SUPPLEMENTAL MATERIAL

Ghost-dune hollows of the eastern Snake River Plain, Idaho: Their genesis, evolution, and relevance to Martian ghost-dune pits

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Optically stimulated luminescence (OSL) methods

Seven samples for OSL dating were collected from three auger sites in two ghost-dune hollows (sites RF and MO). Methods for sample collection, processing and age determination are outlined below, along with additional sample properties and results characteristics.

Sample Collection

OSL samples were collected at pre-determined sites within the ghost-dune hollows based on previous descriptions of the stratigraphy based on bucket auger results (Fig. S1). OSL provides an age estimate of the time since sediment was last exposed to light (Huntley, et al. 1985). Therefore, special considerations were needed to ensure that the target sediments for OSL dating were not exposed to light during sampling. We also ensured that the sediments in the auger hole were not mixed and did not contain hole-slough before sending a special auger head down for OSL sample collection. Auger holes were dug using an open-tine 'Dutch-type' auger head and sediments from each 10-15cm drive were saved for sedimentary description, soil character and grain-size analysis. Once the target depth for OSL sample collection was reached, the hole was cleaned out a special sample collected head was added to the auger. This auger head was solid metal and has a central chamber with a removable metal tube that allows sediment collection in light-safe conditions (Fig. S2). We placed foam rubber in the tube to act as a gasket and ensure tight packing of the sediment during downward rotations of the auger and complete filling of the sample tube. This OSL sample tube was removed from the auger head and capped and sealed for transport to the lab. Samples for moisture content and dose-rate determination were collected from the drive immediately above and below the OSL sample intervals.

Figure S1. Ground-view photos are of RF and MO hollows, whose stratigraphy highlighted in Figure 2. Lower left photo looks across RF to the NE (downwind) towards 5-7-m-high, bounding basalt; polygonal cooling-joint fractures dip away from view. Lower right photo looks across MO to E; outline of Teton Range on horizon; basalt cooling joint fractures largely vertical in this 6-8-m-deep hollow.

Figure S2. Auger head and sample chamber used for OSL sample collection. If you are interested in a similar auger system, co-author T Rittenour can provide detail on the manufacturer and parts numbers.

Sample Processing

OSL samples were processed and analyzed at the Utah State University Luminescence Laboratory in Logan, Utah for small-aliquot single-aliquot regenerative dose (SAR) analysis of quartz sand (Murray and Wintle, 2000). Samples were opened under dim amber light (~590 nm) and sieved to selected size fractions between 63 μm and 250 μm (see Table S1 for exact grain-size ranges for each sample). The grain sizes used were determined based on the nature of the sediment. The quartz fraction was isolated by using 10% hydrochloric acid (HCl) and 5% sodium hypochlorite (bleach) to dissolve carbonates and organic material, sodium polytungstate (2.7 g/cm³) to remove heavy minerals. Feldspar and other non-quartz minerals were removed using three 30-minute etchings in concentrated hydrofluoric (47% HF) followed by hydrochloric (45% HCl) to prevent formation of fluorite precipitates (see Rittenour et al. 2005 for details). Purity of the samples was checked using infrared (IR) stimulation; all aliquots with an IR response signal to background ratio of > 2.0 were rejected and not used for age calculation. Samples with pervasive feldspar contamination received a second HF treatment (USU-2140).

Dose Rate Determination

Following deposition and removal from sunlight exposure, the luminescence signal regrows with time due to exposure to radiation from the surrounding sediments and incoming cosmic radiation. The concentrations of the K, Rb, Th, and U were analyzed using ICP-MS and ICP-AES analyses on subsamples collected above and below the OSL target intervals. The use of in-situ gamma spectrometer measurements were precluded due to the sample depths (>1.3 m) down auger holes. These concentrations were converted to dose rate using conversion factors (Guérin et al. 2011) and corrected for attenuation due to grain-size (Brennan, 2003) and water attenuation (Aitken, 1998). Total dose-rate values include cosmic contribution by using sample depth, elevation, and longitude/latitude following Prescott and Hutton (1994). Dose-rate uncertainties were calculated in quadrature using the methods of Aitken and Alldred (1972) and Aitken (1976, 1985) and include uncertainty in the elemental concentrations related to ICP detection limits (following Rittenour et al., 2005), 10% moisture content variability, 3% uncertainty for dose-rate conversion (Murray and Olley, 2002) and 10% uncertainty in cosmic dose. Elemental concentrations, water content and dose rate values for each sample are shown in Table S1.

Table S1. Dose Rate Information

Sample num.	USU num.	In-situ H ₂ O (%) ¹	Grain size (μm)	K (%) ²	Rb (ppm) ²	Th (ppm) ²	U (ppm) ²	Cosmic (Gy/ka)
<u>Core RF-7</u>								
SAGD-10-10-15-1	USU-2135	6.8	125-212	2.43±0.06	110.0±4.4	15.5±1.4	3.1±0.2	0.24±0.02
SAGD-10-10-15-2	USU-2136	5.2	150-250	2.58±0.06	101.5±4.1	13.4±1.2	2.7±0.2	0.22±0.02
SAGD-10-10-15-3	USU-2137	4.4	180-250	2.97±0.07	125.5±5.0	17.3±1.6	3.4±0.2	0.20±0.02
<u>Core MO-4</u>								
SAGD-10-10-15-4	USU-2138	6.2	90-150	2.33±0.06	106.0±4.2	14.2±1.3	3.1±0.2	0.24±0.02
SAGD-10-10-15-5	USU-2139	3.8	90-150	2.20±0.06	89.0±3.6	11.7±1.1	2.9±0.2	0.22±0.02
<u>Core MO-5</u>								
SAGD-10-10-15-6	USU-2140	9.9	63-125	2.32±0.06	102.5±4.1	13.9±1.3	2.9±0.2	0.23±0.02
SAGD-10-10-15-7	USU-2141	4.5	150-250	1.65±0.04	68.7±2.7	8.5±0.8	2.0±0.1	0.21±0.02

¹ Highest measured water content in each core assumed for all samples in core: 6.8% for core RF-7; 6.2% for core MO-4; 9.9% for core MO-5 for moisture content over burial history.

² Radioelemental concentrations determined using ICP-MS and ICP-AES techniques; dose rate is derived from concentrations by conversion factors from Guérin et al. (2011).

Optical Measurements

OSL samples were analyzed following the SAR technique of Murray and Wintle (2000) on small-aliquot (1 mm diameter, ~20-40 grains per disk) of fine quartz sand. Optical measurements were performed on Risø TL/OSL Model DA-20 readers, with stimulation by blue-green light emitting diodes (LED) (470±30 nm) and the luminescence signal was detected through 7.5-mm UV filters (U-340) over 40 seconds (250 channels) at 125°C with LED diodes at 90% power (36-45 mW/cm²). Luminescence signals were calculated by subtracting the average of the last 5 seconds (background signal) from the sum of first 0.7 seconds (4 channels) of signal. The luminescence signals show rapid decay dominated by the fast component of the signal, essential for accurate quartz OSL results (Wintle and Murray, 2006). Average 'fast ratios' for the samples range from 14 to 181 (Figure S3) and indicate that the samples are dominated by the fast-decay component (Durcan and Duller, 2011).

Equivalent Dose (De) and Error Calculation

We analyzed 28 to 52 aliquots (subsamples, approximately 20-40 sand grains) of each sample to calculate the equivalent dose (De) of radiation the sample received following deposition, or burial dose, to calculate the OSL ages. De values were calculated using interpolation onto dose-response plots fit with saturating-exponential and saturating-exponential plus linear fits to the given regenerative dose points. Data from aliquots were rejected and not used in age calculation if they had evidence of feldspar contamination, corrected signals from repeated doses >15% of unity, recuperation of the zero-dose point >10% of the natural signal, or De greater than the highest regenerative dose given. De distributions for each sample were largely symmetrical and had overdispersion (scatter beyond instrumental error) that range from 11% to 37% (Table S2). Sample from shallower depths had greater overdispersion, suggesting that bioturbation or pedogenic processes may have mixed the eolian sediment.

Representative De values for age determination for each sample were calculated using the central age model (CAM) of Galbraith and Roberts (2012). Errors on De and age estimates are reported at 2-sigma standard error and include errors related to instrument calibration, and dose rate and equivalent dose calculations and were calculated in quadrature using the methods of Aitken and Alldred (1972).

Table S2. Optically Stimulated Luminescence Age Information

Sample num.	USU num.	Depth (m)	Num. of aliquots ¹	Dose rate (Gy/ka)	De ² ± 2σ (Gy)	OD ³ (%)	OSL age ± 1σ (ka)
<u>Core RF-7</u>							
SAGD-10-10-15-1	USU-2135	1.25	22 (36)	4.18 ± 0.20	59.45 ± 7.13	24.3 ± 4.8	14.22 ± 1.62
SAGD-10-10-15-2	USU-2136	2-2.05	19 (49)	4.03 ± 0.19	114.85 ± 21.65	37.5 ± 7.2	28.51 ± 3.85
SAGD-10-10-15-3	USU-2137	2.9-3.0	22 (52)	4.75 ± 0.22	123.26 ± 19.08	29.5 ± 6.4	25.97 ± 3.22
<u>Core MO-4</u>							
SAGD-10-10-15-4	USU-2138	1.25-1.3	17 (34)	4.09 ± 0.19	28.87 ± 4.74	28.1 ± 6.8	7.06 ± 0.89
SAGD-10-10-15-5	USU-2139	2.1-2.15	17 (28)	3.77 ± 0.17	58.38 ± 4.89	11.3 ± 4.1	15.47 ± 1.62
<u>Core MO-5</u>							
SAGD-10-10-15-6	USU-2140	1.55	20 (34)	3.89 ± 0.21	42.56 ± 6.71	32.5 ± 6.0	10.95 ± 2.04
SAGD-10-10-15-7	USU-2141	2.3-2.4	19 (28)	2.75 ± 0.13	39.15 ± 3.95	16.6 ± 4.5	14.22 ± 1.54

¹ Age analysis using the single-aliquot regenerative-dose procedure of Murray and Wintle (2000) on 1mm small-aliquots of quartz sand. Number of aliquots used in age calculation and number of aliquots analyzed in parentheses.

² Equivalent dose (D_E) calculated using the Central Age Model (CAM) of Galbraith and Roberts (2012).

³ Overdispersion (OD) represents variance in D_E data beyond measurement uncertainties, OD >20% may indicate significant scatter due to depositional or post-depositional processes.

USU-2135
OD = 24.3%
n = 22 (36)

USU-2136
OD = 37.5%
n = 19 (49)

USU-2137
OD = 29.5%
n = 22 (52)

USU-2138
OD = 28.1%
n = 17 (31)

USU-2139
OD = 11.3%
n = 17 (28)

USU-2140
OD = 32.5%
n = 20 (34)

USU-2141
OD = 16.6%
n = 19 (28)

Figure S3. Equivalent dose (D_e)

distributions (right) and representative

luminescence signal and dose-response

curve characteristics (left) for ten

representative aliquots from each sample.

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⁴⁰Ar/³⁹Ar Methods

Argon isotopes were measured at Rutgers University on fully automated laser microextraction system in-line with a Mass Analyzer Products (MAP 215–50) noble gas mass spectrometer. Typical extraction line blanks for the Rutgers University system at the mass-to-charge ratios of the pertinent Ar isotopes are: $M/e40 = 2 \times 10^{-16}$ mol, $M/e39 = 4 \times 10^{-19}$ mol, $M/e38 = 5 \times 10^{-19}$ mol, $M/e37 = 4 \times 10^{-18}$ mol, and $M/e36 = 2 \times 10^{-18}$ mol.

Data collection and data reduction were performed using the software “MassSpec” (a hardware control and data reduction package developed and maintained by Al Deino of the Berkeley Geochronology Center. Spectrometer sensitivity and instrumental mass fractionation were determined and tracked by analyzing three consecutive volumetrically calibrated “shots” of atmospheric Ar from a pipette after every nine sample measurements (approximately every 10-12 hours). The measured atmospheric ⁴⁰Ar/³⁶Ar ratio was constant over the measurement period, averaging 287.2 ± 0.2 (standard error of the mean; n=24) indicating a 1.0101 ± 0.0001 a.m.u. instrumental mass fractionation correction (relative to a ⁴⁰Ar/³⁶Ar_{atmos} of 298.56) and an instrument sensitivity of $\sim 1.330 \pm 0.001 \times 10^{-10}$ mol/nA over the three-day measurement period.

The Split Butte (dune ‘molds’ flow, i.e., ghost-dune hollows) sample, a 2.5-by-2.5 cm cylinder for paleomagnetic measurement collected from 44.069 N. Latitude and 111.60 W Longitude, was crushed, wash, and sieved to 250-to-500 μ m and then separated into three splits based on magnetic properties. A hand magnet was first passed over the whole-rock material. The material that was attracted to the hand magnet; this “magnetic” fraction was set-aside and the remaining material was passed through a Franz isodynamic separator which produced an “intermediate” magnetic fraction, and a “non-magnetic” fraction. The non-magnetic fraction contained some matrix/groundmass material but was enriched in plagioclase olivine phenocrysts

The three separates were then encapsulated in an Al disk along with the Alder Creek sanidine mineral standard (1198 ± 5 ka Ma CA-TIMS U-Pb zircon age (Rivera et al., 2013) in a controlled geometry. The sample package was then irradiated at 1 MW with fast neutrons in the Oregon State TRIGA reactor CLICIT facility for ten-minutes.

The irradiation yielded a nominal “J” value of $4.65 \pm 0.01 \times 10^{-5}$. Age calculations are based on the decay constants of Steiger and Jäger, (1977) and the following ratios ($\times 10^{-4}$), are used for making reactor corrections: (³⁶Ar/³⁷Ar)_{Ca} = 2.59 ± 0.003 ; (³⁹Ar/³⁷Ar)_{Ca} = 9.0 ± 0.3 ; (³⁸Ar/³⁷Ar)_{Ca} = 0.196 ± 0.01 ; (⁴⁰Ar/³⁹Ar)_K = 8.6 ± 0.7 ; (³⁸Ar/³⁹Ar)_K = 122 ± 0.3 ; (³⁶Ar/³⁸Ar)_{Cl} = 320 ± 1 .

Irradiated material was transferred into individual 5 mm diameter pits drilled into a 7-cm-diameter stainless steel disk. Step-heating of the samples was by a CO₂ laser focused (through an integrator lens) into a 5-by-5 mm square spot applied for 60 seconds. The released gases, scrubbed of reactive gases such as H₂, CO₂, CO, and N₂ by exposure to a Zr-Fe-V and Zr-Al alloy getter, were then admitted to the mass spectrometer for isotopic measurement.

Ages were calculated from the Ar isotope data, after correcting for “initial/trapped” Ar and for interfering neutron reactions with Ca and K (Brereton, 1970; Dalrymple et al., 1981). The estimated analytical precision ($\pm 1\sigma$) of all data presented is calculated using standard methods of propagation of errors (Taylor, 1997).

Discussion of ⁴⁰Ar/³⁹Ar Results

We calculate ages using the ⁴⁰Ar/³⁶Ar intercept values obtained from the inverse isochron regressions of step-heating data for the “trapped/initial” to calculate Ar, plateau ages and integrated total fusion ages rather than assuming a modern atmospheric ⁴⁰Ar/³⁶Ar value (298.6 Lee et al., 2006 and Valkiers, et al., 2010) for the “trapped/initial”. We commonly see deviations in the isochron-determined ⁴⁰Ar/³⁶Ar intercepts that approach and exceed statistically meaningful differences than modern atmospheric values. Hence, our preference for using the measured ⁴⁰Ar/³⁶Ar intercept values obtained from the inverse isochron regressions of step-heating data for the “trapped/initial” to calculate Ar, plateau ages. We refer to our approach as generating an Isochron Intercept Plateau (IIP).

We start by casting the Ar isotopic data on a ³⁹Ar/⁴⁰Ar (X) versus ³⁶Ar/⁴⁰Ar (Y) isotope correlation diagram (commonly called an inverse correlation diagram or inverse isochron). This type of plot is commonly used in the ⁴⁰Ar/³⁹Ar dating community to determine the “trapped/initial” (TI) ⁴⁰Ar/³⁶Ar ratio and the uncertainty of that ratio. The isochron data are given in Table (1A and 1B) and discussed below.

Sample	Run ID	Age $\pm 1\sigma$ (ka)	⁴⁰ Ar/ ³⁶ Ar _{tr}	$\pm 1\sigma$	MSWD	n/n _{total}
rth-02	20346	60.3 $\pm$ 4.0	299.83	0.49	1.5	12/12
-	20348	65.8 $\pm$ 4.5	298.64	0.67	2.8	12/12
-	-	62.9 $\pm$ 4.7	298.46	0.67	1.3	11/12
-	20349	54.6 $\pm$ 6.5	298.99	0.59	1.8	12/12
Wt. Average		60.2 $\pm$ 2.8				

Table 1A: Summary of Isochron Results. Grey lettered data show result eliminating point “F”.

Run ID Step #	$^{40}\text{Ar}^*/^{39}\text{Ar}$	$^{36}\text{Ar}/^{40}\text{Ar}$	$\pm 1\sigma\%$	$^{39}\text{Ar}/^{40}\text{Ar}$	$\pm 1\sigma\%$	$^{36}\text{Ar}/^{39}\text{Ar}$ Correl. Coef.
20346						
01A	6.0921	0.00333	0.2	0.00095	1.015	0.074
01B	1.5017	0.00332	0.3	0.00630	0.312	0.15
01C	0.8019	0.00325	0.4	0.03664	0.137	0.217
01D	0.8169	0.00315	0.4	0.07149	0.185	0.125
01E	0.7486	0.00320	0.4	0.05991	0.133	0.171
01F	0.8332	0.00324	0.3	0.03926	0.206	0.179
01G	0.8189	0.00328	0.4	0.02611	0.132	0.127
01H	0.5353	0.00331	0.3	0.02249	0.149	0.192
01I	1.0201	0.00328	0.3	0.02147	0.217	0.158
01J	1.1953	0.00327	0.6	0.02095	0.334	0.061
01K	1.3129	0.00326	0.5	0.01955	0.378	0.063
01L	1.2217	0.00327	0.8	0.01850	0.401	0.062
20348						
01A	1.8152	0.00334	0.4	0.00126	1.289	0.024
01B	0.8060	0.00333	0.3	0.00820	0.184	0.226
01C	0.6783	0.00326	0.3	0.03942	0.143	0.248
01D	0.8566	0.00312	0.7	0.07884	0.193	0.076
01E	0.7418	0.00319	0.3	0.06501	0.13	0.207
01F	1.1624	0.00319	0.4	0.03992	0.197	0.101
01G	0.6063	0.00330	0.4	0.02681	0.179	0.112
01H	1.0407	0.00327	0.5	0.02412	0.234	0.076
01I	0.9864	0.00327	0.6	0.02335	0.231	0.076
01J	0.3895	0.00332	0.4	0.02329	0.195	0.152
01K	0.9542	0.00328	0.8	0.02143	0.364	0.057
01L	0.9606	0.00330	0.7	0.01649	0.546	0.054
20349						
01A	2.5729	0.00334	0.2	0.00054	1.677	0.029
01B	1.8791	0.00332	0.4	0.00516	0.482	0.076
01C	0.5771	0.00330	0.5	0.02798	0.239	0.133
01D	0.6513	0.00324	0.6	0.05124	0.216	0.167
01E	0.7591	0.00324	0.8	0.04252	0.332	0.065
01F	0.9215	0.00326	0.4	0.02785	0.186	0.149
01G	0.6008	0.00331	0.4	0.01954	0.236	0.195
01H	0.5304	0.00332	0.4	0.01787	0.239	0.11
01I	1.3394	0.00328	0.7	0.01592	0.399	0.076
01J	1.1929	0.00329	0.8	0.01443	0.53	0.05
01K	-0.7400	0.00338	1	0.01312	0.729	0.035
01L	-1.9504	0.00343	1.4	0.01279	0.958	0.03

Table 1B: Isochron Data

Sample 20346, whole-rock material with intermediate magnetic properties, was extracted in 12-steps. Isochron results: When the Ar isotopic data are cast on an inverse correlation diagram the Ar isotopic data produce a well-defined mixing line (Figure 1A, Table 1A and 1B). The first four steps (A-D) move down and to the right and steps E-H reverse and move back up and to the left along the same array. The last four steps (I-L) cluster near steps G and H (Figure 1A).

The X ($^{39}\text{Ar}/^{40}\text{Ar}$) and Y ($^{40}\text{Ar}/^{36}\text{Ar}$) intercepts of this array correspond to an age of 60.3 ± 4.0 ka and a “trapped/initial” ($^{40}\text{Ar}/^{36}\text{Ar}_{\text{tr}}$) $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 299.83 ± 0.49 , respectively. The MSWD⁽¹⁾ value of 1.5

indicates that the dispersion of the line fit is within the expected range relative to the measurement errors of the individual points.

Plateau: The IIP produces a seven-step (A-G) plateau age of **61.0 ± 2.8 ka** that is comprised of 70% of the total $^{39}\text{Ar}_K$ released, with a total integrated gas age of **60.9 ± 6.8 ka** (Figure 2A and Table 2A). The Ca/K ratios, start at ~4 and increase with increasing temperature to ~12 (Table 2A), indicating that each step is sampling higher Ca phases with each temperature increase. The three different determined ages (isochron, IIP plateau, and integrated age) are analytically indistinguishable at the $\alpha=95\%$ confidence level.

Table 2A: Summary of the plateau data using the isochron intercepts to determine the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of the trapped Ar component; $J = (4.693 \pm 0.001) \times 10^{-5}$. The material is whole-rock material with intermediate magnetic properties and is the “magnetic splits” from a Franz Isodynamic Magnetic Separator.

Run ID 20346	Watts	Ca/K	$^{36}\text{Ar}/^{39}\text{Ar}_K$	$\%^{36}\text{Ar}_{Ca}$	$^{40}\text{Ar}^*/^{39}\text{Ar}_K$	Mol ^{39}Ar $\times 10^{-15}$	%Step	Cum.%	$\%^{40}\text{Ar}^*$	Age $\pm 1\sigma$ (ka)
*01A	1	4.4	3.5084	0	1.6338	2.3	0.6	0.6	0.2	138 ± 213
*01B	2	4.6	0.5262	0.1	0.8337	8.2	2.2	2.8	0.5	71 ± 43
*01C	4	4.5	0.0892	0.7	0.6893	40.7	10.9	13.7	2.5	58.4 ± 8.2
*01D	6	4.4	0.0446	1.4	0.7609	64.3	17.2	31	5.4	64.4 ± 4.6
*01E	8	4.9	0.0540	1.3	0.6808	57.8	15.5	46.5	4.1	57.6 ± 5.45
*01F	10	4.8	0.0830	0.8	0.7285	52.8	14.2	60.6	2.9	61.7 ± 6.2
*01G	12	5.0	0.1260	0.6	0.6596	43.1	11.6	72.2	1.7	55.8 ± 13.5
01H	14	6.0	0.1476	0.6	0.3486	36.0	9.6	81.8	0.8	29.5 ± 10.1
01I	17	7.4	0.1532	0.7	0.8265	29.9	8	89.8	1.8	70 ± 11
01J	20	9.1	0.1566	0.8	0.9975	17.8	4.8	94.6	2.1	84 ± 23
01K	25	12.0	0.1678	1	1.1012	13.1	3.5	98.1	2.2	93 ± 2.1
01L	30	11.2	0.1778	0.9	0.9971	7.0	1.9	100	1.8	84 ± 36
Integ. Age										60.9 ± 6.8
*Plat. Age							72.2	61.0 ± 2.8		

For comparison, we present the plateau results using the standard assumption of atmospheric Ar isotopic composition equilibrium in Table (3A-B). This also produces a seven-step (A-G) plateau. The plateau age, however, is 68.0 ± 2.8 ka and the total integrated gas age is 74.7 ± 6.7 ka.

Sample 20348, whole-rock material with high magnetic properties, was extracted in 12-steps. **Isochron results:** With the exception of point “F”, the Ar isotopic data produce a well-defined mixing line (Figure 1B and Table 1A and 1B). The first four steps (A-D) move down and to the right. Steps E and G reverse and move back, up and to the left along the same array. The last five steps (H-L) cluster near steps G (Figure 1B).

The X ($^{39}\text{Ar}/^{40}\text{Ar}$) and Y ($^{40}\text{Ar}/^{36}\text{Ar}$) intercepts of this array correspond to an age of 65.8 ± 4.5 ka and a “trapped/initial” (TI) $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 298.64 ± 0.67 respectively. The MSWD value of 2.8 indicates that the dispersion of the line fit is greater than the expected range relative to the measurement errors of the individual points. Eliminating a single point “F” reduces the MSWD to 1.3, indicating a dispersion the line fit in accord with the expected dispersion relative to the measurement errors of the individual points. With removal of point F, the X and Y intercepts of this array correspond to an age of **62.9 ± 4.7 ka** and a “trapped/initial” (TI) $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 298.46 ± 0.67 respectively. This is our preferred isochron interpretation of this experiment.

Plateau: The IIP produces a five-step (A-E) plateau age of **62.2 ± 3.1 ka** that is comprised of 46.4% of the total $^{39}\text{Ar}_K$ released and a total integrated gas age of **69.6 ± 5.7 ka** (Figure 2B and Table 2B). The Ca/K ratios, start at ~ 4 and increase with increasing temperature to just less than ~ 8 (Table 2B), indicating that each step is sampling higher Ca phases with each temperature increase. The three different determined ages (isochron, IIP plateau, and integrated age) are analytically indistinguishable at the $\alpha=95\%$ confidence level.

Table 2B: Summary of the plateau data using the isochron intercepts to determine the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of the trapped Ar component; $J = (4.620 \pm 0.001) \times 10^{-5}$. The material is whole-rock material with strong magnetic properties such that this material is strongly attracted to a hand magnet (see text).

Run ID	Watts	Ca/K	$^{36}\text{Ar}/^{39}\text{Ar}_K$	$\%^{36}\text{Ar}_{Ca}$	$^{40}\text{Ar}^*/^{39}\text{Ar}_K$	Mol ^{39}Ar $\times 10^{-15}$	%Step	Cum.%	$\%^{40}\text{Ar}^*$	Age $\pm 1\sigma$ (ka)
*01A	1	3.8	2.6447	0	1.5970	2.5	0.5	0.5	0.2	133.1 ± 274
*01B	2	3.4	0.4058	0.1	0.7725	9.6	2.1	2.7	0.6	64 ± 35
*01C	4	3.3	0.0830	0.5	0.6715	48.4	10.7	13.3	2.6	56.0 ± 6.6
*01D	6	3.1	0.0400	1.1	0.8533	76.8	16.9	30.2	6.7	71.1 ± 6.9
*01E	8	3.6	0.0495	1	0.7377	73.4	16.2	46.4	4.8	61.5 ± 4.2
01F	10	3.6	0.0804	0.6	1.1558	63.3	13.9	60.4	4.6	96.3 ± 8.0
01G	12	4.0	0.1233	0.4	0.5961	53.7	11.8	72.2	1.6	50 ± 13
01H	14	4.5	0.1358	0.5	1.0295	44.3	9.8	81.9	2.5	86 ± 16
01I	17	5.3	0.1406	0.5	0.9749	37.6	8.3	90.2	2.3	81 ± 19
01J	20	6.2	0.1430	0.6	0.3778	21.4	4.7	94.9	0.9	32 ± 14
01K	25	7.7	0.1537	0.7	0.9416	15.0	3.3	98.2	2	79 ± 31
01L	30	8.0	0.2004	0.6	0.9442	8.1	1.8	100	1.6	79 ± 33
Integ. Age										69.6 ± 5.7
*Plat. Age							46.4	62.2 ± 3.1		

For comparison, we present the plateau results using the standard assumption of atmospheric Ar isotopic composition equilibrium in Table (3A-B). This also produces a seven-step (A-E) plateau. The plateau age, however, is 62.6 ± 3.1 ka and the total integrated gas age is 70.4 ± 5.7 ka. The measured (TI) $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 298.64 ± 0.67 , is effectively equivalent to the modern atmosphere, thus explaining the minimal difference between the atmospheric and IIP plateaus.

Sample 20349, whole-rock material with low magnetic properties, was extracted in 12-steps. Isochron results: As with the other two splits, the Ar isotopic data produce a well-defined mixing line (Figure 1C and Table 1A and 1B). The first four steps (A-D) move down and to the right. and steps E-L reverse and move back, up and to the left along the same array with the last two steps “K” and “L”, lifting off above the main array. The X and Y intercepts of this array correspond to an age of **54.6 ± 6.5 ka** and a “trapped/initial” (TI) $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 298.99 ± 0.59 respectively. The MSWD value of 1.8 indicates that the dispersion of the line fit is within the expected range relative to the measurement errors of the individual points. So, all 12 data points are included.

Plateau: The IIP produces a ten-step (A-J) plateau age of **56.1 ± 5.3 ka** and is comprised of 94.5% if the total $^{39}\text{Ar}_K$ released and a total integrated gas age of **51 ± 11 ka** (Figure 2C and Table 2C). The Ca/K ratios start at values of ~8 and progress horizontally until step-H (~85% $^{39}\text{Ar}_K$) and then increases to ~30. The last four steps (~15% $^{39}\text{Ar}_K$) are sampling the high Ca phases. The three different determined ages (isochron, IIP plateau, and integrated age) are analytically indistinguishable at the $\alpha=95\%$ confidence level.

Table 2C: Summary of the plateau data using the isochron intercepts to determine the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of the trapped Ar component; $J = (4.635 \pm 0.001) \times 10^{-5}$. The material is whole-rock material with weak magnetic properties and is the “non-magnetic split” from a Franz Isodynamic Magnetic Separator.

Run ID 20349	Watts	Ca/K	$^{36}\text{Ar}/^{39}\text{Ar}_K$	% $^{36}\text{Ar}_{Ca}$	$^{40}\text{Ar}^*/^{39}\text{Ar}_K$	Mol ^{39}Ar $\times 10^{-15}$	%Step	Cum.%	% $^{40}\text{Ar}^*$	Age ± 1σ (ka)
*-01A		4.1	2.6447	0	1.5970	1.3	0.7	0.7	0	-8.5 ± 369
*01B		7.9	0.4058	0.1	0.7725	4.6	2.6	3.4	0.8	134 ± 67
*01C		8.1	0.0830	0.5	0.6715	20.0	11.5	14.9	1.5	44 ± 14
*01D		8.0	0.0400	1.1	0.8533	28.0	16.1	31	3.2	52.2 ± 8.9
*01E		8.6	0.0495	1.0	0.7377	29.0	16.7	47.8	3.1	61 ± 16
-*01F		7.9	0.0804	0.6	1.1558	25.9	14.9	62.7	2.4	73 ± 12
*01G		7.7	0.1233	0.4	0.5961	20.6	11.9	74.5	1	44 ± 17
*01H		9.0	0.1358	0.5	1.0295	14.6	8.4	83	0.8	38 ± 20
*01I		14.2	0.1406	0.5	0.9749	11.6	6.7	89.6	2	105 ± 36
*01J		21.6	0.1430	0.6	0.3778	8.5	4.9	94.5	1.6	92 ± 47
01K		28.7	0.1537	0.7	0.9416	6.2	3.5	98	-1.1	-71 ± 65
01L		4.1	0.2004	0.6	0.9442	3.4	2	100	-2.6	-173 ± 92
Integ. Age										51 ± 11
*Plat. Age							94.5	56.1 ± 5.3		

For comparison, we present the plateau results using the standard assumption of atmospheric Ar isotopic composition equilibrium in Table (3A-B). This also produces a ten-step (A-J) plateau. The plateau age, however, is 60.2 ± 5.3 ka and the total integrated gas age is 58 ± 11 ka.

Table 3B: Summary of the plateau results assuming atmos. Ar ($^{40}\text{Ar}/^{36}\text{Ar}_{\text{int.}} = 298.6 \pm 0.6$) for the trapped component.

Sample	ID	Material	$J \pm 1s \times 10^{-5}$	Intg. Age (ka)	Plat. Age (ka)	MSWD	Steps	n/n _{tot.}	% ³⁹ Ar _K
rth-02-3	20346	wr int mag	4.693 ± 0.001	60.9 ± 6.8	61.0 ± 2.8	0.2	A-G	7/12	72.2
-	20348	wr mag	4.620 ± 0.001	69.6 ± 5.7	62.2 ± 3.1	0.7	A-E	5/12	46.4
-	20349	wr nonmag	4.635 ± 0.001	51 ± 11	56.1 ± 5.3	0.9	A-J	10/12	94.5

Table 3A: Summary of the IIP plateau age results. Results use the isochron intercepts to determine the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of the trapped Ar component.

Sample	ID	Material	$J \pm 1s \times 10^{-5}$	Intg. Age (ka)	Plat. Age (ka)	MSWD	Steps	n/n _{tot.}	% ³⁹ Ar _K
rth-02-3	20346	wr int mag	4.693 ± 0.001	74.7 ± 6.7	68.0 ± 2.8	0.6	A-G	7/12	72.2
-	20348	wr mag	4.620 ± 0.001	70.4 ± 5.7	62.6 ± 3.1	0.7	A-E	5/12	46.4
-	20349	wr nonmag	4.635 ± 0.001	58 ± 11	60.2 ± 5.3	1.0	A-J	10/12	94.5

Summary of Results

The three isochron ages (60.3 ± 4.0 ka, 62.9 ± 4.7 ka, and 54.6 ± 6.5 ka) yield a variance weighted average of **60.2 ± 2.8 ka** (Figure 3A, Table 1).

The three IIP plateau ages (61.0 ± 2.8 ka, 62.2 ± 3.1 ka, and 56.1 ± 5.3 ka) and integrated total fusion ages (60.9 ± 6.8 ka, 69.6 ± 5.7 ka, 51 ± 11 ka) yield a variance weighted average of **60.8 ± 1.9 ka** and 64.08 ± 4.1 , respectively (Figure 3B and 3C, and Table 2A).

In comparison the standard atmospheric plateau ages (68.0 ± 2.8 ka, 62.6 ± 3.1 ka, 60.2 ± 5.3 ka) and integrated total fusion ages (74.7 ± 6.7 ka, 70.4 ± 5.7 ka, 58 ± 11 ka) yield a variance weighted average of 64.9 ± 1.9 ka and $70.3 \pm 4/1$, respectively (Table 3). Our best age assignment of the Split Butte (ghost-dune hollows) flow is of **60.8 ± 1.9 ka**, the variance weight average of the IIP plateaus (Figure 3B).

(1) The $^{39}\text{Ar}/^{40}\text{Ar}$ vs $^{36}\text{Ar}/^{40}\text{Ar}$ isotope correlation diagram (commonly called an inverse correlation diagram) should form a linear array that yields a mean square of weighted deviates

(MSWD) ≤ 2.5 (Brooks et al., 1972). In a true isochron, analytical errors will express most or all of the error on the age, and a MSWD=1 (Dickin, 1997, p. 35). Nearly all experiments, however, also display “geological” scatter (McIntyre et al., 1966), thus requiring all experiments to have a MSWD near unity would be unrealistic. Accordingly, both Brooks et al. (1972) and Wendt and Carl (1991) recommended rejecting data sets in which there is a $> 95\%$ certainty of excess scatter over analytical error. This 95% confidence limit represents a MSWD of approximately 1.61 to 4.96, depending on the number of samples and the number of duplicates (see Dickin, 1997, Table 2.1; Brooks et al., 1972; and Wendt and Carl (1991) for a more complete discussion. We follow the “rule of thumb” that rejects data arrays with MSWD > 2.5 (Brooks et al. 1972) and Wendt and Carl (1991).

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