PREDICTIONS OF CRUSTAL AGE-RESETTING BY IMPACT BOMBARDMENTS ON EARLY EARTH.

O. Abramov[1], D. A. Kring[2,3], and S. J. Mojzsis[4,5,6], [1]U.S. Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001 (*oabramov@usgs.gov*), [2]Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX, 77058, [3]NASA Solar System Exploration Research Virtual Institute (SSERVI), [4]University of Colorado, Geological Sciences, 2200 Colorado Ave., Boulder, CO 80309-0399, USA, [5]Center for Lunar Origin and Evolution (CLOE), NASA Lunar Science Institute, [6]Hungarian Academy of Sciences, RCAES, Institute for Geological and Geochemical Research, 45 Budaörsi ut, H-1112 Budapest, Hungary.

Introduction: Impact bombardment in the first billion years of solar system history determined in large part the initial physical and chemical states of the inner planets and their potential to host biospheres. Impact heating can lead to localized sterilization of the crust, but can also create hydrothermal oases favorable for life. The range of the consequences of the impact epoch, however, is not well quantified. Here, we assess these effects on the young Earth's crust, as well as the likelihood that a record of such effects could be preserved in the oldest terrestrial rocks and minerals, such as zircon crystals. We place special emphasis on modeling the thermal effects of the Late Heavy Bombardment (LHB) – a putative spike in the number of impacts at about 3.9 Gyr ago [e.g., 1-3] – using several numerical and analytical techniques.

Methods summary: The bombardment model [4,5] consists of (i) a stochastic cratering model which populates the surface with craters within constraints derived from the lunar cratering record, the size/frequency distribution of the asteroid belt, and dynamical models; (ii) analytical expressions that calculate a temperature field for each crater [e.g., 6,7]; and (iii) a three-dimensional thermal model of the terrestrial lithosphere, where craters are allowed to cool by conduction and radiation (Fig. 1). In addition, ejecta volumes and temperatures were calculated as illustrated in Fig. 2, and ejecta blankets deposited on the surface were allowed to cool in both conductive and hydrothermal regimes. Equations for Pb diffusion in zircon [8,9] are coupled to these thermal models to estimate the amount of age-resetting.

Results: Global bombardment models indicate that only a small portion of the crust was melted by the LHB. In the Baseline scenario, a total of ~1.5-2.5% of the upper 20 km of the crust was melted, depending on the geothermal gradient, and only up to ~0.3-1.5% was molten at any given time. In the most "extreme" scenario considered, a 10X bombardment with a 70 °C km^{-1} geothermal gradient, under ~25% of the upper crust was melted. One caveat is that impact melt tends to pool in crater depressions in the near surface; in the Baseline model, ~5–10% of the Earth's surface would have been covered by >1 km deep impact melt sheets; and in the 10X model, this percentage may have exceeded 50%. The largest impactor in the Baseline model, at ~300 km, may have raised the temperature of the global ocean by as much as 100 °C.

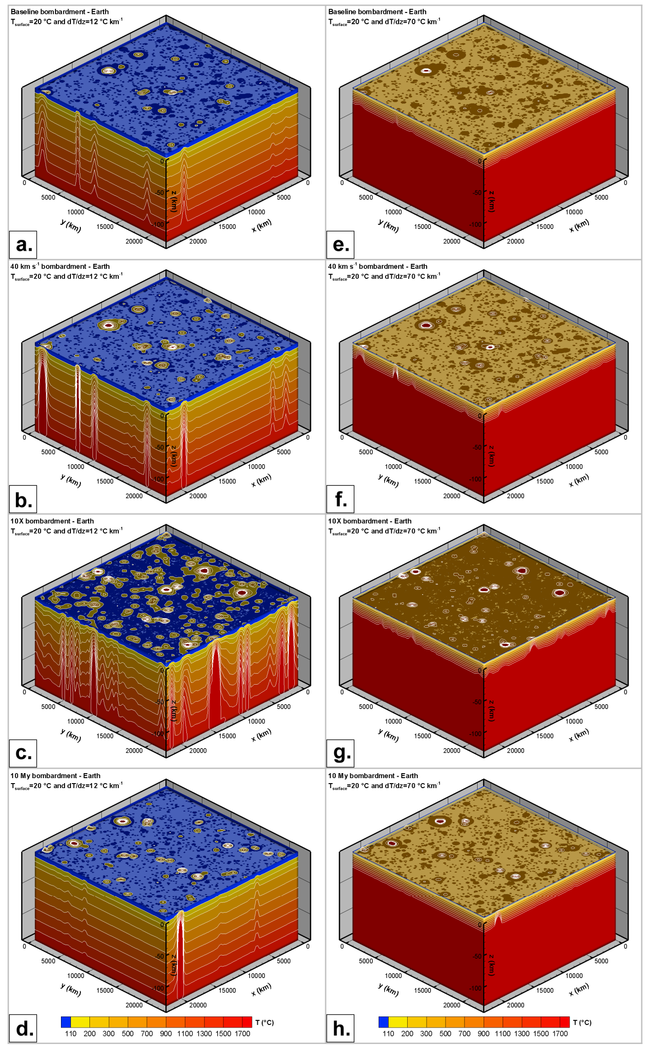

Fig. 1. A three-dimensional thermal model representing the upper 140 km of the Earth at the end of the LHB. Dark circles indicate crater locations, and blueareas indicate the extent of the subsurface habitable zone. The upper boundary shows temperatures at a depth of 4 km. Eight scenarios were tested.

The modeling presented in this work predicts that a global average of ~600–800 m of ejecta and ~800–1000 m of condensed rock vapor would have been deposited by the Baseline LHB. Smaller impacts generate roughly the same cumulative volume of ejecta as larger impacts, but most of the condensed rock vapor is produced by the very largest (>100-km) projectiles.

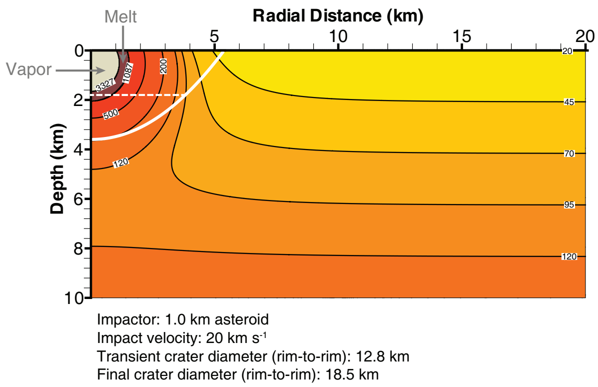

Fig. 2. Graphical illustration of how ejecta volumes and temperatures are calculated. Transient crater (white line), with dimensions derived from Pi-group scaling laws, is superimposed on a postimpact temperature distribution. Temperatures within the transient cavity above the excavation depth (dashed line) are volumetrically averaged.

Mean ejecta temperature increases with increasing projectile diameter, from ~300 °C for a 1-km impactor to ~2500 °C for a 500-km impactor, and melt content in the ejecta increases from a few percent to 100% for the same range.

Once deposited, ejecta blankets cool conductively, radiatively, and likely via hydrothermal interactions depending on water availability. Hydrothermal cooling significantly accelerates heat removal and reduces the penetration depth of the thermal pulse from hot ejecta into the subsurface. However, the initial stages of cooling, when most age-resetting takes place, are nearly identical in the two models, due to the latent heat of fusion and the lack of water and steam circulation through most of the partially molten ejecta blanket.

The temperature range for partial Pb*-loss in zircons within ejecta blankets is estimated at ~1000–1300 °C, varying weakly with ejecta thickness. After accounting for excavation from the mantle by the largest impacts, ejecta-entrained zircons are predicted to have the following distribution in the Baseline LHB scenario: ~59% with no Pb*-loss, ~26% with partial Pb*-loss, and ~15% with complete Pb*-loss or destruction of the grain. In contrast, model zircons within individual impact craters, particularly in the melt sheets, generally exhibit all-or-none age resetting in the Pb* system, and partial resetting is relatively uncommon. The prediction from these models that ~15% of the Hadean zircon population experienced age resetting from the LHB agrees well with the observations of [10], who computed that ~13% of the Jack Hills zircons preserved ca. 3.9 Ga "LHB-era" domains.

The ubiquitous surface presence of ejecta during impact bombardments, its propensity to cause partial Pb*-loss and/or overgrowths in zircons, and its relatively high erodibility suggest that, if some Jack Hills zircons contain a signature of the LHB in the form of ~3.9 Ga zones, these were most likely entrained in impact ejecta.

The results presented here assume a bombardment duration of 100 Myr in the baseline scenario. However, a recently-proposed "sawtooth" LHB model [11] posits a longer duration of ~400 Myr for this event, albeit with a roughly similar total delivered mass. This means that most of the conclusions of this study apply to the "sawtooth" scenario, with the exception of crustal fraction that was molten at a given time (Fig. 3): the infrequent impacts in the ~400 Myr bombardment would have allowed for greater cooling time between events.

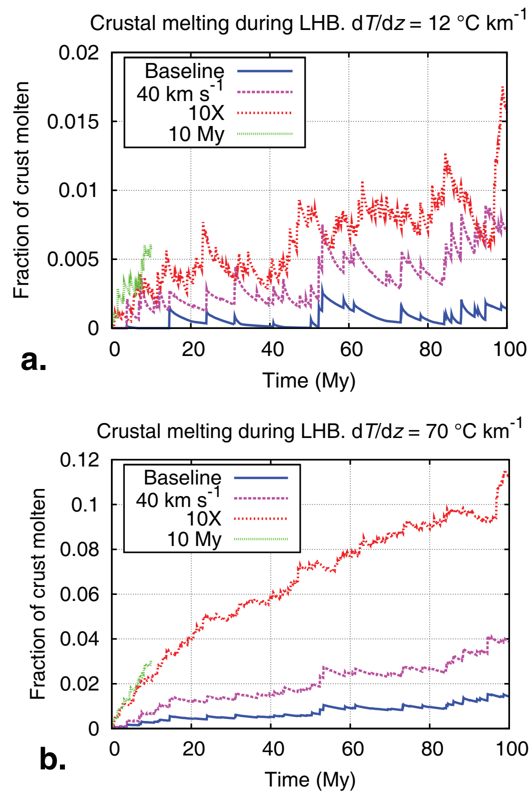

Fig. 3. The degree of melting in the upper 20 km of the crust as the LHB progresses, derived from a three-dimensional transient thermal model (Fig. 1). Melt deposited in ejecta blankets is not included.

References: [1] Turner G. et al. (1973) *Proc. Lunar Sci. Conf.*, 4, 1889–1914. [2] Tera F. et al. (1974) *Earth Planet. Sci. Lett.*, 22, 1–21. [3] Cohen B.A. et al. (2000) *Science*, 290, 1754-1756. [4] Abramov, O., and S.J. Mojzsis (2009) *Nature*, 459, 419-422. [5] Abramov et al. (2013) *Chemie der Erde*, 73, 227-248. [6] Kieffer S. W. and Simonds C. H. (1980) *Rev. Geophys. Space Phys.*, 18, 143-181. [7] Pierazzo E., and H.J. Melosh (2000). *Icarus*, 145, 252-261. [8] Cherniak D.J. et al. (1991) *Geochim.Cosmochim. Acta* 55, 1663-1673. [9] Cherniak D.J., and E.B. Watson (2001) *Chem. Geol.*, 172, 5-24. [10] Abbott S.S. et al. (2012) *Proc. Natl. Acad. Sci.*, 109, 13486-13492. [11] Morbidelli et al. (2012) *Earth Planet. Sci. Lett.*, 355-356, 144-151.