EXPLORING FOR EARLY BOMBARDMENTS ON EARTH FROM PRE-3.83 Ga THERMAL EFFECTS RECORDED IN HADEAN ZIRCONS – A STATUS REPORT. S. J. Mojzsis[1], O. Abramov[1], T.M. Harrison[2], D.A. Kring[3], H.F. Levison[4], D. Trail[5] and E.B. Watson[5], [1]Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309-0399 USA (mojzsis@colorado.edu), [2]Department of Earth and Space Sciences, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567 USA, [3]Lunar and Planetary Institute, Houston, TX 77058 USA, [4]Space Sciences Department, Southwest Research Institute, Boulder, CO 80302 USA, [5]Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, NY 12180 USA

Introduction: In the early solar system, Earth was bombarded by comets and asteroids just as the Moon and other solar system objects were. Crustal recycling mechanisms have very nearly erased the geologic record for the first half-billion years (Hadean eon) that would preserve evidence for such cataclysmic events. Presently, there exists no direct means to measure of the influx of extraterrestrial matter to Earth before ~3.85 Ga during the 'late lunar cataclysm' or 'late heavy bombardment' [1,2; LHB]. Several studies have attempted to acquire information on the rate of accumulation and intensity of impacts at the extreme tail end of the LHB from the study of Earth rocks and minerals: Shock features in quartz [3] and zircon [4,5] from ~3.7-3.8 Ga rocks from the Isua supracrustal belt (West Greenland) yielded no optically resolvable shock deformations [6]; no unequivocal chemical evidence from platinum-group elements for the late heavy bombardment was found in paragneisses with minimum ages of ~3.83 Ga [7,8]; W isotope anomalies in ca. 3.7-3.8 Ga paragneisses from West Greenland and Labrador (Canada) were interpreted to be remnants of the LHB in younger materials [9]. However, follow-up studies with platinoid elements, Cr and other isotopic systems [e.g. 10] could find no corroborating evidence for cosmic materials in the Isua rocks [11]. Significantly, the various studies cited above explored rocks with formation times (≤3.85 Ga) that likely did not overlap with the main period of the LHB [e.g. 12].

Hadean zircons: The only vestiges of Earth's crust known to have been present during the LHB are ≤4.38 Ga detrital zircons captured in younger (3.3 Ga) sediments from the Narryer Gneiss complex in Western Australia. These zircons are the oldest known terrestrial solids [13,14]; they record evidence for hydrosphere-lithosphere interactions [15], continental crust formation [16], crustal temperature regimes in the Hadean [17,18], the presence of extinct radionuclides [19], thermal alterations since igneous crystallization [20] and other key planetary processes [21]. Zircons ($Zr(SiO_4)$) are a common constituent of many rocks, and have been found in lunar rocks and in some meteorites [22]. They have the potential to provide robust input parameters to physical models of early impact regimes in the solar system [23]. Zircon is ideally suited for these purposes because they are stable to ~1700°C at 1 bar [24], virtually insoluble in supercritical C-O-H fluids [25], relatively insoluble in most magmas [26], and diffusion is slow for most elements [e.g. 27].

Here we report on our progress with high-resolution ion microprobe U-Th-Pb depth profiles which show that subsequent to their crystallization in melts under typical crustal conditions on Earth, some Hadean zircons record common age domains with unusual chemical and isotopic characteristics consistent with a high-temperature (possibly impact) origin. We have found evidence for later overprints caused by intense thermal alteration between 3.94-3.97 Ga in six of eight studied grains but no evidence for older events. The immediate significance of these findings is that since they crystallized, the Hadean zircons were not destroyed in some wholesale remelting of the entire crust by "Doomsday"-scale impacts at least since 4.38 Ga. Although an admittedly gross constraint, it directly alerts us to two fundamental things we did not know before about the probiotic potential of the Earth in the early solar system: (i) that the LHB epoch did not result in complete destruction of the Earth's crust [e.g. 28] since the Moon-forming event at ca. 4.5 Ga; and (ii) age limits on both sides of the thermally altered 3.94-3.97 Ga zircon domains are very good and so far our data show that no detectable thermal events appear to have affectted the zircons before ~3.97 Ga up to about 4.3 Ga.

Methods: All zircons were analyzed by ion microprobe (ANU SHRIMP II or UCLA Cameca ims 1270) using our conventional U-Th-Pb protocols [29]. Other studies have shown that Hadean and meteoritic zircons can retain secondary overgrowths [e.g. 30-32] developed after primary core crystallization. All 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. We employ ion microprobe U-Th-Pb depth profiling which provides continuous sub-micron depth vs. age data for single crystals [e.g. 33]. Selected zircons were removed from their epoxy mounts and recast with an original (unpolished) prism face down with zircon standard AS3 (concordant $^{207}Pb/^{206}Pb$ age of 1099 Ma). Single Hadean zircon mounts are left unpolished, but treated in 1N HCl to remove common Pb contamination prior to ion microprobe depth profiling, and intermittently repolished during the course of the analysis.

Results and discussion: We find that most profiled zircons retain mid-Archean overgrowths correlatable with documented regional thermal events known to have affected this part of Australia [20]. Thicker overgrowths are present in the ~3.97-3.94 Ga age interval in six of the eight profiled zircons. The ~3.9 Ga overgrowths are typically <20% of the width of a ~25 μm ion beam. Five zircons preserve less defined 3.8–4.0 Ga domains that may be associated with normal crustal metamorphic conditions. In all cases, overgrowths have $[Th/U]_{Zr}$ chemically distinct from core regions, which argues against substantial mixing between mid-Archean rims and core regions.

The favored view to explain lunar isotopic disturbances reported in [1] is shock heating and metamorphism from impacts. Large impacts could cause significant fractionation of Pb relative to U at 3.9 Ga as originally proposed [1]. This is supported by K-Ar data [2] and reinforced by ^{40}Ar-^{39}Ar ages of lunar meteorite impact melts [34]. Before evidence for a terminal cataclysm became available from other planetary bodies (e.g. Mars, Vesta), it was postulated [1] that impact induced terrestrial metamorphism would have been widespread as well. In some LHB scenarios Earth could have intercepted up to four 500 km diameter impactors and experienced 10-30 impacts from 200 km diameter bodies [35]. Over time (but *not* instantaneously), ~40% of the volume of Earth's Hadean crust would have been thermally metamorphosed [23].

To test for discrete Pb disturbances in 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. Our analysis assumes that a 100% concordant domain indicates significant Pb loss did not occur within that domain. Of the 6 zircons with defined 3.9 Ga overgrowths, five have domains which are markedly less concordant than surrounding regions. This result is consistent with Pb-loss behavior in lunar rocks [1] ascribed to the LHB.

Conclusions: We have depth profiled eight Hadean zircons by ion microprobe and described well-defined ca. 3.9 Ga overgrowths in six grains contemporaneous with the age ascribed the LHB. We are undertaking $[Ti]_{Zr}$ thermometry [17] on individual growth zones of the zircons to provide temperature data for the zones. Our intention is to further expand the data set of depth profiled zircons by a factor of 5. If we find 4.0 Ga and older overgrowths (such as those associated South Pole-Aitken age events on the Moon [36]?), these data could be used to support (or refute) the exponential decay model [37] or cataclysm model [38] for the 4.3 – 3.85 Ga bombardment flux. Thus far, ~3.9 Ga zircon overgrowths with no (preserved) older events appears to favor the cataclysmic model.

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