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RESEARCH ARTICLE

Marvin Lanphere · Duane Champion · Leone Melluso · Vincenzo Morra · Annamaria Perrotta · Claudio Scarpati · Dario Tedesco · Andrew Calvert

$^{40}Ar/^{39}Ar$ ages of the *AD* 79 eruption of Vesuvius, Italy

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Abstract The Italian volcano, Vesuvius, erupted explosively in AD 79. Sanidine from pumice collected at Casti Amanti in Pompeii and Villa Poppea in Oplontis yielded a weighted-mean $^{40}Ar/^{39}Ar$ age of 1925±66 years in 2004 (1σ uncertainty) from incremental-heating experiments of eight aliquants of sanidine. This is the calendar age of the eruption. Our results together with the work of Renne et al. (1997) and Renne and Min (1998) demonstrate the validity of the $^{40}Ar/^{39}Ar$ method to reconstruct the recent eruptive history of young, active volcanoes.

Keywords $^{40}Ar/^{39}Ar$ Geochronology · *AD* 79 eruption · Historic eruption

Introduction

A well-documented eruption of the volcano Vesuvius, near Naples, Italy occurred 24–25 August in AD 79. Many historical facts of the AD 79 eruption come from two letters written by Pliny the Younger to the historian Cornelius Tacitus (Radice 1971). Archaeologists and geologists have reconstructed the history of this eruption using Pliny's letters as well as observations taken at Pompeii, Oplontis, and Herculaneum, cities that were destroyed by the eruption (Lirer et al. 1973; Sigurdsson et al. 1982; 1985; Cioni et al. 1996; Luongo et al. 2003a,b).

Editorial responsibility R. Cioni

M. Lanphere · D. Champion · A. Calvert (✉)
US Geological Survey,
345 Middlefield Road,
Menlo Park, CA 94925, USA
e-mail: alder@usgs.go

L. Melluso · V. Morra · A. Perrotta ·
C. Scarpati · D. Tedesco
Dipartmento di Geofisica e Vulcanologia,
Universita di Napoli Federico II,
Napoli, 081253111, Italy

Vesuvius had explosive eruptions prior to AD 79 (at 3,400, 8,000, and 18,000 years). The last major eruption of Vesuvius before AD 79 occurred in 1200 BC (Sigurdsson et al. 1982). A strong local earthquake in AD 62 did extensive damage in Pompeii and in Herculaneum which was still under repair in AD 79. On 20 August in AD 79, tremors again were felt in the region. Earthquakes occurred with increasing frequency during the next 4 days as magma moved up the feeder pipe of the volcano.

The eruption started on 24 August when, after minor phreatic eruptions, a high-sustained eruptive column rose convectively into the stratosphere reaching an estimated maximum height of 32 km (Sigurdsson et al. 1985). The plinian phase of the eruption lasted for about 18 h, and during this period, Vesuvius produced about 2.6 km^3 of pumice (Sigurdsson et al. 1982). A thick layer of pumice lapilli resulting from the column fallout covered a wide area south of the volcano (Lirer et al. 1973; Fig. 1). This deposit reached its maximum thickness of 280 cm at Pompeii; the deposit totally buried flat roofs and the lower parts of buildings. On the morning of 25 August, the plinian column collapsed and pyroclastic density currents were emplaced which destroyed every settlement within a radius of 10–15 km from the volcano. Luongo et al. (2003a,b) described the effects of the eruption on the inhabitants.

The well-documented historical age of this eruption has been used to extend $^{40}Ar/^{39}Ar$ dating to young events. Renne et al. (1997) first applied $^{40}Ar/^{39}Ar$ dating to this Vesuvius eruption yielding an age of 1925±94 years (1σ uncertainty) for sanidine from Villa Poppea in Oplontis for the eruption (their age is 1932 years ago corrected to the year 2004). They used a series of total fusion analyses on separate aliquants of sanidine, and then pooled these analyses to yield an age. We decided to make incremental-heating analyses of sanidine to see whether this approach would yield results similar to that of Renne et al. (1997) with perhaps better precision. Using incremental-heating we obtained an $^{40}Ar/^{39}Ar$ age of 1921±66 years in AD 2000 (1925 years corrected to the year 2004), the age of the AD 79 eruption.

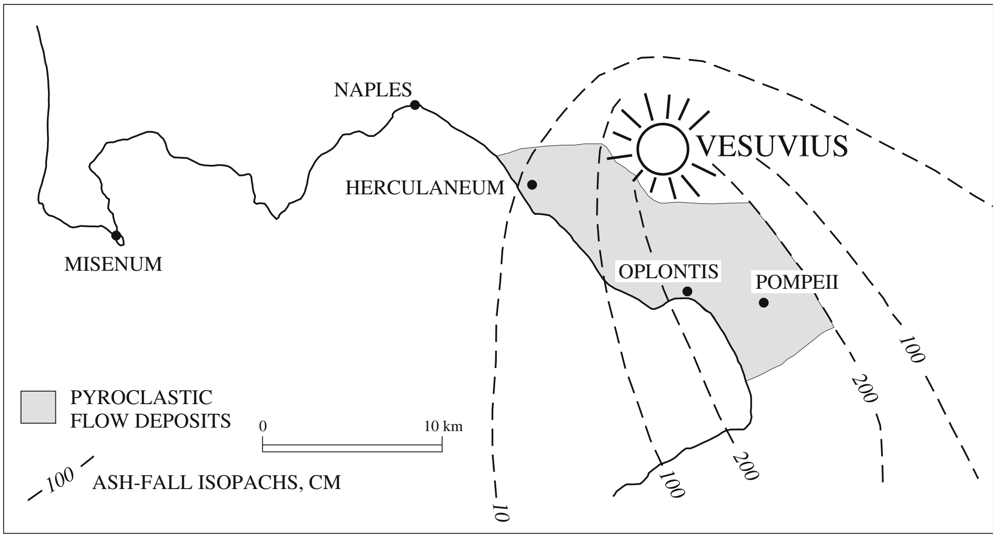

Fig. 1 Map of the Vesuvius region and Bay of Naples (after Sigurdsson et al. 1982), showing the extent of the area affected by pumice and pyroclastic flows during The AD 79 eruption. *Broken lines* are isopachs of the pumice fall during the Plinian phase (Lirer et al. 1973)

Previous work

The first good results for a measured isotopic age of the AD 79 eruption of Vesuvius were reported by Renne et al. (1997). They analyzed 12 aliquants of sanidine from one sample by heating each aliquant in 3–5 steps using a CO_2 laser. Power settings were from a laser, and they produced 46 separate measurements. The temperatures of their heating steps are not known. They plotted the $^{40}Ar/^{39}Ar$ ratios of the 46 determinations on a $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ diagram after making corrections for non-radiogenic and interfering isotopes. On this diagram, the 46 measurements fit an isochron indicating an age of 1925±94 years (in 1997).

Two subsequent irradiations done in the same fashion yielded isochron ages of 1889±132 years (59 measurements) and 1936±207 years (37 measurements; Renne and Min 1998). The number of aliquants measured is unknown. They attributed the larger uncertainties in these ages to larger sample sizes. They said that larger uncertainties resulted from larger corrections for mass discrimination and from non-uniform heating with the laser. They gave no measurements of mass discrimination. Renne and Min (1998) suggested that these uncertainties be ignored and the ages simply be pooled to yield an age of 1917 years with an uncertainty of ±14 years. We believe this to be an incorrect use of statistics. The proper way to pool these three isochrons (Renne et al. 1997; Renne and Min 1998) is weighting by the inverse of the variances of the three determinations which yields a weighted mean age of 1,922 years with an uncertainty of ±72 years. The weighted-mean age has an uncertainty of ±72 years which seems more realistic from the internal uncertainties of the three data sets.

Analytical techniques

For the current study, pumice clasts were collected within two buildings: Casti Amanti in Pompeii and Villa Poppea in nearby Oplontis (Fig. 1). The sample from Villa Poppea is different from the sample analyzed by Renne et al. (1997). Both Pompeii and Oplontis were buried by the AD 79 eruption. Oplontis has been excavated inside the current Naples suburb of Torre Annunziata.

Sanidine for the current study was separated from pumice using standard magnetic and heavy-liquid methods. One sample each from Casti Amanti and Villa Poppea was processed; each sample was from white pumice and was divided into aliquants for irradiation. Aliquants of sanidine weighing 223 to 271 mg were encapsulated in Cu foil and placed in quartz vials along with fluence monitor

Table 1 $^{40}Ar/^{39}Ar$ incremental-heating ages of sanidine from Casti Amanti, Pompeii and Villa Poppea, Oplontis

Aliquant number	Plateau age (years)	Plateau ^{39}Ar (%; steps)	$^{40}Ar/^{36}Ar$ isochron intercept
Casti Amanti−1	2061±181	99(23 of 25)	297.4±2.8
−2	1707±185	87(21 of 26)	298.4±3.0
−4	2099±185	86(17 of 26)	300.1±4.4
−5	1821±200	86(18 of 25)	299.7±1.0
−6	1938±186	100(25 of 25)	290.8±3.6
−7	2181±182	100(825 of 26)	295.9±2.0
−8	1667±184	100(26 of 26)	294.2±3.4
Villa Poppea−2	1867±185	96(22 of 26)	302.1±5.3

Weighted mean age: 1921±66 years (in year 2000)

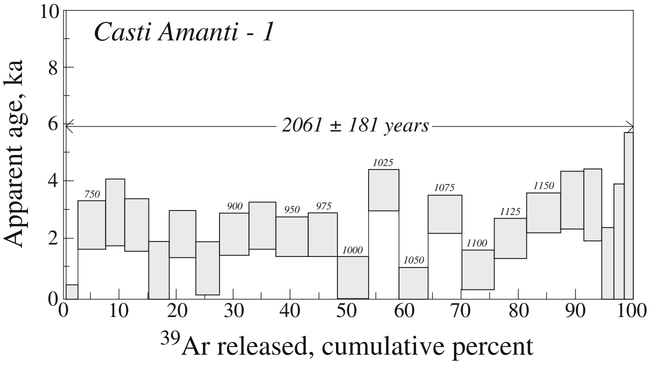

Fig. 2 $^{40}Ar/^{39}Ar$ age spectrum for sanidine from aliquant Casti Amanti-1. Half of the vertical dimension of the increment boxes is the estimated SD (1σ) of precision of the age spectrum age. The error in the weighted-mean plateau age is the weighted SD

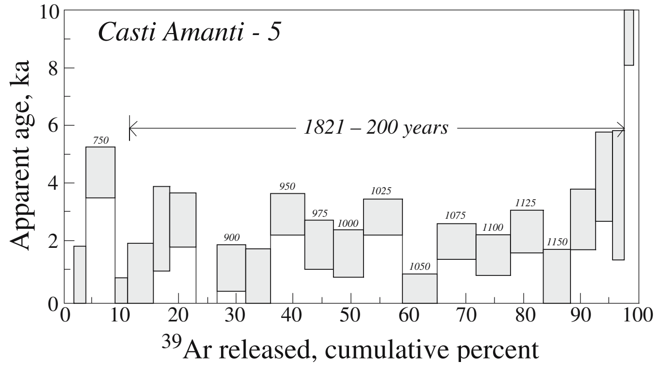

Fig. 4 $^{40}Ar/^{39}Ar$ age spectrum for sanidine from aliquant Casti Amanti-5. See Fig. 2 for explanations

mineral TCR sanidine (t=28.92 Ma). The quartz vials were then wrapped with Cd foil and were irradiated for 30 min in the US Geological Survey TRIGA reactor in Denver, Colorado. Samples were irradiated in two different groups: Menlo Park irradiations CLIX and CLXIII. Shielding a sample with Cd foil dramatically decreases the production of ^{40}Ar from ^{40}K by thermal neutrons. In the USGS TRIGA reactor, the ratio of $^{40}Ar/^{40}K$ in K-glass shielded by Cd foil is 0.0000±0.0000. The calculation of ages for these young samples would be very difficult if the correction for reaction with thermal neutrons was not eliminated with Cd shielding. A total of 3–4 grains of the fluence monitor mineral were fused using an argon-ion laser (Dalrymple 1989).

For each of the eight aliquants in Table 1, a weighted-mean plateau age has been calculated; age-spectrum diagrams are shown for four of these aliquants as Figs. 2, 3, 4, 5. It is important to realize that these age spectra are only pictorial representations to aid in interpretation. Precise correlations of individual gas increments are made analytically. We prefer to make comparisons using the weighted-mean plateau from age spectrum diagrams. The age spectra actually are surprisingly good given that the quantity of $^{40}Ar_{rad}$ in each step is very small, generally in the range 1 to 9×10^{-16} mol; this small amount of radiogenic Ar is difficult to measure precisely. There are small amounts of extraneous Ar in low-temperature steps and these have been eliminated from the plateau age calculations. Three of the eight determinations (Casti Amanti–6, 7, and 8) do not have any extraneous Ar (Table 1). These three determinations have the lowest $^{40}Ar/^{36}Ar$ intercepts. The total amount of extraneous Ar is very small and ranges from 6×10^{-16} mol to 2.7×10^{-15} mol. This amounts to 1–13% of the measured ^{39}Ar.

Samples of irradiated sanidine were heated in a furnace by increments in this study, generally 25 or 26 temperature-controlled increments per sample. Backgrounds were measured on every other step, and backgrounds for the intervening steps were determined by interpolation. Heating was done using a resistance-heated furnace connected to an extraction line and a mass spectrometer (Dalrymple 1989). Mass analyses were made using a MAP-216 mass spectrometer. Mass discrimination of the extraction line and mass spectrometer was monitored using a gas pipette from a reservoir filled with atmospheric Ar. The mass discrimination during this study was 1.009145±0.000041 per mass unit (1σ uncertainty). The incremental-heating temperatures were carefully controlled with an optical-fiber thermometer. Each aliquant of sanidine in the current study yielded a plateau age with an uncertainty of 8–9%. The percent $^{40}Ar_{rad}$ for most temperature steps would be from

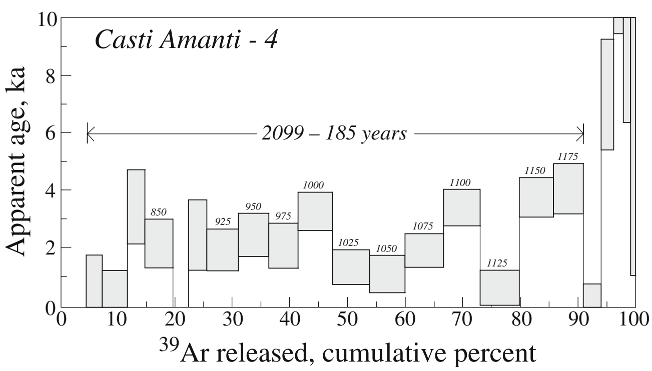

Fig. 3 $^{40}Ar/^{39}Ar$ age spectrum for sanidine from aliquant Casti Amanti-4. See Fig. 2 for explanations

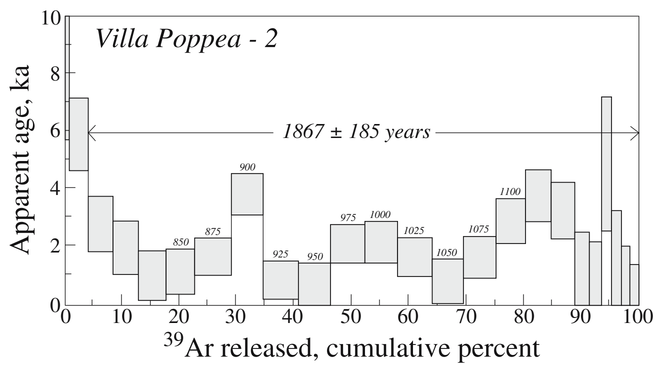

Fig. 5 $^{40}Ar/^{39}Ar$ age spectrum for sanidine from aliquant Villa Poppea-2. See Fig. 2 for explanations

about 1 to 7% with some steps having more than 10% radiogenic Ar.

The background in the mass spectrometer typically is 1.5×10^{-18} mol for m/z=36, 1×10^{-17} for m/z=37, $2\text{x}10^{-18}$ mol for m/z=39, and 1.5×10^{-16} mol for m/z=40. A typical blank, which includes the mass spectrometer background, consists of about 2×10^{-18} mol of m/z=36, 1×10^{-17} mol of m/z=37, 4×10^{-18} mol of m/z=36, 4×10^{-16} mol of m/z=40 (Dalrymple 1989).

Discussion

Eight aliquants of sanidine (Table 1) yielded a weighted-mean age of 1921±66 years during experiments performed in the year AD 2000. Other dating methods have been applied to the AD 79 eruption. ^{14}C ages have been measured on a variety of carbonaceous materials caught up in the eruption. Aciego et al. (2003) recently determined a U-Th/He age of 1,885±188 years on garnet from pumice. This age was determined after correcting for diffusive loss of He, alpha ejection, and initial U-series disequilibrium.

The sample studied by Renne et al. (1997) and Renne and Min (1998) was collected at Villa Poppea in Oplontis. We determined ages on sanidine from a different sample collected at Villa Poppea and a second sample at Casti Amanti in Pompeii. Most of our measurements were made on the Casti Amanti sanidine because percent $^{40}Ar_{rad}$ was slightly higher on sanidine from Casti Amanti.

It is not necessary to make irradiation times extremely short or to use a very young neutron fluence monitor to do $^{40}Ar/^{39}Ar$ dating on young samples. Renne et al. (1997) used an irradiation time of 3 min for samples from the AD 79 eruption and their fluence monitor mineral was sanidine from the Alder Creek Rhyolite (t=1.194 Ma; Turrin et al. 1994). Renne and Min (1998) suggest that very short irradiations require a young monitor in order to keep the dynamic range of isotope ratios low. However, it is not necessary to use such short irradiation times as 3 min to accomplish this. In the present study the irradiation time of sanidine aliquants was 30 min. The dynamic range of $^{40}Ar/^{39}Ar$ ratios in TCR sanidine was an easily measured 144–192. In addition, using an older fluence monitor mineral such as TCR sanidine allows the J-monitor curve to be determined more precisely than if one uses a young fluence monitor mineral and very short irradiation times. Short irradiation times are necessary if one has to correct for $^{40}Ar_K$ (Ar produced from potassium in the sample), but this correction is unnecessary if the sample is shielded with Cd.

Renne et al. (1997) pointed out that their samples contained extraneous Ar (excess or inherited Ar) based on an $^{40}Ar/^{36}Ar$ intercept of 307±1 for the isochron intercept fitted to 46 measurements of 12 aliquants of sanidine. This intercept is significantly different from the atmospheric value of 295.5±1. Renne and Min (1998) also reported $^{40}Ar/^{36}Ar$ intercepts of 309±4 and 308±7 for additional aliquants of sanidine from Villa Poppea. In contrast, the eight sanidine aliquants analyzed by us in all cases (Table 1) have isochron intercepts that agree with the atmospheric composition within 2σ uncertainties.

Villa (1991, 1992) pointed out that other young volcanic provinces (such as the Roman Volcanic Province) contain excess Ar in phenocrysts. However, sanidine from the AD 79 eruption of Vesuvius does not contain excess Ar. At present, the reason for the subtle differences in the $^{40}Ar/^{36}Ar$ values of isochron intercepts from the Vesuvius eruptions are not known.

Conclusions

Sanidine from the explosive eruption of Mount Vesuvius in AD 79 has been dated by incremental-heating of 8 aliquants. These aliquants of sanidine phenocrysts from two samples of white pumice yield an $^{40}Ar/^{39}Ar$ age of 1925±66 years (in 2004), the calendar age of the eruption. Averaging the 7 aliquants from Casti Amanti yields an age of 1925±69 years (in 2004). These results show that the $^{40}Ar/^{39}Ar$ method can be used to reconstruct the recent eruptive history of young volcanoes.

Acknowledgements Forrest McFarland made the sanidine separations from pumice samples from Casti Amanti and Villa Poppea. James Saburomaru assisted with the Ar determinations. Neutrons were provided by Tim Debey and staff of the US Geological Survey reactor center in Denver, Colorado. We are grateful to Professor Guzzo and Dr. A. Ciarallo of the Soprintendenza Archeologica di Pompeii who allowed our field work in archaeological sites. Julie Donnelly-Nolan and Tom Sisson reviewed the manuscript and offered valuable comments. We thank Professor. R. Cioni, and Drs. Villa and Scaillet for valuable comments on the original manuscript.

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