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Differentiation and magmatic activity in Vesta evidenced by ^{26}Al-^{26}Mg dating in eucrites and diogenites

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Abstract

The ^{26}Al-^{26}Mg short-lived chronometer has been widely used for dating ancient objects in studying the early Solar System. Here, we use this chronometer to investigate and refine the geological history of the asteroid 4-Vesta. Ten meteorites widely believed to come from Vesta (4 basaltic eucrites, 3 cumulate eucrites and 3 diogenites) and the unique achondrite Asuka 881394 were selected for this study. All samples were analyzed for their $\delta^{26}Mg^*$ and $^{27}Al/^{24}Mg$ ratios, in order to construct both whole rock and model whole rock isochrons. Mineral separation was performed on 8 of the HED's in order to obtain internal isochrons. While whole rock Al-Mg analyses of HED's plot on a regression that could be interpreted as a vestan planetary isochron, internal mineral isochrons indicate a more complex history. Crystallization ages obtained from internal ^{26}Al-^{26}Mg systematic in basaltic eucrites show that Vesta's upper crust was formed during a short period of magmatic activity at $2.66^{+1.39}_{-0.58}$ million years (Ma) after Calcium-Aluminum inclusions (after CAI). We also suggest that impact metamorphism and subsequent age resetting could have taken place at the surface of Vesta while ^{26}Al was still extant. Cumulate eucrites crystallized progressively from $5.48^{+1.56}_{-0.60}$ to >7.25 Ma after CAI. Model ages obtained for both basaltic and cumulate eucrites are similar and suggest that the timing of differentiation of a common eucrite source from a chondritic body can be modeled at $2.88^{+0.14}_{-0.12}$ Ma after CAI, i.e. contemporaneously from the onset of the basaltic eucritic crust. Based on their cumulate texture, we suggest cumulate eucrites were likely formed deeper in the crust of Vesta. Diogenites have a more complicated history and their ^{26}Al-^{26}Mg systematics show that they likely formed after the complete decay of ^{26}Al and thus are younger than eucrites. This refined chronology for eucrites and diogenites is consistent with a short magma ocean stage on 4-Vesta from which the basaltic eucrites rapidly crystallized. In order to explain the younger age and the complex history of diogenites, we postulate that a second episode of magmatism was possibly triggered by a mantle overturn. We bring a refined chronology of the geological history of Vesta that shows that the asteroid has known a more-complex differentiation than previously thought.

Keywords: Al-Mg dating; Vesta; Eucrites; Diogenites

1. INTRODUCTION

Eucrites and diogenites are igneous rocks belonging to the howardite-eucrite-diogenite meteorite (HED) series. The HED's are widely believed to originate from early magmatic activity on the same parent body, one of the three largest asteroids of the asteroid belt, 4-Vesta (Vesta hereafter) (Lugmair and Shukolyukov, 1998; Drake, 2001; Mittlefehldt, 2015). The common origin of these three types

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of achondrite have been confirmed by similarities in their oxygen isotopic composition (Clayton and Mayeda, 1996; Greenwood et al., 2005; Scott et al., 2009; Greenwood et al., 2014). The matching reflectance spectra between HED achondrites and the surface of Vesta suggests that this asteroid is the parent body of HED series (McCord et al., 1970; Consolmagno and Drake, 1977; Pieters et al., 2006). This hypothesis is supported by recent data from the Dawn mission (Russell et al., 2012; McSween et al., 2013; Russell et al., 2013). Large craters observed on the surface of Vesta could be the source of the abundant small objects with identical reflectance spectra found in the asteroid belt called "Vestoids" that could also be the source of HED meteorite found on Earth (Binzel and Xu, 1993), notwithstanding that some eucrites have recently been identified as being anomalous and possibly originated from other parent bodies than Vesta (Scott et al., 2009; Greenwood et al., 2014; Sanborn and Yin, 2014; Williams et al., 2015).

In terms of petrology and mineralogy, eucrites are basaltic to gabbroic achondrites composed of pyroxenes (pigeonite) and plagioclase (Krot et al., 2003). Eucrites can be subdivided into two groups: basaltic (non-cumulate) and cumulate eucrites (Krot et al., 2003). The mineralogy of these two types of eucrite is similar but they have different grain sizes and texture (Krot et al., 2003). Basaltic eucrites are fine to medium grained while cumulate eucrites are characteristically coarse (Krot et al., 2003). The cumulate eucrites can also be distinguished from basaltic eucrites based on chemical features such as higher Mg# (Mg# ∼ 57–45 in cumulate eucrites as opposed to Mg# ∼ 42–30 in basaltic eucrites), and lower abundance of incompatible trace elements such as LREE (Barrat et al., 2000; Barrat, 2004; Mittlefehldt, 2015). Diogenites are coarser-grained igneous cumulates. These meteorites are orthopyroxenite or harzburgitic achondrites composed of ∼90% of orthopyroxene with minor plagioclase and olivine content (Bowman et al., 1997). Assuming that the HED's originated from the same parent body, likely Vesta, they constitute a unique opportunity to investigate early Solar System planetary evolution such as differentiation and early magmatic activity on a large asteroid.

Eucrites and diogenites have traditionally been considered as co-magmatic. As such, different scenarios for their formation have been suggested. First, eucrites are hypothesized to have crystallized from a residual basaltic melt formed by intensive fractional crystallization of a magma ocean. In this case, diogenites, as ultramafic cumulates, would have crystallized directly from the same magma ocean (Righter and Drake, 1997; Ruzicka et al., 1997; Takeda, 1997; Drake, 2001; Greenwood et al., 2005; Larsen et al., 2011; Mandler and Elkins-Tanton, 2013; Greenwood et al., 2014; Mittlefehldt, 2015; Schiller et al., 2017). A second scenario suggests the formation of eucrites and diogenites by partial melting of the Eucrite Parent Body (EPB) with extraction of basaltic magma forming the eucrite crust and crystallization of residual magma forming diogenites (Stolper, 1977; Jones, 1984). However, chemical features such as incompatible trace element abundances suggest no direct link between the two parent magmas of eucrites and diogenites, and also possibly the existence of more than one parental melt for the diogenites (Mittlefehldt, 1994; Fowler et al., 1995; Shearer et al., 1997; Barrat, 2004; Barrat et al., 2008; Mittlefehldt, 2015). In a third scenario, diogenites could have been produced in plutons or in multiple small magma chambers without any genetic relationship with eucrites (Shearer et al., 1997; Barrat et al., 2008; Beck and McSween, 2010; Yamaguchi et al., 2011; Mittlefehldt, 2015). Chemical signatures in some diogenites have been proposed to be crustal contamination (Barrat et al., 2010), originating when diogenites crystallized as intrusions within a eucritic crust. In a fourth scenario, based on oxygen isotope measurements, it has been proposed that diogenites originated from at least two distinct parent bodies (Day et al., 2012). However a careful revaluation of earlier with new oxygen isotopes has concluded to a small variation range for oxygen isotope data between eucrites and diogenites and thus a single parent body (Greenwood et al., 2014). Finally, based on chronological measurements that Vesta formed on a very rapid timescale (within 3 Ma after CAI formation), Schiller et al. (2011) suggested that the HED series may not have originated from Vesta at all, as this asteroid is too large to have such a brief magmatic activity. A similar hypothesis was also considered by Wasson (2013) due to O and Cr isotope data being more similar to the IIIAB asteroid. However, the recent results obtained from the Dawn mission indicate that the surface of Vesta is consistent with the mineralogy of HED meteorites (McSween et al., 2013). If it is assumed that HED meteorites do come from Vesta, their precise dating is of importance to understand the evolution of this asteroid and the possible scenarios of igneous activities related to the formation of eucrites and diogenites. Howardites will not be considered in the following as they are breccia randomly sampling different lithologies and may also record younger impact ages in addition to igneous activity.

Short-lived radioactive-isotope systems are powerful tools to study the early history of the Solar System as they can provide high-resolution age information during the lifetime of their parent isotopes. As such, they serve as the most effective chronometers for the first few million years (Ma) of the Solar System history. However, some inconsistencies exist between different chronometers, and different ages have been proposed for eucrites and diogenites (Table 1). While a pioneering study found no $^{26}Mg^*$ in eucrites (Schramm et al., 1970), recent studies have shown that some eucrites have a small excess in $^{26}Mg^*$ (Srinivasan et al., 1999; Bizzarro et al., 2005; Schiller et al., 2010a), suggesting the presence of ^{26}Al at the time of their formation. Bizzarro et al. (2005) and Schiller et al. (2010a) showed that asteroidal melting and basaltic magmatism on the EPB occurred ∼3 Ma after the Solar System formation. Other dating results obtained on eucrites using ^{53}Mn-^{53}Cr, ^{26}Al-^{26}Mg, ^{60}Fe-^{60}Ni and ^{182}Hf-^{182}W short-lived radioactive systems indicated that core formation and silicate differentiation of Vesta occurred rapidly, 1–5 Ma, after CAI formation (Lugmair and Shukolyukov, 1998; Quitté et al., 2000; Kleine et al.,