0.055	0.569 $\pm$ 0.008	0.1469
34	88.9	2.05 $\pm$ 0.03	2.001 $\pm$ 0.007	1.3844	38	89.4	0.591 $\pm$ 0.036	0.575 $\pm$ 0.008	0.1738
32	96.3	2.06 $\pm$ 0.04	2.003 $\pm$ 0.007†	1.4109	24	31.3	0.582 $\pm$ 0.025	0.577 $\pm$ 0.006	0.1547
23	98.7	2.06 $\pm$ 0.01	2.018 $\pm$ 0.008	2.2153	30	92.4	0.586 $\pm$ 0.025	0.579 $\pm$ 0.005	0.1462
35	98.9	2.07 $\pm$ 0.02	2.021 $\pm$ 0.008	2.3554	28	82.5	0.593 $\pm$ 0.032	0.581 $\pm$ 0.005	0.1476
27	53.3	2.08 $\pm$ 0.03	2.023 $\pm$ 0.008	2.4002	32	77.1	0.586 $\pm$ 0.016	0.583 $\pm$ 0.004	0.1378
20	96.6	2.13 $\pm$ 0.08	2.024 $\pm$ 0.008	2.3801	33	45.3	0.595 $\pm$ 0.024	0.585 $\pm$ 0.003	0.1461
23	98.3	2.07 $\pm$ 0.01	2.033 $\pm$ 0.007	2.8480	31	94.3	0.612 $\pm$ 0.038	0.586 $\pm$ 0.004	0.1780
73	87.2	2.14 $\pm$ 0.05	2.034 $\pm$ 0.008	2.9003	36	21.9	0.600 $\pm$ 0.021	0.588 $\pm$ 0.004	0.1953
28	70.4	2.14 $\pm$ 0.03	2.036 $\pm$ 0.008	3.1776	27	90.1	0.589 $\pm$ 0.005	0.589 $\pm$ 0.002	0.1812
21	98.0	2.21 $\pm$ 0.05	2.037 $\pm$ 0.008§	3.4311	34	88.7	0.600 $\pm$ 0.015	0.590 $\pm$ 0.002	0.2059
<b>Mesa Falls Tuff (8YC460A)</b>					34	47.6	0.601 $\pm$ 0.015	0.590 $\pm$ 0.002	0.2285
38	93.8	1.26 $\pm$ 0.04	—	—	30	93.0	0.595 $\pm$ 0.006	0.592 $\pm$ 0.002	0.2408
30	92.7	1.27 $\pm$ 0.02	1.268 $\pm$ 0.004	0.0500	38	80.6	0.610 $\pm$ 0.014	0.593 $\pm$ 0.002	0.3217
27	91.1	1.29 $\pm$ 0.04	1.272 $\pm$ 0.006	0.1510	28	82.2	0.619 $\pm$ 0.020	0.593 $\pm$ 0.002	0.3976
32	80.3	1.29 $\pm$ 0.04	1.274 $\pm$ 0.006	0.1607	39	89.8	0.605 $\pm$ 0.003	0.600 $\pm$ 0.002	0.7538
55	84.4	1.30 $\pm$ 0.05	1.276 $\pm$ 0.006	0.1811	33	75.1	0.619 $\pm$ 0.016	0.600 $\pm$ 0.002	0.7892
25	87.6	1.27 $\pm$ 0.01	1.272 $\pm$ 0.003	0.1717	21	68.5	0.619 $\pm$ 0.013	0.600 $\pm$ 0.002	0.8525
43	87.3	1.28 $\pm$ 0.02	1.273 $\pm$ 0.003	0.1654	29	80.6	0.621 $\pm$ 0.012	0.601 $\pm$ 0.002	0.9444
47	88.5	1.28 $\pm$ 0.02	1.274 $\pm$ 0.003	0.1561	33	93.9	0.650 $\pm$ 0.014	0.602 $\pm$ 0.002†	1.4249
34	94.3	1.29 $\pm$ 0.02	1.276 $\pm$ 0.003	0.2069	31	92.6	0.656 $\pm$ 0.017	0.603 $\pm$ 0.003	1.7792
66	56.8	1.31 $\pm$ 0.04	1.277 $\pm$ 0.003	0.2626	39	94.1	0.664 $\pm$ 0.010	0.605 $\pm$ 0.004	3.1439
43	96.7	1.32 $\pm$ 0.05	1.278 $\pm$ 0.004	0.3097	34	86.9	0.943 $\pm$ 0.049	0.606 $\pm$ 0.004	4.8466
40	92.9	1.31 $\pm$ 0.03	1.279 $\pm$ 0.004	0.3831	28	90.3	1.01 $\pm$ 0.04	0.607 $\pm$ 0.006§	9.0506
30	97.9	1.32 $\pm$ 0.03	1.281 $\pm$ 0.004	0.4999					
28	91.3	1.33 $\pm$ 0.03	1.283 $\pm$ 0.005	0.6597					

Note: Running weighted averages (Wtd Avg) are given with  $1\sigma$  posteriori error (including scatter); those in italics have MSWDs greater than the critical value and are not used to calculate preferred ages.

Sample 1R547 is not included in these calculations.

\* Radiogenic Ar; —, not applicable

† Preferred age; § Weighted mean of all samples

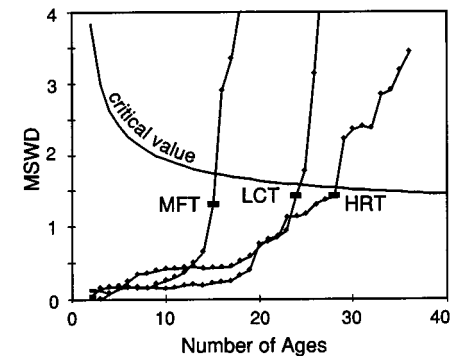


Figure 2. Plot of MSWD vs. number of ages included in running weighted averages. Boxes mark where preferred eruptive ages were taken. HRT—Huckleberry Ridge Tuff; MFT—Mesa Falls Tuff; LCT—Lava Creek Tuff member B. Critical value as defined in text.

Huckleberry Ridge Tuff are from pumice lapilli in the basal ash fall (8YC410B) and from partially welded ignimbrite near the middle of member B (2R577). Mesa Falls Tuff samples are from a pumice lump in the nonwelded base of the ignimbrite (8YC460A) and from whole-rock, devitrified welded tuff in the middle of the ignimbrite (1R547). Lava Creek Tuff samples are from pumice lapilli in the plinian fallout (0YC553), whole-rock welded tuff from the lower part of member A (8YC413) and from the middle part of member B (7YC325), and pumice from the nonwelded top of member B (8YC411). Sanidine grains were separated, prepared, irradiated for 1 hr, and analyzed as in Gansecki et al. (1996). The 0.5- to 1-mm-sized grains were fused individually with a 6 W Ar-ion laser; degassed basalt flux was generally used to aid fusion and maximize Ar extraction, although some grains from the Lava Creek Tuff were run without the flux. Ages from grains fused without the flux are not significantly different from those fused with flux, but the overall percentage of grains that did not fuse and were therefore unusable is much larger. Splits of the feldspar separates used for  $^{40}\text{Ar}/^{39}\text{Ar}$  dating were analyzed by electron microprobe as in Gansecki et al. (1996).

Raw  $^{40}\text{Ar}/^{39}\text{Ar}$  data<sup>2</sup> were reduced and statistically analyzed according to the methods described in Gansecki et al. (1996). Errors are

reported at  $1\sigma$  (Table 1), but are compared at the  $2\sigma$  level throughout the paper. A goodness-of-fit parameter, the MSWD, is used to evaluate the sources of scatter in the data. An MSWD that exceeds the critical value of  $(1 + 2/[2(n - 2)]^{1/2})$  for  $n$  points (e.g., Wendt and Carl, 1991) indicates a greater than 95% probability that the scatter cannot be explained by analytical error alone. In these cases, it is reasonable to assume there is some geologic reason for the observed heterogeneity. We take the view that in young volcanic rocks that have not undergone reheating events, excess Ar or contamination by older xenocrysts is far more likely to be a problem than Ar loss (e.g., McDowell, 1983).

The technique used to calculate preferred ages is similar to that of van den Bogaard (1995) and Gansecki et al. (1996). Running weighted averages with MSWDs are calculated from the single-crystal ages, which are sorted by increasing minimum age (crystal age minus  $1\sigma$  error). The preferred age is taken at the last point where the MSWD is just below the critical value (Fig. 2, Table 1). The  $1\sigma'$  or *posteriori* error given is the weighted error times the square root of the MSWD. Unlike a regular weighted error, which only takes analytical precision into account, the *posteriori* error also incorporates scatter in the data. Our preferred ages are therefore skewed toward the younger apparent ages, unless the variation is small, in which case the result would be the same as a standard weighted average.

## RESULTS

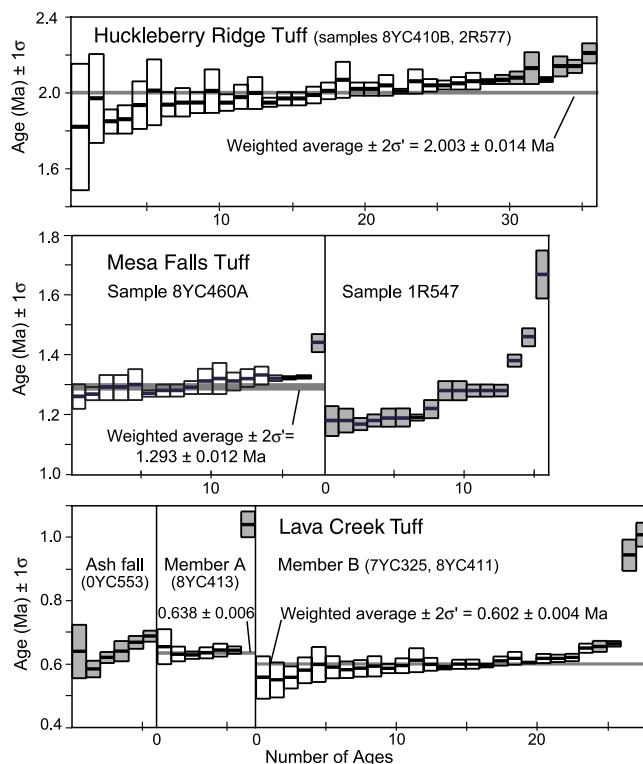
### Huckleberry Ridge Tuff

$^{40}\text{Ar}/^{39}\text{Ar}$  total-fusion ages were measured from 32 sanidine grains from the Huckleberry Ridge Tuff. The preferred age for the Huckleberry Ridge Tuff, both samples 8YC410B and 2R577 combined, is  $2.003 \pm 0.014$  Ma ( $2\sigma'$ , Fig. 3, Table 1). There is no significant difference in age between the ash fall and the ignimbrite, which gave ages of  $1.995 \pm 0.020$  and  $2.024 \pm 0.022$  Ma, respectively. Most of the data points are included in the final age calculation, with the exception of a tail of older ages that fall outside the limit of acceptable analytical scatter. Although compositions of Huckleberry Ridge Tuff sanidine grains from the plinian ash deposit and from the ignimbrite show some variation (Fig. 4), there are no obviously xenocrystic compositions.

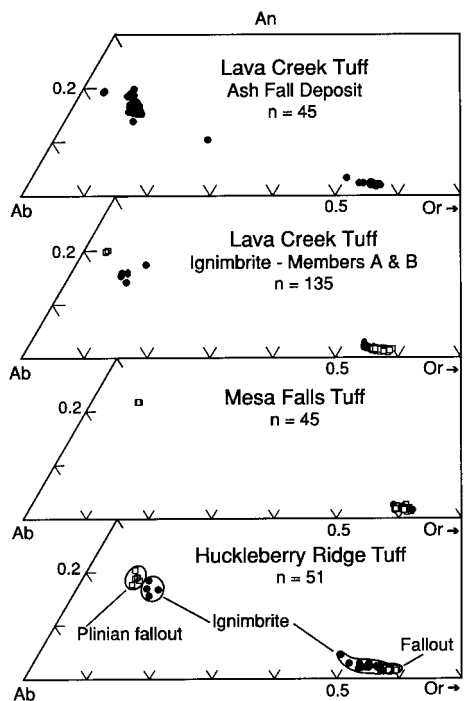
### Mesa Falls Tuff

The  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of the two samples from the Mesa Falls Tuff are distinctly different. The basal pumice sample, 8YC460A, yielded a well-constrained age of  $1.293 \pm 0.012$  Ma ( $2\sigma'$ , Fig. 3) for 17 grains. The sample of devitrified densely welded ignimbrite, 1R547, produced a very wide range of ages, with one cluster apparent at 1.19 Ma and another at 1.28 Ma. We consider sample 1R547 to have been disturbed—possibly made less retentive of Ar by microscopic feldspar exsolution during devitrification—and therefore do not use it in calculating the age. Mesa Falls Tuff

<sup>2</sup>GSA Data Repository item 9839, Yellowstone  $^{40}\text{Ar}/^{39}\text{Ar}$  analytical data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.



**Figure 3. Distributions of  $^{40}\text{Ar}/^{39}\text{Ar}$  apparent ages from the three tuffs. Error bars on individual data points are  $\pm 1\sigma$ . Horizontal bars represent preferred weighted averages of each unit; shaded analyses were omitted from calculations.**



**Figure 4. Electron-microprobe analyses of feldspar splits from the three Yellowstone tuffs. Pairs of core-rim analyses showed no significant differences. Open squares are from pumice from nonwelded base of Mesa Falls Tuff and member A of Lava Creek Tuff.**

sanidines show remarkably little variation in composition (Fig. 4) between grains or cores and rims in either sample, suggesting that the scatter in ages is not the product of xenocrystic contamination.

### Lava Creek Tuff

Our preferred age for member B of the Lava Creek Tuff is  $0.602 \pm 0.004$  Ma ( $2\sigma'$ , Fig. 3), on the basis of 24 analyses from two samples. Member B is correlated with the stratigraphically important distal ash bed Pearlette O. Our data suggest that member A may be somewhat older than the overlying member B (Fig. 3), although the small number of analyses for member A make this conclusion less certain. The number of analyses is small because the basal ash fall and some grains from ignimbrite member A were fused without using basalt flux, yielding fewer usable data. Their apparent ages are  $0.630 \pm 0.030$  Ma ( $2\sigma'$ , five grains) and  $0.638 \pm 0.006$  Ma ( $2\sigma'$ , six grains), respectively. Combining all the data for the Lava Creek Tuff yields an age of  $0.603 \pm 0.004$  Ma ( $2\sigma'$ , 32 grains). Three obvious xenocrysts yield ages greater than 0.9 Ma, but there are also a few grains with ages only slightly too old.

The sanidine compositions from the four samples of the Lava Creek Tuff are tightly clustered (Fig. 4), with most variation in the plinian ash-fall unit, which ranges to slightly more Na-rich compositions. The Ba contents of Lava Creek Tuff sanidine are far lower than those from either of the older ignimbrites, precluding an interpretation of contamination by these units.

### DISCUSSION

A tail of slightly older ages is a common feature in our distributions of single-grain ages. This range of variation would be undetectable in much older rocks or in bulk samples. Diffusion calculations (Gansecki et al., 1996) indicate that  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of older sanidine xenocrysts would be indistinguishable from phenocrysts after a year or two of residence in the magma. This means that to yield anomalously old ages due to incomplete outgassing, xenocrysts must be incorporated in the magma only a short period prior to eruption. The small range of sanidine compositions and the absence in the electron microprobe data for grains of conspicuously xenocrystic material, such as might be derived from the underlying Tertiary mafic volcanic rocks or Precambrian crystalline basement, suggests that the grains yielding slightly old ages may not be truly xenocrystic.

These older grains may instead be evidence of roofward or sidewall cannibalization of previously crystallized cognate material immediately prior to eruption. Between major eruptions, large silicic magma chambers are presumed to undergo periods of gradual cooling and crystallization interrupted by injections of hotter, less-evolved material. These injections may raise the temperature of the magma—causing remelting and/or remobilization of partially crystallized rinds

(Mahood, 1990)—and in many cases may precede or possibly even trigger ignimbrite eruptions (e.g., Hildreth, 1981; Huppert and Sparks, 1988). If liberated and cooled again within less than 1 yr, these pseudophenocrysts might give a range of  $^{40}\text{Ar}/^{39}\text{Ar}$  ages similar to what we see in our data: slightly too old but compositionally indistinguishable from phenocrysts. This process could explain similar age distribution patterns in Mono Craters ashes (Chen et al., 1996) and in tephra layers from the East Eifel volcanic field (van den Bogaard et al., 1989). These effects are likely only visible in systems less than a few million years old, because the analytical errors mask such natural age variations in older systems.

Our  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for the Huckleberry Ridge ( $2.003 \pm 0.014$  Ma), Mesa Falls ( $1.293 \pm 0.012$  Ma), and Lava Creek ( $0.602 \pm 0.004$  Ma) Tuffs are similar to—but better constrained than—previous age determinations. Establishing an accurate chronology of such large ash-forming eruptions is important not only for understanding eruption recurrence intervals and rates of magma chamber processes, but also in providing geochronologic control for studies of regional geology, geomorphology, and climate change.

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