EARLY THERMAL EVENTS IN THE HED PARENT BODY (4 VESTA) RECORDED IN ZIRCON U-TH-PB DEPTH PROFILES FROM MILLBILLILLIE BRECCIATED EUCRITE

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Introduction: Investigation of early thermal events recorded in objects beyond the Earth-Moon system is essential to our understanding of the impact bombardment history and dynamical evolution of the inner solar system. Geochemical analyses of minerals from asteroidal meteorites are a window to these early thermal processes, and are an accessible resource to be compared to what is documented for lunar bombardment history. Eucrites, the E class of the HED achondrite meteorites (howardite—eucrite-diogenite), are the crystallization products of melts from a large asteroid, likely 4 Vesta [1]. These meteorites are documented to contain accessory mineral phases that robustly preserve parent-daughter ratios in long-lived radiogenic (e.g. zircon, apatite, baddeleyite).

We report the results of our investigations of the early thermal evolution of 4 Vesta by comparative ultra-high resolution U-Th-Pb zircon depth profiles from the brecciated eucrite Millbillillie. Preserved $^{235-238}U/^{207-206}Pb$ ratios in different mineral domains (cores, mantles) within individual zircons may be used to identify the timing and intensity of thermal events that affected the asteroids. Domains within zircons can reveal distinct events that can be correlated to previously reported radiometric ages for the eucrites, as well as lunar and ancient terrestrial rocks and minerals that overlap in time with the bombardment epoch. This is a new means to expand on the chronology of impacts to the Moon, Earth and other inner solar system bodies.

Methods: Crushed and sieved ~15g aliquots of powdered material were separated using reagent grade methylene iodide to extract the largest zircons. Four grains (mb1_gr1 ~40µm ∅; mb7_gr1 ~20µm ∅; mb14_gr1 ~10µm ∅; mb17_gr1 ~10µm ∅) were imaged by back-scattered electrons, and the internal distributions of U-Th-Pb in each zircon measured on the UCLA Cameca ims1270 ion microprobe in depth-profile mode [2,3].

Results: Grain mb1_gr1 was analyzed along a ~7 µm depth profile (200 analysis cycles). Data show that mb1_gr1 preserves a concordant $^{207}Pb/^{206}Pb$ core age of 4561±13 Ma (2σ; mswd=0.72; n=7) and a 3 µm-wide overgrowth at 4524±9 Ma (2σ; mswd=2.52; n=19) (Fig.1a). Grain mb7_gr1 (Fig.1b) was depth profiled for ~5 µm and shows one domain $^{207}Pb/^{206}Pb$ age of 4537±10 Ma (2σ; mswd=3.0; n=19) over 135 analysis cycles. A ~3 µm (75 cycles) depth profile of grain mb14_gr1 yields one domain $^{207}Pb/^{206}Pb$ age of 4516±100 Ma (2σ; mswd=0.67; n=13) and ~3 µm profile (50 cycles) of grain mb17_gr1 shows a solitary domain $^{207}Pb/^{206}Pb$ age of 4489±76 Ma (2σ; mswd=0.21; n=10) (data not shown here).

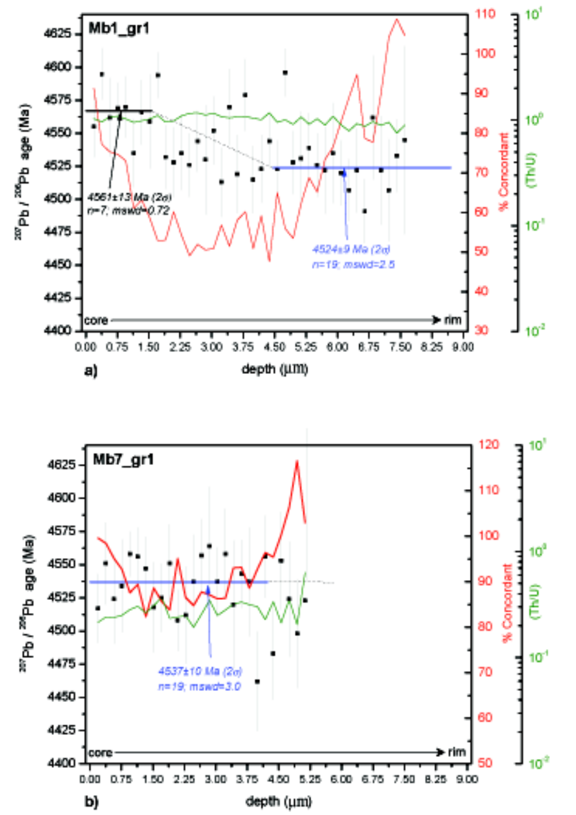

Figure 1- Individual $^{207}Pb/^{206}Pb$ ages for the depth profiles are represented by black squares (1σ errors), where each square represents a block of 5 cycles. U-Pb concordance % is shown in red. Th/U ratios are shown by in green.

Discussion: Grain mb1_gr1 displays a core $^{207}Pb/^{206}Pb$ age (4561±13 Ma) that correlates with other reported crystallization ages for eucrites [4] and ^{40}Ar-^{39}Ar ages of unbrecciated eucrites [5]. The overgrowth region of grain mb1_gr1 is 4524±9 Ma. Since the decay of ^{26}Al was effectively complete 5 Myr after t_0 [6], we propose that the event recorded here – 40 Myr after crystallization of Vesta's crust – was caused by massive thermal resetting. This age is statistically indistinguishable from the younger mantle in zircon mb7_gr1 (4537±10 Ma). Th/U ratio for the mb1_gr1 core yields values (0.8-1) consistent with exchange equilibrium of bulk Millbillillie Th/U (0.75-0.89) [7,8] and is indicative of igneous origin (Fig.1a). Younger mantle age from mb7_gr1 preserve lower Th/U ratios (0.1-0.5) consistent with the Th/U (0.3-0.5) of various fragmented pieces of Millbillillie eucrite [8] and points to a meta-igneous origin for this component (Fig.1b). The core of grain mb1_gr1 is concordant (92%) and decreases to ~55% from mixing of Pb-Pb ages between an old core and younger rim, then returns to 105% as younger rim age is breached (Fig.1a). U/Pb concordance % for grain mb7_gr1 stays mostly concordant throughout depth profile (Fig. 1b).

Due to the small size (~10 µm) of grains mb14_gr1 and mb17_gr1, and the analytical challenge of depth profiling such small grains, data are of lower quality. Results from mb14_gr1 show a $^{207}Pb/^{206}Pb$ age of 4516±100 Ma (2σ); mb17_gr1 yields a $^{207}Pb/^{206}Pb$ age of 4489±76 (2σ). Both statistically overlap with the crystallization and overgrowth ages reported in mb1_gr1 and mb7_gr1. Th/U ratios values are broadly consistent with an igneous origin, however larger internal errors became a problem. U/Pb concordance % is also highly variable throughout each depth profile.

Implications for bombardment history: Crystallization ages of eucrites are constrained at ~4.56 Ga by U-Pb and $^{207}Pb/^{206}Pb$ ages from zircons [4,9,10], whole rock ^{40}Ar-^{39}Ar ages of unbrecciated eucrites [5] and Hf-W data [11]. It is intriguing to compare subsequent thermal events recorded in eucrites to timing of bombardments to the Moon (and Earth). Apollo samples probably show a cataclysmic "spike" in impacts from ~3.8-4.1 Ga [12]. Dynamical models [13] contend that the impact spike would not be limited to the Earth-Moon and should be present in asteroids. Several brecciated eucrites and igneous clasts in howardites show impact ages within the range of 3.4–4.5 Ga [5]. A follow-up study [14] on impact-melt clasts in howardites show a bimodal age distribution with 2 clasts at ~4.3 Ga and remaining clasts spread between 3.9 and 3.4 Ga. Zhou *et al.* [15] reported crystallization ages from 2 eucrite zircons (Cachari-4546±9.9Ma) and (Béréba-4556±22Ma) and later thermal event $^{207}Pb/^{206}Pb$ age of 4195±13Ma from an apatite grain found in Béréba. They suggest the apatite age represents the beginning of the LHB on the asteroids. Our results do not show "events" coinciding with the LHB. This may be due to the small size of Vesta (~530 km diameter) and locally low impact velocities (~5 km/s). An energetically large impact is required to produce sufficient melt to either completely recrystallize or form new zircon.

Ancient thermal events that pre-date the LHB are recorded in eucrites. Bogard and Garrison [5] observed a cluster of ^{40}Ar-^{39}Ar ages at ~4.48 Ga for unbrecciated and cumulate eucrites; it was suggested they were reset by a big impact event that produced the largest crater observed on 4Vesta. Cohen [14] reported 2 impact-melt clasts in howardites with impact ages of ~4.3 Ga. Our eucritic zircon data (Fig. 1a & 1b) document a thermal event at ~4530 Ma. This age (~40 Myr after initial solar system formation) statistically falls within range of proposed Hf-W model ages of the Giant Impact (GI) formation of the Moon 30-110 Myr after t_0 [16-18]. Such "Moon-forming impact ages" in eucrites could mean that the gravitational conditions which precipitated the GI by orbital crossing by a Mars-sized impactor to the Proto-Earth were not restricted to the area around 1 AU. Planetesimal models show that gravitational interactions between planetesimals combine to produce a few tens of Moon-to-Mars-size planetary embryos in roughly 0.1–1 Myr; that these embryos collide to form the planets in 10–100 Myr [19] means that it is plausible that the asteroid belt experienced bombardment events throughout this formative time.

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