40Ar/39Ar ages of L4, H5, EL6, and feldspathic ureilitic clasts from the Almahata Sitta polymict ureilite (asteroid 2008 TC3)

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Abstract–The Almahata Sitta (AhS) meteorite consists of disaggregated clasts from the impact of the polymict asteroid 2008 TC3, including ureilitic (70%–80%) and diverse non-ureilitic materials. We determined the 40Ar/39Ar release patterns for 16 AhS samples (3–1500 μg) taken from three chondritic clasts, AhS 100 (L4), AhS 25 (H5), and MS-D (EL6), as well as a clast of ureilitic trachyandesite MS-MU-011, also known as ALM-A, which is probably a sample of the crust of the ureilite parent body (UPB). Based on our analyses, best estimates of the 40Ar/39Ar ages (Ma) of the chondritic clasts are 4535/C6 +10 (L4), 4537–4555 with a younger age preferred (H5), and 4513/C6 +17 (EL6). The ages for the L4 and the H5 clasts are older than the most published 40Ar/39Ar ages for L4 and H5 meteorites, respectively. The age for the EL6 clast is typical of older EL6 chondrites. These ages indicate times of argon closure ranging up to 50 Ma after the main constituents of the host breccia, that is, the ureilitic components of AhS, reached the >800°C blocking temperatures of pyroxene and olivine thermometers. We suggest that these ages record the times at which the clasts cooled to the Ar closure temperatures on their respective parent bodies. This interpretation is consistent with the recent proposal that the majority of xenolithic materials in polymict ureilies were implanted into regolith 40–60 Ma after calcium–aluminum-rich inclusion and is consistent with the interpretation that 2008 TC3 was a polymict ureilite. With allowance for its 10-Ma uncertainty, the 4549-Ma 40Ar/39Ar age of ALM-A is consistent with closure within a few Ma of the time recorded by its Pb/Pb age either on the UPB or as part of a rapidly cooling fragment. Plots of age versus cumulative 39Ar release for 10 of 15 samples with ≥5 heating steps indicate minor losses of 40Ar over the last 4.5 Ga. The other five such samples lost some 40Ar at estimated times no earlier than 3800–4500 Ma BP. Clustering of ages in the low-temperature data for these five samples suggests that an impact caused localized heating of the AhS progenitor ~2.7 Ga ago. In agreement with the published work, 10 estimates of cosmic-ray exposure ages based on 38Ar concentrations average 17 ± 5 Ma but may include some early irradiation.
INTRODUCTION

The Almahata Sitta (AhS) meteorite fell in 2008 when the small asteroid 2008 TC$_3$ (average ~4 m diameter) impacted over northern Sudan (Jenniskens et al., 2009; Shaddad et al., 2010). The asteroid disintegrated in the atmosphere, with ≥99% of its mass being lost (Jenniskens et al., 2009; Scheirich et al., 2010; Shaddad et al., 2010; Welten et al., 2010). Nevertheless, more than 700 cm-sized stones of disparate types have been recovered from the fall area (Bischoff et al., 2022; Goodrich, Hartmann, et al., 2015; Horstmann & Bischoff, 2014). Based on current statistics (Bischoff et al., 2010, 2015, 2016, 2018, 2019, 2022; Goodrich et al., 2018, 2019; Goodrich, Fioretti, et al., 2015; Horstmann & Bischoff, 2014), ~70%–80% of the AhS stones are main group ureilites, which are a group of ultramafic achondrites that represent the mantle of a partially differentiated asteroid (Goodrich, Hartmann, et al., 2015; Mittelfeldt et al., 1998). The other AhS stones represent every major class of chondrite and many groups, subgroups, and petrologic types within those classes.

Based on the predominance of ureilites among the recovered stones, AhS is classified as a polymict ureilite, but is considered anomalous because, unlike other (typical) polymict ureilites, it disintegrated in the atmosphere and its clasts landed on Earth as separate stones (Goodrich et al., 2019; Goodrich, Hartmann, et al., 2015). The range and distribution of types of materials in AhS are similar to those of other polymict ureilites, which are fragmental and regolith breccias that consist mostly of mixed ureilitic materials but also contain an array of foreign (xenolithic) clast types (Downes et al., 2008; Goodrich et al., 2004; Goodrich, Bottke, et al., 2021; Goodrich, Sanborn, et al., 2021; Ikeda et al., 2000).

The classification of AhS as a polymict ureilite does not necessarily extend to its immediate parent asteroid, 2008 TC$_3$, because 99% of the mass of the asteroid was lost in the atmosphere and its composition cannot be unambiguously determined from the pre-impact reflectance spectrum (Goodrich et al., 2019; Goodrich, Hartmann, et al., 2015; Hiroi et al., 2010). Nor can it be assumed that the recovered stones are representative of the asteroid, because the physical properties that facilitated their preferential survival (greater strength, larger clast size) may be correlated with composition. Hiroi et al. (2010) showed that the reflectance spectrum of 2008 TC$_3$ is consistent with being dominantly ureilitic. However, Goodrich et al. (2019) showed that, within error, it is also consistent with 2008 TC$_3$ being dominated by C1 carbonaceous chondrite material similar to some AhS clasts. Based on the latter observation, Bischoff et al. (2022) argued that 2008 TC$_3$ should be classified as a polymict carbonaceous chondrite breccia and therefore its genesis must be distinct from that of polymict ureilites. In contrast, Goodrich, Bottke, et al. (2021) argued that even if dominated by C1 material, 2008 TC$_3$ could have originated in the same regolith environment as typical polymict ureilites.

The 40Ar/39Ar chronology of samples from AhS is potentially of interest for understanding the assembly and impact history of 2008 TC$_3$ more accurately, the progenitor from which it broke off, and for testing the relationship of 2008 TC$_3$ to polymict ureilites. Main group ureilite clasts in polymict ureilites are difficult to date by 40Ar/39Ar or other isotopic systems such as $^{87}$Rb/$^{87}$Sr, $^{146,147}$Nd, $^{142,143}$Sm, $^{40}$K/$^{40}$Ar, or $^{26}$Al/$^{26}$Mg. The reason is that the ureilite clasts are olivine + pyroxene assemblages devoid of feldspar, the main host for the radioactive parents. Feldspar-bearing clasts, which likely represent ureilitic crustal rocks, do occur in typical polymict ureilites but are rare and small (Cohen et al., 2004; Goodrich et al., 2017; Ikeda et al., 2000). While some chondritic (xenolithic) clasts in polymict ureilites contain feldspar, they, too, are generally small (μm to mm) and hard to separate (Goodrich et al., 2017; Ikeda et al., 2000). More favorably, xenolithic clasts in AhS are mostly larger (0.5–0.6 cm), have fallen separately (e.g., Horstmann & Bischoff, 2014; their table 2), and may have potassium concentrations 40 or more times larger (e.g., Riebe et al., 2017; their table S1a) than do ureilite clasts. As such, chondritic clasts in AhS appear to be better—from an analytical standpoint—candidates for 40Ar/39Ar dating than the ureilitic material itself.

In a prior 40Ar/39Ar study of four main group ureilites, Bogard and Garrison (1994) found no Ar release patterns with plateaus. Those authors inferred $^{40}$Ar* (radiogenic $^{40}$Ar) loss in the period between 3.1 and 3.8 Ga ago. Riebe et al. (2017; their table 7) presented five K/Ar ages ranging from 3.47 Ga for EL3-5 sample MS-179 to 4.52 Ga for unique R-like sample MS-CH, concluding that only the youngest age showed clear evidence of gas loss. They also revised the K/Ar ages of L4 clast A100 and H5 clast 25 originally reported by Meier et al. (2012); the revised ages are 4100 and 4400 Ma, respectively. Beard et al. (2013) presented results from $^{39}$Ar/$^{40}$Ar dating of these same L4 and H5 clasts. Although the argon release patterns showed signs of disturbance, the authors concluded that, “There is no hint of any substantial thermal event on the Almahata Sitta parent body more recently than 4100 Ma ago,” an observation in accord with the mostly old (≥4.0 Ga) K/Ar ages, which point toward small losses of $^{40}$Ar* from the parent body of 2008 TC$_3$.

We present a 40Ar/39Ar study of samples from four AhS clasts: AhS A100 (L4), AhS 25 (H5), MS-D (EL6),
and MS-MU-011 (ureilite trachyandesite). As noted above, Meier et al. (2012; noble gases) and Beard et al. (2013; $^{40}\text{Ar}/^{39}\text{Ar}$) analyzed both A100 and 25; Riebe et al. (2017; noble gases) also analyzed clast MS-D. The main goal of the work is to identify and examine the timing of the major thermal events that affected AhS and its diverse components. For the xenolithic (chondritic) clasts, these events may mark the end of metamorphic heating on their original (chondritic) parent bodies; the assembly of the polymict ureilite host (i.e., the progenitor of small asteroid 2008 TC$_3$) from its various constituents; collisions that took place after assembly; losses due to solar heating in space; and/or ablative heating during arrival at Earth.

For the ureilitic trachyandesite, they may record the timing of the disruption of the UPB and its diverse components. For the xenolithic (chondritic) clasts, these events may mark the end of metamorphic heating on their original (chondritic) parent bodies; the assembly of the polymict ureilite host (i.e., the progenitor of small asteroid 2008 TC$_3$) from its various constituents; collisions that took place after assembly; losses due to solar heating in space; and/or ablative heating during arrival at Earth.

The rapid recovery of samples (Horstmann & Bischoff, 2014; Shaddad et al., 2010). Preliminary accounts of this work have appeared in abstracts by Turrin et al. (2013), Turrin, Lindsay, Herzog, et al. (2015), and Delaney et al. (2015).

**SAMPLES AND EXPERIMENTAL METHODS**

**Samples**

We bought a 20 mg sample of MS-MU-011, also known as ALM-A (Bischoff et al., 2013, 2014; note 12), from Dr. Stephan Decker of the Meteorite Museum, Oberwesel Rhein, Germany. Dr. A Bischoff (Inst. Planetologie, Münster) provided small chips of material (~34 mg in total) from sample MS-D (EL6) (Figure 1). Dr. Kees Welten (University of California, Berkeley, California) sent us coarsely ground material from AhS 25 (H5) (~250 μm, 23 mg; <250 μm, 44 mg) and AhS A100 (L4) (1 chip, 154 mg); Meier et al. (2012) had previously analyzed these same AhS samples for noble gases and cosmogenic radionuclides. Petrologic descriptions of the chondritic clasts have been given in Horstmann and Bischoff et al. (2014) and Zolensky et al. (2010). MS-MU-011 has been described by Bischoff et al. (2014). We examined a small piece of MS-MU-011 by scanning electron microscopy to check for consistency with the observations of Bischoff et al. (2014) and to search for K-rich phases.

**Sample Preparation and Electron Microprobe Analysis**

Plagioclase was separated from L4 clast AhS A100, H5 clast AhS 25, and EL6 clast MS-D by handpicking after a preliminary density separation. For the density separations, masses of ~100 mg were gently crushed and then sieved. Grains no larger than 125 μm were collected, transferred to 15-mL plastic centrifuge tubes, and suspended in ~4 mL of lithium polytungstate solution with a density of 2.85 g cm$^{-3}$. After centrifugation (5 min @ 4000 rpm), the bottom-most portion of each vial was immersed in liquid N$_2$ to freeze a “sink” fraction. A “float” fraction, which included plagioclase, was collected on a polymer filter, washed three times with Milli-Q (19 MΩ) water, and dried in air. We picked clear grains by hand.

To check mineral identity of the grains and search for high-K contents favorable for $^{40}\text{Ar}/^{39}\text{Ar}$ dating, we carried out semiquantitative elemental analysis using the JEOL JXA 8200 electron microprobe at the Rutgers University Microanalytical Laboratory. For the purpose, we mounted the grains on 2.5-cm glass disks using conductive double-sided carbon tape; the grains were oriented on the tape to provide a surface as close as possible to orthogonal to the electron beam. A first survey of composition was made in energy-dispersive (EDS) mode with the aid of an integrated system supplied by JEOL. A few high-K spots were then selected for quantitative, wavelength-dispersive analysis. Most of the analyses were done with an accelerating voltage of 15 keV, a current of 15 nA, and a spot size of 1 μm. Lindsay et al. (2014, 2021) and references therein provide details. Taken together, the energy- and wavelength-dispersive measurements are regarded as a rough guide to the composition of a grain but may not be fully representative.

One surface of a small chip of MS-MU-011 was polished, mounted as described above, and examined optically. The section was then surveyed by backscattered electron (BSE) imaging and EDS analysis using the JEOL JXA 8200. The BSE images were processed using ImageJ to determine the volumetric abundance of major and minor phases at different spatial scales. Minor and trace phase abundances were extracted from high magnification images. The aggregated results were combined (by modal recombination) with appropriate scaling to provide a volumetric mode of the sample. The density of each phase was used to transform the mode into a weight fraction of each phase, which, in turn, were used to determine the bulk composition of the sample (Table 1). After the survey, we excavated four samples: RU22357, plagioclase; RU22359, primarily plagioclase but with other phases present that we did not characterize further; and RU22360 and RU22362, pyroxene containing small K-rich inclusions.

**Sample Irradiation**

The samples of AhS, along with $^{40}\text{Ar}/^{39}\text{Ar}$ monitor materials Fish Canyon sanidine (28.201 Ma; Kuiper
et al., 2008) and Hb3gr (1080 Ma; Jourdan & Renne, 2007), were loaded into separate wells that had been drilled in Al disks. Each disk was irradiated for 80 h in the (internally water-cooled) central thimble at the TRIGA reactor of the United States Geological Survey in Denver. The samples were irradiated in three different runs, 59, 66, and 68: Only irradiation 59 was Cd shielded. Unshielded reactor constants were as follows:

\[
\frac{^{36}\text{Ar}}{^{37}\text{Ar}} = 2.75 \times 10^{-4}, \quad \frac{^{38}\text{Ar}}{^{37}\text{Ar}} = 2.1 \times 10^{-5}; \\
\frac{^{39}\text{Ar}}{^{37}\text{Ar}} = 6.62 \times 10^{-4}, \quad \frac{^{37}\text{Ar}}{^{39}\text{Ar}} = 2.2 \times 10^{-3}; \\
\frac{^{40}\text{Ar}}{^{39}\text{Ar}} = 1.319 \times 10^{-2}, \quad \frac{^{39}\text{Ar}}{^{40}\text{Ar}} = 9.808 \times 10^{-3}.
\]

Cd shielded reactor constants were as follows:

\[
\frac{^{36}\text{Ar}}{^{37}\text{Ar}} = 2.81 \times 10^{-4}, \quad \frac{^{38}\text{Ar}}{^{37}\text{Ar}} = 3.29 \times 10^{-5}; \\
\frac{^{39}\text{Ar}}{^{37}\text{Ar}} = 7.1 \times 10^{-4}, \quad \frac{^{37}\text{Ar}}{^{39}\text{Ar}} = 3.32 \times 10^{-4}; \\
\frac{^{40}\text{Ar}}{^{39}\text{Ar}} = 1.314 \times 10^{-2}, \quad \frac{^{39}\text{Ar}}{^{40}\text{Ar}} = 1.003 \times 10^{-3}.
\]

Ar Isotope Analysis

We used a modified MAP 215-50 mass spectrometer at Rutgers University (Lindsay et al., 2014; Turrin et al., 2010) to analyze $^{36,37,38,39,40}\text{Ar}$ isotopes. The samples were heated incrementally for fusion with a CO$_2$ laser. We analyzed most samples in a single series of 8–10 heating steps carried out over a period of 6–8 h. In the case of sample RU22316, however, we completed the extraction of gas (steps M, N, and O) 5 days after running step L. We monitored instrumental sensitivity by bracketing analyses of samples with repeated analyses of air from an online pipette system, taking care to correct for depletion of the source gas. For both standards and samples, total pressures in the instrument were comparable, lessening the likelihood of pressure-dependent errors in the corrections for mass-dependent fractionation. Instrumental mass discrimination was $\sim 7\%$ per AMU.

Typically, we analyzed a sample in a single series of heating steps carried out over a period of 6–8 h. In the case of sample RU22316, however, we completed the extraction of gas (steps M, N, and O) 5 days after running step L.

Blanks for the mass spectrometer were measured every four analyses without firing the laser. In the rare case when there were significant temporal changes in the blanks, they were detrended. Typical blanks for $^{36–40}\text{Ar}$ were $6.7 \pm 0.3$, $36 \pm 0.4$, $2.3 \pm 0.3$, $7.6 \pm 0.6$, and $272 \pm 6 \times 10^{-18}$ mol. Instrumental sensitivity ranged from $\sim 3$ to $6 \times 10^{-18}$ counts s$^{-1}$ mol$^{-1}$. In the age calculations, and other reported quantities, all errors are propagated including those of the blank and reflect the potential impact of blanks to data quality.
Signal-to-blank ratios ranged from less than 1 to greater than $1 \times 10^6$, depending on the total Ar concentration of the sample and on the amount of Ar extracted with each heating step. The fractional blank corrections averaged over all steps and samples for each isotope were as follows: $^{36}$Ar, $0.53 \pm 0.36$; $^{37}$Ar, $0.27 \pm 0.29$; $^{38}$Ar, $0.50 \pm 0.34$; $^{39}$Ar, $0.37 \pm 0.32$; and $^{40}$Ar, $0.10 \pm 0.16$. The data for each step in the step-heating experiments are listed in Supplement S1.

RESULTS

Petrology of Ureilite Clast MS-MU-011

The small, polished chip of MS-MU-011 that we examined is dominated by Na-rich feldspar, with less abundant, interstitial pyroxenes. Some high-Ca pyroxene grains have inclusions of K-Si-rich glass, as well as minor oxide and phosphate grains (Figure 2a and see Table 1). Many pyroxene–feldspar and pyroxene–glass phase boundaries are arcuate or scalloped (Figure 2b). The modal mineralogy (vol.) of the sample studied is feldspar, 81%–85% (Figure 2a); pyroxene, 10%–12% (Figure 2b); K-glass, 3%–5% (Figure 2a); oxides/sulfides, 0.5%–1%; and vesicles $\ll$0.5%. Modal abundances are consistent with the criteria to classify the sample as a trachyte, trachyandesite, or syenite. They are also consistent with the detailed descriptions of MS-MU-011 given by Bischoff et al. (2014) and Horstmann and Bischoff (2014) but show a higher feldspar/pyroxene ratio. While the small size of the fragment we examined may have resulted in unrepresentative modal mineralogy, the low-K content of the pyroxene suggests that the Ar data should be controlled mainly by the feldspar.

Comparison of K and Ca from EDS and Neutron Activation

Figure 3 summarizes the results of K and Ca analyses obtained either by EDS or from the results of the neutron irradiation at TRIGA. For clasts A100 (L4), MS-D (EL6), and MS-MU-011, the overall agreement is probably as good as might be expected considering the mismatch between the volumes probed by the two methods, that is, the entire sample ($\sim 1 \times 10^5 \mu m^3$ for a 10 $\mu g$ mass) by neutron irradiation versus one or a few activation volumes of a few cubic microns by EDS. The difficulty of controlling for the geometry of (unpolished) grains adds to the uncertainties of the EDS analyses. For H5 clast ALS 25, the EDS analyses for both K and Ca seem to exceed the Ar results. If real, this difference may reflect a sampling bias toward high-K spots during preliminary EDS scans. Agreement with literature values is fair.

Argon Isotope Analyses

Supplement S1 gives the results of the argon isotope analyses in tabular form; the figures there show the release patterns and conventional argon isochrons plotted without corrections for cosmogenic $^{36}$Ar. We discuss below isochrons that incorporate such corrections.

Cosmic-Ray Exposure Ages

Table 2 presents the concentration of cosmogenic $^{38}$Ar in each of the samples along with two calculated production rates, $P_{38}$, and the corresponding cosmic-ray exposure (CRE) ages; the CRE ages are plotted in Figure 4. Supplement S2 explains the two methods used.
to estimate the production rates: One of them includes only Ca and estimates of Fe content; the other includes Ca, K, and estimates of Fe content.

Comparison of the upper and lower panels in Figure 4 suggests that the inclusion of K in \( P^{38} \) leads to a tighter and more realistic distribution of CRE ages. The (unweighted) mean CRE age obtained with \( P^{38(K,Ca,Fe)} \) is 20\( \pm \)18 Ma (\( N = 15 \)). Omission of the three oldest and the three youngest CRE ages yields unweighted and weighted means of 17\( \pm \)5 Ma and 16.6\( \pm \)0.2 Ma, respectively.

The two estimates of the mean CRE age that exclude outliers are in the range of published values. Ott et al. (2010) reported \( ^{21}\text{Ne} \) CRE ages of 13.2 Ma and 14.2 Ma for ureilitic specimens #1 and #47; Nagao et al. (2014) estimated older values of \( \sim 20 \) Ma based on \( ^{3}\text{He} \) and \( ^{21}\text{Ne} \) analyses of the same specimens. Welten et al. (2010; their table 5) calculated \( ^{3}\text{He} \), \( ^{21}\text{Ne} \), and \( ^{21}\text{Ne}/^{26}\text{Al} \) ages (Ma) ranging from 12.9 to 16.7, 13.3 to 15.6, and 18.0 to 21.1, respectively, for four ureilitic AhS samples; they (and we) consider the \( ^{21}\text{Ne}/^{26}\text{Al} \) ages to be the most reliable. Murty et al. (2010) obtained \( ^{3}\text{He} \) and \( ^{21}\text{Ne} \) CRE ages of 13.8 and 16.0 Ma, respectively, for ureilitic specimen #36. In a detailed study, Riebe et al. (2017; their table 5) presented CRE ages calculated from measurements of \( ^{38}\text{Ar} \) (hereafter T\(_{38}^{\text{Ar}}\)) and in other ways for five AhS samples. Three of the samples that they considered came from clasts analyzed here: EL6 clast MS-D, L4 clast A100, and H5 clast 25. Riebe and co-workers used their own \( ^{36,38,40}\text{Ar} \) measurements to obtain T\(_{38}^{\text{Ar}} = 19.8 \pm 2.8 \) Ma for MS-D. To calculate T\(_{38}^{\text{Ar}} = 18.1 \pm 2.8 \) Ma for L4 clast A100 and T\(_{38}^{\text{Ar}} = 15.1 \pm 2.3 \) Ma for H5 clast 25, they revised the measurements of \( ^{36,38,40}\text{Ar} \) reported earlier by Meier et al. (2012). A sixth sample analyzed by Riebe and colleagues, one from another E chondritic clast, had a considerably younger CRE age of 11 Ma. In a later study, Goodrich et al. (2019) found evidence for a still younger CRE age, in the range 5–9 Ma, for a C1 carbonaceous clast.

Riebe et al. (2017) reported a maximum CRE age of 25 Ma for a sample of MS-CH-2 (unique, R-like). They concluded, however, that the most recent cosmic-ray irradiation of asteroid 2008 TC\(_3\) lasted only 11 Ma, the CRE age measured for EL3-5 clast MS-179. In this scenario, the older CRE ages of other clasts reflect their pre-irradiation as small (\( \leq 1 \) m) bodies, perhaps in transit to or in a regolith on the AhS daughter body (Goodrich et al., 2019). Pre-irradiation of either the L4 or the H5 xenolith on the relevant parent body seems less likely inasmuch as evidence for multiple stages of CRE in the general population of H chondrite and L chondrite is uncommon (Herzog & Caffee, 2014). In addition, if the H5 xenolith formed many meters below the surface of a layered parent body, then the production of cosmogenic nuclides would have been negligible.

Unaccountably, two samples listed in Table 2, namely RU22317 from EL6 clast MS-D and RU22359 from MS-MU-011, have CRE ages >60 Ma, a value
Calculation of $^{40}$Ar/$^{39}$Ar Ages

To calculate $^{40}$Ar/$^{39}$Ar ages, we used the $^{40}$K decay constant $\lambda_{40K} = 5.543 \times 10^{-10}$ year$^{-1}$ of Steiger and Jäger (1977). $J$-values were obtained by irradiating weighed samples of Fish Canyon sanidine (200–1000 µg) for which we adopted an age of 28.201 Ma (Kuiper et al., 2008). $J$-values ranged from $(1.800 \pm 0.003) \times 10^{-2}$ to $(1.994 \pm 0.003) \times 10^{-2}$. Separate analyses of core-irradiated Hb3gr reproduced the accepted age of 1080.4 Ma (Jourdan & Renne, 2007).

A $^{40}$Ar/$^{39}$Ar age for any sample $x$, $t_{x,0}$ as calculated with a decay constant $\lambda_{x}$ assuming an age $t_{\text{std,0}}$ for a standard or monitor, may be converted to an adjusted value, $t_{x,\text{adj}}$, appropriate for another $^{40}$K decay constant, $\lambda_{\text{adj}}$, and/or different choice of standard (a) and standard age, $t_{\text{std,adj}}$ through the relation

$$t_{x,\text{adj}} = t_{x,0} \frac{\lambda_{\text{adj}}}{\lambda_{x}}.$$
Ar/Ar ages of Almahata Sitta

FIGURE 4. Cosmic-ray exposure ages of Almahata Sitta samples. (Color figure can be viewed at wileyonlinelibrary.com.)

\[
t_{n,a} = \frac{1}{\lambda_a} \ln \left[ \frac{e^{x_{n,a} - 1}}{R_{a,0}(e^{x_{n,0} - 1}) + 1} \right]
\]

where

\[
R_{a,0} \equiv \frac{\frac{40}{39}Ar^*}{\frac{39}{39}Ar_K}_{\text{Std,a}} / \frac{\frac{40}{39}Ar^*}{\frac{39}{39}Ar_K}_{\text{Std,0}} = \frac{R_{a,\text{FCS}}}{R_{0,\text{FCS}}}
\]

In Equation 2, FCs denotes Fish Canyon sanidine; the numerical values of \( R_{a,\text{FCS}} \) and \( R_{0,\text{FCS}} \) may be obtained from, for example, Renne et al. (2011, their table 2); see also Mercer and Hodges (2016).

\[40\text{Ar}/39\text{Ar} \text{ Ages}\]

Tables 3 and 4 list and Figure 5, Figures S4.1, and S4.2 show the integrated, plateau, and isochron ages for the four clasts studied. The integrated ages are useful for comparisons with published K/Ar ages. We define a “plateau” on a temperature-release plot (Supplement S1) as three or more consecutive steps that satisfy two criteria: (1) the \( \frac{39}{39}Ar \) “in” the plateau constitutes at least 50% of the total \( \frac{39}{39}Ar \) for all steps; and (2) the age difference, \( \Delta t \), between every pair of successive step ages \( t_n \) and \( t_{n+1} \) is less than a certain confidence limit (CL), usually 95% so that \( |t_{n+1} - t_n| < 1.96 \times (\sigma_n + \sigma_{n+1}) \). A plateau age is then the weighted average of the ages of each of the steps in the plateau. Plateau ages obtained with a slightly more permissive CL, namely \( |t_{n+1} - t_n| < 2.00(\sigma_n + \sigma_{n+1}) \), agree with these values for all samples except RU22359 (MS-MU-011). For RU22359, the CL-95 criterion for inclusion in the plateau yields a plateau age of 4515 \pm 19 Ma (steps F–H; 50% of the \( \frac{39}{39}Ar \)) while the “2-\( \sigma \)” criterion yields an age of 4549 \pm 10 (steps A–I; 95% of the \( \frac{39}{39}Ar \)). For this sample only, we prefer the “2-\( \sigma \)” plateau age of 4549 \pm 10 (1-\( \sigma \)) Ma for its smaller uncertainty and greater inclusivity.

Isochron ages were calculated with two different computer programs. First, we obtained isochrons with no cosmogenic corrections using Mass Spec Version 7.816 (Alan Deino, University of California, Berkeley). Second, to assess the importance of corrections for cosmogenic \( \frac{39}{39}Ar \), we used IsoPlotR software (Vermeehs, 2018). As explained in Supplement S4, in constructing the IsoPlotR isochrons, we considered four different choices of cosmogenic \( \frac{39}{39}Ar \) (none and three others) for each sample. With a few exceptions, the fitting parameters of the four isochrons agreed within their respective 1-\( \sigma \) uncertainties (Figure S4.1). Results without cosmogenic corrections are shown in the plots of Supplement S3 and compiled in Table 3. Isochron ages and intercepts obtained from IsoPlotR and from MassSpec (both without cosmogenic corrections) agree within their respective 1-\( \sigma \) uncertainties in all cases.

Almahata Sitta L4 Clast AhS A100

Summary: The mean weighted (1/\( \sigma \)\(^2 \)) average of the 12 ages from four samples of L4 clast AhS A100 (Table 4) is 4529 \pm 6 Ma. The most precise of these results are from bulk sample RU21889, for which two plateau ages point to an age between 4521 and 4539 Ma. Our preferred value, 4530 \pm 10 Ma, is the midpoint of this range and is nearly the same as the integrated age. Small grains separated from this clast evidently lost some \( \frac{40}{39}Ar \). Recapture of such lost \( \frac{40}{39}Ar \) by adjacent material may help explain the older ages of the “bulk” sample RU21889.

RU21889: Our most precise ages for clast AhS A100 (L4) come from the results for the 847-\( \mu \)g “bulk” sample RU21889. The integrated age is 4535 \pm 9 Ma. Having adopted the \( \frac{40}{40}K \) decay constant of Renne et al. (2010) and an age of 1080.4 for Hb3gr (PP-20; Jourdan & Renne, 2007), Beard et al. (2013) reported an integrated age of 4575 \pm 6 Ma for AhS A100, which translates to 4579 \pm 6 Ma with the \( \frac{40}{40}K \) decay constant of Steiger and Jäger (1977) and the same Hb3gr standard age adopted here (1080.4 Ma). Beard and co-workers inferred from their integrated age the presence of unsupported \( \frac{40}{40}Ar \) in their sample. Riebe et al. (2017; their table S6a) presented a K/Ar age of 4100 Ma for AhS A100 based on a \( \frac{40}{40}Ar \) concentration of \(~6000 \times 10^{-8} \) cm\(^3\) STP g\(^{-1}\) and a measured K concentration of 955 ppm (Meier et al., 2012; their table 2).

The temperature release pattern of RU21889 (Supplement S1) begins with a hint of a peak (maximum apparent age of 4651 \pm 55 Ma for step G) over the first 7% of the \( \frac{39}{39}Ar \) evolved. Thereafter, the pattern flattens and MassSpec software returns two acceptable plateaus...
<table>
<thead>
<tr>
<th>Clast</th>
<th>Type; Mass (g) b</th>
<th>Subsample</th>
<th>RUID</th>
<th>Mass (μg)</th>
<th>$T_{\text{Int}}$</th>
<th>$T_{\text{Plat}}$</th>
<th>Steps/% $39\text{Ar}$</th>
<th>$T_{\text{Iso}}$</th>
<th>$y_0$</th>
<th>MSWD</th>
<th>Steps c</th>
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<tr>
<td>A100</td>
<td>L4; 11.4</td>
<td>Plag + ol</td>
<td>RU21883</td>
<td>12</td>
<td>$4.551 \pm 0.065$</td>
<td>$4.523 \pm 0.049$</td>
<td>DI/95</td>
<td>$4.60 \pm 0.19$</td>
<td>$-50 \pm 170$</td>
<td>0.92</td>
<td>AI</td>
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<td>px high K</td>
<td>RU21887</td>
<td>6</td>
<td>$3.56 \pm 0.70$</td>
<td>$3.20 \pm 0.60$</td>
<td>AF/100</td>
<td>$4.8 \pm 1.6$</td>
<td>$-1100 \pm 2800$</td>
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<td>Plag (high K)</td>
<td>RU21888</td>
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<td>$3.58 \pm 0.42$</td>
<td>$4.00 \pm 0.32$</td>
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<td>$-340 \pm 780$</td>
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<td>Bulk</td>
<td>RU21889</td>
<td>847</td>
<td>$4.535 \pm 0.009$</td>
<td>$4.539 \pm 0.010$</td>
<td>HO/67 LR/82</td>
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<td>25</td>
<td>H5; 222</td>
<td>Plag+px/bulk</td>
<td>RU21898</td>
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<td>$4.565 \pm 0.009$</td>
<td>AI/86</td>
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<td>RU21899</td>
<td>17</td>
<td>$4.26 \pm 0.10$</td>
<td>$4.375 \pm 0.092$</td>
<td>BJ/85</td>
<td>$4.50 \pm 0.47$</td>
<td>$-200 \pm 1000$</td>
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<td>Plag</td>
<td>RU21900</td>
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<td>$4.372 \pm 0.074$</td>
<td>$4.508 \pm 0.064$</td>
<td>CG/73 F1/55</td>
<td>$4.49 \pm 0.14$</td>
<td>$-30 \pm 120$</td>
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<td>RU21902</td>
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<td>$4.492 \pm 0.021$</td>
<td>$4.509 \pm 0.015$</td>
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<td>Bulk</td>
<td>RU22316</td>
<td>212</td>
<td>$4.555 \pm 0.009$</td>
<td>$4.556 \pm 0.007$</td>
<td>CL/96 d</td>
<td>$4.554 \pm 0.017$</td>
<td>$19 \pm 83$</td>
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<td>Plag</td>
<td>RU22317</td>
<td>404</td>
<td>$3.615 \pm 0.010$</td>
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<td>$3.054 \pm 0.017$</td>
<td>$236 \pm 6$</td>
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<td>Pure plag</td>
<td>RU22318</td>
<td>10</td>
<td>$4.490 \pm 0.021$</td>
<td>$4.513 \pm 0.017$</td>
<td>BI/95</td>
<td>$4.539 \pm 0.089$</td>
<td>$-24 \pm 82$</td>
<td>0.078</td>
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<td>Bulk</td>
<td>RU22319</td>
<td>3</td>
<td>$4.57 \pm 0.11$</td>
<td>$4.619 \pm 0.098$</td>
<td>AH/100</td>
<td>$4.33 \pm 0.19$</td>
<td>$109 \pm 54$</td>
<td>0.27</td>
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<td>RU22321</td>
<td>1510</td>
<td>$4.587 \pm 0.035$</td>
<td>$4.592 \pm 0.023$</td>
<td>AL/100</td>
<td>$4.469 \pm 0.098$</td>
<td>$140 \pm 100$</td>
<td>0.31</td>
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<td>Plag</td>
<td>RU22357</td>
<td>26</td>
<td>$3.415 \pm 0.015$</td>
<td>—</td>
<td></td>
<td>$4.321 \pm 0.098$</td>
<td>$-30 \pm 570$</td>
<td>1.3</td>
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<td>Plag mix</td>
<td>RU22359</td>
<td>91</td>
<td>$4.529 \pm 0.013$</td>
<td>$4.515 \pm 0.019$</td>
<td>FGH/53</td>
<td>$4.548 \pm 0.013$</td>
<td>$1 \pm 3$</td>
<td>1.6</td>
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<td>RU22360</td>
<td>31</td>
<td>$4.23 \pm 0.61$</td>
<td>$4.549 \pm 0.010$</td>
<td>AF#100</td>
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<td>132</td>
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</table>

a $T_{\text{Int}} =$ integrated age. $T_{\text{Plat}} =$ plateau age (95% confidence limit) except RU22359. $T_{\text{Iso}} =$ isochron age and $y_0 =$ intercept of isochron plotted without corrections for cosmogenic $36\text{Ar}$. Isochron ages and intercepts are from Supplement S1 and were obtained with MassSpec software. These values may differ slightly from the results shown in Table S4.1, which were obtained with IsoPlotR (Vermes, 2018) and incorporate corrections for cosmogenic $36\text{Ar}$. MSWD = mean square weighted deviation (reduced $\chi^2$).
b Clast mass from Horstmann and Bischoff (2014).
c # denotes omitted.
d Omits steps MNO from cumulative $39\text{Ar}$ calculation; see text.
e $2\sigma$ rather than 95% confidence limit used in identifying plateau; see text.
TABLE 4. Best estimates and summary of 40Ar/39Ar ages, t ± 1-σ Ma.

<table>
<thead>
<tr>
<th>Sample</th>
<th>L4</th>
<th>H5</th>
<th>EL6</th>
<th>Feldspathic</th>
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<tr>
<td>Sample ID</td>
<td>RU21889</td>
<td>RU21898 and RU22316</td>
<td>RU22318</td>
<td>RU22359</td>
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<tr>
<td>Composition</td>
<td>Bulk</td>
<td>Bulk</td>
<td>Plag mix</td>
<td>Bulk</td>
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<tr>
<td>Integrated</td>
<td>4535 ± 9</td>
<td>4550 ± 10</td>
<td>4549 ± 10</td>
<td>4521 ± 9</td>
</tr>
<tr>
<td>Plateau</td>
<td>4550 ± 9</td>
<td>4550 ± 10</td>
<td>4550 ± 10</td>
<td>4550 ± 10</td>
</tr>
<tr>
<td>Isochron (raw)</td>
<td>4535 ± 9</td>
<td>4550 ± 10</td>
<td>4550 ± 10</td>
<td>4550 ± 10</td>
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<tr>
<td>Isochron (lever)</td>
<td>4550 ± 9</td>
<td>4550 ± 10</td>
<td>4550 ± 10</td>
<td>4550 ± 10</td>
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<tr>
<td>Isochron (minimum 36Ar/37Ar)</td>
<td>4543 ± 10</td>
<td>4543 ± 10</td>
<td>4543 ± 10</td>
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<tr>
<td>Isochron (T&lt;sub&gt;CRE&lt;/sub&gt; = 20 Ma)</td>
<td>4551 ± 12</td>
<td>4551 ± 12</td>
<td>4551 ± 12</td>
<td>4551 ± 12</td>
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<tr>
<td>Isochron (mean)</td>
<td>4554 ± 10</td>
<td>4554 ± 10</td>
<td>4554 ± 10</td>
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<td>Best estimate</td>
<td>4535 ± 10&lt;sup&gt;c&lt;/sup&gt;</td>
<td>&gt;4537 ± 11&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4513 ± 17&lt;sup&gt;e&lt;/sup&gt;</td>
<td>4549 ± 10&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Weighted mean&lt;sup&gt;g&lt;/sup&gt;</td>
<td>4531 ± 5</td>
<td>4550 ± 4</td>
<td>4529 ± 11&lt;sup&gt;h&lt;/sup&gt;</td>
<td>4537 ± 7&lt;sup&gt;i&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>The rationale for the choices made are given in notes c-f and discussed in the text. In general, we chose results for the sample(s) that yielded the most precise and internally consistent ages.

<sup>b</sup>Integrated and plateau ages from Table 3; isochron ages from Table S4.1.

<sup>c</sup>Integrated age; plateau shows signs of Ar redistribution.

<sup>d</sup>Lower of the two plateau ages; isochron ages discounted because of negative intercepts.

<sup>e</sup>Plateau age; isochron ages discounted because of lower precision.

<sup>f</sup>Plateau age; isochron age with no cosmogenic corrections is indistinguishable from the average of the different isochron ages.

<sup>g</sup>The weighted mean includes the integrated, plateau, and isochron ages measured for all samples of the clast (Table 3), not only those of the sample(s) used for the best estimate with exceptions as noted in notes h and i. We included in the weighted mean (weighting factor = 1/σ<sup>2</sup>) only the isochron ages obtained without cosmogenic corrections because with few exceptions these corrections did not lead to statistically significant and persuasive changes in age and/or intercept. For details, see Table S4.1.

<sup>h</sup>Excludes integrated and isochron ages of RU21898.

<sup>i</sup>Excludes integrated age of RU22317.

(AC95), 4539 ± 11 Ma (steps H–O; 67% of the 39Ar) and 4521 ± 8 Ma (steps L–R; 70% of the 39Ar). Unsurprisingly, the forced inclusion of steps H–R yields an intermediate plateau age of 4526 ± 7 Ma (90% of the 39Ar; MSWD = 0.7). None of these ages includes corrections for trapped 40Ar, a choice consonant with the small magnitudes of the intercepts of the isochrons discussed below.

Four isochron ages for RU21889 range from 4543 ± 10 Ma by the minimum 40Ar/39Ar method to <4551 ± 10 Ma by the other calculations. These values are about 10 Ma or one standard deviation older than our preferred age. Although small in magnitude, <10, all the intercepts are negative and non-physical. For this reason, we believe that the younger plateau age is more reliable.

RU21887 and RU21888: These two very small samples—3 μg pyroxene and 6 μg plagioclase, respectively—have notably younger integrated and plateau ages of <4.0 Ga. With uncertainties ranging upward from ±0.4 Ga, the precision is poor but some loss of 40Ar seems clear.

Almahata Sitta H5 Clast AhS 25

Summary

The mean weighted (1/σ<sup>2</sup>) average of the 15 ages from 5 samples is 4550 ± 4 Ma (Table 4), which is unusually old for the 40Ar/39Ar age of an H chondrite (see Table S6.2 and see the Discussion section, below). Mini-bulk samples RU21898 (114 μg) and RU22316 (212 μg) control the weighted average by virtue of their more precise plateau ages, 4565 ± 9 and 4565 ± 7 Ma, and similar isochron ages. Based on detailed considerations explained below, however, we conclude that the 40Ar/39Ar age of AhS 25 is likely younger, between 4537 and 4555 Ma. We take as the lower bound the integrated age of RU21898. Isochron intercepts scattering around zero provide no evidence that RU21898 contains significant amounts of trapped 40Ar that might have raised this lower bound, although unsupported 40Ar, an imponderable, may have done so. The upper bound is the oldest of four isochron ages
calculated for RU22316 (Table S4.1). Ages in the younger part of the range seem more likely based on the shapes of the release patterns of RU21898 and RU22316: Both release patterns bend toward younger ages at higher temperatures although possibly for different reasons.

The most reliable ages from the smaller (~17 µg) separates, those for RU21902, are younger by ~50 Ma and indicate a later disturbance. By mass balance, the 4500 Ma age estimate for the separates and the upper limit of 4567 Ma set by calcium–aluminum-rich inclusion (CAI) formation preclude the presence in AhS 25 of a major mineral fraction with an age much younger than 4500 Ma.

**RU21898**—The temperature release pattern for the mini-bulk sample, RU21898 (114 µg), shows the classic signs of recoil redistribution (Huneke & Smith, 1976; Turner & Cadogan, 1974), viz., higher ages and higher K/Ca ratios at lower temperatures and the converse at higher temperatures. A plateau age of 4565 ± 9 Ma for steps A–I (MSWD 0.9, 85% 39Ar) exceeds by ~2σ the integrated age, 4537 ± 11 Ma, and crowds the solar system limit. Four isochrons constructed in different ways (Table S4.1) all give negative, nonphysical intercepts of ~100 ± 50, and implausible apparent ages of >4567 ± 10 Ma. We think that argon redistribution has compromised the isochrons for RU21898 by shifting high-temperature, low K/Ca data points close to the origin rightward, thereby increasing the slope. For completeness, we fit the low-temperature data to their own isochron and obtained an age of 4568 ± 14 Ma and an intercept of ~26 ± 93 (steps A–I; MSWD = 0.92).

Beard et al. (2013) reported 40Ar/39Ar results for another sample of AhS 25. After applying a correction for atmospheric Ar, they obtained an integrated age of 4435 ± 6 Ma, about 100 Ma younger than the value of 4537 ± 11 for RU21898. The shapes of their 18-step and our 13-step release spectra resemble each other insofar as both show apparent ages decreasing to ~4200 Ma at higher temperatures accompanied by a decrease in the K/Ca ratio. Beard and co-workers characterize the release spectrum as disturbed, but with a plateau at 4200 Ma for the last 25–35% of the 39Ar released.

We conclude that the release spectrum of RU21898 reflects redistribution of 40Ar, a possibility also considered by Beard et al. (2013) and regard the integrated age as the most reliable result.

**RU22316**—Our age results are based on release steps A–L. The analysis of step M yielded argon at blank levels. Higher laser power applied in steps N and O released appreciable amounts of Ar. Our prior laboratory experience and the anomalously high K and Ca contents calculated by including the 39Ar and 37Ar data for steps N and O suggest that the sample cover slip melted under the high laser power and released extraneous argon. Total K and Ca contents for steps A–L are 0.11 wt% and 2.1 wt% Ca, respectively, and give an integrated age of 4555 ± 9 Ma; totals for steps A–O are 0.16 wt% K and 7.6 wt% Ca and give an integrated age of 4478 ± 8 Ma. The K and especially the Ca content for steps A–O are >5x larger than the H chondrite means of 0.078 wt% K and 1.2 wt% Ca and suspect for this reason.

The data for steps C–L form a good plateau (age 4555 ± 9 Myr) that include 96% of the 39Ar with no indication of a significant decrease in age at higher temperatures. It is possible, however, that discarded steps N and O included some argon released from the sample itself. Isochrons for steps A–L (Table S4.1) yield ages ranging from 4536 ± 17 Ma (CRE-age-based trapped corrections) to 4555 ± 16 Ma (no trapped corrections), with small (~35 ± 130 to 100 ± 90) intercepts.

In summary, the analytical indications of a 40Ar/39Ar age > 4550 Ma for sample RU22316 are difficult to dismiss. Enough doubt attaches to them, however, for us to favor ages closer to 4535 Ma. Additional 40Ar/39Ar dating of this sample would be desirable.

**RU21899, RU21900, and RU21902**—Based on EDS spot analyses, we originally identified all three of these

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**FIGURE 5.** 40Ar/39Ar ages of Almahata Sitta samples. The dashed vertical line plotted at T = 4.50 Ga is shown for reference. (Color figure can be viewed at wileyonlinelibrary.com.)
17 μg samples as plagioclase with promisingly high (0.2–2.0 wt%) K contents in a few spots. As it turned out, Ar/Ar analyses indicated adequate but lower values of 0.04, 0.04, and 0.2 wt% K, respectively. 

RU21902 gave the best of the results obtained for these three samples. It has an integrated age of 4492 ± 21 Ma, which is ~2σ younger than the integrated age of 4537 ± 11 Ma of mini-bulk sample RU21898. All steps for sample RU21902 contribute to a plateau at 4507 ± 15 Ma (MSWD = 0.4) and show no indication of a high-temperature drop-off. Isochron ages lie between 4465 ± 49 Ma and 4494 ± 32 Ma. Positive but highly uncertain intercepts for RU21902 (e.g., 198 ± 206) suggest the presence of some terrestrial atmospheric 40Ar.

The integrated ages of both RU21899 (4260 ± 100 Ma) and RU21900 (4372 ± 79 Ma) are nominally younger than the ages adopted for RU21898, RU22316 (a lower limit), and RU21902, but have larger uncertainties. For RU21899, MassSpec software identifies a plateau at 4375 ± 92 Ma (steps B–J; MSWD = 0.4); the forced addition of step K lowers that age to 4312 ± 87 (MSWD = 0.8). For RU21900, plateau ages calculated in various ways range from a low of 4404 ± 71 Ma (steps F–I) to a high of 4508 ± 68 Ma (steps C–G). The isochron ages of RU21899 and RU21900 are older, vary little (from ~4461 ± 189 Ma to 4498 ± 295 Ma), and agree better with the ages of RU21902. Isochron intercepts scatter around an average value of ~−100 with large uncertainties (~±300). The apparent step ages of both RU21899 and RU21900 tend toward lower values at higher temperatures: 3798 ± 265 Ma (step K) for the former and 4238 ± 140 Ma (step I) for the latter, echoing both our own observations and those of Beard et al. (2013) for bulk samples from this clast. 

Considering RU21899, RU21900, and RU21902 as a group, we prefer the more precise plateau and isochron ages of RU21902, take as tentative corroboration the isochron ages of RU21899 and RU21900, and adopt an age ~4500 ± 15 Ma.

Almahata Sitta EL6 Clast MS-D

Summary

The mean weighted (1/σ^2) average of 9 of the 11 ages from four samples is 4526 ± 11 Ma (Table 4); omitted from this mean are two outliers, namely the much younger integrated and isochron ages (<3.6 Ga) of RU22317. The small plagioclase separate RU22318 (10 μg) yields the most precise and internally consistent 40Ar/39Ar ages (4490–4540 Ma). Bulk sample RU22321 (1510 μg) gives implausibly old integrated and plateau ages, ~4590 ± 30. Although less precise, isochron fitting parameters for RU22321 (Table S4.1) point toward the presence of some trapped 40Ar and ages younger than 4555 Ma.

Our best estimate of the 40Ar/39Ar age of MS-D is 4513 ± 17 Ma, the plateau age of RU22318. The integrated and apparent ages of bulk sample RU22317 indicate substantial losses of radiogenic 40Ar from portions of MS-D.

RU22318—This 10 μg plagioclase-rich sample gave the most convincing results. Data for all steps except the first form a plateau with an age of 4513 ± 17 Ma. The marginally younger integrated age of 4490 ± 22 Ma reflects lower 40Ar in step A. Isochron ages agree well (4532–4539 Ma; average 4536 ± 4 Ma; weighted average 4535 ± 39 Ma), but isochron intercepts are nominally slightly negative (~24 ± 82 to ~30 ± 88), which likely explains why the isochron ages are ~20 Ma older than the plateau age. On balance, the plateau age of 4513 ± 17 Ma, which is nearly the same as the age obtained by forcing an isochron through the origin, seems the most reliable choice for this sample. It is also consistent (1σ + 1σ) with the findings of Hopp et al. (2014), who proposed a closure age of 4.490 ± 0.010 Ga for EL5 and EL6 chondrites. Riebe et al. (2017; their table 7) presented a “nominal retention age” of 4350 Ma for MS-D based on K = 632 ppm and 40Ar/38Ar contents of 4220 × and 4800 × 10^−6 cm^3 STP g^−1.

RU22317—The young integrated age of 3350 ± 11 Ma for mini-bulk sample RU22317 (404 μg) sets it apart from its older MS-D siblings as does its temperature release pattern. Starting at step B, ages increase from 2787 ± 12 to ~3700 ± 20 Ma and form no plateau. The generally rising age spectrum of RU22317 differs from those of most other EL chondrites (Bogard, 2011; Hopp et al., 2014) but resembles those of the EH-5 chondrite St Marks and the EL-6 chondrite Happy Canyon (McCoy et al., 1995). The range of step ages observed in the spectrum of RU22317 is included within the range of ages that Müller and Jessberger (1985) obtained by single-step, laser melting of grains of djerfisherite, a K-bearing sulfide, in the Qingzhen (EH3) chondrite. By omitting steps A–D, we can craft isochrons for RU22317 with ages between 3000 and 3400 Ma and intercepts between 200 and 260, which approximate the value for the terrestrial atmosphere (298.56 ± 0.31; Lee et al., 2006); and MSWDs from 0.04 (minimum 36Ar/37Ar method) to 11 (no corrections) (see Table S4.1), but do not regard the results as persuasive.

RU22321—Despite having a mass 150 times that of plagioclase grain mix RU22318, bulk sample RU22321 (1500 μg) contained relatively little gas and gave scattered results of comparable or poorer precision. The differences among the results for the two samples show that MS-D is heterogeneous on a scale of a few micrometers. The integrated and plateau ages of RU22321, 4557 ± 34 Ma
and $4592 \pm 26$ Ma, respectively, are surprisingly old even with a 1-$\sigma$ allowance. Figure S1 of Supplement S1 hints weakly that step age decreases with temperature, from $4742 \pm 190$ Ma for step B to $4454 \pm 443$ for step L. Three of the four correction procedures for cosmogenic $^{36}$Ar—all but the minimum $^{36}$Ar/$^37$Ar method—produced isochrons. The isochron ages, $4.50 \pm 0.12$ Ga (no corrections), $4.61 \pm 0.16$ Ga (lever rule), and $4.63 \pm 0.06$ Ga (CRE correction), confirm the antiquity ($>4.4$ Ga) of RU22321. Their precision is poor, however, and negative values for two of the three, highly uncertain intercepts ($106 \pm 30$, $-38 \pm 340$, and $-7 \pm 200$) may signal some inflation of the ages. It is tempting to attribute older ages measured in RU22321 to the capture of $^{40}$Ar* lost from nearby materials such as RU22317 that may have contained djerfisherite (Müller & Jessberger, 1985).

In a $^{40}$Ar/$^39$Ar study of bulk E chondrite samples, Hopp et al. (2014) called attention to differences between the isochrons formed by low- and by high-temperature data. By treating the two data sets separately, they obtained for each of four samples two isochrons of nearly the same age but different intercepts: well-defined positive ones for the low-temperature data and near-zero ones for high-temperature data. Inclusion of all the data for a given meteorite led to negative intercepts and higher ages. We reviewed our results for RU22318 and RU22321 by taking the approach of Hopp and co-workers but saw no substantial improvement in the isochrons’ fit after corrections for cosmogenic $^{36}$Ar assuming a CRE age of 20 Ma (see Supplement S3).

RU22319—The argon data for sample RU22319 (3 $\mu$g) define a plateau at $4600 \pm 100$ Ma and isochrons with ages of $4400 \pm 200$ Ma. While these ages confirm an age older than 4400 Ma for the clast, their uncertainties are too large to add much to the interpretation.

Combined isochron for 22318, 22319, and 22321—Standard isochron plots combining the results for RU22318, 19, and 21 give ages of $4527 \pm 36$ Ma (Deino software, no trapped corrections), $4442 \pm 41$ Ma (minimum $^{36}$Ar/$^37$Ar method), $4549 \pm 30$ Ma (leaver-rule method), and $4491 \pm 39$ Ma (CRE-exposure age method). Only the minimum $^{36}$Ar/$^37$Ar method yields a significant intercept, $83 \pm 38$. The mean of these ages, $4502 \pm 47$ Ma, is close to the plateau age of 22318 but has larger uncertainty.

**AhS Feldspathic Clast MS-MU-011**

**Summary**—Of the four samples of MS-MU-011 analyzed, two consisting mostly of pyroxene enclosing small glassy inclusions (RU22360 and RU22362) yielded chronometric results of limited or no usefulness. One (RU22357, mainly plagioclase) showed significant $^{40}$Ar loss. Our preferred estimate for the $^{40}$Ar/$^39$Ar age of MS-MU-011 is $4549 \pm 10$ Ma and is based on the plateau age of the fourth sample, RU22359, a 91 $\mu$g collection of plagioclase grains. In a preliminary report, Turrin, Lindsay, Herzog, et al. (2015) and Turrin, Lindsay, Delaney, et al. (2015) misidentified RU22359 as a 31 $\mu$g sample of glass-bearing pyroxene. Taken at face value, the plateau age of $4549 \pm 10$ Ma indicates that the $^{40}$Ar/$^39$Ar system closed $\sim$13 Ma after the $^{26}$Al/$^{26}$Mg system did (Bischoff et al., 2014).

RU22357—The young integrated age of $3404 \pm 15$ Ma shows a significant loss of radiogenic $^{40}$Ar*. The release pattern has no plateau. Isochrons fit to various treatments of the data consistently give ages of about 4.2 Ga, but with negative intercepts of large magnitude, $-500$. Assuming this sample contains no trapped $^{40}$Ar, the maximum step age (RU22357-01D) of 4352 ± 66 Ma sets a crude lower bound on the formation age.

RU22359—For reasons discussed in the section $^{40}$Ar/$^39$Ar Ages, we favor the “2-$\sigma$” plateau age of $4549 \pm 10$ Ma over the CL-95 plateau age of $4515 \pm 19$ Ma for this sample. The integrated age of $4529 \pm 13$ Ma occupies a middle ground within $\pm 1$-$\sigma$ of both plateau ages. All four isochrons have intercepts indistinguishable from zero and MSWDs of about 1.6.

With no weighting, the four isochron ages (Table S4.1) average to $4552 \pm 23$ Ma, a value that supports, albeit weakly, the choice of the older, “2-$\sigma$” plateau age.

RU22360 and RU22362—These two samples consisted mostly of pyroxene. They excited our interest because they contained small, K-rich inclusions. Only the heating steps A, B, and C for RU22360 (31 $\mu$g) yielded measurable amounts of Ar, however, and step C, the best of the lot, produced an age of only marginal utility, $4.20 \pm 0.52$ Ga. The amounts of $^{40}$Ar released from RU22362, typically $\sim 2 \times 10^{-16}$ mol, were large enough to measure with a precision of $\pm 10\%$ in nine steps (A–I). Unfortunately, the corresponding amounts of $^{39}$Ar for steps B–I, were very small, $<2 \times 10^{-18}$ mol, and had uncertainties of $\sim 100\%$. From the total $^{39}$Ar content of $2 \pm 1 \times 10^{-9}$ cm$^3$ STP g$^{-1}$, we wrung an integrated age of $2.7 \pm 0.6$ Ga. The data for RU22360 and RU22362 did not produce useful release plots or isochrons.

The integrated age of $4200 \pm 300$ Ma for RU22360 is broadly consistent with the ages presented above. The integrated age of $2800 \pm 600$ for RU22362 suggests gas loss. The total $^{39}$Ar concentrations are 5x and 50x lower, respectively, than the average of $2.5 \times 10^{-8}$ cm$^3$ STP g$^{-1}$ for the two plagioclase-rich samples RU22357 and RU22359 discussed above. Had these samples been pure pyroxene, we would have expected the concentrations of $^{36}$Ar even lower than those measured. We infer, therefore, that the measured concentrations and the ages reflect the contributions of the glassy inclusions. A
common, low $^{36}\text{Ar}/^{40}\text{Ar}$ ratio of $\sim 0.001$ for RU22362 and the plagioclase-rich samples RU22357 and RU22359 suggests that the $^{40}\text{Ar}$ observed is radiogenic rather than trapped. On the other hand, the $^{36}\text{Ar}/^{40}\text{Ar}$ ratio of RU22360 is higher, 0.0025 $\pm$ 0.0002, which suggests that the pyroxene may also contain a small amount of trapped $\text{Ar}$.

DISCUSSION

Age of L4 Clast AhS A100 in Relation to Other L Chondrite Ages

A summary of $^{40}\text{Ar}/^{39}\text{Ar}$ impact ages for 39 L chondrites compiled by Swindle et al. (2014) sets a context for the $^{40}\text{Ar}/^{39}\text{Ar}$ age of the L4 clast AhS A100, for which our best estimate is 4535 $\pm$ 10 Ma. A search of the literature turned up four additional L chondrites with $^{40}\text{Ar}/^{39}\text{Ar}$ ages published since ~2014; Figure 6a and Table S6.1 show all the results. Most of the ages tabulated preserve the choices made by the original authors for both the $^{40}\text{K}$ decay constant (that of Steiger & Jäger, 1977) and the ages assigned to the co-irradiated standards. A few exceptions discussed below required minor adjustments.

Among the meteorites considered by Swindle and co-workers, only L-melt rock MIL 05029 has an age older than 4500 Ma. Two stones analyzed more recently have unusually “old” ages: Park (L6; 4525.8 $\pm$ 4.6 Ma; Ruzicka et al., 2015) and Baszkówka (L5; 4505 $\pm$ 17 Ma; Friedrich et al., 2014). The $^{40}\text{Ar}/^{39}\text{Ar}$ age of Park is based on the $^{40}\text{K}$ half-life proposed by Renne et al. (2010) and an age of 1080.4 $\pm$ 1.1 Ma for the standard Hb3gr (Patrice Clay, personal communication, 2019). The $^{40}\text{Ar}/^{39}\text{Ar}$ age of Baszkówka is based on the $^{40}\text{K}$ half-life of Renne et al. (2011) and an age of 1081.0 Ma for Hb3gr. Recalculation of these ages with the half-life of Steiger and Jäger (1977) and an age of 28.2 Ma for Fish Canyon gives 4522 $\pm$ 5 Ma for Park and 4493 $\pm$ 17 Ma for Baszkówka.

Our preferred age of 4535 $\pm$ 10 Ma for AhS L4 clast A100 is senior, if only by a little, to all other dated L chondrites (Figure 6a). Park (L6; 4522 Ma) comes closest
and only Baszkówka and impact melt MIL 05209 are older than 4490 Ma. We consider next the ages for AhS A100 and for Park (L6) in the framework of a thermal evolution model for an L chondrite parent body presented by Gail and Trieloff (2019; their figure 2a copied here as Figure 7).

To compare their modeling results with experimental data, Gail and Trieloff (2019; their table 1) compiled the ages, \( t_x \), determined with chronometers, \( x \), having different closure temperatures, \( T_x \) (Table 1H-W = 1148 K; \( T_{U-Pb-Pb} = 720 \) K; \( T_{I-Xe} = 650–770 \) K; \( T_{Ar-Ar} = 550 \) K) for selected L chondrites. They then plotted \( T_x \) (y-coordinate) versus elapsed time, \( t (Ma) = 4562 - t_x \), that is, against the time that elapsed between chondrule formation, set at 4562 ± 1 Ma BP, and the measured age. In plotting the data for \( ^{40}Ar/^{39}Ar \), any published age originally referenced to the \( ^{40}K \) decay constant of Steiger and Jäger (1977), which those authors considered doubtful, was increased by 30 Ma (see Schwarz et al., 2011). In comparing their modeled predictions of temperature versus elapsed time with meteorite data, Gail and Trieloff found good agreement.

Age increases of 30 Ma would move the Ar closure times of AhS A100 and Park to over 4560 Ma, placing them on the prograde portion of the L chondrite heating curve of Figure 7. Such a placement may be possible but seems unlikely and we have not increased the age of AhS A100 or Park in this way when plotting it in Figure 7. Bogard (2011) argued that any adjustment to the \( ^{40}Ar/^{39}Ar \) ages based on the decay constant should not exceed 20 Ma.

Conceivably, Ar isotopes in AhS A100 could have been reset during the assembly of 2008 TC3. If so, the launch of AhS A100 from its parent body is pushed back in time by an interval equal to its transit time from the parent body, which may have been brief. We prefer, however, a simpler history in which AhS A100 completed thermal metamorphism and cooled to Ar closure on its parent body ~4535 Ma ago and preserved most of the \( ^{40}Ar* \) produced since that time. Either way, the \( ^{40}Ar/^{39}Ar \) age sets an upper limit on the time at which AhS 100 was last reheated above the argon closure temperature. The mostly undisturbed release profiles of the mini-bulk samples provide direct evidence of \( ^{40}Ar* \) preservation. The small positive age difference of 8 ± 12 Ma between the older A100 (L4, 4535 Ma) and the slightly younger Park (L6, 4522 Ma) is statistically insignificant but in the direction expected on petrographic grounds.

Age of H5 Clast AhS 25

Swindle et al. (2014) summarized the \( ^{40}Ar/^{39}Ar \) ages of 32 impact melt samples taken from 27 H chondrites. Only one of those samples, a melt clast from Dhofar 323, is older than 4499 Ma. On broadening the survey to include samples other than impact melts and data from more recent publications, we found 58 \( ^{40}Ar/^{39}Ar \) ages for 47 H chondrites (Figure 6b and Table S6.2). In all, seven (15%) of those meteorites have ages ≥4500 Ma, the two oldest being Ste. Marguerite (H4, 4532 ± 16 Ma; Trieloff et al., 2003) and Monahans Light (H5, 4530 ± 8 Ma; Bogard et al., 2001).

Our preferred range of ages for AhS 25 (Table 4 and Figure 6b) is 4537–4555 ± 10 Ma with younger values favored. The older values lie at or beyond the older end of the H chondrite distribution of \( ^{40}Ar/^{39}Ar \) ages and approach the Pb/Pb ages (Blackburn et al., 2017; see Kleine et al., 2008). With a preferred age of 4500 ± 15 Ma, three small (<20 μg), plagioclase-rich samples are younger by about 2σ, implying later heating. Nearby material may have captured the \( ^{40}Ar \) lost from such grains, which would help explain the oldest step ages measured in the “bulk” samples RU21898 and RU22316.

As with the L-clast A100, a plausible history for AhS25 ends metamorphism on an H chondrite parent body at about 4535 Ma with cold ejection and cold capture by 2008 TC3 to follow. An early cosmic-ray irradiation of ~10 Ma on the H-parent body seems unlikely for a type 5 but might have occurred during transit to 2008 TC3 or afterward in a 2008 TC3 regolith. Again, the \( ^{40}Ar/^{39}Ar \) age sets an upper limit on the time at which AhS 100 was significantly reheated.

FIGURE 7. Thermal evolution model for an L chondrite parent body with a radius of 115 km from Gail and Trieloff (2019, figure 2), model LM2 with results for Park and L4 clast A100 (RU21889) added. Elapsed time, \( t (Ma) = 4562 - t_x \), that is, against the time that elapsed between chondrule formation, set at 4562 ± 1 Ma BP, and the measured age. (Color figure can be viewed at wileyonlinelibrary.com.)
Age of EL6 Clast MS-D

$^{40}\text{Ar}/^{39}\text{Ar}$ ages of EL chondrites from the literature are compiled in Table S6.3. Figure 6c shows the age distribution for EL6 and EL7 chondrites along with our preferred age for EL6 clast MS-D, 4513 ± 17 Ma. This age falls close to the centroid of the distribution, although it is at the old end of the range of 4.48–4.51 Ga cited by Hopp et al. (2014) for most EL5 and EL6 chondrites.

An interval of 22 ± 20 Ma separates the preferred $^{40}\text{Ar}/^{39}\text{Ar}$ age of MS-D from those of the L4 and H5 clasts, 4535 ± 10 Ma. Taken at face value, the separation suggests a later arrival time for MS-D at 2008 TC$_3$. A possible interpretation is that the age of MS-D was reset upon later arrival at 2008 TC$_3$. We do not favor this interpretation, in part because the difference in ages has an uncertainty comparable to its magnitude. In any event, the simplest interpretation is once again that the $^{40}\text{Ar}/^{39}\text{Ar}$ age marks the time of MS-D’s cold ($< -250^\circ\text{C}$, the argon closure temperature) ejection from its parent body with up to ~10 Ma of early irradiation by cosmic rays to follow either while in transit from the parent body or on 2008 TC$_3$ itself.

Age of MS-MU-011 (ALM-A)

Our best estimate of the age of MS-MU-011 is 4549 ± 10 Ma for RU22359. The interpretation of this age must be placed in the context of the history of the UPB. Based on thermal modeling, $^{26}\text{Al}/^{26}\text{Mg}$ isotopic data, and $^{182}\text{Hf}/^{182}\text{W}$ isotope systematics, the UPB is thought to have accreted within 0.6–1.7 Ma of CAI, and to have differentiated very shortly thereafter (Baker et al., 2012; Budd et al., 2015; Goodrich, Hartmann, et al., 2015; Kita et al., 2013; van Kooten et al., 2017; Wilson et al., 2008; Yamakawa et al., 2010). The earliest melts were extracted rapidly, possibly as early as 1 Ma after CAI, while the last melts may have been extracted 1–2 Myr later (Collinet & Grove, 2020a; Goodrich, Collinet, Treiman, et al., 2022; van Kooten et al., 2017).

There are no known meteorites that represent the crustal rocks that crystallized from these melts, but feldspathic clasts found in polymict ureilites, including MS-MU-011 and other feldspathic clasts in AhS, appear to be remnants of such rocks (Barnes et al., 2019; Bischoff et al., 2014; Cohen et al., 2004; Goodrich et al., 2017; Goodrich, Collinet, Jercinovic, et al., 2022; Ikeda et al., 2003; Mikouchi et al., 2018).

$^{26}\text{Al}/^{26}\text{Mg}$ and $^{53}\text{Mn}/^{53}\text{Cr}$ dating of feldspathic clasts in typical polymict ureilites yields ages of ~5.4 Ma after CAI (Goodrich et al., 2010). The Pb isotopic isochron age of MS-MU-011 (Amelin et al., 2015) is consistent with this age. A $^{26}\text{Al}/^{26}\text{Mg}$ model age of 6.5 Ma after CAI for six homogeneous plagioclase grains in MS-MU-011 (Bischoff et al., 2014) is younger, but confirmation awaits an internal isochron. The interpretation of the ~5.4-Myr-after-CAI age remains uncertain (e.g., Goodrich et al., 2010; Goodrich, Collinet, Treiman, et al., 2022; van Kooten et al. 2017). Goodrich et al. (2010) and Herrin et al. (2010) argue that it is most plausibly interpreted as the time of catastrophic disruption of the UPB (see below), that is, impact excavation with quenching of melts, rather than an undisturbed internal cooling history. In any case, this age represents the youngest possible time for crystallization of ureilite crustal rocks.

History of the UPB and the Assembly of Polymict Ureilites Including the Progenitor of 2008 TC$_3$/AhS

Ureilites have distinctive properties that indicate a unique history for their parent body. One of these properties is high carbon contents, which range up to ~8 wt% and average ~3 wt% (Cloutis et al., 2010; Goodrich, Hartmann, et al., 2015, and references therein), values comparable, among meteorites, only with those of the most carbon-rich carbonaceous chondrites. They also have oxygen isotope compositions that plot along the carbonaceous chondrite anhydrous mixing line on a standard three-oxygen isotope plot (Rumble et al., 2010).

These two properties led to the hypothesis that ureilite precursors were similar to known carbonaceous chondrites and thus that the UPB accreted in the outer solar system, beyond the ice line (Clayton & Mayeda, 1988; Goodrich, Bottke, et al., 2021; Goodrich, Sanborn, et al., 2021; Scott, 2006). However, the high pyroxene/olivine ratios of ureilites appear to require precursor materials with Si/Mg ratios more like those of ordinary chondrites (OCs) than carbonaceous chondrites (Collinet & Grove, 2020a, 2020b; Goodrich, 1999; Warren, 2012). In addition, nucleosynthetic isotope compositions now show unambiguously that ureilites belong to the non-carbonaceous, rather than to the carbonaceous reservoir of early solar system materials (Budde et al., 2016; Sanborn et al., 2019; Warren, 2011). Thus, the UPB most likely accreted in the inner solar system, along with ordinary and enstatite chondrites and
most other groups of achondrites (Budde et al., 2016; Kruijer et al., 2017).

As mentioned above, the UPB accreted within ~1 Myr of CAI and was partially differentiated shortly thereafter via rapid silicate melt extraction. Numerous lines of evidence indicate that it was then catastrophically disrupted before the mantle had cooled substantially below peak temperatures, probably at ~5–5.4 Myr after CAI, and promptly reassembled into numerous daughter bodies (Downes et al., 2008; Goodrich et al., 2004; Herrin et al., 2010; Michel et al., 2015). Polymeric ureilites subsequently formed as regolith that developed on the surfaces of these daughter bodies, among them being the progenitor from which 2008 TC3/AhS broke off (Downes et al., 2008; Goodrich et al., 2004; Goodrich, Fioretti, et al., 2015; Goodrich, Hartmann, et al., 2015). Based on numerous lines of evidence, Goodrich, Sanborn, et al. (2021) and Goodrich, Kring, et al. (2021) deduce that most of the xenoliths in polymeric ureilites were implanted into ureilitic regolith 40–60 Myr after CAI, or even later.

Thermal History of AhS and Other Polymeric Ureilites

With sufficiently rapid cooling, UPB fragments might have recorded ancient (≥4560 Ma) 40Ar/39Ar ages for UPB crustal material such as MS-MU-011, that is, ages comparable to the Pb–Pb age. On the other hand, cooling calculations for spheres discussed below (Criss & Hofmeister, 2015) suggest that the reassembly of the asteroid might have slowed cooling appreciably, thus delaying the start of the Ar clock and leading to younger ages. Below we consider the likely duration of such a delay and show that it was probably brief, <10 Ma. The calculations ignore the effects related to porosity, shape, atmospheric blanketing, impact-related heating, and internal heat production, which for the most part would have slowed cooling further. Ren et al. (2022) present a more general treatment of these subjects.

Herrin et al. (2010) describe a thermal history for AhS. Mean cooling rates in its ureilite clasts are 0.05–0.2°C h⁻¹ for the temperature interval from 1200–1300 to 800°C, implying that cooling to 800°C took less than 1 year. The relative rapidity of these rates is widely interpreted to indicate disruption of the UPB into small bodies. If we assume a closure temperature of 500°C for the Pb/Pb clock, then the Pb isochron of 4562 ± 3.4 Ma for MS-MU-011 (Amelin et al., 2015) means that by this time temperatures had likely fallen from 800°C by another 300°C.

The thermal history of the reassembled ureilite daughter bodies (UDBs) is less clear at the lower temperatures relevant to 40Ar closure, ~250°C (e.g., Cassata & Renne, 2013). Herrin et al. (2010) conclude that the reassembling fragments were likely <~10 m in size. Patzer et al. (2022) confirmed this result by examining FeO profiles in reduction rims of ureilite olivine. They also refined the estimate of the mean size to 2 m, although they noted the possibility of some larger objects.

Fragment sizes of <10 m imply continued rapid cooling to temperatures well below 800°C. Herrin et al. (2010) state that reassembly “must have followed sufficient lag time for cooling.” Minimum and maximum lifetimes calculated for asteroid ejecta clouds set first-order bounds on that lag time. Reassembly time scales, τ ~ (Gρ⁻¹)⁻¹/₂, are expected (e.g., Michel et al., 2002; here G is the gravitational constant and ρ the density. Leinhardt and Stewart (2009) quote reassembly times of hours for 1 < ρI [g cm⁻³] < 3. Love and Ahrens (1996, p. 143) state that the “lifetimes of bound asteroidal debris clouds lie between ~1 h and ~1 y.” Herrin et al. (2010, p. 1799) attribute to Love and Ahrens (1996) the conclusion that “the majority of a catastrophically disrupted asteroid should reaccrete ... within hours to days.” Goodrich, Hartmann, et al. (2015) and Goodrich, Fioretti, et al. (2015) incorporate these earlier results, writing that the reassembly of the UDB took place within days to weeks.

Calculated cooling rates (Figure 8) based on the formulas of Criss and Hofmeister (2015) are consistent with these observations. At an ambient temperature of 0°C, unperturbed spherical UPB fragments with radii R of 10 m cool from 1250°C to a mean temperature (Tmean) of 800°C, the silicate blocking temperature (e.g., Ganguly et al., 1994). It takes another 11 weeks for the Tmean to get to 500°C, a widely adopted Pb closure temperature, and an additional 21 weeks to arrive at Ar closure—typically, 250°C. These results depend weakly on the choice of surface temperature. We chose a relatively high ambient temperature so as not to under-estimate the cooling times of small fragments. The use of a more realistic, lower surface temperature does not affect the order of magnitude of the results: At an ambient temperature of ~100°C, for example, the time intervals listed above are reduced to 4, 9, and 15 weeks, respectively. The times on the x-axis of Figure 8 scale as the square of the object radius. Thus, a few days would suffice to lower the mean temperature of a 1-m fragment to 250°C, thereby ensuring a cold target for material arriving in later impacts.

On the other hand, if fragments with radii of more than 10 m accounted for much of its mass, then at first the UDB may have been too warm to retain 40Ar. In a UDB with a newly established radius of, say, tens or hundreds of km, the mean cooling rate would have fallen substantially, thus delaying the start of the argon clock. The delay would not have lasted long. Assuming a radius
Timing of Addition of Chondritic Clasts to Typical Polymict Ureilites and to AhS

Scott et al. (2018) suggest that the xenolithic materials in polymict ureilites were added to the UDBs at the time of their original formation, tying the disruption of the UPB and the availability of diverse xenoliths to events associated with the Grand Tack dynamical event (Walsh et al., 2012) in the first 5 Ma of the solar system. Citing Turrin, Lindsay, Herzog, et al. (2015) and Turrin, Lindsay, Delaney, et al. (2015), however, they note that the young 40Ar/39Ar age of MS-D indicates that some clasts were acquired over a period of ~50 Ma and “not solely during the reaccretion of the ureilite parent body.” Horstmann and Bischoff (2014) argue that “Asteroid 2008 TC3 was part of a late-formed ureilitic second generation body in the main belt” that formed with synchronous or near-synchronous acquisition of ureilite and xenolithic materials (their figure 18, part 2a). They do not define “late” but note that “Between the formation of Ca,Al-rich inclusions and chondrules, and the accretion of asteroid 2008 TC3 considerable time has passed,” that is, a time long enough to produce, for example, an H5 clast and transport it to the AhS’s point of assembly. Horstmann and Bischoff (2014) do not address what appears to be an implied delay between UPB disruption and the formation of 2008 TC3. In more recent work, Bischoff et al. (2022) specify this time interval, stating that 2008 TC3 was “a polymict C1 object that may have formed by late accretion at least 50–100 Ma after calcium–aluminum-rich inclusions.”

Goodrich, Sanborn, et al. (2021) and Goodrich, Kring, et al. (2021) argue that UDBs, including the progenitor(s) of both typical polymict ureilites and 2008 TC3, formed ~5 Ma after CAI. The ancient 40Ar/39Ar age of the ureilite crustal clast MS-MU-011 (4549 ± 10 Ma) is consistent (1-σ) with this result. The UDBs developed regoliths and acquired xenoliths later. Pb–Pb ages (Blackburn et al., 2017) and Ar–Ar ages (Gail & Trieloff, 2019; Trieloff et al., 2003) indicate that H- and L OCs evolved on their respective parent bodies over periods lasting tens of Ma after CAI formation: 50–60 Ma for type 6 OC, ~20–30 Ma for types H5 and L5, respectively, and ~7 Ma for type 4. Blackburn et al. (2017) propose that “H and L chondrite parent bodies were catastrophically disrupted at ~60 Ma.” If so, then polymict ureilites likely acquired their H chondrite, L chondrite, and by extension EL chondrite and other clasts, no earlier than 50–60 Ma after CAI and perhaps slightly later, ~70 Ma after CAI (Goodrich, Kring, et al., 2021; Goodrich, Sanborn, et al., 2021). Goodrich and co-authors note that some type 4 OC material may have been launched from its parent body and caught earlier by 2008 TC3 but suggest that such material should be volumetrically rare.

Our best estimates of the 40Ar/39Ar ages of the chondritic clasts (Table 4) in AhS are 4535 ± 10 Ma (L4), ~4540 Ma (H5), and 4513 ± 17 Ma (EL6). Goodrich, Sanborn, et al. (2021), and Goodrich, Kring, et al. (2021) present evidence that 2008 TC3 acquired carbonaceous chondrite and other xenolithic clasts under mild thermal conditions. If the xenolithic material in AhS remained essentially unperturbed on and after ejection from their parent bodies, then the 40Ar/39Ar ages do not constrain the assembly time of 2008 TC3: It could have

of 100 km, an initial temperature of 500°C as required by the ancient Pb isotope age, and a surface temperature of 73 K, it would take the UDB ~10 Ma to cool to argon closure.

From these considerations, we affirm others’ observation that the initial mean temperature of the freshly assembled ureilitic daughter body is sensitive to both the size distribution of the constituent fragments and the duration of assembly. If UPB fragments were small ≤ 10 m radius, as suggested by rapid cooling rates at higher temperatures, and if assembly of the UDB took place after the fragments had cooled to 500°C, then ancient 40Ar/39Ar ages (≥4560 Ma) might be preserved in some AhS components provided that later heating of 2008 TC3 did not overprint the early record. On the other hand, if UPB fragments were larger, the oldest 40Ar/39Ar ages preserved could be up to 10 Ma younger. Finally, younger 40Ar/39Ar ages (≤4540 Ma) in MS-MU-011 and low-temperature step ages of other samples probably record events postdating assembly of 2008 TC3.
been happened at any time after 4513 Ma. It seems unlikely that the debris of three parent bodies collected in precisely the same place at the same time suggesting instead that the clasts arrived serially at a cold ureilitic daughter body. The $^{40}$Ar/$^{39}$Ar ages are, however, compatible with arrival over a limited time period centered 50–60 Ma after CAI as described in the previous paragraph, and this is our preferred interpretation. However, our data do not exclude synchronous or near-synchronous arrival. Either way, whether polymict ureilitic regoliths acquired OC clasts quickly (<1 Ma) or gradually, subsequent residence in a regolith at depths of a few decimeters on 2008 TC$_{3}$ could explain the differences in the CRE ages of AhS clasts noted by Riebe et al. (2017). For two reasons, we do not regard the failure to find noble gases from the solar wind in the clasts as problematic. First, regolith irradiation is a stochastic and highly depth-dependent process (e.g., Nishizumi et al., 1985) and not all grains need have spent appreciable time at the surface (see also Goodrich et al., 2019; Goodrich, Hartmann, et al., 2015; Krietsch et al., 2021). Second, the clasts analyzed had dimensions (cm) large in comparison to the range of solar wind particles (<1 μm) and so, even assuming that the clasts did get to the surface, only their outermost portions would contain solar wind.

The Effects of More Recent (<4.3 Ga) Thermal Disturbances in AhS

Several of the $^{40}$Ar/$^{39}$Ar step ages reported in Supplement S1 and Table 3 are younger than 4.5 Ga, indicating late heating. Their uncertainties are typically large however and so we set two criteria for deciding when the evidence for $^{40}$Ar* loss is persuasive. We do not consider ALM-A sample RU22360 because its release spectrum has only three steps.

The first criterion for loss is an integrated age more than 2-σ younger than 4.5 Ga; the second is at least one measured step age among those measured for the first 20% of argon released that is more than 2-σ younger than 4.5 Ga. While this net may fail to catch samples with smaller losses, by definition, such losses do not mark major thermal events and will have had little influence on the measured ages.

Two samples pass both tests for $^{40}$Ar loss: EL6 (MS-D) sample RU22317 comfortably, and H5 sample RU21899 marginally. The former has an integrated age of 3350 ± 11 Ma and a rising release pattern. Judging from the ages of high-temperature steps (I and J), resetting took place ≤3.8 Ga ago. The H5 sample RU21899 has an integrated age of 4260 ± 100 Ma. The step A age of 2277 ± 425 Ma pertains to 4.4% of the $^{39}$Ar released. The ages in the downward-sloping release pattern decrease from an imprecise maximum of 4510 ± 370 Ma (step D) to a minimum of 3800 ± 260 (step I), suggesting some redistribution of $^{40}$Ar.

Feldspathic sample RU22357 from MS-MU-011, with an integrated age of 3404 ± 15 Ma, passes the first, but not the second test. If, as we suspect, redistribution of $^{40}$Ar explains the mostly downward-sloping shape of the release pattern, then the maximum step D age of 4364 ± 66 Ma sets an upper bound on the time of $^{40}$Ar* loss.

Two samples meet the second criterion (significant low temperature $^{40}$Ar* loss), but not the first (young integrated age). The release spectrum for L4 plagioclase RU21888 begins with an age of 700 ± 400 Ma (step A; 22% of the $^{39}$Ar) and generally rises, terminating close to 4.1 Ga. The large uncertainties of the step ages (>300 Ma) for this 3-μg sample prevent a meaningful estimate of the resetting time. Heating steps A and B for H5 plagioclase separate RU21900 give ages of 2.2 ± 0.6 (3.2% of the $^{39}$Ar) and 2.7 ± 0.5 Ga (7.7% of the $^{39}$Ar), respectively. The results for the remaining steps are uniformly older, but trend downward from a maximum of 4590 ± 100 (step D) toward 4.40 Ga at high temperatures, again suggesting redistribution of $^{40}$Ar and resetting no earlier than 4.5 Ga B.P.

In summary, 5 of 15 samples with at least one from each of four clasts of different types meet one or both of our criteria for significant, late $^{40}$Ar* loss, that is, loss post-dating parent-body ejection. Their earliest possible resetting times range from 3800 Ma (EL6 bulk sample RU22317) to 4500 Ma (H5 plagioclase separate RU21900).

A more detailed examination of the step ages hints at a specific time for late Ar losses. The step A or B ages are similar for the five samples with the strongest evidence for $^{40}$Ar* loss. Specifically, we have (sample; age step A; age step B [Ma]): RU21888, 0.72 ± 0.39, 2.3 ± 1.6; RU21899, 2.28 ± 0.42, 4.33 ± 0.36; RU21900, 2.19 ± 0.63, 2.67 ± 0.51; RU22317, 3.74 ± 0.03, 2.79 ± 0.01; and RU22357, 2.54 ± 0.22, 3.62 ± 0.26. The average of the U/Th/He ages presented by Riebe et al. (2017; their table 7) is comparable, 2.4 ± 0.8 Ga. Three of those ages (MS-D, EL6, 3.24 Ga; MS-179, EL3-5, 3.04 Ga; and MS-197, LL4-5, 2.69 Ga) match particularly well, thereby increasing to 6 the number of clast types showing signs of the same heating event. A possible interpretation is that assembly of TC$_{3}$ 2.7 Ga ago partially reset the clast ages. In the absence of independent evidence for major disruptions in asteroidal parent bodies at this time (cf. Blackburn et al., 2017), however, the probability seems small that clasts of so many different types should have come together all at once. We infer therefore that an impact caused some localized heating of intact 2008 TC$_{3}$ about 2.7 Ga ago.
The much older ages of most of the higher-temperature steps suggest that the heating was too mild and/or short to cause extensive Ar loss.

Younger $^4\text{He}/\text{U}/\text{Th}$ ages of two AhS clasts (1.96 Ga, MS-CH, unique R-like and 1.34 Ga, MS-52, EL6) show further loss of $^4\text{He}$ within the last 2.7 Ga (Riebe et al., 2017). As noted by Riebe et al. (2017), young, apparent $^4\text{He}$ exposure ages for four of five AhS clasts indicate helium loss during the most recent exposure to cosmic rays, which lasted at least 10 Ma (Goodrich et al., 2019).

The following timeline accommodates the age data:

1. $\sim$4.50 Ga BP (60 Ma after CAI formation): assembly of the progenitor of TC3 (this work and references cited above);
2. $\sim$2.7 Ga BP: a collision heated the progenitor of TC3, causing the loss of $^4\text{He}$ and some $^{40}\text{Ar}$ (this work);
3. $\sim$10 Ma BP: launch of TC3 as an independent body by a collision (Goodrich et al., 2019; Riebe et al., 2017);
4. Launch to fall (October 7, 2008): CRE with solar heating and He loss (Goodrich et al., 2019; Riebe et al., 2017).

CONCLUSIONS

Our best estimates for the $^{40}\text{Ar}/^{39}\text{Ar}$ ages of one L4 and one H5 chondrite clast from AhS, $\geq$4535 Ma, are among the oldest measured for meteorites of their respective types. The $^{40}\text{Ar}/^{39}\text{Ar}$ age of 4513 $\pm$ 17 Ma for EL-6 clast MS-D is more typical for meteorites of its type. These ages set an upper limit on the time at which the clasts were last heated to temperatures above the argon closure temperature for more than a few hours. Cooling rate calculations indicate that the age estimates were not lowered much—$<10$ Ma—by incorporation of the clasts into a hot 2008 TC3, the parent asteroid for AhS. The clast ages are mute as to where the heating of chondritic clasts ended and argon closure was reached, that is, on the parent bodies or on AhS progenitor 2008 TC3, and under what circumstances, that is, in a slowly cooling parent body or in collisional fragment rapidly cooling from higher temperatures. We favor the former choices, which are consistent with the conclusions of Goodrich, Sanborn, et al. (2021) and Goodrich, Kring, et al. (2021) and Bischoff et al. (2022) that AhS acquired its xenoliths 50–60 Ma after the formation of UDBs.

Taken alone, our age data do not exclude the launch of the L4 and H5 chondritic clasts from their parent bodies as early as 4540 Ma. Indeed, and although we consider them less reliable, some older apparent $^{40}\text{Ar}/^{39}\text{Ar}$ ages (>4550 Ma) for sample RU22316 of H5 clast AhS 25 raise the possibility of ejection close to the time of peak-temperature metamorphism on an H chondrite parent body. This surprising result might be checked by independent chronometry and a search for petrographic evidence of rapid cooling from high temperature. Such an ejection would require at least partial disruption of an H parent body 30 Ma earlier than inferred in current models of their thermal evolution and seems unlikely. Redistribution of $^{40}\text{Ar}$ offers an alternative explanation for the old apparent age. In a few samples, younger ages determined for the lowest-temperature heating steps point to a limited and heterogeneous thermal disturbance $<$2.7 Ga ago.

ALM-A (clast MS-MU-011) is widely regarded as crustal material from the UPB. With allowance for its 10-Ma uncertainty, its 4549-Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age is open to two interpretations. At the older 1-$\sigma$ limit, the age is consistent with closure within a few Ma of the time recorded by its Pb/Pb age of 4562 $\pm$ 3.4 Ma (Amelin et al., 2015) either on the UPB or as part of small fragment produced by its catastrophic break-up. Less probably, at the younger 1-$\sigma$ limit, it could indicate slowed cooling of the reassembled progenitor of TC3. Two samples of ALM-A consisting of pyroxene surrounding some K-rich glass (RU22560 and RU22362) contained too little Ar for a convincing age measurement. To the degree that pyroxene armors such glass against Ar loss and detection limits for Ar can be improved, similar samples would make interesting targets for future work.

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**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of this article.

**Supplement S1.** Argon release patterns, isochrons, and Ar isotope concentrations.

**Supplement S2.** Calculation of cosmic-ray exposure ages from $^{36}\text{Ar}$.

**Supplement S3.** Calculation of trapped $^{36}\text{Ar}$ for isochrons.

**Supplement S4.** Comparison of isochron fitting parameters.

**Supplement S5.** Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ ages.

**Supplement S6.** $^{40}\text{Ar}/^{39}\text{Ar}$ ages of chondrites.