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High-precision Al–Mg dating of NWA 15118 challenges a primary anorthositic crust on Vesta

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Supplementary Information

The Supplementary Information includes:

- Methods (Sample Preparation and Mg isotope analysis)
- The Predicted Present Radiogenic Mg Isotope Estimation for Meteorites with Known $^{27}Al/^{24}Mg$
- Tables S-1 to S-3
- Figure S-1
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Methods

Sample preparation

Sample preparation, Mg purification, and isotopic analyses were conducted at the Institut de physique du globe de Paris (IPGP), France. Samples were prewashed in an ultrasonic bath with purified water (20 min, three times) before gentle crushing in an agate mortar. Mineral fractions were hand-picked under binocular microscopes using tweezers or primarily separated using a hand magnet.

Mineral separates and whole-rock powders were digested in 7 ml PFA beakers on a hot plate. In detail, mineral and whole rock fractions (4–20 mg) were digested in 2 mL of 1:1 concentrated HNO_3 and HF at 120°C for 48 hours, then evaporated to dryness and redissolved in 2 mL of 1:1 concentrated HNO_3 and HCl. After being evaporated to dryness, samples were refluxed with 1 mL of 2 mol/L HNO_3 and redissolved in 1 mL of 2 mol/L HNO_3 and 0.5 mol/L HF for column chemistry. Approximately 5% of each sample solution was extracted for $^{27}Al/^{24}Mg$ ratio analysis with an Agilent 7900 Quadrupole ICP-MS at Institut de physique du globe de Paris (IPGP), France. Mg isotopes ratios were measured on a Thermo Scientific Neptune Plus MC-ICP-MS at IPGP.

Magnesium isotope analysis

The Mg purification procedure is modified from An *et al.* (2014), and the elution curve is presented in Fang *et al.* (2025), using 8.5 mL of AG 50W×12 (200-400 mesh) resin. Leachates were purified twice to remove K and Na. Mg yields exceeded 99%. The total procedural blank was <2 ng, negligible compared to the Mg loading onto the column. The Mg isotopes were analyzed using Thermoscientific Neptune Plus MC-ICPMS, with an Apex HF introduction system and standard-sample bracketing (SSB) method at Institut de physique du globe de Paris (IPGP), France. The international standard DSM-3 was utilized as a bracketing standard during the measurements at medium resolution. The intensity of ^{24}Mg, ^{25}Mg, and ^{26}Mg were measured by L3, central, and H3 cups, respectively. The samples were introduced at 300 to 600 ppb, with the signal intensity of ^{24}Mg at 11 to 22 V. Stable Mg isotopes were calculated as:

$$\delta^{x}Mg=[(^{x}Mg/^{24}Mg)_{sample}/(^{x}Mg/^{24}Mg)_{DSM3} - 1] \times 1000,\ x = 25 \text{ or } 26 \quad \textbf{(S-1)}$$

Radiogenic Mg isotopes were calculated as:

$$\delta^{26}Mg^* = \delta^{26}Mg - \delta^{25}Mg/\beta. \quad \textbf{(S-2)}$$

with β = 0.511, according to the kinetic mass-dependent fractionation law (Young *et al.*, 2002). The external reproducibility was assessed through replicate analyses of BHVO-2 and AGV-2, which yielded $\delta^{26}Mg^*$ of 0.00 ± 0.03 (2SE, N = 5) and 0.01 ± 0.01 (2SE, N = 25), respectively.

The Predicted Present Radiogenic Mg Isotope Estimation for Meteorites with Known $^{27}Al/^{24}Mg$

The predicted present radiogenic Mg isotope for individual meteorites with known $^{27}Al/^{24}Mg$ formed at a given time t (ΔT_{CAI}, Ma) can be obtained through Eq. S-3, where $(^{27}Al/^{24}Mg)_{sample,p}$ is the present $^{27}Al/^{24}Mg$ ratio of the sample, which is equivalent to the initial value as ^{27}Al and ^{24}Mg are both unradioactive and unradiogenic. The $(^{26}Al/^{27}Al)_{sample,i}$ is the initial $^{26}Al/^{27}Al$ ratio for the individual meteorite when it is generated and can be obtained from Eq. S-4. The $(^{26}Al/^{27}Al)_{ss,i}$ is the initial value for the solar system, which is 5.23×10^{-5} estimated from CAIs (Jacobsen *et al.*, 2008) and λ is the decay constant of ^{26}Al. The $(^{26}Mg/^{24}Mg)^*_{ss,t}$ is the radiogenic $^{26}Mg/^{24}Mg$ ratio of the solar system at time t relative to CAIs, which can be calculated from Eq. S-5, where $(^{27}Al/^{24}Mg)_{ss,i}$ adopts the chondrite value of 0.101 (Baker *et al.*, 2005; Bizzarro *et al.*, 2005). Since the ^{27}Al and ^{24}Mg are both non-radioactive and non-radiogenic, the $(^{27}Al/^{24}Mg)_{sample,i}$ also equals to the present $^{27}Al/^{24}Mg$ ratio of the meteorite.

$$(^{26}Mg/^{24}Mg)^*_{sample,p} = (^{26}Al/^{27}Al)_{sample,i} \times (^{27}Al/^{24}Mg)_{sample,p} + (^{26}Mg/^{24}Mg)^*_{ss,t} \quad \textbf{(S-3)}$$

$$(^{26}Al/^{27}Al)_{sample,i} = (^{26}Al/^{27}Al)_{ss,i} \times e^{-\lambda t} \quad \textbf{(S-4)}$$

$$(^{26}Mg/^{24}Mg)^*_{ss,t} = -(^{26}Al/^{27}Al)_{ss,i} \times (^{27}Al/^{24}Mg)_{ss,i} \times e^{-\lambda t} \quad \textbf{(S-5)}$$

The $\delta^{26}Mg^*$ notion can be calculated by Eq. S-6, where $(^{26}Mg/^{24}Mg)_{DSM3}$ adopts 0.13932 (Catanzaro *et al.*, 1966).

$$\delta^{26}Mg^* = (^{26}Mg/^{24}Mg)^*_{sample} / (^{26}Mg/^{24}Mg)_{DSM3} \times 1000 \quad \textbf{(S-6)}$$

Supplementary Tables

Table S-1 The Al/Mg ratio, Mg isotope result, and model age limit of this study. Magnetic and non-magnetic fractions were separated using a hand magnet

Table S-2 Major element results for standard materials by ICP-MS**.** RSD is relative standard deviation, and RD is relative deviation; reference values (Ref.) for rock standards are the preferred values from GeoRem (Jochum *et al.*, 2016): http://georem.mpch-mainz.gwdg.de/sample_query_pref.asp**.**

Tables S-1 and S-2 are available for download (.xlsx) from the online version of this article at https://doi.org/10.7185/geochemlet.2548.

Table S-3 Al-Mg age of this study and HEDs in the literature. Δt_{CAI} was anchored to CAIs with ($^{26}Al/^{27}Al)_0$ = (5.23 ± 0.13) × 10^{-5} (Jacobsen *et al.*, 2008), using a half-life of ^{26}Al decay of 0.717 Myr (Kondev *et al.*, 2021); Model age is calculated by combining Mg isotope data with a bulk solar system $^{27}Al/^{24}Mg$ = 0.101 and the terrestrial Mg isotope composition ($\delta^{26}Mg^*$ = 0) (Bizzarro *et al.*, 2005). Cumulate eucrite A-881394 (Nyquist *et al.*, 2003; Hublet *et al.*, 2017) is not included because it has anomalous O and Cr isotopes compared with HEDs (Wimpenny *et al.*, 2019).

Sample	$(^{26}Al/^{27}Al)_0 \pm 2\sigma$	$\Delta t_{CAI} \pm 2\sigma$ (Myr)	References
Internal isochron			
Basaltic eucrites			
Camel Donga	2.93 ± 2.79 × 10^{-6}	$2.98^{+3.15}_{-0.69}$	Hublet *et al.* (2017)
Piplia Kalan	7.5 ± 0.9 × 10^{-7}	$4.39^{+0.13}_{-0.12}$	Srinivasan *et al.* (1999)
Y-792510	8.66 ± 7.54 × 10^{-8}	$6.62^{+2.12}_{-0.65}$	Hublet *et al.* (2017)
Y-793591	1.01 ± 0.53 × 10^{-6}	$4.08^{+0.77}_{-0.44}$	Hublet *et al.* (2017)
Cumulate eucrites			
Y-980433	9.60 ± 1.13 × 10^{-8}	$6.52^{+0.13}_{-0.12}$	Hublet *et al.* (2017)
A-881819	2.89 ± 2.24 × 10^{-7}	$5.38^{+1.54}_{-0.59}$	Hublet *et al.* (2017)
Model age			
Basaltic eucrites			
Camel Donga	3.22 ± 0.42 × 10^{-6}	$2.88^{+0.15}_{-0.13}$	Bizzarro *et al.* (2005)
Camel Donga	2.97 ± 0.61 × 10^{-6}	$2.97^{+0.24}_{-0.19}$	Schiller *et al.* (2010)
HaH262	1.99 ± 0.65 × 10^{-6}	$3.38^{+0.41}_{-0.29}$	Bizzarro *et al.* (2005)
Ibitira	2.46 ± 0.54 × 10^{-6}	$3.16^{+0.26}_{-0.21}$	Bizzarro *et al.* (2005)
Juvinas	2.78 ± 0.60 × 10^{-6}	$3.04^{+0.25}_{-0.20}$	Bizzarro *et al.* (2005)
Juvinas	2.62 ± 0.42 × 10^{-6}	$3.10^{+0.18}_{-0.15}$	Schiller *et al.* (2010)
Millbillillie	1.62 ± 0.63 × 10^{-6}	$3.59^{+0.51}_{-0.34}$	Bizzarro *et al.* (2005)
Millbillillie	2.39 ± 0.70 × 10^{-6}	$3.19^{+0.36}_{-0.27}$	Schiller *et al.* (2010)
Stannern	1.26 ± 0.37 × 10^{-6}	$3.85^{+0.36}_{-0.27}$	Bizzarro *et al.* (2005)
Cumulate eucrites			
Dhofar 007	3.06 ± 0.91 × 10^{-6}	$2.94^{+0.37}_{-0.27}$	Bizzarro *et al.* (2005)
Dhofar 007	3.32 ± 1.40 × 10^{-6}	$2.85^{+0.57}_{-0.36}$	Schiller *et al.* (2010)
Talampaya	2.26 ± 1.05 × 10^{-6}	$3.25^{+0.65}_{-0.40}$	Bizzarro *et al.* (2005)

Supplementary Figure

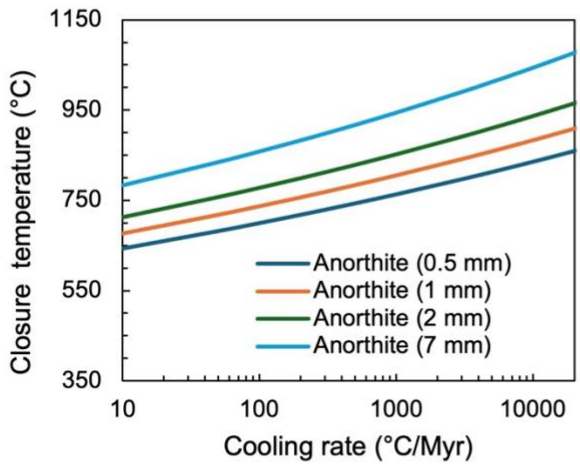

Figure S-1 Estimated closure temperature of anorthite using the Dodson equation (Dodson, 1973). The Mg diffusion rate is calculated from the experimental result of Van Orman *et al.* (2014) at X_{An}=0.93.

Supplementary Information References

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