

# **Age Determination of Lava Flows at Wupatki National Monument**



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## **Introduction**

Wupatki and Sunset Crater National Monuments lie in the eastern part of the San Francisco Volcanic Field (SFVF) in northern Arizona. This field, one of several late Cenozoic volcanic fields located along the southern margin of the Colorado Plateau, is host to over 600 volcanoes. Activity began ~6 million years ago in the western portion of the field, and continued intermittently with the locus of volcanism progressing eastward (Tanaka et al., 1986). Eruptive activity culminated in the eastern portion of the field with the eruption of Sunset Crater Volcano just over 900 years ago. At Wupatki, lava flows are present as caps on many of the mesas, in the Little Colorado River channel, and along the Doney Fault associated with the Doney Cinder cones.

The purpose of this study is to determine the age of lava flows from Wupatki NM in an effort to give a more complete picture of the volcanic history. First, older ages were reevaluated with the more accurate  $^{40}\text{Ar}/^{39}\text{Ar}$  dating methods and more precise instrumentation. Second, new dates from flows that could not be correlated to volcanic centers of known age were obtained.

## **Previous Work**

Moore and Wolfe (1987) and Ulrich and Bailey (1987) completed cursory examinations of basalt flows in the eastern and northeastern portions of the SFVF respectively. These authors suggest that there were at least four different periods of volcanic activity beginning 2.43 million years ago and ending 15,000 years ago. A more detailed geochemical investigation by Hanson (2006a) identified at least 9 individual lava flows in Wupatki NM (Figure 1). These flows include the Black Point, Citadel, Arrowhead Sink, Red House Basin, and Gem City flows in western Wupatki, the Woodhouse Mesa, Wukoki, and Grand Falls flows as well as the Doney Crater cinder cones and flows in eastern WUPA. Correlation of these flows, based on petrographic analyses and geochemistry, suggests there were at least five individual partial melting events responsible for producing volcanic activity at Wupatki NM (Hanson, 2006a, Hanson 2006b). Because of poor exposure, the Gem City flow was not sampled during this or the previous study.

Absolute ages for several of these flows were previously determined using K-Ar age dating techniques (Moore and Wolfe, 1987 and Ulrich and Bailey, 1987). However, caution should be used in evaluating these ages for several reasons. First, sample inhomogeneity may introduce error because K and Ar are measured on separate samples. Second, the basalt may contain mantle source region  $^{40}\text{Ar}$  (excess Ar) trapped in the glassy groundmass or in fluid inclusions in crystals (Kelly, 2002). This problem is exacerbated in basalt younger than 0.5 Ma because the half-life of  $^{40}\text{Ar}$  is so long ( $1.25 \times 10^9$  yr) and the basalt contains so little potassium. Duffield et al. (2006) suggest that the problem of excess Ar in basaltic lavas of the SFVF may be widespread as Ar could be inherited from incompletely degassed magma from the mantle source region and/or contamination contained in xenocrysts. As a result, K-Ar methods often yield ages that are older than the time of eruption. For this reason, age determinations were revisited using  $^{40}\text{Ar}/^{39}\text{Ar}$  methods.

## Methods

Analyses of thin sections were used to determine the degree of weathering of samples from each of the flows. Samples that exhibited the least alteration were chosen for age determinations. They were sent to the US Geological Survey, Denver Argon Geochronology Laboratory, where ground mass concentrates were prepared. Samples were irradiated for up to 3 hours at the U.S Geological Survey TRIGA reactor in Denver, Colorado (Dalrymple et al., 1981). Argon isotopic compositions were then measured at the U.S. Geological Survey Argon Geochronology Laboratory in Denver, Colorado. Analytical techniques are given in Table 1 and in general followed procedures given in Miggins et al. (2002, 2004). Standard methods were employed to produce  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra and isochron diagrams (Snee, 2002).

The  $^{40}\text{Ar}/^{39}\text{Ar}$  dating method is applicable to basaltic rocks as young as 50,000 years old based on the half-life of  $^{40}\text{K}$ . This method offers a significant advantage over the conventional K-Ar dating technique because only the Ar isotopes need to be measured in order to determine the  $^{40}\text{K}/^{40}\text{Ar}$  ratio and age. Because only a single sample is analyzed, problems associated with sample inhomogeneity are eliminated. The most significant advantage of the  $^{40}\text{Ar}/^{39}\text{Ar}$  dating method, however, is the ability to step-heat samples to higher and higher temperatures until the sample is fused. Ages are calculated for each step. This step-heating method provides information on the internal systematics of potassium and argon (ie the internal distribution of potassium relative to argon). Using isochron plots from these data, excess Ar can often be detected and corrected for.

## Results

Incremental heating results are given in Table 1 and age spectra are shown in Figure 2. Total gas ages were calculated by weighting individual steps of the fraction of  $^{39}\text{Ar}$  released and are equivalent to the K-Ar method of dating. Differences between the total gas ages and the K-Ar ages from Moore and Wolfe (1987) and Ulrich and Bailey (1987) are attributed to reasons described above. Plateau ages were determined by measuring the percent  $^{39}\text{Ar}$  released during step-wise heating and plotting these ages versus the percent  $^{39}\text{Ar}$  released. As used herein, the term "plateau" refers to two or more contiguous temperature steps with apparent dates that are indistinguishable at the 95% confidence interval and represent  $\geq 50\%$  of the total  $^{39}\text{Ar}_K$  released (Fleck et al., 1977);  $^{39}\text{Ar}_K$  is given in Table 1. Failure of a sample to reach a plateau during the analysis can be attributed to several factors including excess Ar, Ar loss, and/or large analytical errors resulting from low values of radiogenic  $^{40}\text{Ar}_K$  in very young samples, especially those with low concentrations of whole rock  $\text{K}_2\text{O}$ . Because of the potential problem with excess Ar in SFVF basalt, isochron analyses (York, 1969) were used to assess if extraneous radiogenic argon components were trapped in any samples. Isochron ages are corrected for the determined excess Ar, thus may represent the most accurate ages. In many of the samples, the problem of excess Ar was minimal as total gas ages, plateau ages and isochron ages are indistinguishable within analytical error. In cases where they are not, the isochron ages, which take into account excess argon, are interpreted to represent the maximum age of the flow.

A comparison of the K-Ar ages (Moore and Wolfe, 1987 and Ulrich and Bailey, 1987) with  $^{40}\text{Ar}/^{39}\text{Ar}$  isochron ages (this study) is given in Figure 3. A discussion of each of the flows is given below.

### *Black Point and Citadel Flows*

In western Wupatki, Black Point and Citadel lava flowed to the northeast but cannot be traced back to a source vent as younger lava flows cover the southwestern portion of the flows. Mineralogical, textural and geochemical similarities suggest that these flows are genetically related and *may* represent two separate lobes of a single flow (Ulrich and Bailey, 1987, Hanson, 2006a, Hanson, 2006b).

A single K-Ar age determination for the Black Point Flow yielded an age of  $2.43 \pm 0.32$  Ma (Ulrich and Bailey, 1987). By inference, these authors assigned the same age to the Citadel flow. The Black Point flow (WEM-3) yielded an  $^{40}\text{Ar}/^{39}\text{Ar}$  isochron age of  $0.873 \pm 0.008$  Ma and two samples from the Citadel Flow (EM-4 and SM-2a) yielded isochron ages of  $0.85 \pm 0.02$  Ma and  $0.87 \pm 0.04$  Ma respectively. These ages correspond within analytical error further suggesting that these flows are related. Regardless of whether they represent separate lobes of a single flow, or two individual flows from a short lived eruption, the age of the flow can be further constrained to the time when the three ages overlap. Thus, these flows effused from an undetermined vent, or vents, to the southeast between 865,000 and 870,000 years before present.

### *Red House Basin flow*

The Red House Basin Flow exhibits slight geochemical and mineralogical differences from the Black Point and Citadel flows. For this reason, it was interpreted by Hanson (2006a, 2006b) to represent a separate melting event, perhaps related to the Wukoki flow. A single  $^{40}\text{Ar}/^{39}\text{Ar}$  age determination (HC-6) yielded a plateau age of  $0.89 \pm 0.17$  Ma and an isochron age of  $0.872 \pm 0.006$  Ma. The correspondence of this age to those of the Black Point and Citadel flows suggests that all three may be related. Slight differences in chemistry could be attributed to either fractional crystallization of the source melt or perhaps a slightly greater degree of crustal contamination for the Red House Basin flow. Thus, the Red House Basin flow resulted from the same volcanic event to the southwest as the Black Point and Citadel flows, but whether it effused from the same or an associated vent just before, at the same time as, or subsequent to the Citadel and Black Point flows cannot be ascertained.

### *Arrowhead Sink Flow*

The Arrowhead Sink flow, the most evolved flow in western Wupatki, also exhibits a northeastward flow direction. While no K-Ar age was measured from this flow, Ulrich and Bailey (1987) suggest that it originated from Vent 3705 to the southwest of Wupatki. However, the degree of weathering of Vent 3705 suggests that it is much too young to be the source vent. Alternatively, Hanson (2006a and 2006b) suggested that this flow may have resulted from fractional crystallization of Black Point and Citadel magma. A single sample (HC-5) yielded a total gas age of  $0.60 \pm 0.06$  Ma, a plateau age of  $0.60 \pm 0.06$  Ma and an isochron age of  $0.61 \pm 0.03$  Ma. This is nearly 300 thousand years younger than the Black Point and Citadel flows, thus this flow cannot be related to that volcanic event. The Arrowhead Sink flow must represent a separate volcanic event that effused from another undetermined vent to the southwest.

### *Wupatki Flow*

This is the most laterally extensive of several flows in and near eastern Wupatki. It terminates to the northeast of the Wupatki pueblo and is stratigraphically the lowest, thus the oldest, of a series of flows that originated from the south-southwest. A single K-Ar date on basalt from this flow yielded age of  $0.50 \pm 0.09$  Ma (Moore and Wolfe, 1987). A single  $^{40}\text{Ar}/^{39}\text{Ar}$  analysis yielded a total gas age of  $0.42 \pm 0.05$  Ma, a plateau age of  $0.30 \pm 0.3$  Ma and an isochron age of  $0.15 \pm 0.07$ . The disparity of these ages is attributed to significant excess Ar, a problem exacerbated by the younger age of this flow. For this reason, the isochron age is interpreted to be the most accurate and should be regarded as a maximum age for the flow. This is significantly younger than the Red House Basin flow, thus not likely related to that event as suggested by Hanson (2006b)

### *Woodhouse Mesa Flow*

The Woodhouse Mesa flow exhibits a unique chemical composition in that it has higher whole rock Ti as well as higher Ti in the olivine and pyroxene phenocrysts. Although this flow is present only on an eroded mesa top giving no indication of flow direction, younger flows in the area originated from vents to the south, thus it is likely that the Woodhouse Mesa flow did as well. The K-Ar age of Moore and Wolfe (1987) is  $1.07 \pm 0.15$  and lies within analytical error of the  $^{40}\text{Ar}/^{39}\text{Ar}$  age for sample WM-1a ( $0.96 \pm 0.03$  Ma). Thus, this is the oldest flow exposed in Wupatki National Monument.

### *Doney Mountain Flows*

The Doney Mountain cinder cones and lava flows crop out along the trace of the Doney Fault, which formed a conduit for magma to move upward. While no quantitative age dates are available for these volcanics, they exhibit minimal weathering and erosion suggesting they are very young. Two samples, one from the Doney Mountain flow (DM-1b) and one from the Little Doney flow (DM-4) yielded isochron ages of  $0.251 \pm 0.008$  Ma and  $0.51 \pm 0.03$  Ma respectively. Although these analyses show no evidence of excess Ar, these ages are not consistent with the degree of weathering, which suggests that they are much younger. Thus, it is likely that these cinder cones may be simply too young to date using  $^{40}\text{Ar}/^{39}\text{Ar}$  methods.

### *Grand Falls Flow*

Physiographic relationships suggest that the Grand Falls flow originated from Merriam Crater, The Sproul or one of the two smaller vents at the east base of Merriam Crater (Moore and Wolfe, 1987; Duffield et al., 2006). A review of whole rock analyses from Moore and Wolfe (1987) suggests that, based on chemical similarities, this flow may instead be related vent 3028. Regardless of the source vent, approximately 20,000 years ago, this flow spilled into the Little Colorado River channel creating Grand Falls and continued downstream to just north of Wupatki (Duffield, et al., 2006).

## **Conclusions**

Sporadic volcanic activity over the last million years has shaped and reshaped the landscape at Wupatki National Monument. Each individual lava flow, or group of flows, represent discrete melting events where molten mantle material ascended quickly producing short-lived eruptions (Hanson 2006a and Hanson, 2006b). To that end, each of

the flows at Wupatki are not genetically related via a single large magma chamber but instead represent individual melting events. Six, rather than five, partial melting events have been identified from Wupatki NM. Additionally, if the Gem City flow is not related to the Arrowhead Sink flow, this would represent a seventh. The chronological order of these events is included on Figure 1 and is summarized below.

The Woodhouse Mesa flow (shown in light green) in eastern Wupatki effused from a vent to the south approximately 960,000 years ago and was the first flow to encroach on the land that is now preserved at Wupatki NM. Subsequent weathering has left this flow exposed only on a mesa top in the eastern portion of the monument behind the Visitor Center. Approximately 865,000 to 870,000 years ago one, or several, cinder cones to the southwest of Wupatki produced the Black Point, Citadel and Red House Basin flows (all shown in pale purple). The Arrowhead Sink flow (shown in maroon) may represent the next episode of volcanic activity occurring approximately 600,000 years before present. It is impossible to ascertain whether the Gem City flow (shown in orange), which lies stratigraphically above the Black Point and Citadel flow, resulted from an eruption that predates, postdates, or is contemporaneous with the eruption that produced the Arrowhead Sink flow. Regardless of the sequence, these flows were last to encroach on western Wupatki. Since that time the area has undergone erosion and minor faulting. While the Black Point, Red House Basin and Arrowhead Sink flows remain nearly continuous, all that remains of the Citadel flow are a series of basalt capped mesas (East, West, South, Middle, and Magnetic Mesas).

Several hundred thousand years elapsed between the events that impacted western Wupatki and those that subsequently encroached upon eastern Wupatki. Volcanic activity resumed in eastern Wupatki approximately 150,000 years ago with the eruption of the Wukoki flow (shown in red), the oldest of a series of flows that originated from an undetermined vent to the south-southeast of the monument in the far eastern portion of the SFVF. This activity continued for an undetermined time with subsequent flows covering much of the southern portion of this flow. Following another hiatus in the eastern Wupatki area, the eruption of the Doney Mountain cinder cones produced three several hundred foot tall cinder cones and two lava flows along the Doney Fault (shown in yellow). Additionally, an undetermined vent to the south-southeast produced the Grand Falls flow (20,000 a) which, after spilling into the Little Colorado River channel creating Grand Falls, flowed downstream to just north of the Wupatki boundary (also shown in yellow). Because the Doney Mountain cinder cones are too young to produce an accurate  $^{40}\text{Ar}/^{39}\text{Ar}$  age, the relative sequence of these two eruptions cannot be determined.

The final event that altered the landscape at Wupatki was the eruption of the youngest volcano in the SFVF, Sunset Crater Volcano, in ~A.D. 1080. While the lava flows did not reach Wupatki, cinders and ash from the eruption blanketed the landscape. This ash may have acted as mulch, temporarily enhancing farming in this arid area and resulting in the large population growth at Wupatki in AD 1100 (Hooten et al., 2001).

The final phase of this project lies outside the monument boundaries and will focus on using geochemical correlations to determine the source vent for each of these flows. Field work for this phase of the project was initiated in the summer of 2008.

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**Table 1.**  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental heating data

Temp (°C)	$^{40}\text{Ar}_R$	$^{39}\text{Ar}_K$	$^{40}\text{Ar}_R/^{39}\text{Ar}_K$	$^{39}\text{Ar}/^{37}\text{Ar}^2$	% $^{40}\text{Ar}_R$	% $^{39}\text{Ar}$	Apparent Age <sup>3</sup> (Ma at ± 1 sigma)
<b>EM-4/#11/DD95 Citadel Flow (East Mesa)</b>							
<b>Groundmass Concentrate; 242.2 mg; J-value=0.0010692±0.1%</b>							
650	0.00257	0.00244	1.053	0.41	2.5	2.1	2.03 ± 1.70
750	0.01144	0.02339	0.489	0.87	25.0	19.8	0.94 ± 0.11
850	0.01799	0.04092	0.440	0.86	34.5	34.6	0.85 ± 0.08
950	0.01009	0.02255	0.447	0.76	37.3	19.1	0.86 ± 0.27
1050	0.00494	0.01129	0.437	0.47	19.3	9.5	0.84 ± 0.15
1250	0.00790	0.01677	0.471	0.16	11.8	14.2	0.91 ± 0.31
1400	0.00043	0.00088	0.494	0.03	1.6	0.7	0.95 ± 1.91
<b>Total gas age: 0.90 ± 0.19 Ma</b>							
<b>Plateau age (steps 2-6): 0.88 ± 0.18 Ma</b>							
<b>Isochron age (steps 1-7): 0.85 ± 0.02 Ma; (<math>^{40}\text{Ar}/^{36}\text{Ar}</math>)<sub>i</sub>= 298 ± 2</b>							
<b>HC-5/#21/DD96 Arrowhead Sink Flow</b>							
<b>Groundmass Concentrate; 454.5 mg; J-value=0.002518±0.1%</b>							
700	0.02483	0.01736	1.430	1.00	3.4	20.7	0.65 ± 0.06
800	0.03432	0.02603	1.318	1.28	13.5	31.1	0.60 ± 0.01
950	0.02463	0.01807	1.363	1.10	14.2	21.6	0.62 ± 0.05
1100	0.01445	0.01179	1.225	0.72	11.4	14.1	0.56 ± 0.06
1250	0.01099	0.00820	1.341	0.21	10.7	9.8	0.61 ± 0.10
1400	0.00203	0.00223	0.909	0.14	1.8	2.7	0.41 ± 0.36
<b>Total gas age: 0.60 ± 0.06 Ma</b>							
<b>Plateau age (steps 2-5): 0.60 ± 0.06 Ma</b>							
<b>Isochron age (steps 1-6): 0.61 ± 0.03 Ma; (<math>^{40}\text{Ar}/^{36}\text{Ar}</math>)<sub>i</sub>= 295 ± 2</b>							
<b>DM-1B/#24/DD96 Doney Mountain Flow</b>							
<b>Groundmass Concentrate; 506.7 mg; J-value=0.002266±0.1%</b>							
700	0.00319	0.00439	0.727	0.35	0.5	6.6	0.30 ± 0.21
800	0.00767	0.01087	0.706	0.53	3.2	16.3	0.29 ± 0.05
950	0.01200	0.01943	0.618	0.58	7.5	29.1	0.25 ± 0.04
1100	0.01365	0.02291	0.596	0.47	6.2	34.3	0.24 ± 0.03
1250	0.00456	0.00788	0.578	0.10	3.2	11.8	0.24 ± 0.18
1400	0.00075	0.00125	0.604	0.04	1.8	1.9	0.25 ± 0.75
<b>Total gas age: 0.26 ± 0.08 Ma</b>							
<b>Plateau age (steps 3-4): 0.25 ± 0.04 Ma</b>							
<b>Isochron age (steps 1-6): 0.251 ± 0.008 Ma; (<math>^{40}\text{Ar}/^{36}\text{Ar}</math>)<sub>i</sub>= 296 ± 1</b>							
<b>DM-4/#25/DD96 Little Doney Mountain Flow</b>							
<b>Groundmass Concentrate; 493.5 mg; J-value=0.002448±0.1%</b>							
700	0.01761	0.01251	1.408	0.71	3.9	12.3	0.62 ± 0.21
800	0.03482	0.03116	1.117	1.46	16.8	30.8	0.49 ± 0.01
950	0.02874	0.02309	1.245	1.53	23.4	22.8	0.55 ± 0.01
1100	0.03031	0.02323	1.305	0.74	14.8	22.9	0.58 ± 0.07
1250	0.01525	0.01044	1.461	0.21	7.5	10.3	0.65 ± 0.11
1400	0.00202	0.00090	2.246	0.04	3.2	0.9	0.99 ± 0.68
<b>Total gas age: 0.56 ± 0.06 Ma</b>							
<b>Plateau age (steps 3-5): 0.55 ± 0.08 Ma</b>							
<b>Isochron age (steps 1-6): 0.51 ± 0.03 Ma; (<math>^{40}\text{Ar}/^{36}\text{Ar}</math>)<sub>i</sub>= 300 ± 2</b>							
<b>WM-1a/#23/DD96 Woodhouse Mesa Flow</b>							
<b>Groundmass Concentrate; 457.8 mg; J-value=0.002415±0.1%</b>							
650	0.00331	0.00031	10.673	0.25	1.3	0.4	4.64 ± 2.44
800	0.05760	0.02522	2.284	0.79	19.6	31.9	0.99 ± 0.03
950	0.07379	0.03409	2.165	1.12	37.9	43.1	0.94 ± 0.06
1100	0.01857	0.00873	2.127	0.48	11.5	11.0	0.93 ± 0.10
1250	0.01907	0.00929	2.052	0.11	6.4	11.7	0.89 ± 0.09
1400	0.00119	0.00149	0.796	0.06	1.2	1.9	0.35 ± 0.75
<b>Total gas age: 0.96 ± 0.10 Ma</b>							
<b>Plateau age (steps 3-5): 0.93 ± 0.08 Ma</b>							
<b>Isochron age (steps 1-6): 0.96 ± 0.03 Ma; (<math>^{40}\text{Ar}/^{36}\text{Ar}</math>)<sub>i</sub>= 295 ± 2</b>							

**Table 1.**  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental heating data (cont.).

Temp (°C)	$^{40}\text{Ar}_R^1$	$^{39}\text{Ar}_K$	$^{40}\text{Ar}_R/^{39}\text{Ar}_K$	$^{39}\text{Ar}/^{37}\text{Ar}^2$	% $^{40}\text{Ar}_R$	% $^{39}\text{Ar}$	Apparent Age <sup>3</sup> (Ma at ± 1 sigma)
<b>EEM-2B/#22/DD96 Wukoki Flow</b>							
<b>Groundmass Concentrate; 453.4 mg; J-value=.0002504±0.1%</b>							
650	0.00643	0.00053	12.020	0.18	3.3	0.8	5.42 ± 0.54
800	0.02290	0.03502	0.654	0.59	7.2	53.1	0.30 ± 0.02
950	0.01151	0.01765	0.652	0.59	8.0	26.8	0.29 ± 0.04
1100	0.00902	0.00873	1.034	0.28	8.4	13.2	0.47 ± 0.09
1250	0.00821	0.00365	2.246	0.04	7.3	5.5	1.01 ± 0.23
1400	0.00381	0.00039	9.654	0.02	11.2	0.6	4.36 ± 2.25
<b>Total gas age: 0.42 ± 0.05 Ma</b>							
<b>Plateau age (steps 2-3): 0.30 ± 0.03 Ma</b>							
<b>Isochron age (steps 1-5): 0.15 ± 0.07 Ma; (<math>^{40}\text{Ar}/^{36}\text{Ar}</math>)<sub>I</sub>= 311 ± 4</b>							
<b>WEM-3/#8/DD92 Black Point Flow</b>							
<b>Groundmass Concentrate; 483.4 mg; J-value=.0011571±0.1%</b>							
650	0.00234	0.00072	3.245	0.32	1.3	0.2	6.76 ± 5.09
750	0.01949	0.04780	0.408	0.64	5.0	12.9	.85 ± 0.08
850	0.06263	0.14697	0.426	1.08	20.6	39.7	.89 ± 0.05
950	0.03670	0.08651	0.424	0.99	24.2	23.4	.89 ± 0.06
1050	0.12930	0.03005	0.430	0.56	12.9	8.1	.90 ± 0.06
1150	0.01387	0.03278	0.423	0.45	13.4	8.9	.88 ± 0.16
1250	0.00833	0.01876	0.444	0.08	8.7	5.1	.93 ± 0.31
1400	0.00266	0.00679	0.392	0.04	2.7	1.8	.82 ± 0.27
<b>Total gas age: 0.90 ± 0.08 Ma</b>							
<b>Plateau age (steps 3-5): 0.89 ± 0.05 Ma</b>							
<b>Isochron age (steps 3-7): 0.873 ± 0.008 Ma; (<math>^{40}\text{Ar}/^{36}\text{Ar}</math>)<sub>I</sub>= 297 ± 1</b>							
<b>HC-6/#9/DD92 Red House Basin Flow</b>							
<b>Groundmass Concentrate; 471.7 mg; J-value=.0011641±0.1%</b>							
650	0.00855	0.00343	2.492	0.98	7.2	1.0	5.23 ± 0.38
750	0.00917	0.01667	0.550	0.40	2.3	5.0	1.15 ± 0.03
850	0.02376	0.05593	0.425	0.74	19.8	16.7	0.89 ± 0.14
950	0.07435	0.17563	0.423	0.82	32.4	52.3	0.89 ± 0.04
1050	0.01513	0.03488	0.434	0.45	16.8	10.4	0.91 ± 0.19
1150	0.00949	0.02177	0.436	0.40	10.0	6.5	0.92 ± 0.31
1250	0.00947	0.01981	0.478	0.09	6.5	5.9	1.00 ± 0.59
1400	0.00515	0.00754	0.682	0.04	2.6	2.2	1.43 ± 0.52
<b>Total gas age: 0.97 ± 0.14 Ma</b>							
<b>Plateau age (steps 3-6): 0.89 ± 0.17 Ma</b>							
<b>Isochron age (steps 2-8): 0.872 ± 0.006 Ma; (<math>^{40}\text{Ar}/^{36}\text{Ar}</math>)<sub>I</sub>= 298 ± 1</b>							
<b>SM-2A/#7/DD92 Citadel Flow (South Mesa)</b>							
<b>Groundmass Concentrate; 476.0 mg; J-value=.0011237±0.1%</b>							
650	0.01146	0.01527	0.750	0.53	5.4	3.9	1.52 ± 0.07
750	0.01446	0.02545	0.568	0.62	26.6	6.5	1.15 ± 0.30
850	0.04123	0.09282	0.444	0.98	32.0	23.8	0.90 ± 0.08
950	0.07678	0.17658	0.435	1.00	37.1	45.3	0.88 ± 0.06
1050	0.01733	0.03029	0.572	0.48	18.4	7.8	1.16 ± 0.23
1150	0.01358	0.02419	0.561	0.40	11.0	6.2	1.14 ± 0.10
1250	0.01324	0.01977	0.670	0.09	6.9	5.1	1.36 ± 0.22
1400	0.00629	0.00548	1.148	0.02	4.4	1.4	2.33 ± 0.59
<b>Total gas age: 1.01 ± 0.11 Ma</b>							
<b>Plateau age (steps 3-4): 0.89 ± 0.07 Ma</b>							
<b>Isochron age (steps 1-8): 0.87 ± 0.04 Ma; (<math>^{40}\text{Ar}/^{36}\text{Ar}</math>)<sub>I</sub>= 306 ± 6</b>							

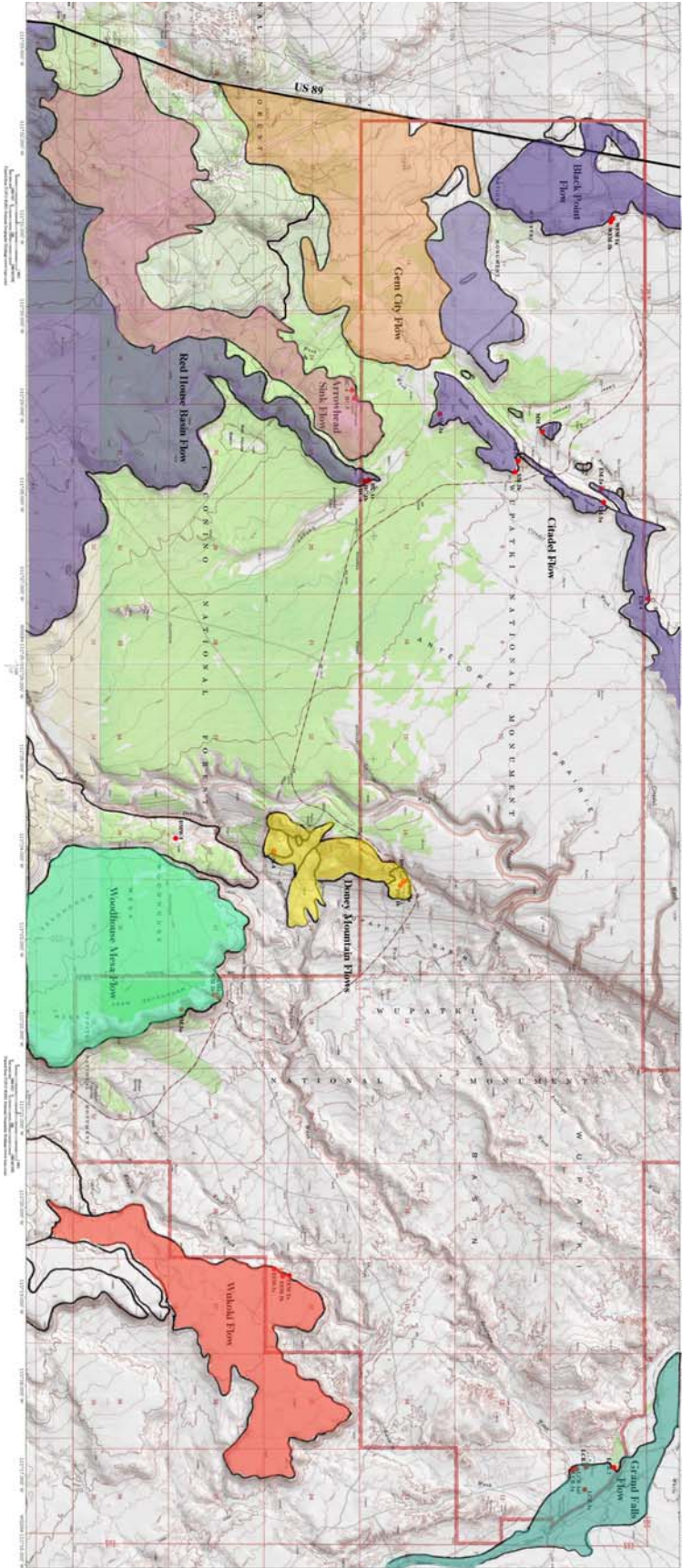


Figure 1. Topographic map of Wupatki NM showing sample locations and lava flows as mapped by Moore and Wolfe (1987) and Ulrich and Bailey (1987). Colors represent  $^{40}\text{Ar}/^{39}\text{Ar}$  ages and are as follows: Green (~960,000 years) Purple (~870,000 years), Orange (not measured - younger than 870,000 years) Maroon (~600,000 years) Pale red (<150,000 years) Yellow ( $\leq 20,000$  years). Base topographic map was created using TOPO, a program produced by National Geographic.

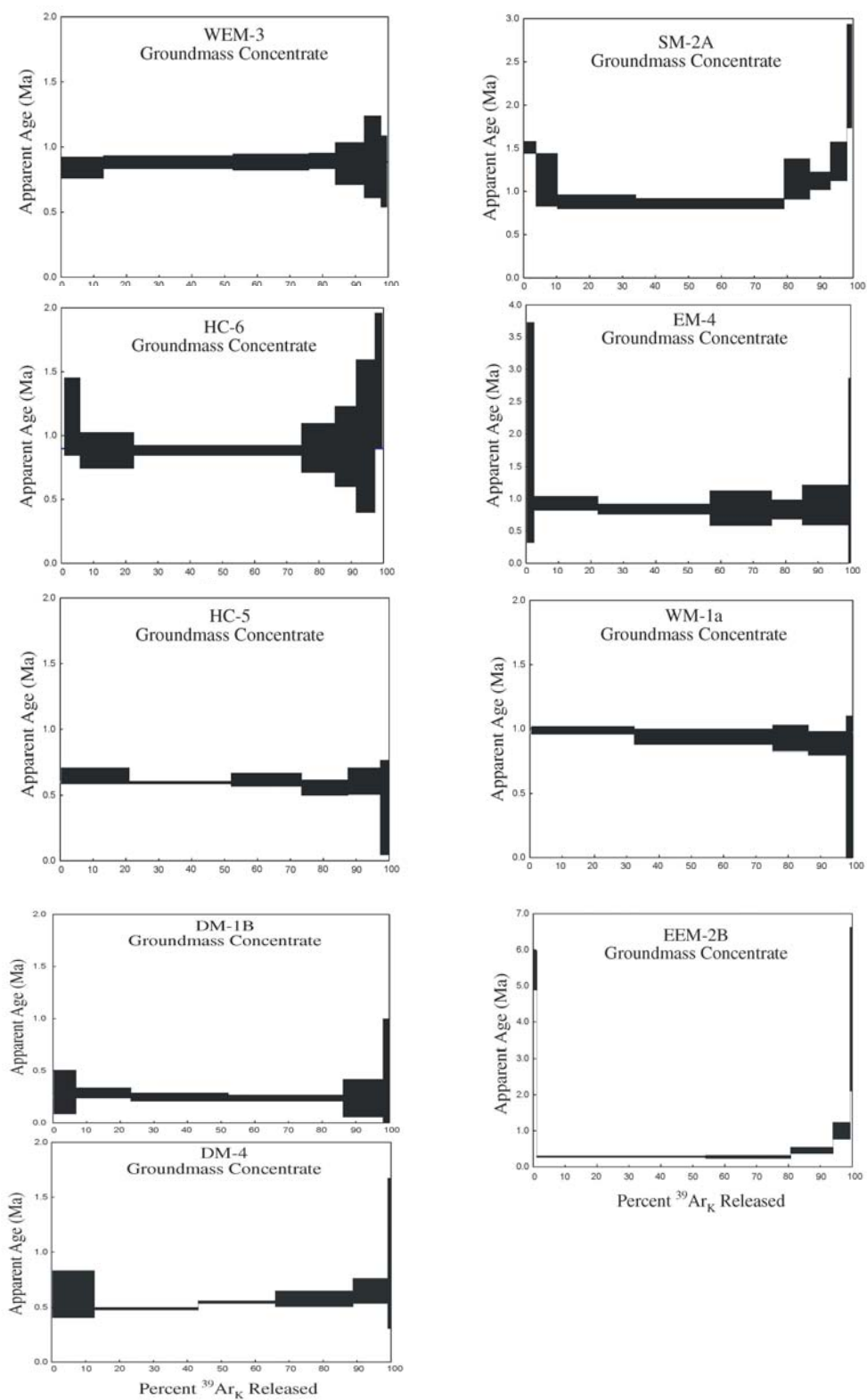


Figure 2. Age spectra for Wupatki lava flows. Sample numbers are as in Table 1.

## Relative and Absolute Ages of Lava Flows in Wupatki National Monument

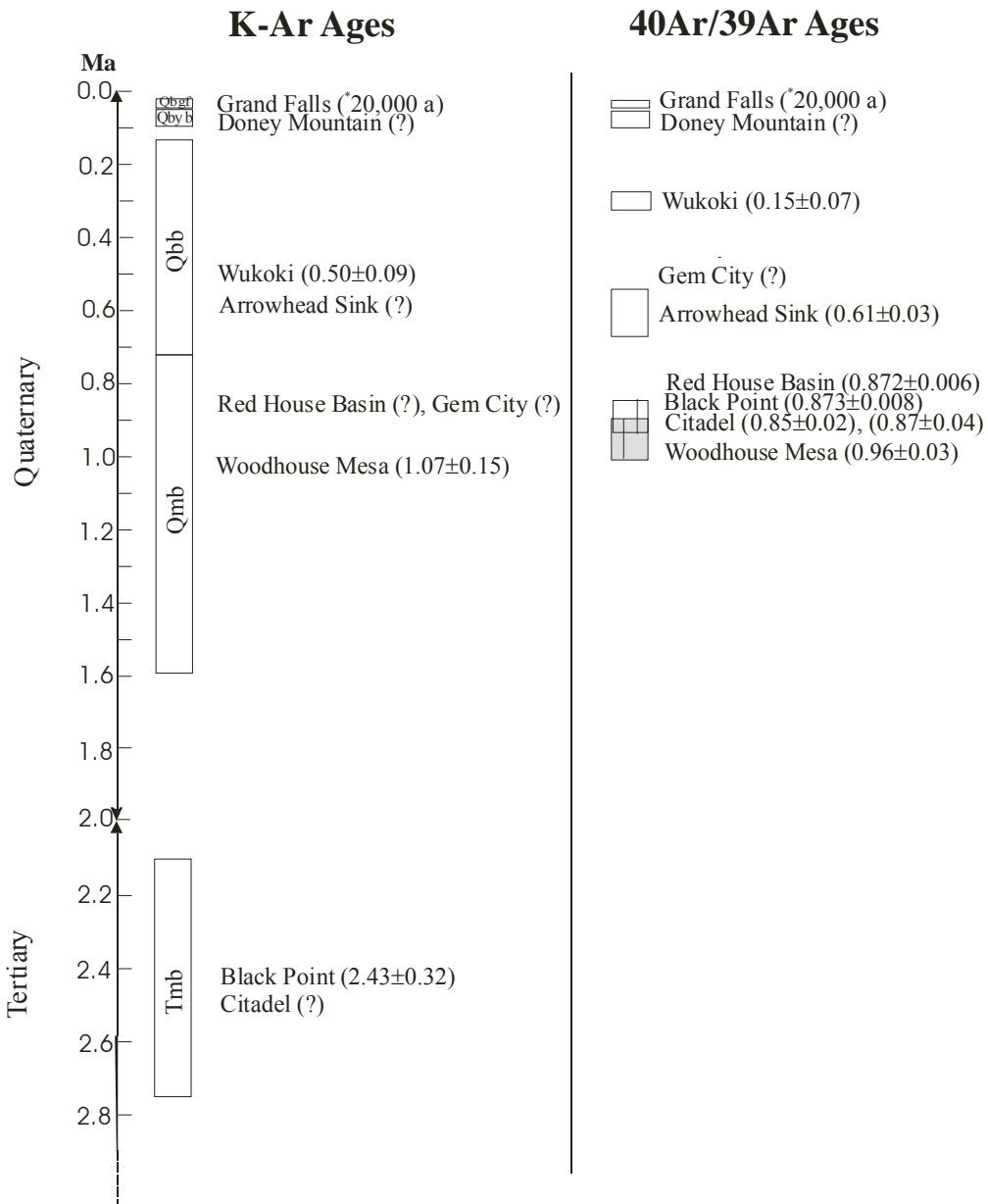


Figure 3. Comparison of K-Ar ages (Moore and Wolfe, 2000 and Ulrich and Bailey, 1987) to  $^{40}\text{Ar}/^{39}\text{Ar}$  ages (this study). Radiometric ages are shown in parenthesis and flows lacking age dates are shown with a question mark. All ages are given in millions of years with the exception of the Grand Falls flow, which is in years. The Grand Falls age is from Duffield et al. (2006).