EARLY THERMAL EVENTS RECORDED IN ZIRCON U-TH-PB DEPTH PROFILES FROM EUCRITE METEORITES AND LUNAR IMPACT BRECCIAS. M.D. Hopkins[1,2,#] and S.J. Mojzsis[1,2,3], [1]University of Colorado, Geological Sciences, Boulder, CO, 80309 USA; [2]NASA Lunar Science Institute, Center for Lunar Origin and Evolution (CLOE); [3]Laboratoire de Géologie de Lyon, Université Claude Bernard Lyon 1, Villeurbanne, France. [#](michelle.hopkins@colorado.edu)

Introduction: Improved constraints on the temporal evolution of early thermal events in the asteroid belt and Moon can help unlock the impact bombardment history and dynamical evolution of the inner solar system. Eucrites are the crystallization products of melts from a large asteroid, likely 4 Vesta [1]. They contain accessory minerals (e.g. zircon, apatite, baddeleyite) that robustly preserve parent-daughter ratios in U-Pb. A cataclysmic "spike" in impacts termed the Late Heavy Bombardment (LHB) may have affected the Moon from ~3.8-4.1 Ga [2]. A symmetrical record of ancient thermal events on the Moon could be preserved in meteorites from the asteroid belt.

We report results of our preliminary investigations of the early thermal evolution of 4 Vesta and the Moon via comparative ultra-high resolution U-Th-Pb depth profiles of zircons from the brecciated eucrite Millbillillie, and extracts from 3 bulk Apollo 14 lunar samples. Preserved $^{235\text{-}238}U/^{207\text{-}206}Pb$ ratios in within individual zircon domains (cores, mantles) may be used to identify the timing and intensity of thermal events. The domains can be correlated to previously reported radiometric ages for these samples.

Methods: Powdered ~15g aliquots of Millbillillie were introduced to reagent grade methylene iodide to extract the largest zircons. Four zircons (mb1_gr1 ~40µm ∅; mb7_gr1 ~20µm ∅; mb14_gr1 ~10µm ∅; mb17_gr1 ~10µm ∅) were identified. Lunar samples 14305, 14163 and 14311 are being processed. Zircons were imaged in BSE and CL, and their internal distributions of U-Th-Pb measured on the UCLA Cameca ims1270 ion microprobe in depth-profile mode [3,4].

Results: Eucrite zircon mb1_gr1 was analyzed along a ~7 µm depth profile; 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 overgrowth at 4524±9 Ma (2σ; mswd=2.52; n=19) (**Fig.1a**). Zircon mb7_gr1 (**Fig.1b**) was profiled for ~5 µm showing one domain age of 4537±10 Ma (2σ; mswd=3.0; n=19). A ~3 µm profile of mb14_gr1 yielded one domain at 4516±100 Ma (2σ; mswd=0.67; n=13), and a ~3 µm profile of mb17_gr1 showed a solitary domain at 4489±76 Ma (2σ; mswd=0.21; n=10; data not shown here).

Lunar grain mt1_14305_gr1 was depth profiled to ~7.5 µm and shows one domain at 4279±22 Ma (2σ; mswd=0.55; n=33). Lunar zircon mt2_14163_gr18 was profiled for ~10 µm and records one domain at 4264±19 Ma (2σ; mswd=0.42; n=43). Another ~7.5 µm depth profile of grain mt2_14305_gr5 shows one domain age of 4240±13 Ma (2σ; mswd=1.02; n=40).

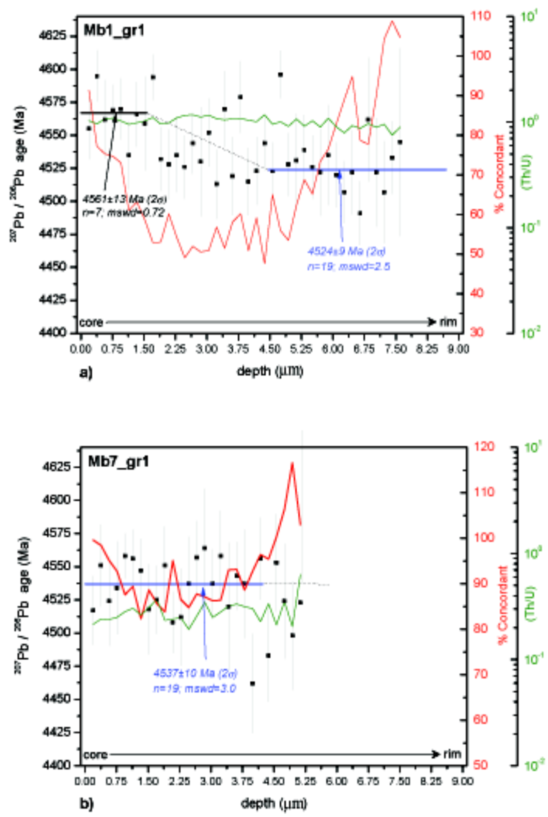

Figure 1. Individual $^{207}Pb/^{206}Pb$ ages for the depth profiles are represented by black squares (1σ errors), where each square represents a block of 5 cycles. U-Pb concordance % is shown in red. Th/U ratios are shown by in green.

Discussion: Eucrite zircon mb1_gr1 has a core age coinciding with reported crystallization ages for eucrites [5], and $^{40}Ar\text{-}^{39}Ar$ ages of unbrecciated eucrites [6]. The overgrowth on grain mb1_gr1 is 4524±9 Ma. Since ^{26}Al was effectively extinct 5 Myr after t_0 [7], the event recorded here – 40 Myr after crystallization of Vesta's crust – was likely caused by thermal resetting. This age resembles a younger mantle domain in zircon mb7_gr1 (4537±10 Ma). Core Th/U for mb1_gr1 yields values (0.8-1) consistent with exchange equilibrium of bulk Millbillillie Th/U (0.75-0.89) [8,9] indicative of igneous origin. Younger mantle ages from mb7_gr1 preserve lower Th/U (0.1-0.5) consonant with Th/U (0.3-0.5) exchange with Millbillie matrix breccias [9]. Grain mb1_gr1 has a concordant core (92%) that decreases to ~55% from mixing U-Pb values between an (old) core and (younger) rim overgrowth, then returns to 105% as the rim is breached. U/Pb concordance % for grain mb7_gr1 is mostly ~100%.

The analytical challenge of measuring small (~10 µm) zircons such as mb14_gr1 and mb17_gr1 means that these data are of lower quality. Results from mb14_gr1 show an age of 4516±100 Ma (2σ); mb17_gr1 yields ages of 4489±76 (2σ). Both statistically overlap with the crystallization and overgrowth ages from mb1_gr1 and mb7_gr1. Th/U values are broadly consistent with an igneous origin, but U/Pb concordance % are highly variable.

Th/U of lunar grain mt2_14305_gr5 yields igneous values (0.7-0.8). U/Pb concordance % for grain mt2_14305_gr5 is reversely discordant (120%) at the rim of the grain and decreases to ~55% as the profile approached the core.

Implications for bombardment history: Initial crystallization ages of eucrites are constrained at ~4.56 Ga by U-Pb and $^{207}Pb/^{206}Pb$ ages from zircons [5,10,11], ^{40}Ar-^{39}Ar ages of unbrecciated eucrites [6] and Hf-W data [12]. It is intriguing to compare thermal events in eucrites to to lunar record. Dynamical models [13] contend that the LHB should have affected the asteroids. Brecciated eucrites and igneous clasts in howardites show impact ages from 3.4–4.5 Ga [6]. These are within the range of U-Pb, K-Ar, and Rb-Sr ages (3.8-3.9 Ga) from lunar highland breccias [14]. Lunar meteorite NWA 4485 was reported to contain a 100 µm zircon with an average $^{207}Pb/^{206}Pb$ core age of 4211 ± 7 Ma and overgrowth at 3927 ± 23 Ma [15]. Smaller matrix zircons and a baddeleyite in NWA 4485 had $^{207}Pb/^{206}Pb$ ages of ~3.9 Ga in line with the LHB. Impact-melt clasts in howardites [16] have bimodal age distributions with 2 clasts at ~4.3 Ga and others spread between 3.9 and 3.4 Ga. Zhou *et al.* [17] 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 a Béréba apatite. They suggested the apatite age represents onset of the LHB. Our results do not show "events" coinciding with this time perhaps due to the small size of Vesta (~530 km diameter) and generally low impact velocities (~5 km/s). Only an energetically large impact can produce sufficient melt to either completely recrystallized, or to form new zircon.

Ancient thermal events that pre-date the LHB are recorded in eucrites and lunar rocks. Bogard and Garrison [6] observed a cluster of ^{40}Ar-^{39}Ar ages at ~4.48 Ga for unbrecciated and cumulate eucrites perhaps from a big impact. Cohen [16] reported 2 impact-melt clasts in howardites with ages of ~4.3 Ga. A "pomegranate"-clast zircon in lunar breccia 73235 registers two ages; 4.31 Ga restricted to zircon fragments, and 4.18 Ga for the surrounding zircon matrix formed by impact shock [17]. Lunar melt breccia 73217 has 3 different zircon "types" and anhedral apatites [18]. Types-1 and -2 zircons yielded ages of ~4.33 Ga and Ti ppm temperatures from 1300-900 °C. Type-3 zircon aggregates rim a baddeleyite and yield and age of 3929±10 Ma similar to the 3936 ±17 Ma age of co-existing apatites. That study [18] and a follow-up by Pidgeon et al. [19] considered these observations as evidence for a protracted lunar impact history of intense bombardment interspersed with quite periods.

Our eucritic zircon data document a thermal event at ~4530 Ma. This age falls within proposed Hf-W model ages for the Giant Impact (GI) formation of the Moon 30-110 Myr after t_0 [20-22]. Could the gravitational conditions which precipitated the GI by orbital crossing by a Mars-sized impactor to the Proto-Earth have been solar system-wide? Planetary embryos collide to form the planets in 10–100 Myr [23]. Hence, it is plausible that the asteroid belt has a memory of bombardment at this formative time.

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