DO HADEAN ZIRCONS RETAIN A RECORD OF THE LATE HEAVY BOMDARDMENT ON EARTH?

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Introduction: The Late Lunar Cataclysm [1] or "Late Heavy Bombardment" (LHB) between 4000–3800 Ma represents a flux of comets and/or asteroids several orders of magnitude above present values [2, 3], in contrast to the exponential bombardment decay model since planetary accretion [4]. The LHB is hypothesized based on lunar meteorite impact melts [5], shock events recorded in the martian meteorite ALH84001 [6], and the oldest shock ages for asteroid-belt-derived meteorites [7, 8]; all contain ages which cluster around 3.9 Ga. Conversely, it is argued that the record of pre-3.9 Ga impact events was reset, or that earlier (lunar) impact ejecta are buried [3]. The search for evidence of the LHB on Earth requires a different approach since Earth lacks a continuous rock record from before ca. 3.7 Ga. Therefore, we have studied Hadean (≥4.0 Ga) zircons which pre-date the bombardment epoch. Zircons from the Jack Hills and Mt Narryer metasediments, Western Australia have yielded ages up to 4.4 Ga [e.g. 9-16]. The utility of these zircons is that they (i) are robust crystals that have survived crustal recycling and thermal events; and (ii) span the time period several hundred million years prior to the hypothesized bombardment epoch, a crucial interval for comparing competing models.

Methods: Zircons were analyzed by ion microprobe (ANU SHRIMP II or UCLA Cameca ims 1270) using our conventional U-Th-Pb protocols [17]. It has been demonstrated that Hadean zircons retain secondary overgrowths [e.g. 9, 12, 15] developed after primary core crystallization during ≥4.0 Ga crustal residence times [e.g. 10,11,13-15]. These rim overgrowths can record discrete thermal events subsequent to zircon formation and provide a unique window in crustal processes before the beginning of the terrestrial rock record [16]. However, previous studies investigated these rims in conventional U-Th-Pb spot mode, and overgrowths smaller than typical ion microprobe spots (10-30 µm) are not resolvable. To overcome this limitation, we have employed ion microprobe U-Th-Pb depth profiling which provides continuous sub-micron depth vs. age data for single crystals [e.g. 17]. Selected zircons were removed from their epoxy mounts and recast with an original (unpolished) prism face down with zircon standard AS3. Single Hadean zircon mounts were left unpolished, but cleaned with 1N HCl in order to remove common Pb contamination prior to ion microprobe depth profiling and intermittently repolished during the course of the analysis.

Results and discussion: All profiled zircons retain mid-Archean overgrowths from documented regional thermal events in the Narryer Gneiss Complex [16]. Thicker and more defined overgrowths are present in the ~3.97-3.94 Ga interval in four of the six profiled zircons. The ~3.9 Ga overgrowths are typically <20% of the width of a ~25 µm ion beam demonstrating that conventional spots would be contaminated by other domains. Two zircons preserve less defined 3.8–4.0 Ga domains. In all cases, overgrowths have $[Th/U]_{Zr}$ chemically distinct from core regions, mitigating against substantial mixing between mid-Archean rims and core regions. Because the detrital Jack Hills zircons are separated from their host rocks, the source of 3.9 Ga overgrowths cannot be directly evaluated. Given that the Hadean zircons represent crustal relics as opposed to mantle material [9-16], then two possibilities exist for the origin of the observed ca. 3.9 Ga overgrowths. These are discussed in-tandem with lunar data.

First, late ca. 3.9 Ga mantle differentiation could have triggered widespread metamorphism on the Moon [1]. However, much of the lunar highlands formed by 4.3 Ga, so it is difficult to validate the presence of a widespread ~3.9 Ga event [1]. Metamorphism at 3.9 Ga associated with internal magma generation implies mantle differentiation occurred, possibly creating large volumes of crust [1]. While this cannot be ruled out, it must be reconciled with lunar and terrestrial geochemistry. The Moon experienced major Rb-Sr fractionation at 4.5 Ga, but no evidence exists from Rb-Sr model ages for a major crustal formation event at 3.9 Ga [1].

A paradigm is emerging that global differentiation of the silicate Earth occurred in the first 50 Ma, [18] and substantial volumes of continental crust existed by 4.4 to 4.5 Ga [15]. Significant crustal formation at 3.9 Ga - while possible - is less likely when considering the constraints of this model.

The favored view to explain lunar isotopic disturbances ca. 3.9 Ga is shock heating and metamorphism from the LHB. Large impacts could cause fractionation of different elements due to differences in volatilization. While the Rb-Sr system shows relatively closed behavior with well-defined model ages of 4.6–4.4 Ga, the U-Pb system contains significant fractionation of Pb relative to U at 3.9 Ga [1]. This is supported by K-

Ar data [1] and reinforced by ^{40}Ar-^{39}Ar ages of lunar meteorite impact melts [5].

Before evidence for a terminal cataclysm became available from other planetary bodies (e.g. Mars, Vesta), Tera et al. [1] postulated that impact induced terrestrial metamorphism would have been widespread as well. The Earth could have intercepted up to four 500 km diameter impactors and experienced 10-30 impacts from 200 km diameter bodies [19], many of which may have occurred in the first 800 Myr. Crustal rocks would have been thermally metamorphosed within or beneath large, hot impact ejecta blankets or impact plumes. To test for discrete Pb disturbances in putatively exogenic induced ca. 3.9 Ga zircon rims, we examined changes in % concordance (i.e. [$^{207}Pb^*/^{206}Pb^*$ age]/[$^{206}Pb^*/^{238}U$ age]) vs. the depth-age relationship of individual crystals. In our analysis, we assume that a 100% concordant domain indicates significant Pb loss did not occur within that domain. Of the 4 zircons which demonstrated defined 3.9 Ga overgrowths (Figure 1) three have LHB domains which are markedly less concordant than surrounding regions. This result is completely consistent with that obtained for lunar rocks [1] that overlap in age with the bombardment epoch.

Dynamical implications: There are two competing models for the origin of the impactor flux vs. time. The first describes an impactor flux that increases dramatically at 3.9 Ga. An alternative model argues that the record of pre-3.9 Ga impact events was reset, or that earlier impact ejecta are buried [4]. A direct test of these models would be if Hadean zircon rims record thermal events possibly associated with impacts prior to 3.9 Ga, especially on older (>4.2 Ga) grains. As yet, no overgrowths - whatever the origin - have been found between the 3.9 Ga rims and the zircon (igneous) core ages. It has been demonstrated that the origins of the Hadean zircons are not related to impacts or associated melts [14]. However, the possibility that older, pre-3.9 Ga overgrowths are removed or blurred by other processes should be investigated. Recent results indicate that the migration of Jupiter and Saturn entering a 1:2 mean motion resonance could lead to late stage flux of debris into the inner solar system lasting ~200 Myr [3]. This event may have caused a delayed delivery above an otherwise declining flux of comets and asteroids into the inner solar system. While the planetary migration scheme suggests a predominantly cometary origin, objects from the asteroid belt also contributed to the LHB increased mass flux [3].

Conclusions: We have depth profiled Hadean zircons by ion microprobe and described well-defined ca. 3.9 Ga overgrowths in four of the six grains contemporaneous with the age ascribed the LHB. If the overgrowths can be authenticated as impact-related by e.g. $[Ti]_{Zr}$ thermometry [14], it is within the realm of possibility that the age resolution of U-Th-Pb depth profile method can directly date different mega-impacts. A larger data set of pre-4.2 Ga and older depth profiled zircons is warranted; 4.0 Ga and older overgrowths could be used to support (or refute) the exponential decay model [4]. Thus far, ~3.9 Ga zircon overgrowths with no (preserved) older events provide evidence that favors the cataclysmic model [2,3,5].

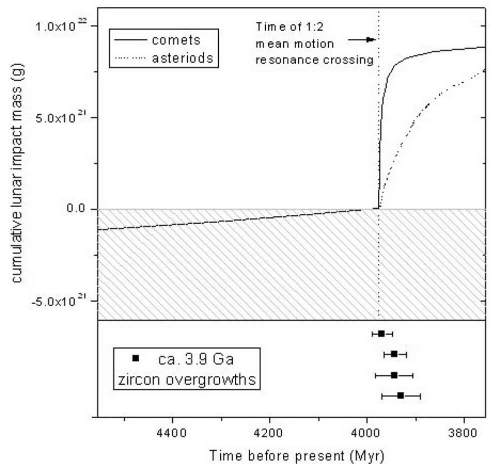

Figure 1. Lunar accretion model from Gomes et al. [3] predicting a spike in the mass flux into the inner solar system. This occurs at the time of the 1:2 mean motion resonance crossing of Jupiter and Saturn consistent with the timing of the LHB. The "rapid pulse" result agrees with the small time dispersion of the four depth profiled zircons that preserve defined ca. 3.9 Ga overgrowths (age uncertainties are $\pm 1\sigma$).

Acknowledgments: We thank K. McKeegan, A. Schmitt, M. Grove and G. Jarzebinski for technical assistance with the UCLA ion probe. Support from the NASA Exobiology Program (NAG5-13497) "Mission to Really Early Earth" to SJM, and the NSF Instrumentation and Facilities Program and Australian Research Council to TMH are greatly appreciated. DT acknowledges the NAI Student Research Scholarship. We have benefited from extensive discussions with D. Kring, and R. Pidgeon. **References:** [1] Tera, F. et al. EPSL 22: 1-21 (1974). [2] Ryder, G. J. Geophys. Res. 107, 6-[1-13] (2002). [3] Gomes, R. et al. Nature 435: 466-469. (2005). [4] Hartmann W.K. Meteoritics & Planetary Science 38: 579-593. (2003). [5] Cohen, B. A. et al. Science 290, 1754-1756. (2000). [6] Turner, G. et al. Knott S. F., Ash R. D. and Gilmour J. D. GCA. 61, 3835-3850. (1997). [7] Bogard D. D. (1995) Meteoritics 30, 244-268. [8] Tera, F. et al. GCA 61, 1713-1731. (1997). [9] Maas et al. GCA 56: 1281-1300 (1992). [10] Mojzsis, S.J. et al., Nature 409:178-180 (2001). [11] Wilde, S.A. et al. Nature 409: 175-178. (2001). [12] Cavosie, A.J. et al. Precamb. Res. 135: 251-279. (2004). [13] Cavosie, A.J. et al. EPSL 235, 663-681. (2005). [14] Watson E.B. and Harrison T.M. Science 308, 841-844. (2005). [15] Harrison et al. Science 310, 1947-1950 (2005). [16] Trail, D. et al. Chem Geol. (submitted). [17] Mojzsis, S.J. and Harrison, T.M. EPSL 202: 563-576 (2002). [18] Boyet, M. and Carlson, R. W. Science 309: 576-581 (2005). [19] Sleep, N.H. and Zahnle, K. JGR. 103: 28529-28544. (1998).