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Prolonged magmatism on 4 Vesta inferred from Hf–W analyses of eucrite zircon

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ABSTRACT

The asteroid 4 Vesta is the second most massive planetesimal in the Solar System and a rare example of a planetary object that possibly can be linked to a specific group of differentiated meteorites, the howardite–eucrite–diogenite suite. The ^{182}Hf–^{182}W chronometry of individual zircon grains from six basaltic eucrites revealed distinct growth episodes ranging from 4532 $-11/+6$ Ma to 4565.0 $\pm$ 0.9 Ma and constrains the early thermal history of 4 Vesta, indicating that its mantle generated basaltic melts for at least 35 million years (Myr). Initially, the energy needed for melting was provided by decay of short-lived isotopes, mostly ^{26}Al. The long duration of magmatism despite the short lifetime of ^{26}Al implies that the asteroid must have accreted within the first ~4 Myr of Solar System formation, similar to the formation of iron meteorite parent bodies, and that its interior must have been thermally well insulated by an early-formed crust that prevented heat loss.

1. Introduction

Planetesimals represent an intermediate stage in the evolution from the first solids of the Solar System to chemically differentiated planets. Most meteorites recovered on Earth are derived from planetesimals that populate the asteroid belt between Mars and Jupiter. These small rocky bodies, arrested in different stages of planetary evolution, preserve information about early Solar System processes that has been obliterated on larger planets owing to their prolonged geologic activity. A single group of mineralogically, isotopically, and chemically similar meteorites — the howardite, eucrite, and diogenite (HED) suite — appears to have originated from a specific observable parent body, 4 Vesta, in the asteroid belt. This planetary body is 4th largest asteroid to have survived disruptive collisions. Remote sensing spectroscopy (Gaffey et al., 1989) and visible and infrared spectroscopy by the Dawn spacecraft (De Sanctis et al., 2012) of the asteroid 4 Vesta suggest that its composition resembles that of the HED meteorites. These mineral-chemical similarities, coupled with the existence of plausible delivery mechanisms of fragments from 4 Vesta make this ~520-km diameter planetesimal one of the most likely sources of the HED samples (e.g., Consolmagno and Drake, 1977; Binzel and Xu, 1993). This inferred link between a suite of meteorites and a specific planetesimal provides a unique opportunity to directly study the evolution of a differentiated planetesimal through a combination of geochemical and isotopic analyses of rock samples, remote sensing and spectroscopic studies of the planetary surface, and thermal modeling constrained by measured planetary parameters.

The depleted siderophile element budget in HEDs as compared to that of chondrites (e.g., Righter and Drake, 1997) and the homogeneity of their oxygen isotope compositions (Greenwood et al., 2005) support the hypothesis that a global magma ocean on the eucrite parent body (EPB) differentiated into a metal core and a silicate mantle (e.g., Righter and Drake, 1997; Ruzicka et al., 1997). Radioisotope ages obtained with both short- and long-lived chronometers, e.g., U–Pb, Sm–Nd, Rb–Sr, and Al–Mg, indicate that the HED meteorites are among the oldest igneous rocks in the Solar System (e.g., Carlson and Lugmair, 2000, and references

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therein), and the textural features of eucrite mineral assemblages are indicative of their magmatic origin as near-surface lava flows or as shallow intrusions. However, the primary crystallization record of most basaltic eucrites has been significantly disturbed to varying degrees by thermal- and shock metamorphism such that their interval of formation is not easily discerned. Evidence for the initial presence of short-lived radionuclides (e.g., ^{26}Al, ^{53}Mn, and ^{182}Hf) in some basaltic eucrites requires rapid accretion, heating, melting, and differentiation of the HED parent body within the first ~10 Myr after the beginning of condensation in the Solar System (e.g., Lugmair and Shukolyukov, 1998; Srinivasan et al., 1999; Kleine et al., 2004). From the Hf–W systematics of eucrites, it has also been inferred that core formation preceded mantle differentiation by ~4 Myr (Kleine et al., 2004; Wadhwa et al., 2007). Radioisotope dates from short- and long-lived systems suggest that cumulate eucrites may be 100–150 Myr younger than basaltic eucrites (e.g., Nyquist et al., 1997; Blichert-Toft et al., 2002; Touboul et al., 2015). It is not clear, however, whether these dates reflect (re)crystallization or delayed isotopic closure during slow subsolidus cooling at depth (e.g., Nyquist et al., 1997).

Model calculations for thermal evolution of asteroids >50 km in diameter, heated by radioactive decay of ^{26}Al, and insulated by a crust, do not predict rapid cooling of the interior (e.g., Ghosh and McSween, 1998; Gupta and Sahijpal, 2010). For example, for a Vesta-sized body (~270 km radius), temperatures at depths of 15 km and ~45 km exceed 1000 K for nearly 30 Myr and 100 Myr, respectively (Ghosh and McSween, 1998). Such a prolonged cooling history could have enabled high-temperature metamorphism or magmatism on Vesta long after heat production by ^{26}Al had become negligible. The oxygen isotope data, together with diogenite trace element data (Greenwood et al., 2005; Barrat et al., 2010), led Greenwood et al. (2014) to suggest a rapid transition from a global magma ocean (Greenwood et al., 2005) to serial magmatism. A similar scenario was also discussed in Neumann et al. (2014), who suggested that a magma ocean, although covered by a crust, would have been thin and short-lived, yet silicate melts could have persisted in the mantle for up to 150 million years. Alternatively, considering a thermal evolution model of a magma ocean without a radioactive heat source and no thermal insulation, a Vesta-sized body would rapidly cool below basalt-forming temperatures within ~100 years (Elkins-Tanton et al., 2008). Such calculations in the absence of ^{26}Al are analogous to the evolution of a magma ocean on Vesta after ^{26}Al had completely decayed, underscoring the importance of an insulating crust in slowing down heat loss and prolonging the cooling history.

Model calculations by Mandler and Elkins-Tanton (2013) show that equilibrium- and fractional crystallization processes can reproduce the major element compositions of eucritic melts and the approximate range of mineral compositions observed in diogenites. However, the trace element compositions of diogenites from Barrat et al. (2010) are not reproduced in such a model. Nevertheless, the model demonstrates that a diverse range of meteorites could indeed originate from a single differentiated asteroid. The early formation of eucrites is accommodated in the model calculations through rapid destruction of an insulating crust by impacts, which resulted in the transfer of hot mantle material to the surface and thus accelerated cooling of the EPB (Gupta and Sahijpal, 2010). Evidence for the presence of short-lived radionuclides, particularly ^{26}Al, in eucrites requires that mantle differentiation by melting and crystallization of the resulting melts started within the first several Myr of the EPB evolution (e.g., Srinivasan et al., 1999). However, constraints on the *duration* of the basaltic activity are difficult to extract from these measurements because of resetting of isotope chronometers during later metamorphism. Accurate and precise measurement of this duration requires a short-lived decay system having a half-life suitable for covering the first few tens of millions of years, i.e., the interval predicted by slow cooling models for 4 Vesta (see Supplementary Materials, Fig. S3). Also required is fractionation between parent and daughter elements during igneous processes that is sufficient to generate measurable isotope excesses, and a high closure temperature, such that host minerals resist re-equilibration during metamorphism. The ^{182}Hf–^{182}W system (with a half-life of ~8.9 Myr) in zircon fulfills these requirements and provides an ideal combination of high age resolution and robustness against resetting.

Zircon occurs as a primary, but late-stage accessory phase in many basaltic eucrites and is one of the most refractory and chemically stable minerals present (e.g., Roszjar et al., 2014; Haba et al., 2014). It has a high Hf concentration (HfO_2 ~1–2 wt%, Roszjar et al., 2014) but negligible initial W. The high parent (Hf) to daughter (W) ratio thus makes zircon ideally suited for application of the ^{182}Hf–^{182}W chronometer, as long as this phase crystallized while ^{182}Hf was extant. Provided the Hf–W system in zircon was not affected by later disturbance, zircon grains can date the crystallization of basaltic eucrites and thus constrain the duration of magmatism on their parent body.

2. Samples and analytical methods

The investigated eucrite samples – Dhofar (Dho) 182, Northwest Africa (NWA) 1908, NWA 4523, NWA 5073, NWA 5356, and Hammadah al Hamra (HaH) 286, are basaltic rocks of low shock degree (S1–S3), except HaH 286 (S4). All investigated samples, except NWA 5073 (Roszjar et al., 2011), have been thermally metamorphosed to varying degrees as evidenced e.g., by the occurrence of augite lamellae of varying thickness in pigeonite grains (Takeda and Graham, 1991). Northwest Africa 5073 and 5356 are unbrecciated. All other samples (Dho 182, NWA 1908, NWA 4523, and HaH 286) are monomict breccias. For further details, see Supplementary Materials. Zircon grains from all studied eucrite samples are subhedral to irregular and mainly occur within silicate-rich mesostasis areas, in interstices or along interfaces between larger grains, and in apparent equilibrium with the surrounding igneous mineral assemblages (Fig. 1). They are typically enriched in the heavy rare earth elements (HREE, e.g., Haba et al., 2014; Roszjar et al., 2014; this study). However, the REE enrichments can vary among grains within individual eucrite samples indicating chemical variation of residual melt pockets on a sub-cm scale (Roszjar et al., 2014; this study). The chemical compositions of zircon grains were obtained by electron microprobe analysis using routine procedures and are provided together with details on mineral associations in Roszjar et al. (2014). The HfO_2 contents of zircon grains range from 0.85 wt% in NWA 1908 to 2.11 wt% in HaH 286 (Roszjar et al., 2014), which is within the compositional range previously reported for eucrite zircon (e.g., Misawa et al., 2005; Srinivasan et al., 2007). The 25 grains selected for ion microprobe analysis typically have diameters ranging from ~4 to ~35 μm, with most being 10 to 20 μm.

The Hf–W compositions and rare earth element (REE) concentrations were determined with high-spatial resolution using a Cameca IMS-1280 ion microprobe at the Swedish Museum of Natural History (NRM), Stockholm. For details on the analysis procedures, see Supplementary Materials. Further details of the REE measurement protocol and concentration results for selected zircon grains are presented in Roszjar et al. (2014). Replicate LREE analyses of selected grains in NWA 5356 were performed in this study using modified measurement and data reduction procedures designed to eliminate the possibility of isobaric interferences (see Supplementary Materials).

The initial ^{182}Hf/^{180}Hf values, i.e., (^{182}Hf/^{180}Hf)$_i$ and corresponding uncertainties for each zircon (Table 1) are calculated