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GEOLOGY

Pliny the Younger advances geochronology

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The eruption of Vesuvius volcano witnessed by Pliny the Younger in 79 CE is dated by the argon-40/argon-39 (⁴⁰Ar/³⁹Ar) method to 1938 ± 13 years (SD) before measurement in 2025 CE. Achievement of 0.7% precision and 0.4% accuracy at such a young age marks a precedent for ⁴⁰Ar/³⁹Ar dating and signals improved applicability of the method for constraining magma systems' evolution, including volcanic hazard assessment. Improvements in mass spectrometry, neutron irradiation strategy, and determination of interfering neutron-induced isotopes enable this result. The data serve to determine the decay constant for the radioactive decay of potassium-40 (⁴⁰K) to ⁴⁰Ar that is twice as precise as the value determined by disintegration counting, thus improving the accuracy of ⁴⁰Ar/³⁹Ar dating throughout geologic time, and serves as an important datum for intercalibrating ⁴⁰Ar/³⁹Ar with other dating methods.

INTRODUCTION

Accurate and precise dating of prehistoric volcanic eruptions is critical to understanding many aspects of Earth's evolution. Among the various modes of eruption, pyroclastic flows resulting from large-volume explosive eruptions are of particular interest for several reasons. Such eruptions, typified by sustained columns of ash and gas rising into the stratosphere before collapse, are termed Plinian in homage to Pliny the Younger, who witnessed and described this phenomenon in the 79 CE eruption of Vesuvius. Distal deposits of these eruptions provide unique time markers whose ages are used to calibrate the geological timescale and to infer links between diverse geological phenomena, such as between climate cycles and orbital variations (1–3), understanding the environmental effects of volcanism (4) and constraining the causes of mass extinctions over geologic time (5).

Pyroclastic flows from Plinian eruptions pose exceptional risk to nearby human populations, causing an estimated 150,000 mortalities from 18 such eruptions worldwide in the past 2000 years (6). Today, tens of millions of people are at risk from pyroclastic eruptions of historically active volcanos near densely populated areas including Naples (Italy), Yogyakarta (Indonesia), and Mexico City (Mexico). Dating such events in the younger range of prehistory is important for assessing long-term volcanic hazards. Adequately precise eruption ages can be used to establish recurrence intervals, which inform physics-based volcano monitoring that may enable short-term eruption forecasting (6, 7). The importance of dating eruptions for volcanic hazard assessment is exemplified by the recent documentation of a caldera-forming eruption at 29 thousand years (ka) (8) from the Campi Flegrei magma system encompassing Naples, which occurred between previously documented super-eruptions at 40 ka (9) and 15 ka (10). This discovery, “has drastically reduced the expected repose interval for caldera-forming eruptions at Campi Flegrei” (11).

In addition to its implications for volcanic hazards, high-precision geochronology enables researchers to infer magma system properties including magma residence times, recharge, and eruptive behavior over short geological timescales (2). Volcanic deposits dated accurately

and precisely by one method also provide critical benchmarks for testing and refining other dating techniques (1, 12, 13).

One of the most important methods of dating volcanic eruptions is the ⁴⁰Ar/³⁹Ar technique. Like most radioisotope-based methods except radiocarbon, the relative precision of ⁴⁰Ar/³⁹Ar dating increases with the eruption's age, with all other factors being equal. Thus, the method has larger relative uncertainties at younger ages. The youngest ⁴⁰Ar/³⁹Ar ages yet published to our knowledge are for lavas that erupted 510 ± 180, 550 ± 120, and 1640 ± 370 years ago (uncertainties here and throughout are 1 SD unless otherwise stated) on Ascension Island (14). These were challenging samples lacking separable K-rich minerals, and, despite the large relative uncertainties (>22%), these results were useful in classifying the island as an active volcanic system. The youngest ⁴⁰Ar/³⁹Ar ages that can be compared with historical records are for the 79 CE Plinian eruption of Vesuvius, which destroyed the cities of Pompeii and Herculaneum. These measured ages (15, 16) as reported agree with the historically recorded age within their ~5% relative uncertainties (~100 years) at 68% confidence, although both are less precise when corrected for overlooked factors and updated calibrations (see the Supplementary Materials). Thus, the historical records serve to validate the ⁴⁰Ar/³⁹Ar ages, albeit at relatively low precision. The eruption is widely cited as having begun on 24 August and lasted for ~2 days, although some authors argue that it occurred 1 or 2 months later in the same year (17). The basis for the 79 CE calendar age is somewhat complex; hence, we reviewed the records as summarized in Results.

Other dating methods, (U+Th)/He (18) and ¹⁴C (19), have also produced ages indistinguishable from the historical 79 CE age, but at substantially lower precision than the ⁴⁰Ar/³⁹Ar results. Tephra from the 79 CE eruption has been tentatively identified in a Greenland (GRIP) ice core at depths corresponding to 79 to 80 CE based on an age model using multiparameter annual layer counting with an estimated uncertainty of ±0.5% (20). While the chemical composition of glass shards in this material is consistent with 79 CE Vesuvius tephra, two eruptions in the Azores with comparable estimated volcanic explosivity indices (21) of 4 to 5, or unrecognized coeval eruptions elsewhere cannot be definitively ruled out as the source.

When dating volcanic eruptions, the standards of precision and accuracy depend on the questions being asked. To establish eruptive histories that can help to forecast future hazards, dating methods should be as precise and accurate as possible. Dating past eruptions

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is trivial if reliable historical records are available, but, for prehistoric eruptions, researchers must rely on other methods such as $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Obtaining precise $^{40}\text{Ar}/^{39}\text{Ar}$ ages is especially challenging for relatively young eruptions just beyond the limits of historical records, which is inconvenient because relatively recent eruptions are the most critical for evaluating future eruption probabilities. Because Vesuvius' 79 CE eruption is a near ideal case for $^{40}\text{Ar}/^{39}\text{Ar}$ dating at the limit of historical records, significant improvement over the existing ~ 100 year uncertainty is clearly desirable.

Here, we report new $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the 79 CE Vesuvius eruption with greater accuracy and an order of magnitude better precision than previous work using this or any other method aside from historical records. This result is achieved through improved mass spectrometry and experimental design, and the most definitive measurement of an important interfering isotope correction yet determined. Besides establishing a new benchmark for dating young pyroclastic eruptions, we use the results to derive an improved estimate of the rate constant for the radioactive decay of ^{40}K to ^{40}Ar .

RESULTS

Historical dating of the 79 CE eruption

Because the date of the 79 CE Vesuvius eruption is constrained by historical records, it can serve as a benchmark for radiometric dating methods. However, historical and archeological misunderstandings have created confusion surrounding the eruption date, e.g., (22). We therefore review the evidence for the date of the eruption.

Reconstructions of the 79 CE Vesuvius eruption rely on two letters written by Pliny the Younger, which provide an eyewitness account of the event (23). At the time of the eruption, Pliny the Younger was 17 years old. His letters are often cited as a source for the eruption date. Actually, the letters only record the day and month (24 August), but not the year of the eruption. The year must be inferred from other sources.

The earliest surviving mention of the year comes from Lucius Cassius Dio (early third century CE). Dio's original text does not survive but is preserved in later paraphrases by medieval historians. Cassius Dio associates the eruption with achievements of the emperor Titus: "As a result of these events in Britain, Titus received the title of *imperator* for the fifteenth time. [...] In Campania remarkable and frightful occurrences took place, for a great fire suddenly flared up at the very end of the summer" (24). Thus, we can identify the year of the eruption (the "great fire") by dating Titus's 15th acclamation as *imperator*, an honorific granted to military commanders.

In ancient Rome, years were identified by significant happenings or by the names of the two consuls—the Roman Republic's highest elected officials, elected annually—in office at the time. Cassius Dio records that Titus received his 15th *imperator* title the same year his father, the emperor Vespasian, died. According to the Roman historian Suetonius, Vespasian was born "in the consulate of Quintus Sulpicius Camerinus and Gaius Poppaeus Sabinus" and died "at the age of sixty-nine years, seven months and seven days" (25). We can therefore calculate the year of Titus's 15th *imperator* title if we know when Q. S. Camerinus and G. P. Sabinus were consuls.

The conversion from consular to Common Era dates (BCE/CE) was defined by the sixth-century monk Dionysius Exiguus in 525 CE, who anchored his calendar to consular years (26). Using Dionysius Exiguus's system, earlier consular dates can be converted to the modern calendar. This places the consulship of Q. S. Camerinus and G. P.

Sabinus in 9 CE and, by extension, the death of Vespasian in 79 CE. As Titus's 15th acclamation occurred in the same year, the Vesuvius eruption can be confidently assigned to 79 CE.

What about the month and day of the eruption? Pliny writes that the eruption began on the ninth day before the *kalends* of September (*non. kal. Septembres*) or 24 August. This is consistent with Cassius Dio's account, which suggests an eruption date at the end of summer. Dio's translators tend to render the relevant passage as "right at the end of summer". This agrees with the ancient Roman definition of the start of autumn, which was typically placed in early August [e.g., (27)].

Despite Pliny's and Dio's testimony, the 24 August eruption date has been contested. Archeological finds are sometimes used to support an eruption date in late autumn. In the late 18th century, Carlo Maria Rosini proposed an autumn eruption on the basis of archaeological finds at Herculaneum—braziers, carpets, and fruits typically harvested later in the year, including chestnuts, dates, figs, and raisins (28). But other archeologists and historians have pointed out that braziers, autumn fruits, and warm clothing worn by victims do not preclude an August eruption date (22). In 2018, a charcoal graffito beginning *xvi k nov* (17 October) was found on a wall in Pompeii (29). The graffito has been used to argue that Vesuvius could not have erupted before October because charcoal writing is too fragile to survive many months in the open. However, an experiment conducted in Pompeii showed that charcoal graffiti can easily last from 17 October until 24 August the following year (30).

Proponents of a late autumn eruption sometimes refer to a coin hoard found in Pompeii's "House of the Golden Bracelet". One of the coins was once thought to reference Titus's 15th *imperator* title, which was not granted until after 8 September 79 CE. The coin found in Pompeii was initially interpreted to read *IMP XV*, implying that it was minted after that date and precludes a 24 August eruption (31). However, a recent reevaluation found that the coin, which is in poor condition, had been misinterpreted and instead reads *IMP XIII* (32). Thus, the coin may have been minted before 8 September and can neither confirm nor refute an August eruption date.

We conclude that, although later reinterpretations have proposed autumn or even November dates, there is no solid reason to doubt Pliny's and Cassius Dio's accounts. The best available evidence points to 24 August 79 CE as the date of the Vesuvius eruption, and that is the date that we use as a reference point. A more detailed discussion of ancient Roman chronology and evidence supporting the August eruption date can be found in the Supplementary Materials.

$^{40}\text{Ar}/^{39}\text{Ar}$ geochronology

Data obtained from the Vesuvius 79 CE AM1 sanidine grains extracted from 8 of 10 irradiation wells are shown on an inverse isochron diagram ($^{36}\text{Ar}/^{40}\text{Ar}$ versus $^{39}\text{Ar}/^{40}\text{Ar}$) in Fig. 1. Grains from two irradiation wells (lab nos. 39209 and 39210; see the Supplementary Materials) were excluded because of contamination by older material. Data from these samples yielded ages ranging from within uncertainty of 79 CE to over 20 ka. Aside from samples derived from the two contaminated irradiation wells, all 153 incremental heating steps from all aliquots are colinear on the inverse isochron diagram (Fig. 1). Given that each irradiation well was filled with material from the same prepared sanidine mineral separate, it appears the two irradiation wells that we excluded from the isochron were contaminated during the loading or unloading process. The similarity in K/Ca between the contaminated and uncontaminated (table S1)

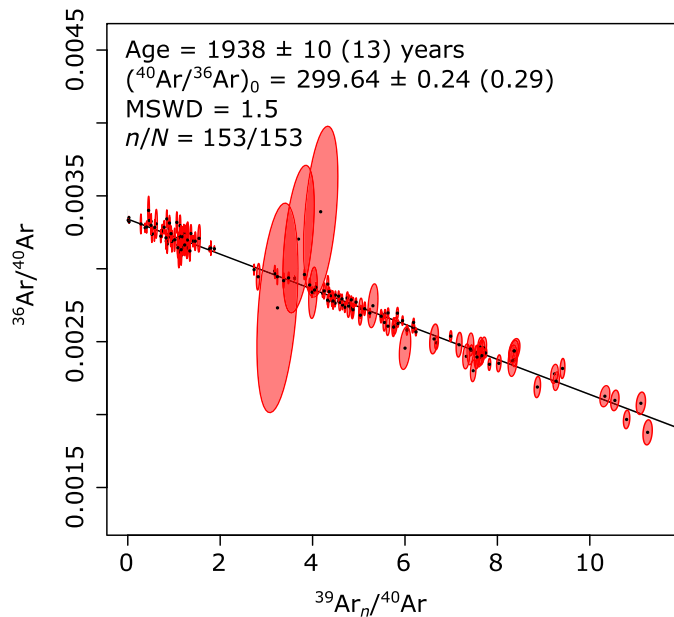


Fig. 1. Inverse isochron diagram obtained from the incremental degassing of 48 aliquots of Vesuvius AM1 sanidine collected near Pompeii. Ellipses denote 1 SD uncertainties, with rotation reflecting uncertainty correlations. The data were regressed with and the figure was modified from IsoplotR (34). The numbers in parentheses that follow uncertainties represent the expanded 1 SD uncertainties. Subscript n in $^{39}\text{Ar}_n/^{40}\text{Ar}$ indicates values normalized to a uniform J value.

aliquots suggests that dust or fine grains from adjacent coirradiated 1.18-million-year (Ma) Alder Creek sanidine (ACs), which yield indistinguishable K/Ca ratios, were the source of contamination. The remaining 153 analyses, collectively derived from ~700 mg of sanidine, define an isochron (Fig. 1) with an age of 1938 ± 10 years, a trapped $^{40}\text{Ar}/^{36}\text{Ar}$ of 299.64 ± 0.24 , and a mean squared weighted deviation (MSWD) (33) of 1.5 calculated using IsoplotR (34). The percentage of ^{40}Ar that is radiogenic ($\%^{40}\text{Ar}^*$) as distinct from atmospheric or nucleogenic in individual steps is as high as 43.9% (table S1), a key factor in the precision of the isochron. To account for the excess scatter indicated by the $\text{MSWD} > 1$, we expand the uncertainty by a factor of $\sqrt{\text{MSWD}}$, which yields ± 13 years. Thus, the calendar age that we determine is 87 ± 13 CE, indistinguishable at the 1σ level from the historically determined age of 79 CE. A useful metric to represent this result in terms of actual measurements is the R value, defined as the $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ of a sample relative to that of a standard. Accordingly, $R_{\text{ACs}}^{\text{AM1}}$, the R value of AM1 relative to that of the ACs standard, is $(1.6359 \pm 0.0110) \times 10^{-3}$.

The trapped $^{40}\text{Ar}/^{36}\text{Ar}$ derived from the isochron is distinct at 95% confidence from the atmospheric value of 298.56 ± 0.31 (35), which argues against calculating $^{40}\text{Ar}/^{39}\text{Ar}$ ages assuming that value (and ignoring its uncertainty, as is common practice). The supra-atmospheric ratio suggests a minor component of magmatic excess ^{40}Ar , as was reported in a previous study (15).

DISCUSSION

Key factors in precision and accuracy

Reproducing the known age of a <2000-year-old eruption by $^{40}\text{Ar}/^{39}\text{Ar}$ methods within ~0.7% relative uncertainty is unprecedented

and portends substantial improvement in the resolution of geologic time with this technique, especially in the late Quaternary Period. The specific factors that enable this improvement include the following:

1) The abundance of the K-rich mineral sanidine is a crucial requirement. Because silicic pyroclastic eruptions tend to be K-rich, sanidine is a common phenocryst in such deposits. In the chemically zoned deposits of the 79 CE Vesuvius eruption, the dated sanidine from the lower white pumice unit exhibits an extremely homogeneous K/Ca that was plausibly in equilibrium with the erupted magma, hence unlikely to contain xenocrysts or antecrysts (36).

2) Incremental heating with a laser (cf resistance furnace) enables low atmospheric backgrounds and relatively efficient progressive degassing of trapped (nonradiogenic) argon, allowing the measurement of radiogenic argon exceeding 40% at higher laser power. The resulting spread of data on an isochron and the large number of analyses enables detection of and correction for a slightly supra-atmospheric component.

3) Multicollector mass spectrometry enables high throughput and minimizes uncertainties associated with extrapolating ion beam intensities measured by peak hopping to a common time. ATONA detectors (37) enable precise measurement of low-intensity but high-stability ion beams for ^{40}Ar and ^{39}Ar .

4) Minimal duration (6 min) of irradiation time, cadmium shielding, and precise determination of both (i) the ^{40}Ar produced from K by neutron irradiation, which reduces the correction for this interfering reaction to 20 years, with 1 year of uncertainty, and (ii) the production of ^{36}Ar from potassium that allows for more accurate corrections for nonradiogenic ^{40}Ar (38).

5) Rigorous accounting for spatial variations in neutron fluence during irradiation by closely bracketing the unknowns with standards, which reduces the uncertainty associated with the J values to <0.1%.

Broader implications

This study was motivated by a desire to provide additional constraints (priors) to the recently proposed Bayesian calibration of the K-Ar radioisotopic system (39), which can be readily expanded to incorporate and jointly intercalibrate additional geochronometers to the K-Ar and U-Pb radioisotopic systems. Radiocarbon (^{14}C) dating, in particular, could benefit from improved $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology applied to events within the method's range of applicability (the past ~55 ka). Because atmospheric $^{14}\text{C}/^{12}\text{C}$ has varied over time, radiocarbon dates must be calibrated by other means and different calibrations have been developed for different reservoirs (e.g., marine versus nonmarine) and hemispheres (Southern versus Northern). $^{40}\text{Ar}/^{39}\text{Ar}$ dating is an excellent calibrant as it extends past the tree-ring record and can be applied to volcanic deposits that contain charred woody materials that are suitable for ^{14}C dating, e.g., (9). The radiocarbon community routinely assimilates new calibration data and has developed extensive computational tools for that application, e.g., (40). Further, because a given measured $^{14}\text{C}/^{12}\text{C}$ ratio can correspond to multiple ages [(40) and references therein], improved $^{40}\text{Ar}/^{39}\text{Ar}$ ages with precision on par with or better than radiocarbon ages (i.e., decadal-scale uncertainties) could resolve degenerate ages. Comparison with other volcanic eruptions whose ages are reliably constrained by historical records could further advance intercalibrations between $^{40}\text{Ar}/^{39}\text{Ar}$, radiocarbon, and other dating methods, specifically through the improved determination of the ^{40}K decay constant provided by the present study.

A noteworthy case that may ultimately contribute to intercalibrating the ^{14}C with K-Ar and other radioisotopic systems is the so-called Millennium Eruption (ME) of Changbaishan volcano, which straddles the China-North Korea border. The eruption was dated by $^{40}\text{Ar}/^{39}\text{Ar}$ at 1240 ± 205 years (864 ± 205 CE) (41), while ^{14}C and various proxy records led to an inferred age of 946 CE (42) (no uncertainty reported). Unfortunately, the $^{40}\text{Ar}/^{39}\text{Ar}$ data of (41) reveal a large proportion of anomalously old apparent age steps, attributed to excess ^{40}Ar , such that 20 of the 56 steps were rejected from the isochron. Anomalously old $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the ME were also reported in another study (43) that attributed the results to xenocrystic contamination and concluded that no eruption age could be determined from their data. Despite these documented challenges to $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the ME, further effort could conceivably yield useful results.

Improved determination of the ^{40}K to ^{40}Ar decay constant

Beyond demonstrating the temporally extended capability of the $^{40}\text{Ar}/^{39}\text{Ar}$ method, our results presented here foreshadow improved calibration of the method over its entire range of applicability. Our data represent a controlled ingrowth experiment from which the partial decay constant for ^{40}K decay to ^{40}Ar via electron capture and positron emission can be determined with subpercent uncertainty as described below. Now, the best available experimental determination of this parameter is from liquid scintillation counting and has a relative uncertainty of 1.4% (44). A more precise value was inferred from a recent Bayesian intercalibration of the K-Ar and U-Pb systems (39). However, the underlying U-Pb decay constants in ubiquitous use are based on a single study (45) with poorly quantified systematic uncertainties (46). Thus, improved constraints on the ^{40}K decay scheme and, in particular, the branching ratio of ^{40}K decay to ^{40}Ar could significantly improve the absolute calibration of both the K-Ar and U-Pb decay schemes.

Our Vesuvius data allow for an even more precise intercalibration. The standard K-Ar age equation is

$$t = \frac{1}{\lambda_{\text{tot}}} \ln \left(1 + \frac{\lambda_{\text{tot}}}{\lambda_{\text{EC},\beta+}} \cdot \frac{{}^{40}\text{Ar}^*}{{}^{40}\text{K}} \right) \quad (1)$$

where λ_{tot} is the total decay constant and $\lambda_{\text{EC},\beta+}$ is the partial decay constant for ^{40}K decay to radiogenic ^{40}Ar ($^{40}\text{Ar}^*$), which includes electron capture to both an excited and ground state and positron emission. For ingrowth periods that are short compared to the half-life of ^{40}K , $\lambda_{\beta-}$ can be neglected and $(e^{\lambda_{\text{tot}} t} - 1) \approx \lambda_{\text{tot}} t$. For a ~2000-year-old sample like Vesuvius AM1, this approximation is accurate at the ppm level. Equation 1 can thus be simplified and rearranged in terms $\lambda_{\text{EC},\beta+}$ as follows

$$\lambda_{\text{EC},\beta+} \approx \left(\frac{{}^{40}\text{Ar}^*}{{}^{40}\text{K}} \right)_{\text{AM1}} \cdot \frac{1}{t} \quad (2)$$

For the Vesuvius AM1 samples, t is known from historical records and $({}^{40}\text{Ar}^*/{}^{40}\text{K})_{\text{AM1}}$ can be inferred by intercalibrating the Vesuvius AM1 sanidine data to various K-Ar standards for which the concentrations of ^{40}K and $^{40}\text{Ar}^*$ have been determined by first principles. There are four such K-Ar standards: GA-1550, GHC-305, Hb3gr, and NL-25, which have been intercalibrated by $^{40}\text{Ar}/^{39}\text{Ar}$ with the neutron fluence monitor Fish Canyon sanidine (FCs), enabling determination of ${}^{40}\text{Ar}^*/{}^{40}\text{K} = (1.6407 \pm 0.0047) \times 10^{-3}$ for FCs (47). Using an updated value of ${}^{40}\text{K}/\text{K}$ (48), this value becomes

${}^{40}\text{Ar}^*/{}^{40}\text{K} = (1.6413 \pm 0.0047) \times 10^{-3}$ for FCs. From this, we can determine ${}^{40}\text{Ar}^*/{}^{40}\text{K}$ of the Vesuvius AM1 sanidine as follows

$$\left(\frac{{}^{40}\text{Ar}^*}{{}^{40}\text{K}} \right)_{\text{AM1}} = R_{\text{FCs}}^{\text{AM1}} \cdot \left(\frac{{}^{40}\text{Ar}^*}{{}^{40}\text{K}} \right)_{\text{FCs}} = R_{\text{ACs}}^{\text{AM1}} \cdot R_{\text{FCs}}^{\text{ACs}} \cdot \left(\frac{{}^{40}\text{Ar}^*}{{}^{40}\text{K}} \right)_{\text{FCs}} \quad (3)$$

where $R_{\text{ACs}}^{\text{AM1}}$ is determined in this study and $R_{\text{FCs}}^{\text{ACs}}$ is from (49). The resulting ${}^{40}\text{Ar}^*/{}^{40}\text{K}$ of Vesuvius AM1 sanidine is $(1.1195 \pm 0.0081) \times 10^{-7}$. Taking the midpoint of the analytical session (1 June 2025) as the analysis time with a 1-month uncertainty to encompass the analytical window and an eruptive date of 24 August 79 CE with an assumed 2-month uncertainty to account for vagaries in the historical records (see the Supplementary Materials) yields a total ingrowth time of 1945.77 ± 0.12 years (0.01%).

Solving Eq. 2 using the above values for t and ${}^{40}\text{Ar}^*/{}^{40}\text{K}$ yields $\lambda_{\text{EC},\beta+} = (5.7551 \pm 0.0422) \times 10^{-11}$. This is indistinguishable from the partial decay constant reported by Kossert *et al.* (44), but with almost two times higher precision (Fig. 2). For completeness, we also explored the full posterior of $\lambda_{\text{EC},\beta+}$ using a parallelized affine-invariant Monte Carlo sampler (50). Both pathways converge on the same result (see the Supplementary Materials).

MATERIALS AND METHODS

Sanidine was separated from ~2 kg of 2- to 5-cm pumice lapilli collected as sample AM1 at the Villa Poppea, Oplontis, ~1.8 km WNW of Pompeii. The sampled unit corresponds to the widespread EU2 white pumice fall layer of Cioni *et al.* (51), which contains the highest sanidine concentration and most K-rich sanidine of any of the erupted units comprising the stratigraphically zoned sequence recognized here and elsewhere (51). The lapilli were crushed with a mortar and pestle, rinsed ultrasonically in 5% HF solution for 5 min, and then repeatedly rinsed ultrasonically with distilled water. After drying overnight at 110°C in an oven, samples were sieved to obtain

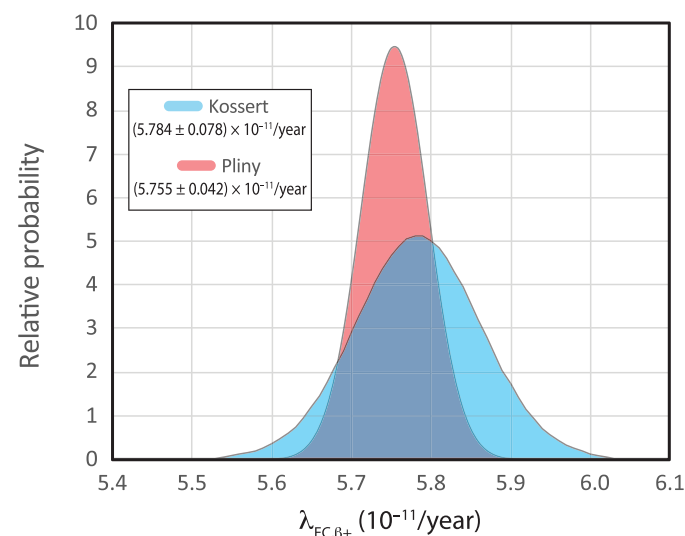


Fig. 2. Comparison of the partial decay constant for production of radiogenic ^{40}Ar from ^{40}K , $\lambda_{\text{EC},\beta+}$ from an independent experimental determination and this work. Blue Gaussian shows the experimentally determined $\lambda_{\text{EC},\beta+}$ value of Kossert *et al.* (44); red Gaussian labeled Pliny shows the $\lambda_{\text{EC},\beta+}$ inferred in this work from the Vesuvius calibration. The means $\pm$ SD is shown for each estimate.

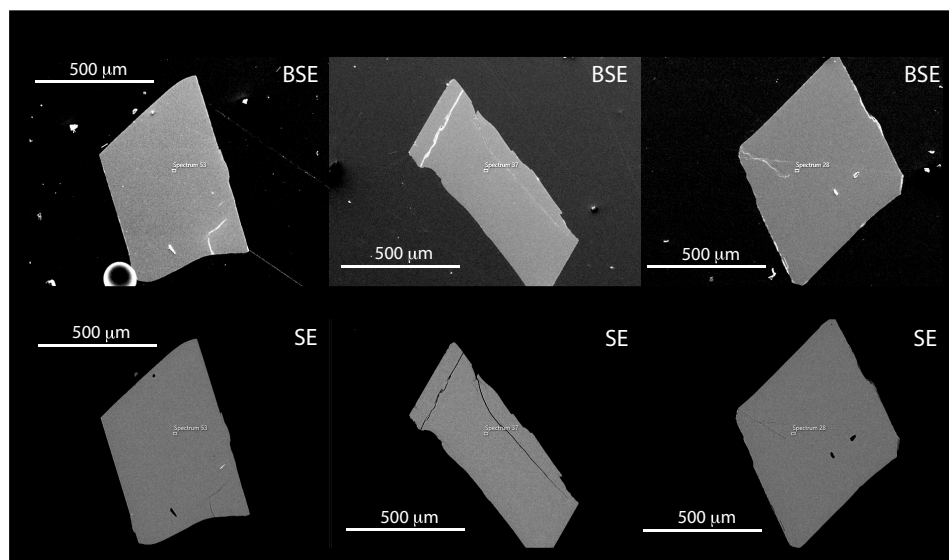


Fig. 3. Backscattered electron (BSE; top row) and corresponding secondary electron (SE; bottom row) images for three grains of AM1 sanidine.

a 0.71- to 0.42-mm-size fraction, from which pure sanidine crystals devoid of perceptible inclusions or adhesions were handpicked. Fifty grains were analyzed quantitatively by scanning electron microscopy (36) and proved to be unzoned as reflected in backscattered electron images (Fig. 3). Note that the bright curvilinear features in the BSE images are artifacts of cracks and voids as seen in the SE images, rather than compositional anomalies.

Sample grains were loaded into wells in two Al discs (see the Supplementary Materials) interspersed with wells containing the 1.18-Ma ACs standard (49) with an age recalculated per Carter *et al.* (39), in the 0.84- to 0.42-mm-size fraction. The wells of ACs and AM1 each contained an estimated 16 and 87 mg of sanidine, respectively. The two discs were irradiated for 6 min in the Cadmium-Lined Irradiation Tube of the Oregon State University TRIGA reactor on 28 April 2025. Analyses of the ACs and AM1 were completed between 14 May and 17 June 2025. Gas extraction was by total fusion (ACs) or step heating (AM1) with a 55-W CO₂ laser. ACs was degassed by total fusion of five grains at a time, with four to seven aliquots per irradiation well. AM1 was degassed by step heating in three to four steps at laser power between 1 and 30 W. The laser beam diameter was 3.0 and 4.5 mm for the ACs and AM1 samples, respectively. Each aliquot of AM1 comprised an estimated 144 grains of sanidine. The neutron fluence parameter *J* was determined for each well containing ACs, with average relative precision of 0.154%. Spatial variation of *J* is evident in both irradiation disks but does not conform to a simple geometry; hence, *J* values for each well containing AM1 were determined as the inverse variance weighted average of values from the three wells of ACs most closely bracketing it, which produced average relative precision of 0.07% for all *J* values.

Following extraction, the released gas was purified by exposure to two SAES GP-50 getters: one at room temperature and one operated at 14.7 V and 1.55 A. Isotopic abundances were measured using an Isotopx NGX mass spectrometer equipped with nine Faraday detectors fitted with ATONA amplifiers and one discrete dynode electron multiplier. All isotopes were measured on the Faraday detectors, except ³⁶Ar (see the Supplementary Materials). Signals on the ATONA

amplifiers were integrated for 20 s. Total counting durations were 1800 s. Detector baselines were measured at the end of each run as signals at off-peak masses (0.4 u above and below peak center) for 200 s. These baselines were fitted on a time-dependent basis and subtracted from all measured signals. Baseline uncertainties were not explicitly propagated into isotopic measurement uncertainties as background corrections already include noise arising from variations in detector baselines. Background analyses were interspersed with the sample heating steps at typical frequency of one per sample heating step.

A second series of experiments were conducted on K-rich synthetic glass to obtain the (⁴⁰Ar/³⁹Ar)_K and (³⁶Cl/³⁹Ar)_K needed to correct the data as described in the Supplementary Materials. Additional nuclear interferences, with much smaller effect on the computed ages, are listed in table S1. All Ar isotope data corrected for baselines, backgrounds, radioactive decay, mass discrimination, detector intercalibration, and interfering nucleogenic isotopes are shown in table S1. All ages were determined relative to the calibration of Carter *et al.* (39).

Supplementary Materials

The PDF file includes:

Supplementary Text
Figs. S1 to S4
Table S1
Legend for data S1
References

Other Supplementary Material for this manuscript includes the following:

Data S1

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Supplementary Materials for
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The PDF file includes:

Supplementary Text
Figs. S1 to S4
Table S1
Legend for data S1
References

Other Supplementary Material for this manuscript includes the following:

Data S1

Age of the eruption from historical records

Pliny's letters

Reconstructions of the date of the Vesuvius eruption typically refer to two letters written by Pliny the Younger to the historian Tacitus. These are known as letters 6.16 and 6.20, the 16th and 20th letters in Book 6 of Pliny's collected correspondence (22,23), and are the only surviving eyewitness accounts of the eruption that destroyed Pompeii and Herculaneum.

At the time of the eruption, Pliny the Younger was seventeen years old. His uncle, the famous naturalist and military commander Pliny the Elder, died during a voyage to inspect the eruption more closely, likely overwhelmed by a pyroclastic density current. Pliny the Younger's letters, written almost thirty years later, state the day and month (August 24th), but not the year of the eruption.

Cassius Dio and the year of the eruption

The earliest surviving mention of the year comes from the Roman historian and politician Lucius Cassius Dio, who published his *Roman History* (24) in the early 3rd century CE (ca. 207-219 CE). Cassius Dio's original text does not survive, but is preserved in later paraphrases by the 11th-century historian Xiphilinus and the 12th-century historian Zonaras. In Book 66 of his *Roman History*, Cassius Dio associated the eruption with certain achievements of the emperor Titus: "As a result of these events in Britain, Titus received the title of *imperator* for the fifteenth time. [...] In Campania remarkable and frightful occurrences took place, for a great fire suddenly flared up at the very end of the summer" (24). Xiphilinus's Greek is: ἐν μὲν τῇ Βρετανίᾳ ταῦτ' ἐγένετο, καὶ ἀπ' αὐτῶν ὁ μὲν Τίτος αὐτοκράτωρ τὸ πεντεκαίδεκατον ἐπεκλήθη [...] ἐν δὲ τῇ Καμπανίᾳ φοβερά τινα καὶ θαυμαστὰ συνηνέχθη: πῦρ γὰρ μέγα κατ' αὐτὸ τὸ φθινόπωρον ἐξαπναιῶς ἐξήφθη. Zonaras replaces κατ' αὐτὸ τὸ φθινόπωρον with κατὰ τὸ φθινόπωρον ἄθρόον (ἄθρόον = "suddenly").

Dio was writing more than a century after the eruption and did not always follow chronological order. For example, in the same chapter, Dio assigns the circumnavigation of Britain to the same year as "these events in Britain"—but in reality, the circumnavigation happened later, in 83-84 CE (52). However, Dio's association of the Vesuvius eruption with the year of Titus's military campaign is generally thought to be reliable. Thus, we can identify the year of the eruption by dating Titus's fifteenth acclamation as *imperator*, an honorific granted to military commanders after a great victory.

Roman chronology: From consuls to the Common Era

In ancient Rome, years were typically identified by significant happenings or by the names of the two consuls—the Roman Republic's highest elected officials, elected annually—who held office at the time. Cassius Dio records that Titus received his fifteenth *imperator* title the same year his father, the emperor Vespasian, died. According to the Roman historian Suetonius's *The Twelve Caesars*, written ca. 121 CE, Vespasian was born "in the consulate of Quintus Sulpicius Camerinus and Gaius Poppaeus Sabinus" (the Latin is: *Vespasianus natus est in Sabinis ultra Reate vico modico, cui nomen est Falacrinae, XV. Kal. Decb. vesperi, Q. Sulpicio Camerino C. Poppaeo Sabino cons., quinquennio ante quam Augustus excederet*) and died "at the age of sixty-nine years, seven months and seven days" (*extinctus est VIII. Kal. Iul. annum agens aetatis sexagensimum ac nonum superque mensem ac diem septimum*) (25). We can therefore

calculate the year of Titus's fifteenth *imperator* title if we know when Quintus Sulpicius Camerinus and Gaius Poppaeus Sabinus were consuls.

The Roman Republic and the later Roman Empire kept detailed records of consuls. Consular dating continued to be used in the Eastern Roman Empire until the mid-sixth century CE, when the emperor Justinian introduced a dating system based on the years of emperors' reigns. The list of Roman consuls spans 1,050 years—from 509 BCE to 541 CE.

The conversion from consular to Common Era dates (BCE/CE) is defined by the sixth-century monk Dionysius Exiguus (26). In 525 CE, Dionysius was asked by Pope John I to calculate the upcoming dates of Easter, which was required to fall on the first Sunday after the spring full moon (the first full moon occurring after March 21st). This required consulting astronomical charts compiled by the church of Alexandria. Dionysius was irritated by the fact that the Egyptian church continued to count the years since the accession of the emperor Diocletian (284 CE), whom Dionysius considered an enemy of the church due to his bloody persecution of Christians. To remedy this, Dionysius decided to introduce a new dating system that counted the years *ab incarnatione Domini*—since the birth of Christ. In his completed Easter table, Dionysius stated that the year in which he was writing was 525 *ab incarnatione*, or 525 CE (53). Crucially for the conversion from consular to Common Era dates, Dionysius also named one of the acting consuls, Probus Junior. Anchoring Probus Junior to 525 CE, we can convert all consular dates to Common Era dates.

It follows that Q. S. Camerinus and G. P. Sabinus were consuls in 9 CE. Titus's father Vespasian was born that same year and—according to Suetonius's biography—died in June 79 CE. Titus thus became emperor and received his 15th *imperator* title in 79 CE, which, according to Cassius Dio, was the same year Vesuvius erupted.

The conversion of consular to Common Era dates is robust from ~300 BCE onwards, as shown by comparisons with Greek history and Egyptian astronomical tables (26). Therefore, the Vesuvius eruption can be confidently assigned to 79 CE.

The day of the eruption

When referring to a specific day of the month, ancient Romans counted forwards to the next of three principal days: the *kalends* (the first day of each month), the *nones* (the 7th day of March, May, July, and October, and the fifth day of every other month), and the *ides* (eight days after the *nones*). The Romans counted days inclusively, meaning they counted both the first and last days of a given interval. For instance, according to inclusive counting, the first and second day of the month are two days apart instead of one.

This system is relevant to Pliny's letters describing the 79 CE Vesuvius eruption. In letter 6.16, Pliny states that the eruption began on the ninth day before the *kalends* of September (*nonum kal. Septembres*), or August 24th. This is consistent with Cassius Dio's account, which suggests an eruption date at the end of summer. Xiphilinus writes: κατ' αὐτὸ τὸ φθινόπωρον (αὐτὸ = "right at"). Translations from the Greek, here and elsewhere, are from Foss (22). Zonaras writes: κατὰ τὸ φθινόπωρον ἄθρόον (ἄθρόον = "suddenly"). Both agree on κατ' τὸ φθινόπωρον, suggesting this is the core of Dio's original phrase (50). The word φθινόπωρον ("autumn") is a compound of φθιν(ω) = "decay, wane" and ὥρωα = "harvest season, late summer". Dio's translators tend to render this as "right at the end of summer". This agrees with the ancient Roman definition of the start of autumn, which was typically placed in early August, e.g. (27).

The date debate

Despite Pliny's and Dio's testimony, the August 24th eruption date has been contested. In the late 18th century, Carlo Maria Rosini, a bishop and scholar who had worked on the papyrus scrolls excavated at Herculaneum, doubted the eruption had occurred in August because the excavations had unearthed braziers, carpets, and fruits typically harvested later in the year, including chestnuts, dates, figs, and raisins, e.g. (28). Rosini turned to Dio's chapter about the eruption. Because Dio's text had been copied and translated many times in the 1600 years since its publication, various versions were available to Rosini. A 1551 version translated the Greek as *sub Autumni tempus* ("on the eve of autumn"), but included a marginal note suggesting the alternative *autumni extremi tempore* ("at the very end of autumn"). Rosini adopted this alternative. He then proceeded to suggest an eruption date of *non. kal. Decembris*, or November 23rd.

It is important to acknowledge that Rosini's adoption of an "end of autumn" eruption was not based on or supported by the best available manuscripts of Dio's and Pliny's work, and that his proposed date of November 23rd was entirely arbitrary. Nevertheless, the idea that the eruption occurred in the autumn has persisted, enabled by inaccurate transcriptions and translations of Pliny's letters. The oldest known copies of Pliny's correspondence that contain the Vesuvius letters date to the early 9th century and state that the eruption occurred on *nono* (or *nonum*) *kal. Septembres* (August 24th). However, in later manuscripts, *nonum* was sometimes misspelled as *novum*. Because the phrase *novum kal. Septembres* is nonsensical, it was "corrected" by later editors, who changed it to *nou* and then to *novemb*. This error was included in a printed edition in the late 15th century, which was widely circulated and is still occasionally cited as evidence that the eruption occurred in late autumn. However, that is not what Pliny wrote. The oldest, most reliable manuscripts of Pliny's letters read *non. kal. Septembres*, cementing August 24th as the most likely date of the eruption. For more information about the manuscript tradition of Pliny's letters, interested readers are referred to Pedar W. Foss's *Pliny and the Eruption of Vesuvius* (22).

Archeological finds are often used to support a late autumn eruption date and they tend to attract considerable media attention. For example, in 2018, a charcoal graffito beginning *xvi k nov* (October 17th) was found on a wall in Pompeii (29). The graffito has been used to argue that Vesuvius could not have erupted before October because charcoal writing is too fragile to survive many months in the open. However, an experiment conducted recently in Pompeii showed that charcoal graffiti can easily last from October 17th until August 24th the following year (30). As for the presence of braziers, autumn fruits, and warm clothing worn by victims of the eruption: Braziers can be used for cooking, not just for heating in cold weather; people in Pompeii and Herculaneum may well have donned heavy woolen clothing to protect themselves from the scorching eruption fallout (Pliny the Younger described people tying pillows to their heads for the same purpose); and dried fruits such as raisins, dates, or chestnuts found at Pompeii could be consistent with an end-August eruption. In any case, dried fruits should not be used to date the eruption because they can be stored for many months and could have been harvested in previous years (27).

Proponents of a late autumn eruption often refer to a coin hoard found in Pompeii's "House of the Golden Bracelet". One of the coins celebrates Titus's fifteenth *imperator* title—the same event Cassius Dio used to date the eruption. However, Dio did not specify whether the eruption occurred before or after Titus's title, only that both events occurred in the same year.

The coin from Pompeii is corroded and the inscriptions are not easily legible, but by comparing it to similar coins in better condition, D'Ambrosio *et al.* (31) inferred that its reverse inscription reads: *IMP TITUS CAES VESPASIAN AVG PM / TR P VIII IMP XV COS VII PP* (*Imperator Titus Caesar Vespasianus Augustus pontifex maximus, tribunicia potestate VIII, imperator XV, consul VII, pater patriae*). For the purpose of dating the Vesuvius eruption, the relevant part is *IMP XV*, which implies the coin was minted after Titus received the title of *imperator* for the fifteenth time.

Titus's fifteenth *imperator* title can be dated using historical documents. A bronze copy of a letter from Titus to the Spanish city of Munigua is signed *IMP XIII* and dated September 7th (54). A bronze military diploma from Egypt bears the same signature and is dated *ad vi idus sept* (September 8th) (55). We know these documents date to 79 CE because Titus signs himself *P P* (*pater patriae* = "father of the fatherland"), a title borne by Roman emperors; thus, when the documents were written, Titus had already succeeded his father after the latter's death in June 79 CE. The two documents show that Titus was still signing himself *IMP XIII* until at least September 8, 79 CE. The coin found in Pompeii apparently reads *IMP XV* and so, the argument goes, it must have been minted after that date.

However, the original catalog by D'Ambrosio *et al.* (31) did not include an image of the Pompeii coin. Abdy (32) reexamined the coin and found that it had been misinterpreted. Comparing it to coins in better condition, he concluded that the Pompeii coin was more similar to a mint reading *IMP XIII* rather than *IMP XV*. This indicates Titus was still *IMP XIII* when the Pompeii coin was minted—perhaps earlier than September 8th. Importantly, if the coin reads *IMP XIII*, it can neither confirm nor refute an August eruption date.

Abdy (32) notes that, based on Titus's political career, three generations of coins are candidate analogs for the Pompeii coin. Titus did not become emperor until after his father's death on June 23rd, 79 CE, and he did not receive his fifteenth *imperator* title until autumn, so coins minted with his image before June 23rd should name him *TR P VIII IMP XIII COS VII* (*tribunicia potestate VIII, imperator XIII, consul VII*). When Titus became emperor, he gained the title *pater patriae*, so coins minted after that date should read *TR P VIII IMP XIII COS VII P P*. Sometime after September 14th, Titus received his fifteenth *imperator* title and coins minted after that read *TR P VIII IMP XV COS VII P P*.

Crucially, there is no sign of the initials *P P* on the Pompeii coin, suggesting that it was minted before Titus became emperor in June 79 CE. This and other important features are highlighted in Fig. S1.

Concluding remarks

Although later reinterpretations have proposed autumn or even November dates, there is no solid reason to doubt Pliny's and Cassius Dio's accounts. The best available evidence points to August 24th, 79 CE as the date of the Vesuvius eruption, and that is the date we use as a reference point.

Previous ⁴⁰Ar/³⁹Ar Dating

Renne *et al.* (15) analyzed samples from pumice collected at the Villa Poppea in Oplontis. The pumice was described by Renne *et al.* (15), who did not collect the sample, as coming from the lower white pumice eruptive unit. However, that pumice is distinctly darker in

color than the pumice sample used in the present study, which was collected by Andrea Marzoli. We suspect that the previous sample was actually taken from the upper grey eruptive unit (EU3) described by Cioni et al. (51). Renne et al. (15) performed laser incremental heating $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of 12 multigrain aliquots of sanidine and reported an inverse isochron age of 1925 ± 94 years (trapped $^{40}\text{Ar}/^{36}\text{Ar} = 306.9 \pm 1.5$, MSWD = 0.51) for all 46 steps. These results were based on a neutron irradiation of 3 min duration and an age of 1.194 Ma for the Alder Creek sanidine (ACs) standard, an atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ of 295.5, and a value of $(8 \pm 3) \times 10^{-4}$ for reactor-produced $^{40}\text{Ar}/^{39}\text{Ar}$ derived from K. The reported age in calendar years is 72 CE $\pm$ 94 CE. Renne and Min (56) reported additional isochron ages of 1889 ± 132 and 1936 ± 207 years (uncorrected for time since publication) but these results were fraught with analytical problems and are not considered reliable enough to warrant further discussion.

Lanphere et al. (16) analyzed samples from pumice in unspecified eruptive units of the 79 CE deposits in Pompei and Oplontis. They used resistance furnace incremental heating $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of 8 multigrain aliquots of sanidine. to obtain plateau ages whose weighted mean was reported as 1921 ± 66 years (in 2000 CE). These results were based on a neutron irradiation of 30 min duration and an age of 28.92 Ma for the Taylor Creek sanidine (TCs) standard. This age must be a typographical error, as in other USGS publications of this vintage the age of TCs is reported as 27.92 Ma; we use this latter value to recalculate the Lanphere *et al.* (2007) results. Lanphere *et al.* (2007) reported a value of 0.0000 ± 0.0000 for reactor-produced $^{40}\text{Ar}/^{39}\text{Ar}$ derived from K. The reported age in calendar years is 79 CE $\pm$ 66 CE.

There are some important differences between the parameters used in these two studies; these differences must be accounted for in order to compare the results. Although different standards were used in the two studies, the results can be normalized to a common standard (Fish Canyon sanidine; FCs) using methods outlined by Reiners et al. (57) equations 9.30-9.32b and using the intercalibration factors between FCs and ACs of Niespolo et al. (49) and between FCs and TCs of Fleck et al. (58) to normalize the results of (15) and (16), respectively. This procedure produces *R*-values of Vesuvius relative to FCs of 6.8149×10^{-5} (15) and 6.9769×10^{-5} (16), corresponding to calendar ages of 61 CE $\pm$ 94 CE and 125 CE $\pm$ 66 CE, respectively, using the calibration of Carter et al. (39). Within the relatively large uncertainties, both are indistinguishable from the canonical age of 79 CE.

The second difference between the two studies is the correction for reactor-produced $^{40}\text{Ar}/^{39}\text{Ar}$ derived from K ($^{40}\text{Ar}/^{39}\text{Ar}$)_K. Lanphere et al. (16) reported using a remarkably precise value of 0.0000 ± 0.0000 without any documentation, which was ascribed to the use of Cd shielding to reduce the thermal neutron fluence. This is difficult to reconcile with the 7 values for various reactors summarized by McDougall and Harrison (59), wherein all the values reported for irradiations with Cd shielding are $>1 \times 10^{-4}$. Moreover, using the same reactor (Geological Survey Triga Reactor; GSTR) as Lanphere et al. (16), Fleck et al. (58) reported data from 9 Cd-shielded irradiations whose weighted mean ($^{40}\text{Ar}/^{39}\text{Ar}$)_K is $(1.04 \pm 1.00) \times 10^{-3}$. Thus we find that a value of 0.0000 ± 0.0000 lacks credibility.

Importance of the potassium correction

Lanphere et al. (16) did not report J -values for their samples, hence the neutron fluence in their irradiations is not directly known as the reactor power was not specified. However, GSTR records indicate that the two irradiations in question were conducted at 1MW, corresponding to J /hour of 2.5×10^{-2} /hour (60). For a 0.5 hour irradiation, this translates to spurious age excesses of 23 to 227 years for values of $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ between 10^{-4} and 10^{-3} , respectively (Figure S1). Assuming that the $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = (4.54 \pm 0.26) \times 10^{-4}$ in the GSTR reactor is the same as the OSTR (see section below), and neglecting $(^{36}\text{Ar}/^{39}\text{Ar})_{\text{K}}$, the excess age would be 102 years. Thus, the updated and corrected calendar age of Lanphere et al. (16) would be 23 CE. This is probably still indistinguishable from the calendar age of 79 CE when all sources of uncertainty are considered. Analogously, the updated calendar age of Renne et al. (15) is 73 CE when corrected to the same value of $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$. We assume that the delay between irradiation and analysis was brief for Lanphere et al. (16), which we can verify for Renne et al. (15), hence the ingrowth of $^{36}\text{Ar}_{\text{K}}$ was insignificant.

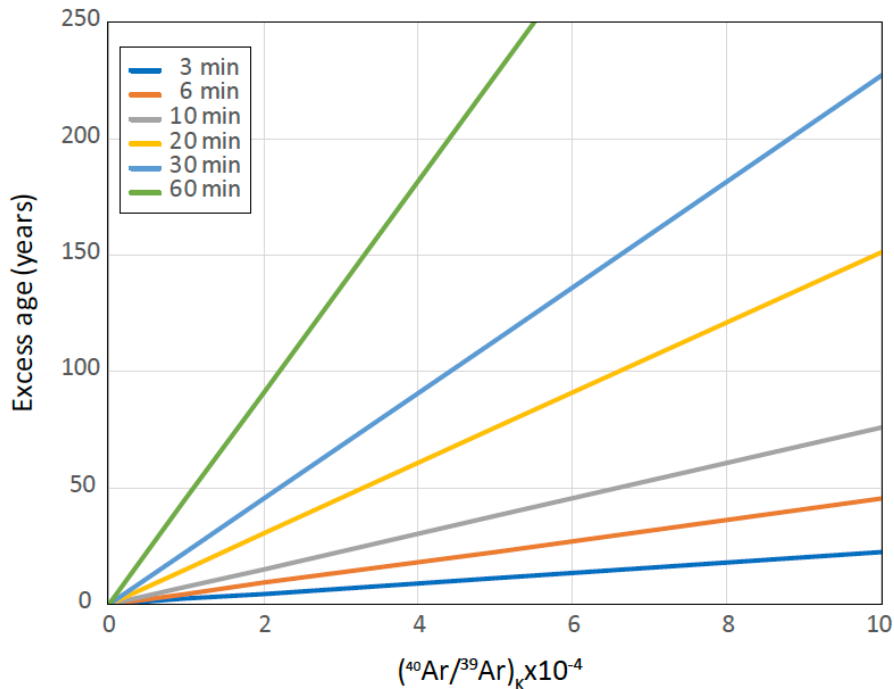


Fig. S1. Excess (spurious) age as a function of $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ for various irradiation times from 3 to 60 minutes duration. Specific values based on data for the OSTR reactor (see text).

As shown above, knowledge of the $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ is critical to accurate and precise $^{40}\text{Ar}/^{39}\text{Ar}$ dating on the millennial timescale. The customary method for determining this value is to irradiate high K material lacking elements with Z greater than that of potassium so that all Ar isotopes produced are derived from K via the reaction $^{39}\text{K}(\text{n}, \text{p})^{39}\text{Ar}$ and to a lesser extent $^{40}\text{K}(\text{n}, \text{d})^{39}\text{Ar}$. Accurate determination of this value is challenging due to the small amount of ^{40}Ar produced in the reactor compared with the inevitable contamination from atmospheric ^{40}Ar . The correction for atmospheric ^{40}Ar is complicated by the fact that ^{36}Ar is also produced from K in the reactor by the $^{39}\text{K}(\text{n}, \alpha)^{36}\text{Cl}$ reaction followed by β^- decay of ^{36}Cl to ^{36}Ar (38). Due to the long (3.01×10^5 years) half-life of ^{36}Cl , ^{36}Ar

ingrowth is generally negligible if analysis occurs within a few months after neutron irradiation (38), but the effect is largest for very young samples that are proportionately most affected by $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$. Further, as discussed below, ppm level concentrations of Ca in K-bearing minerals contribute ^{36}Ar that must be quantified and corrected. To our knowledge, none of the previous determinations of $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ have taken $^{36}\text{Ar}_{\text{K}}$ into account.

The value of $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ is determined as:

$$\left(\frac{^{40}\text{Ar}}{^{39}\text{Ar}}\right)_{\text{K}} = \frac{(^{40}\text{Ar}_T - ^{40}\text{Ar}_A)}{(^{39}\text{Ar}_T - ^{39}\text{Ar}_{\text{Ca}})} \quad (1)$$

$$\text{where } ^{40}\text{Ar}_A = ^{36}\text{Ar}_A \cdot 298.56 \quad (2)$$

$$\text{and } ^{39}\text{Ar}_{\text{Ca}} = ^{37}\text{Ar}_T \cdot \left(\frac{^{39}\text{Ar}}{^{37}\text{Ar}}\right)_{\text{Ca}} \quad (3)$$

$$\text{and } ^{36}\text{Ar}_A = ^{36}\text{Ar}_T - ^{36}\text{Ar}_{\text{K}} - ^{36}\text{Ar}_{\text{Ca}} \quad (4)$$

$$\text{and } ^{36}\text{Ar}_{\text{K}} = ^{39}\text{Ar}_T \cdot \left(\frac{^{36}\text{Ar}}{^{39}\text{Ar}}\right)_{\text{K}} \quad (5)$$

$$\text{and } ^{36}\text{Ar}_{\text{Ca}} = ^{37}\text{Ar}_T \cdot \left(\frac{^{36}\text{Ar}}{^{37}\text{Ar}}\right)_{\text{Ca}} \quad (6)$$

$$\text{and } \left(\frac{^{36}\text{Ar}}{^{39}\text{Ar}}\right)_{\text{K}} = \left(\frac{^{36}\text{Cl}}{^{39}\text{Ar}}\right)_{\text{K}} \frac{(1 - e^{-\lambda_{36} \cdot \Delta t})}{(e^{-\lambda_{39} \cdot \Delta t})} \quad (7)$$

Subscripts in the above indicate sources: atmospheric (*A*), potassium (*K*), and total measured (*T*) values corrected for background, mass discrimination, detector gain variations, and decay. λ_{36} and λ_{39} are the decay constants of ^{36}Cl and ^{39}K , respectively.

The above equations assume ^{37}Ar is produced entirely from Ca, which deviates from the general assumption that ^{37}Ar is also produced from K. Correction factors for ^{37}Ar production from K have traditionally been determined in experiments on high K material assumed to be devoid of Ca. However, the reaction threshold for the production of ^{37}Ar from K is ca. 10 MeV and therefore production should be dominated by Ca at ppm level concentrations in high K materials. For example, ORIGEN simulations of the GODIVA critical assembly (fission spectrum neutrons) yield flux-averaged cross sections for $^{40}\text{Ca}(n,\alpha)^{37}\text{Ar}$ and $^{39}\text{K}(n,n+d)^{37}\text{Ar}$ of 2.27×10^{-2} and 2.48×10^{-8} barns, respectively (61). Thus, the crossover at which production from Ca exceeds that from K would be ca. 1 ppm Ca in pure K, or a fraction of a ppm in K-bearing silicates. Even trace-metal grade reagents contain 10s of ppm contaminants, and it is unlikely such reagents were feedstock in the manufacturing of the K- glass (nominally Fe-doped KAlSiO_4 composition) utilized to determine reactor interference corrections. Further, on a plot of $^{38}\text{Ar}/^{39}\text{Ar}$ vs. $^{37}\text{Ar}/^{39}\text{Ar}$ obtained from K-glass data (Table S1), a linear correlation with a non-zero y-intercept is observed, which suggests there are two sources of ^{38}Ar , one of which is more closely associated with ^{39}Ar and one of which is more closely associated with ^{37}Ar . In this case, the intercept likely reflects $(^{38}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ and the second component is a mixture of $^{39}\text{Ar}_{\text{Ca}}$, $^{38}\text{Ar}_{\text{Ca}}$, and $^{37}\text{Ar}_{\text{Ca}}$ (with atmospheric ^{38}Ar contributing scatter). It is therefore likely that the production of ^{37}Ar from K can be neglected in geochronology.

Strictly speaking, the value of $(^{36}\text{Cl}/^{39}\text{Ar})_{\text{K}}$ in equation (5) is specific to a given neutron energy spectrum, hence may vary between reactors or even at different locations within a reactor, and whether or not any shielding is used. Carter et al. (38) estimated this value to be 0.4 ± 0.01 for the Cadmium-lined in-core irradiation tube (CLICIT) facility at the Oregon State University Triga reactor. We determined this value independently along with the $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ as follows.

Determination of $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ and $(^{36}\text{Cl}/^{39}\text{Ar})_{\text{K}}$

We determined the relative production rates of ^{36}Cl with respect to ^{39}Ar from K $(^{36}\text{Cl}/^{39}\text{Ar})_{\text{K}}$ and ^{40}Ar with respect to ^{39}Ar from K $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ by analyzing “zero-age” K-rich glass from two irradiations, one from 2009 (100 hours) and one from 2025 (40 hours). Complete analytical data are provided in Table S1. The K-glass has the composition of Fe-doped kalsilite (KAlSiO_4). It was manufactured in ca. 1990 by Corning Inc. in air and subsequently degassed under UHV conditions in a resistance furnace to reduce atmospheric Ar contamination. The radiogenic ingrowth $^{40}\text{Ar}^*/^{39}\text{Ar}_{\text{K}}$ ratio is $<0.2\%$ of the nucleogenic production ratio and was therefore neglected in our calculation. To determine $(^{36}\text{Cl}/^{39}\text{Ar})_{\text{K}}$ and $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$, we used three isotope plots of $^{36}\text{Ar}/^{40}\text{Ar}$ vs. $^{39}\text{Ar}/^{40}\text{Ar}$, where the slope (m) is proportional to the production ratios according to the following:

$$m = \left(\frac{^{36}\text{Cl}}{^{39}\text{Ar}} \right)_K (1 - e^{-\lambda_{\text{Cl}}t}) \mathcal{B} - \left(\frac{^{40}\text{Ar}}{^{39}\text{Ar}} \right)_K b, \quad (8)$$

where $\mathcal{B}$ is the branching fraction (98.1%) for ^{36}Cl β^- decay to ^{36}Ar , λ_{Cl} is the ^{36}Cl decay constant ($3.013 \pm 0.015 \times 10^5 \text{ y}^{-1}$; (62)), t is the time elapsed since the end of irradiation, and b is the y-intercept, assumed here to be the atmospheric $^{36}\text{Ar}/^{40}\text{Ar}$ ratio. All data were corrected for contributions from Ca as described above. The two irradiations yield distinct slopes, from which $(^{36}\text{Cl}/^{39}\text{Ar})_{\text{K}}$ can be determined according to the following:

$$\left(\frac{^{36}\text{Cl}}{^{39}\text{Ar}} \right)_K = \frac{1}{\mathcal{B}} \left(\frac{m_1 - m_2}{e^{-\lambda_{\text{Cl}}t_2} - e^{-\lambda_{\text{Cl}}t_1}} \right). \quad (9)$$

One can then determine $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ by solving Eq. (1) using either of the two slopes and the associated time elapsed since the end of irradiation. For both regressions, we fixed the y-intercept (b) to the isotopic composition of atmospheric Ar ($^{36}\text{Ar}/^{40}\text{Ar} = 0.003349$; (35)). We neglected uncertainties in $\mathcal{B}$ and λ_{Cl} . Data are shown in Figure S2A and S2B. The inferred $(^{36}\text{Cl}/^{39}\text{Ar})_{\text{K}}$ and $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ ratios are $(2.835 \pm 0.025) \times 10^{-1}$ and $(4.54 \pm 0.26) \times 10^{-4}$, respectively.

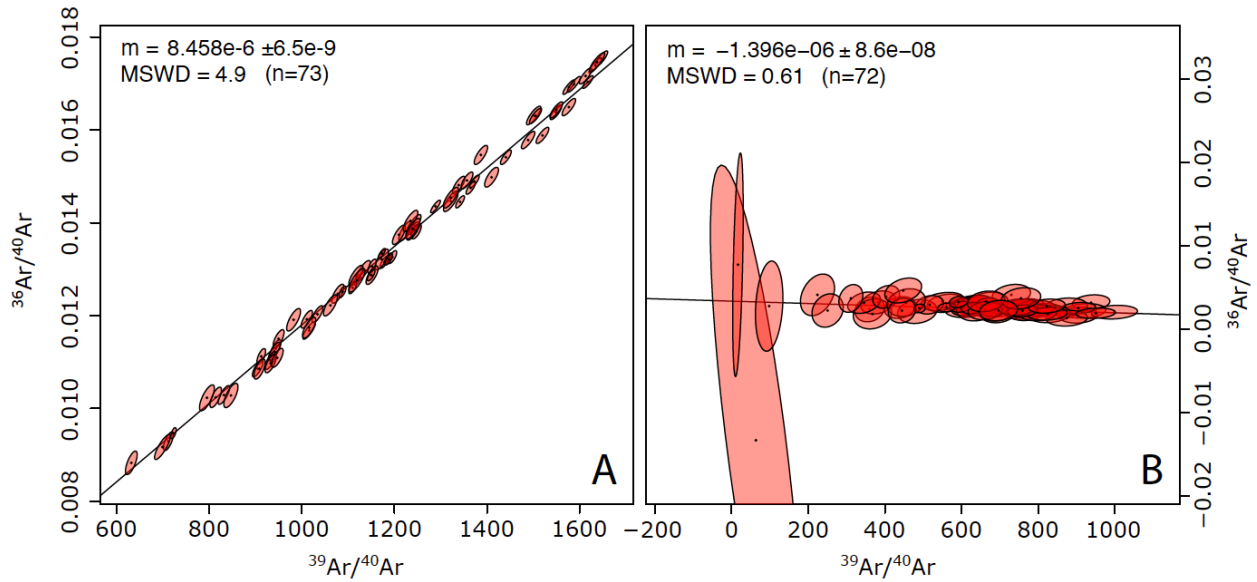


Fig. S2. Three isotope plots of data obtained from the analysis of “zero-age” K-glass. Ellipses denote 1σ uncertainties, with rotation reflecting uncertainty correlations. The data were regressed with and the figures were modified from IsoplotR (34). The left panel (A) shows data from samples that were irradiated in 2009, which allowed for significant ingrowth of ^{36}Ar from ^{36}Cl . The right panel (B) shows data from samples that were irradiated in 2025. Both datasets were generated in 2025.

Determination of full posterior of $\lambda_{EC,\beta+}$

We used an affine-invariant Markov Chain Monte Carlo (MCMC) sampler (50) to jointly estimate the ^{40}K decay constants and calibration parameters needed to place the Vesuvius measurements on an absolute timescale. Sampled parameters include the eruption age (t_{AM1}), the K-Ar isotopic composition of Fish Canyon sanidine (FCs) ($^{40}\text{Ar}^*/^{40}\text{K}$)_{FCs}, and the R -value relating AM1 to FCs, R_{FCs}^{AM1} . Sampling these quantities together allows uncertainties in measurements and priors, as well as parameter covariances, to be handled consistently through the model (Figure S4). This joint posterior sampling yields a tightly constrained estimate of $\lambda_{EC,\beta+}$, which is the key result of this analysis (Table S1). Posterior summaries are reported in Table S1 and illustrated in Figure S3.

Chains were initialized near the centers of their prior distributions and run with 64 parallel walkers/chain for 10^5 steps. The first 5×10^4 steps were discarded as burn-in and the remaining chains were thinned to reduce autocorrelation effects. Convergence was assessed using integrated autocorrelation times estimated from the chains and by verifying that the total chain length exceeded at least 50 times the largest autocorrelation time across parameters. Mean acceptance rates were additionally monitored ($\sim 59\%$ of proposed samples were accepted) to ensure efficient sampling. Together, these diagnostics indicated adequate mixing and effective sampling of the posterior.

The resulting posterior yields a tightly constrained estimate of $\lambda_{EC,\beta+}$ (Table S1; Figure S3). This value is statistically indistinguishable from the approximation presented in the main text, demonstrating that the simpler approach and complete Bayesian treatment converge on the same result.

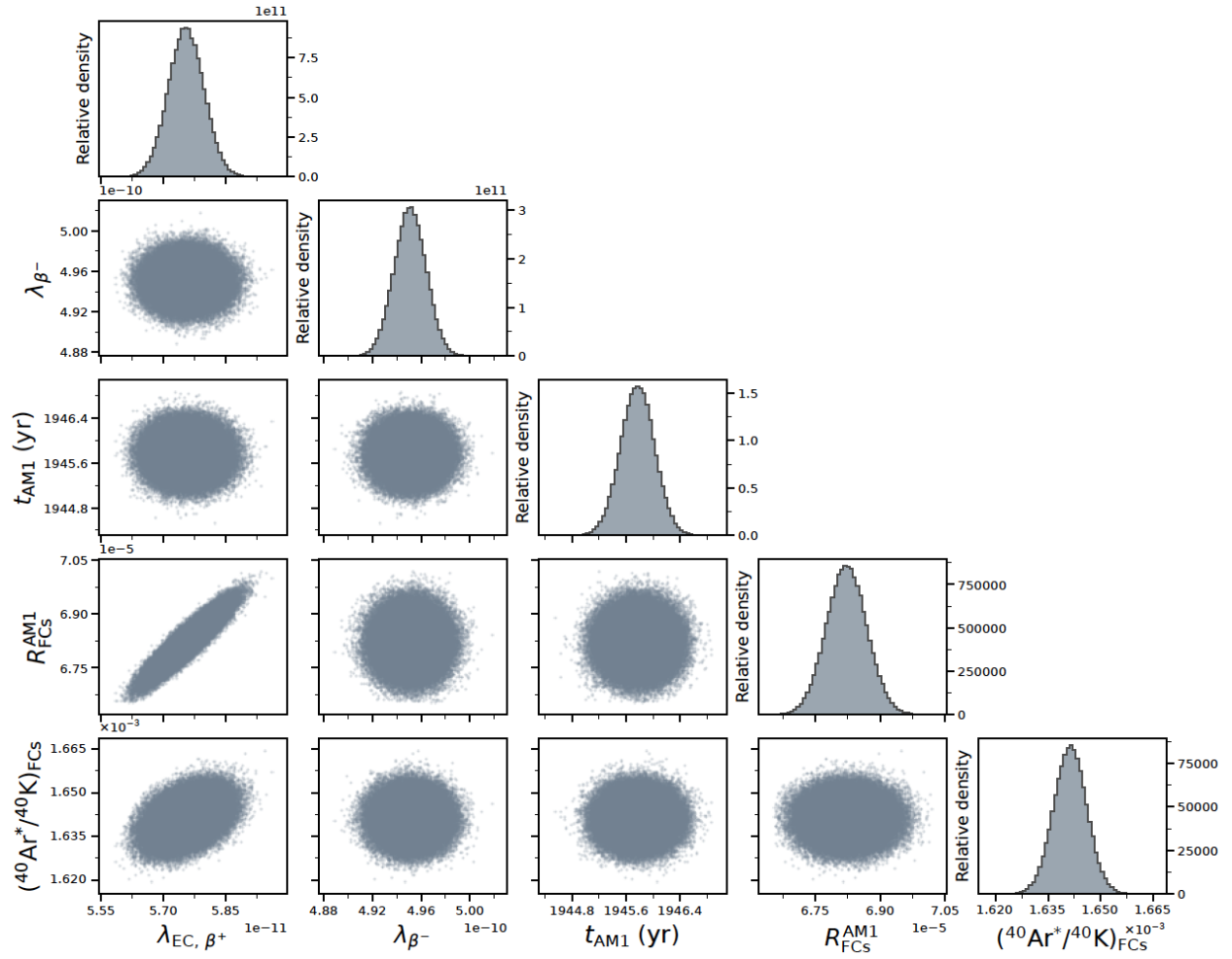


Fig. S3. Corner plot showing the joint posterior distributions of the ^{40}K decay constants, $^{40}\text{Ar}^*/^{40}\text{K}$ of FCs and $R_{\text{FCs}}^{\text{AM}-1}$. The diagonal panels show the marginal posterior for each parameter (normalized histograms), and off-diagonal lower left panels show pairwise relationships using plots of the retained MCMC samples. Elongated or tilted point clouds indicated posterior correlations among parameters – for example both $\lambda_{\text{EC},\beta^+}$ and $R_{\text{FCs}}^{\text{AM}-1}$.

Table S1. Summary of MCMC results

Parameter	Prior	Posterior (68% credible level)
$\lambda_{\text{EC},\beta^+}$	$\text{U}(0.0, 6 \times 10^{-10}, 5.9 \times 10^{-10}) \text{ a}^{-1}$ ^a	$(5.7550 \pm 0.042) \times 10^{-10} \text{ a}^{-1}$
λ_{β^-}	$(4.9510 \pm 0.0131) \times 10^{-9} \text{ a}^{-1}$ ^b	$(4.9510 \pm 0.0131) \times 10^{-9} \text{ a}^{-1}$
$R_{\text{FCs}}^{\text{AM}1}$	$(6.8223 \pm 0.0460) \times 10^{-5}$ ^c	$(6.8225 \pm 0.046) \times 10^{-5}$
$(^{40}\text{Ar}^*/^{40}\text{K})_{\text{FCs}}$	$(1.6413 \pm 0.0047) \times 10^{-3}$ ^c	$(1.6413 \pm 0.0047) \times 10^{-3}$
$t_{\text{AM}1}$	$1945.77 \pm 0.25 \text{ a}$ ^d	$1945.77 \pm 0.25 \text{ a}$

^a Denotes uniform (U) distribution bounded between lower and upper values stated in the brackets.

^b Prior is taken from Kossert et al. (27)

^c Derivation of prior is given in the main text.

^d AM1 prior is constructed from time of analysis to the 24th August eruption date and with 3 month uncertainty.

Sample-Standard Irradiation Geometry

Accurate and precise determination of the neutron fluence parameter J corresponding to each sample's position in the reactor is an important factor in the age uncertainty budget. In this study we used the weighted average of analyses from each well containing standards (ACs) to assign a J -value to that well. J -values for each well containing AM-1 were then determined as the weighted mean of J -values determined from the three wells most closely bracketing it.

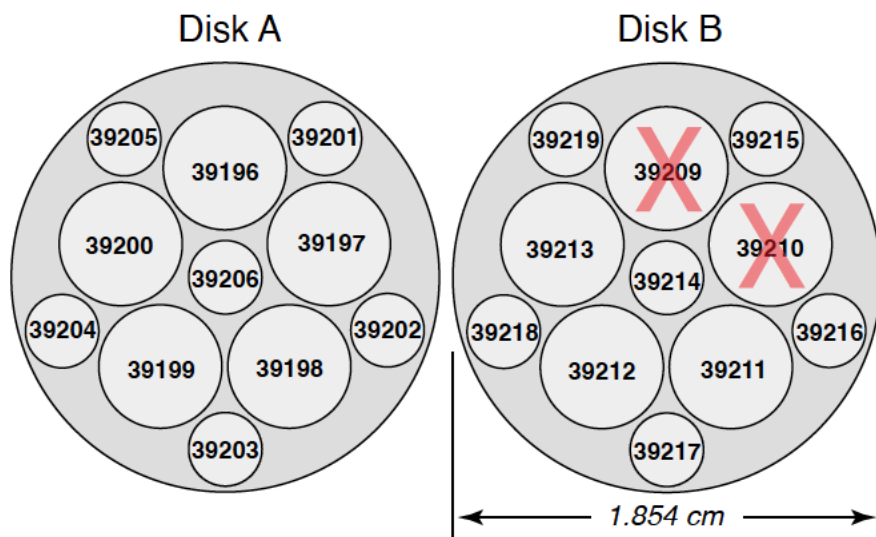


Fig. S4. Irradiation disks showing spatial relations between standards (ACs) and unknowns (AM-1) during neutron irradiation. Small circles represent wells 2.87 mm diameter x 2.03 mm deep, containing ACs. Large circles represent wells 5.33 mm diameter x 3.30 mm deep, containing AM-1. Large wells of AM-1 with X (#s 39209 and 39210) are suspect of contamination and all analyses of material from these wells are excluded from the age determination.

Data S1. (separate file) Argon isotope data

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