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

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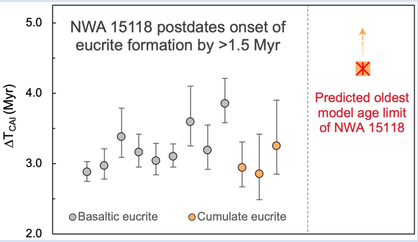
Abstract



A lunar-like magma ocean model has been proposed for the asteroid 4 Vesta, where a global primary anorthositic crust formed from buoyant plagioclase floating above complementary diogenitic cumulates. In this hypothesis, the crystallization of the anorthosite should predate the formation of eucrites that are thought to reflect secondary magmatism at the surface of Vesta. To test this model, we present the first ^{26}Al-^{26}Mg age of the anorthosite Northwest Africa (NWA) 15118. The NWA 15118 yields a model ^{26}Al-^{26}Mg age younger than 4.35 ± 0.03 Myr after CAIs formation. However, eucritic crust formation initiated at ~2.88 Myr after CAIs, and predating NWA 15118 by over 1.5 Myr, contradicting the proposed global primary anorthositic crust of Vesta formed from a magma ocean. Instead, anorthosite NWA 15118 more plausibly represents a fragment of regional crust formed after the primary crustal differentiation of Vesta, potentially related to late stage basaltic eucrites with negative Eu anomalies or derived from a chemically distinct source.

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Introduction

The formation and crystallisation of the magma oceans, possibly a prevalent process during the early development of asteroids and planets, are crucial for understanding the evolution of solar system materials (Greenwood *et al.*, 2014). The Moon is believed to have formed *via* a giant impact that induced a global lunar magma ocean, during which buoyant anorthitic plagioclase floated to the surface, forming a global primordial anorthositic crust (Elkins-Tanton *et al.*, 2011). However, other planetary bodies have not observed such a global primary anorthositic crust. The asteroid 4 Vesta is among the most suited solar system objects for the presence of such a primitive anorthositic crust (Li *et al.*, 2024). The main reasons are that 1) Vesta is widely regarded as the largest surviving differentiated protoplanet (Russell *et al.*, 2012), 2) The homogeneous Δ^{17}O (*e.g.*, Greenwood *et al.*, 2014) and siderophile element depletion (*e.g.*, Steenstra *et al.*, 2016) of the Howardite-Eucrite-Diogenite (HED) meteorite clan, which is one of the largest differentiated meteorite groups and thought to originate from Vesta (De Sanctis *et al.*, 2012; Russell *et al.*, 2012), support the existence of a global magma ocean, and 3) the newly discovered anorthositic meteorite Northwest Africa (NWA) 15118 with ~94 vol. % plagioclase and ~6 vol. % orthopyroxene from Vesta shares petrology and composition similarities with lunar anorthosite (Li *et al.*, 2024).

In the original magma ocean scenario for Vesta, diogenites and eucrites are thought to represent a continuous crystallisation sequence, with diogenites as early cumulates forming the deep crust, and eucrites crystallising from residual melts to form the upper crust (*e.g.*, Righter and Drake, 1997). However, the variability in heavy rare earth elements (HREE; *e.g.*, variability in Dy/Yb) enrichment in diogenites contradicts their crystallisation from a single, homogeneous magma ocean or shallow magma chambers, replenished by magma ocean-derived melt (*e.g.*, Barrat *et al.*, 2008). In addition, the absence or weak Eu anomaly in eucrites also contradicts their complementary role to diogenites, as the latter exhibit a strong negative Eu anomaly (*e.g.*, Barrat *et al.*, 2010; Dhaliwal *et al.*, 2023). Therefore, HREE variability in diogenites is thought to reflect diverse parental magmas (Barrat *et al.*, 2008), possibly involving eucritic crustal contamination (Barrat *et al.*, 2010).

Based on the similar Cr and O isotopic composition of the newly discovered anorthositic meteorite NWA 15118 with HEDs, Li *et al.* (2024) proposed a lunar-like hypothesis for the

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presence of an anorthositic crust on Vesta. In this model, the anorthosite (with a strong positive Eu anomaly) and diogenite layers crystallised simultaneously from the magma ocean, with buoyant plagioclase flotation forming the anorthositic crust, while dense pyroxene sank to the bottom, forming the diogenitic layers; eucrites formed later from the residue. This model requires that anorthosites be coeval with diogenites and predate eucrites, which has not yet been tested by precise chronology. Compared with long-lived (*e.g.,* Pb-Pb) and other short-lived systems (*e.g,* Mn-Cr), the ^{26}Al-^{26}Mg system is particularly suited for high resolution age constraints on early solar system magmatic activities due to 1) the short half-life of ^{26}Al decay (0.717 Myr; Kondev *et al.,* 2021), and 2) the high abundance of Al and Mg as major rock-forming elements. In this study, we apply Al-Mg chronology to anorthosite NWA 15118 to test the lunar-like magma ocean hypothesis and to improve our understanding of Vestan crustal evolution.

Sample Description

NWA 15118 is an anorthositic achondrite with a cataclastic texture (Li *et al.,* 2024; Sheen *et al.,* 2025). The sample used for this study (a 1.2 g chunk and 180 mg powder) derives from the meteorite investigated by Li *et al.* (2024). It is dominated by plagioclase (~94 vol. %), with subordinate orthopyroxene, trace amounts of clinopyroxene, chromite, olivine, and troilite (Li *et al.,* 2024; Sheen *et al.,* 2025). Clasts of plagioclase (up to 7 mm) and orthopyroxene (up to 0.6 mm) are embedded within a fine grained matrix mainly composed of plagioclase. Minor clinopyroxene (μm size width) is present exclusively as veins within large anorthite grains (Li *et al.,* 2024). Oxygen and chromium isotopes suggest that this meteorite shares an affinity with the HED group (Li *et al.,* 2024).

Results

The ^{27}Al/^{24}Mg ratios and the Mg isotope data are presented in Table S-1. Repeated measurements of international standards (AGV-2, BCR-2) ensured a precision better than 3 % (r.s.d.) for ^{27}Al/^{24}Mg ratios (Table S-2). The ^{27}Al/^{24}Mg ratios range from 0.05 to 230.37 for NWA 15118. The repeated analyses of international standards and samples yielded a conservative 2 s.e. estimate of radiogenic δ^{26}Mg* (δ^{26}Mg* = δ^{26}Mg − δ^{25}Mg/β, β = 0.511; according to the kinetic mass dependent fractionation law) better than 0.03 ‰ (Table S-1). All phases in NWA 15118 show no resolvable radiogenic ^{26}Mg excess, preventing meaningful internal isochron ages from being determined. However, an oldest model age limit can be obtained by combining their Al-Mg data and our conservative 2 s.e. estimate (0.03 ‰) of δ^{26}Mg* with a chondritic bulk solar system ^{27}Al/^{24}Mg = 0.101 and terrestrial δ^{26}Mg* = 0 ‰ (Bizzarro *et al.,* 2005; Wimpenny *et al.,* 2019). The absence of radiogenic ^{26}Mg excess in the bulk sample yields an upper limit of initial $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 = (7.81 \pm 0.24) \times 10^{-7}$ for NWA 15118, corresponding to an oldest model age limit of 4.35 ± 0.03 Myr after CAIs (CAIs have a U-corrected Pb-Pb age of about 4567 Ma) (Table S-1). The highest Al/Mg fraction in NWA 15118 yields an upper limit of the initial $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 = (1.82 \pm 0.05) \times 10^{-8}$, corresponding to an oldest model age limit of 8.24 ± 0.03 Myr after CAI formation (Table S-1).

Discussion

Young Vestan magmatism recorded by the ^{26}Al-^{26}Mg chronology of NWA 15118. All phases in NWA 15118 show no radiogenic Mg excesses (Table S-1). An oldest model age limit can be obtained from a binary isochron combining the Al-Mg data with our conservative 2 s.e. estimate (0.03 ‰) of δ^{26}Mg*, assuming a chondritic bulk solar system ^{27}Al/^{24}Mg = 0.101 and terrestrial δ^{26}Mg* = 0 ‰, using the canonical solar initial $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ of $5.23 \pm 0.13 \times 10^{-5}$ (Baker *et al.,* 2005; Jacobsen *et al.,* 2008; Hublet *et al.,* 2017). The use of the terrestrial δ^{26}Mg* = 0 ‰ is justified by the absence of radiogenic δ^{26}Mg* excesses in the bulk chondrites, terrestrial basalt, the Moon, and Mars (at a precision better than ~0.007 ‰; Baker *et al.,* 2005), which has been widely accepted by the later studies (*e.g.,* Hublet *et al.,* 2017; Wimpenny *et al.,* 2019). With this assumption and the canonical solar initial $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$, the calculated solar initial δ^{26}Mg* (−0.038 ‰; *e.g.,* Wimpenny *et al.,* 2019) is in line with the CAI isochron result (Villeneuve *et al.,* 2009). Although mass independent Mg isotope heterogeneity of the solar system has been proposed (Larsen *et al.,* 2011), this **will not affect the relative model age differences among meteorites from the same parent body.**

The absence of radiogenic Mg excess in plagioclases (with ^{27}Al/^{24}Mg up to 230.37; Table S-1) of NWA 15118 indicates a ^{26}Al-^{26}Mg closure age >8.24 ± 0.03 Myr after CAIs (Fig. 1 and Table S-1), anchored to the canonical solar initial $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ of Jacobsen *et al.* (2008). Discrepancies between Pb-Pb and Al-Mg ages in early differentiated meteorites and chondrites may reflect reduced $(^{26}\mathrm{Al}/^{27}\mathrm{A})_0$ ratios in parts of the solar protoplanetary disk (Larsen *et al.,* 2011; Krestianinov *et al.,* 2023), but the closure differences of these two chronometers have also been suggested (*e.g.,* Wimpenny *et al.,* 2019). Whether the eucrite parent body accreted in a disk region with distinct ^{26}Al/^{27}Al ratios from CAI-forming reservoirs remains debated (Nyquist *et al.,* 2003; Wimpenny *et al.,* 2019). However, the choice of the anchoring initial $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ will also not affect the "relative" ages of meteorites from a single parent body. For consistency, all comparison data sets were also anchored to the canonical initial $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ value from Jacobsen *et al.* (2008).

The relatively young model age of NWA 15118, constrained from the mineral fraction with the highest Al/Mg,

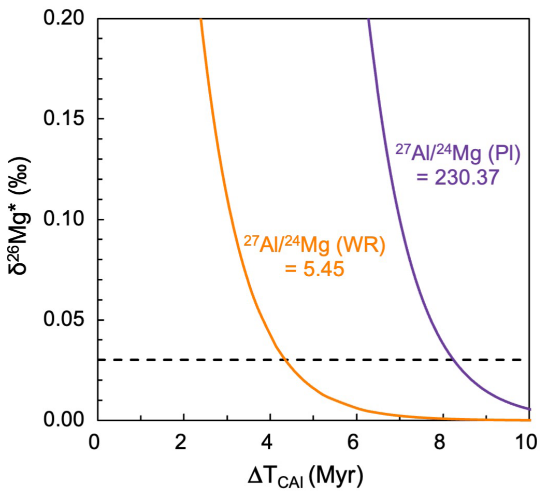

Figure 1 Predicted present δ^{26}Mg* based on known ^{27}Al/^{24}Mg ratios and expected ages. The black dashed line represents the conservative 2 s.e. estimate of δ^{26}Mg*. Calculation details are provided in the Supplementary Information. The oldest age limit of NWA 15118 constrained from the plot using the 2 s.e. estimate matches the model age result since both assume a chondritic Al/Mg ratio and initial δ^{26}Mg*. WR = whole rock; Pl = plagioclase. Numbers along the lines denote measured molar ^{27}Al/^{24}Mg ratios; the Pl fraction of NWA 15118 uses the highest measured ^{27}Al/^{24}Mg ratio.

may reflect partial resetting by later thermal events. Its fragmental breccia texture indicates the impact shock influence; however, the absence of melt veins and even diaplectic glass suggests that shock intensity was insufficient to induce melting of the meteorite (Li *et al.*, 2024; Sheen *et al.*, 2025). Sub-solidus Mg diffusion from Mg-rich (*e.g.*, olivine, orthopyroxene) to Mg-poor phases (*e.g.*, anorthite in this study) could disturb the Al-Mg system (Van Orman *et al.*, 2014). The absence of augite exsolution lamellae in orthopyroxenes of NWA 15118 indicates a lack of significant sub-solidus thermal metamorphism and rapid cooling (Li *et al.*, 2024; Sheen *et al.*, 2025), likely >10,000 °C/Myr, since the exsolution lamellae in eucrite pyroxene could reach such a cooling rate (*e.g.*, Miyamoto *et al.*, 1996). The Dodson equation yields a high closure temperature for anorthite of 1–2 mm in radius (the primary crystal size selected for highest Al/Mg analysis, *i.e.* Pl-3) of about >880–940 °C at this cooling rate (Fig. S-1). Although minor clinopyroxene veins within large anorthites indicate localised modification, the transect of major and minor elements of plagioclases and orthopyroxenes in NWA 15118 shows fractional crystallisation trends, consistent with preservation of the primary igneous compositions (Li *et al.*, 2024; Sheen *et al.*, 2025). Nevertheless, partial sampling of such veins in the plagioclase fraction (though rare; Li *et al.*, 2024) may slightly bias the crystallisation age limit. However, resetting of the bulk rock Al-Mg system, which is not susceptible to secondary redistribution of Al-Mg among mineral phases, would require open system fluid metamorphism (Hublet *et al.*, 2017 and references therein), while no fluid alteration minerals are observed in NWA 15118 (*e.g.*, halite, sylvite, carbonate, phyllosilicates, *etc.*; Zolensky *et al.*, 2017). Thus, we can constrain a more conservative age limit using the bulk rock Al-Mg data, and this yields >4.35 ± 0.03 Myr after CAI formation but still younger than most eucrites (Fig. 2).

Reassessing the anorthositic crust hypothesis on Vesta. The lunar magma ocean hypothesis, supported by chronology, experimental evidence for absence of plagioclase at the liquidus of mare basalts, and complementary Eu anomalies in lunar anorthosites and mare basalts, proposes extensive fractional crystallisation, where early formed mafic minerals (*e.g.*, olivine, pyroxene) sank to form the mantle, while buoyant plagioclase floated to form a global anorthositic crust (Elkins-Tanton *et al.*, 2011). By analogy, Li *et al.* (2024) proposed a similar differentiation model for Vesta, suggesting a global anorthositic crust (represented by NWA 15118) overlying a diogenitic layer, with eucrites forming from subsequent magmatism. This model requires anorthosites to be the oldest Vestan crustal rocks, coeval with diogenites and predating eucrites.

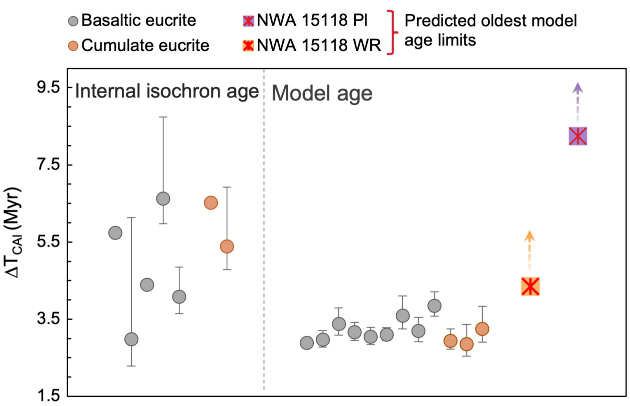

Figure 2 Comparison of ^{26}Al-^{26}Mg ages from this study with previous HEDs results. The oldest model age limits for NWA 15118 estimated from both the bulk rock (WR) and mineral fraction (Pl) with the highest Al/Mg ratio, are shown. All the ^{26}Al-^{26}Mg ages in comparison were recalculated using the ^{26}Al half-life of 0.717 Myr (Kondev *et al.*, 2021) and anchored to the solar initial (^{26}Al/^{27}Al)$_0$ ratio of 5.23 ± 0.13 × 10^{-5} (Jacobsen *et al.*, 2008). Literature data sources are listed in Table S-3.

Limited ^{26}Al-^{26}Mg data exist for diogenites, and the available ages remain controversial, partly due to their sub-chondritic ^{27}Al/^{24}Mg ratios, hindering the detection of radiogenic ^{26}Mg. Hublet *et al.* (2017) attributed the absence of radiogenic ^{26}Mg anomaly to diogenite formation >7.25 Myr after CAIs; however, this prediction is rather arbitrary without considering the low Al/Mg of diogenites. Schiller *et al.* (2011) reported small radiogenic ^{26}Mg excesses in diogenites and suggested early formation (0.6 to 2.5 Myr after CAIs) based on the ε^{54}Cr-μ^{26}Mg* correlation. However, the positive radiogenic ^{26}Mg excess in some diogenites conflicts with their sub-chondritic ^{27}Al/^{24}Mg and may indicate contamination by eucrites (Hublet *et al.*, 2017). Despite the limited constraints on diogenites, existing ^{26}Al-^{26}Mg model ages on basaltic and cumulate eucrites show similar and homogeneous results, indicating eucritic crust formation initiated at ~2.88 Myr after CAIs, and the primary crust building lasted for ~1 Myr (Fig. 2). Internal isochron ages of basaltic and cumulate eucrites show a wider range, from 2.98 to 6.62 Myr after CAIs, mostly younger than the model ages (Fig. 2), which has been suggested to be related to metamorphic resetting or slow cooling of the magma (Hublet *et al.*, 2017). Our Al-Mg model age demonstrates that NWA 15118 postdated the onset of eucrite formation by at least ~1.5 Myr (Fig. 2). This relatively young crystallisation age challenges the hypothesis that NWA 15118 represents a primary global crust from a Vestan magma ocean, as proposed by Li *et al.* (2024).

Genetic links of NWA 15118 with HEDs. Although the Al-Mg age constraints for diogenites remain debated, Barrat *et al.* (2010) proposed, based on the negative Eu anomalies and wider Dy/Yb variation in diogenitic orthopyroxenes compared to those in eucrites, that diogenites represent late stage intrusions contaminated by overlying eucritic crust. The positive radiogenic ^{26}Mg excess in some diogenites may also indicate such contamination (Schiller *et al.*, 2011; Hublet *et al.*, 2017). In addition, three dimensional modelling of impact basins and gravity mapping on Vesta indicate that the absence of large-scale exposures of pure diogenites is inconsistent with a layered structure derived from a global magma ocean, instead supporting an intrusive origin for diogenites (Clenet *et al.*, 2014; McSween *et al.*, 2019). On Earth, Archean calcic anorthosites with An >90 % (comparable to lunar ferroan anorthosite and NWA 15118) also occur as small intrusions (10–30 km^2) (Ashwal, 2010). The positive Eu anomaly and young age of NWA 15118 are consistent with its complementary relationship to diogenites as intrusive crustal fragments. A simple mass balance calculation shows that to generate a parental melt with chondrite normalised Eu/Eu* = 1 (*i.e.* no Eu anomaly), the required volume proportion of anorthosite to diogenite would be ~3 %, using density of 3.46 g/cm^3 for diogenite (Consolmagno *et al.*, 2008) and 2.23 g/cm^3 for lunar ferroan anorthosite (Li *et al.*, 2024). Visible and near-infrared spectroscopy (VNIR) data from the Dawn mission revealed widespread diogenitic lithologies on Vesta; however, no definitive anorthosite, even in the largest diogenite exposures in the Rheasilvia basin (De Sanctis *et al.*, 2012). However, the VNIR instrument measures the average spectrum within a pixel (nominal resolution: 70–700 m, depending on orbit), so anorthositic exposures smaller than the spatial resolution could remain undetected (De Sanctis *et al.*, 2013). Nevertheless, the lower trace element ratios (*e.g.*, Ti/Y, Ti/Yb, La/Sm) of NWA 15118 in orthopyroxene and plagioclase compared to those expected if equilibrated with diogenitic melts challenge their complementary origin (Sheen *et al.*, 2025). The Al-Mg age of basaltic eucrites (fine to medium grained non-cumulate eucrites, ∼2.88 to 6.51 Myr after CAIs) overlaps with NWA 15118, and some basaltic eucrites also show negative Eu anomalies (Dhaliwal *et al.*, 2023), suggesting potential genetic links. Alternatively, the distinct trace element characteristic of NWA 15118 may indicate derivation from a chemically distinct source (Sheen *et al.*, 2025). The ungrouped achondrite Wan Zawatin 001, with high anorthite content (76 vol. %) and similar O isotopes with HEDs, may also originate from Vesta (Sheen *et al.*, 2025 and references therein). Further investigation of its Al-Mg age and potential relationship with NWA 15118 could provide additional insights into the magmatic evolution of Vesta. In summary, the present evidence suggests that NWA 15118 **more plausibly represents a fragment of regional crust formed after the primary crustal differentiation of Vesta, potentially related to some late-stage basaltic eucrites or from a chemically distinct source.**

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Author Contributions

Conceptualisation: FM. Methodology: LF and HR. Investigation: HR and FM. Visualisation: HR, LF. Supervision: FM. Writing–original draft: HR. Writing–review and editing: all authors.

Additional Information

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