Exploring the Geochemical, Geochronologic, and Thermal History of HED Meteorites using Zircon

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Introduction: The Howardite-Eucrite-Diogenites (HEDs) represent the largest suite of achondritic material from a differentiated asteroid, likely 4 Vesta[1-4]. Astrophysical modeling of planetary body accretion timescales puts Vesta forming nearly 0.8 Ma after CAIs[5], therefore providing the earliest known insight to early planetesimal formation. Diogenites and eucrites provide insights to upper mantle and crustal magmatic and differentiation processes occurring within the parent body. Howardites and polymict breccias represent a mixing of these materials from impact events on the parent body. Therefore, HED's might have recorded both the primary, differentiation history and subsequent impact related processes occurring on early differentiated planetesimals.

Zircon, an accessory phase in HEDs, is a powerful tool to link chemical processes with time through the use of the dual U-Pb chronometers and multiple chemical tracers[6,7].

Samples: Among 19 meteorite samples from the HED clan, 78 zircon were discovered. From this study, zircons have been discovered in all HED families and sub families, which include melt breccia eucrites, monomict eucrites, polymict eucrites, genomict eucrites, unbrecciated eucrites, howardites and diogenites. This will be the first study to thoroughly document the nature of zircon in HEDs, linking both the geochronology with the geochemistry and texture of the individual grains. All zircons were imaged by back-scatter electron (BSE) and polychromatic Cathodoluminescence (CL) to characterize the texture of zircon and surrounding material. We also present U-Pb ages, as well as Thorium and Uranium signatures to discuss the potential origin of the zircons and their link to the history of the planetesimals.

Results*:* **1. Texture**

Highly and Moderately Shocked Zircon

Among the diverse families of HEDs, the Melt Breccia Eucrites (MBEs) are the most intensely shocked material with pervasive shock melt pockets and veins throughout the different samples (**Fig 1a**). The shock melt within the MBEs are typically coarse, acicular crystal assemblages of plagioclase and pyroxene. The zircons in MBEs are all found near (< 100 µm) or entrained local shock melt. Those not directly entrained in the shock melt display evidence of shock deformation as shown by multi-domain features seen in BSE and CL images and fractures, while those within the shock melt show extreme anhedral, granular textures (**Fig. 1a**). More moderately shocked zircon are found in monomict eucrite samples as shown by multi-domain features, fractures are pervasive shock melt entrained within the sample (**Fig. 1b**).

Impact Brecciated Zircon

The zircon in these samples do not contain shock melt, however, the samples have undergone extensive brecciation as a result of impact. Many zircons in this sample are isolated in the brecciated matrices and present fractures that offset or fault the grain. Other zircon in these brecciated regions are broken into multiple fragments and dispersed in the surrounding material (**Fig. 1c).** These impact brecciated zircon are typically found in howardites, diogenites and polymict eucrite samples.

Unaltered Zircon

Zircons that do not have any apparent impact or shock alteration visible in BSE or Cl imaging primarily come from the unbrecciated eucrites. These grains have well preserved crystal morphologies with borderline prismatic shapes (**Fig. 1d**). These zircon are likely pristine relicts of the primary magmatic processes occurring on the HED parent body.

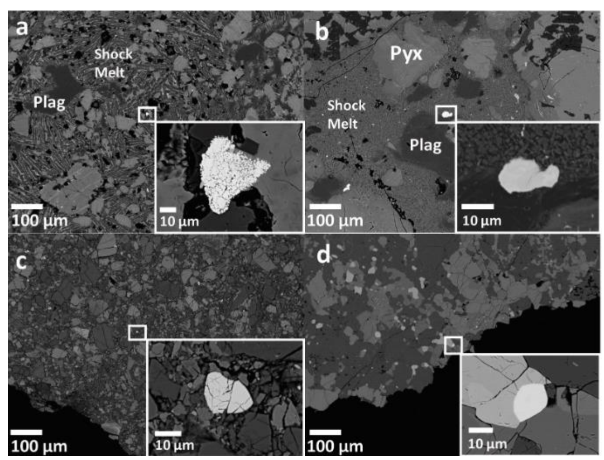

Figure 1: Back-scatter electron images from 4 different HED samples. Inset image of highly shocked granular/neoblastic zircon situated in well-developed shock melt composed of plagioclase (Plag) and pyroxene (Pyx; a). Inset of weakly shocked zircon entrained in a fine-grained shock melt pocket (b). Inset of weakly shocked zircon with extensive fracturing and broken fragments isolated in the breccia matrix (c). Inset of unaltered zircon from an unbrecciated eucrite that shows very pristine crystal morphology (d)

Results: 2. ^{207}Pb-^{206}Pb Ages of HED Zircon: SIMS Pb-Pb ages are shown in **Fig. 2c**. Zircons from all samples mostly have ages between 4500 and 4560 ± 20

Ma (n=31, **Fig. 2a**), with some ages falling between 4200 and 4500 Ma, consistent with previous studies[8-10]. Two zircons are exceptionally young when compared to the other HED groups with recorded ages of 4234 and 4327 Ma (**Fig. 2a**). Interestingly, the zircon from the monomict eucrite that records an age of 4234 Ma appears relatively unshocked, whereas the zircon from the MBE that records an age of 4327 is the zircon with extreme shock features and a completely granular morphology (**Fig. 1a).**

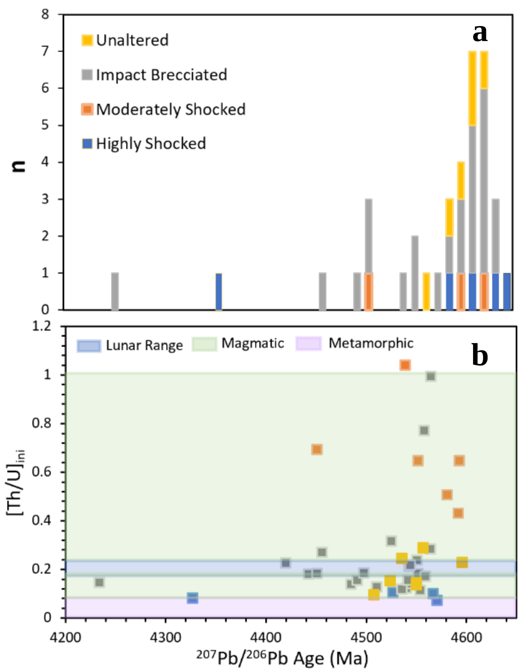

Fig. 2: Plot of $[U]_{ini}$ vs $^{207}Pb/^{206}Pb$ age in Ma (a). Plot of $[Th/U]_{ini}$ vs $^{207}Pb/^{206}Pb$ age in Ma with added fields to visual metamorphic and magmatic ranges of terrestrial zircon and the average range of Th/U for lunar zircon (Trail et al. (2020; b).

Results: 3. Th/U of HED Zircon: Th/U ratios can be used to track the environment in which the grains formed, for example, by identifying whether zircon are magmatic or metamorphic[11]. The zircons which texture records the highest degree of shock have the lowest $[Th/U]_{ini}$ (0.07; Fig. 2b). However, low Th/U is not characteristic of all shocked samples, as grains within moderately shocked samples have higher $[Th/U]_{ini}$ ratios (0.64-1.0). Zircon from impact brecciated and unaltered samples have moderately low and relatively homogenous $[Th/U]_{ini}$ ratios (0.10-0.40; Fig. 2b).

Discussion: Zircons from the HED suite of meteorites show complex texture among all samples, ranging from unshocked and unaltered to highly shocked grains. The highly shocked zircons from the MBEs in particular appear to have undergone extensive shock metamorphism as evidenced by the extreme granular nature of the crystals (**Fig. 2b**). In particular, the zircon with the age of 4327 Ma is likely a record of a large impact that resulted in high temperature (and possibly high pressure) shock conditions as it retains similar characteristics to those zircon from other large impacts on the Earth (Sudbury[12]) and the moon (South-Pole Aitken[13]). This impact recrystallization of the zircon is also likely responsible for the low Th/U ratio, where the larger Th^{4+} is preferentially purged from the structure upon recrystallization and thus results in exceptionally low Th/U values[14].

The higher $[Th/U]_{ini}$ ratios of the moderately shocked zircon suggests that shock conditions likely had the largest effect on these ratios. Because these highly shocked grains are noted to have multi-domain features, it is possible that lattice distortions can affect the trace element chemistry[15]. These defects in the zircon crystal structure can provide fast diffusion pathways within the lattice and locally move trace elements into defect locations within the crystal.

A particularly interesting case of zircon crystallization are those zircon discovered in diogenites. Diogenites are ultramafic products from the upper mantle of Vesta, therefore it is notably very difficult to saturate zircon in these conditions as they preferentially crystallize in intermediate-felsic and low-temperature conditions[16,17]. One hypothesis for zircon in diogenite crystallization is that an incompatible enriched melt, like KREEP (Potassium, REE, and Phosphorous) on the moon[18], too existed on Vesta. A KREEP-like component that is enriched in incompatible elements like Zirconium can best explain how zircon saturation is achieved in these ultramafic conditions and has also been documented as the mechanism for mafic-ultramafic lunar zircon crystallization[6,12,19,20].

Altogether, the HEDs and zircon within will provide the crucial data in understanding how magmatic, differentiation and impact processes have evolved through time on the parent body and later comparing this to the detailed history of the moon[6].

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