MODELING OF IMPACT-INDUCED AGE RESETTING AND PARTIAL PB-LOSS IN ZIRCON GRAINS.

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Introduction: Impact bombardment in the first billion years of the solar system fundamentally altered several key aspects of the terrestrial planets, and continues to be the subject of intense research interest within and beyond the planetary sciences. Effects of bombardments include: Changes in surface morphology, expressed as cratered terrains; chemical composition changes via delivery of materials, melt mixing and differentiation; changes to primordial atmosphere compositions and atmospheric densities, and thereby of paleoclimate; and perhaps the overall thermal structures of terrestrial planets. Also, heating due to impacts may have had important biological consequences.

One promising approach in understanding the bombardment history of the early solar system lies in the study of zircons, minerals that significantly predate the Late Heavy Bombardment (~3.9 Ga), some of which are almost 4.4 Ga. In particular, in addition to well-documented complete age-resetting of zircons in impact melts [e.g., 1,2], several studies have suggested partial resetting. These include: (i) Ultra-high spatial resolution ion microprobe depth-profiles of pre-3.9 Ga terrestrial zircons from the Jack Hills (Western Australia) that recorded ~3.95 Ga, 2 to 4 μm mantles over the old igneous zircon cores (up to 4.3 Ga). These minute mantles show Pb-loss (up to 90% discordance) over narrow domains that could be the result of impact-induced heating [3]. (ii) Zircons from the K/T distal ejecta, as well as from the Onaping Formation of Sudbury crater, appear to contain two components, based on $^{207}Pb/^{206}Pb$ ages: one with the age of target lithologies, and another with the time of impact, with the relative proportion of the latter increasing with the degree of impact shock [2,4].

This preliminary study explores conditions under which zircons may suffer complete or partial Pb loss, with the aim of making laboratory data easier to interpret, as well as making predictions for future studies.

Methods: We use well-constrained, laboratory-derived equations for diffusion of Pb in zircon, in both undamaged [5] and radiation-damaged crystals [6]. These equations require as inputs: (i) temperature and (ii) time spent at that temperature, and thus can be readily coupled to 1-, 2-, or 3-dimensional thermal models. We have previously developed a model of the response of zircons to impact bombardments on a global scale [7], and here we examine individual impact structures in an attempt to further understand the mechanism(s) behind age-resetting of zircons by impacts. Two numerical models are used in this study:

Crater cooling model: We use a previously-published simulation of the post-impact cooling of the ~180-km Sudbury crater (Ontario, Canada) [8] and model Pb-loss in zircons emplaced within the structure. The model includes cooling by hydrothermal activity, and was performed using modified version of the publicly available program HYDROTHERM, which simulates water and heat transport in a porous medium [9]. Rock properties appropriate for the Sudbury site are used. The initial temperature distribution of the Sudbury crater was previously calculated using the SALEB hydrocode [10]. The crater cooling simulation was coupled to equations of Pb-loss in zircon [5,6], which were solved numerically at each model time step.

Ejecta cooling model: Because the crater cooling model did not incorporate the deposition of hot ejecta outside the rim, an important process for larger (>100 km) impact craters, a separate 1-dimensional ejecta cooling model was constructed. The program used for this model is HEATING 7.3, a general-purpose, finite-difference heat transfer code. Thermal and physical parameters of the ejecta were based on those of granite, as specified in the HEATING materials library. The hot ejecta overburden was modeled on a 1000-node grid with a radiative upper boundary, overlying a 2000-node original surface with an initial temperature of 0 °C. Thickness and initial temperature of the ejecta are specified as inputs.

Results: *Crater cooling model:* In the case of undamaged zircons (Figure 1a), there is a rather strong dichotomy -- either 100% Pb-loss within zircon grain or none at all, with very few areas of partial Pb-loss. This result is remarkably independent of grain diameter. The areas of the crater that have 100% Pb-loss are central uplift (initial temperature of ~1,000 °C) the central melt sheet, as well as the small melt sheet in the annular trough (initial temperature of ~1700 °C). In addition, since the thermal decomposition temperature of zircon is 1673 °C [11], complete loss of grains emplaced within the melt is likely.

In addition, we modeled Pb-loss in shock-damaged zircons. Wittmann et al. [12] described granular textures within a variety of shocked zircon grains from several impact structures, which exhibit Raman characteristics that overall follow the trend of natural radiation damage. As a first-order approximation of this, we used the diffusion equation for radiation-damaged zircons [6], which have a significantly faster rate of Pb-loss. The results, illustrated in Figure 1b, show a significantly larger rock volume within the crater that suffers complete Pb-loss, as well as a somewhat wider band of partial Pb-loss.

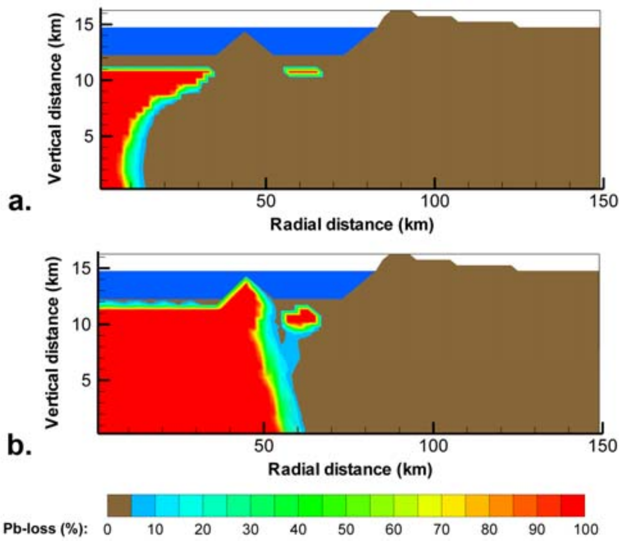

Figure 1. Percentage of Pb-loss in 50-µm zircon grains within a 180-km terrestrial impact crater. Pb-loss in the ejecta is not included in this model. a) Normal zircon grain. b) Shock-damaged zircon grain.

Ejecta cooling model: Much like the crater cooling model, the ejecta cooling model results indicate that there is a fairly narrow parameter space that yields partial Pb-loss. In the case of undamaged zircon grains (Figure 2a), only a temperature of 1200 °C results in partial Pb-loss in zircon grains within the ejecta. Other initial temperatures tested (300 °C, 600 °C, and 900 °C) result in no appreciable Pb-loss. In the case of shock-damaged zircons (Figure 2b), initial temperatures of 1200 °C and 900 °C resulted in complete Pb-loss throughout most of the ejecta blanket, 300 °C resulted in zero Pb-loss, and only 600 °C resulted in partial Pb-loss.

Concluding remarks: The models presented above suggest either complete Pb-loss or none at all within most impact structures. Since this appears at odds with evidence for partial Pb-loss presented above, it is likely that another mechanism needs to be invoked. For example, Krogh et al. [4] suggest that partial loss results from a post-impact thermal pulse during the grain's residence in the fireball cloud. Based on the equations used here, this does not appear likely, as Pb needs ~1 hour at ~1673 °C (thermal decomposition temperature of zircon) to diffuse 1 µm, in both damaged and undamaged grains. However, even with a fireball a few hundred km in diameter, ejecta traveling at half escape velocity would take only ~30 s to clear it. Other possibilities include rapid quenching of the breccias within the crater, for example, by post-impact flooding, and shock-heating, where the grain experiences very high temperatures for very short periods of time between the passages of compression and rarefaction waves. These possibilities continue to be investigated.

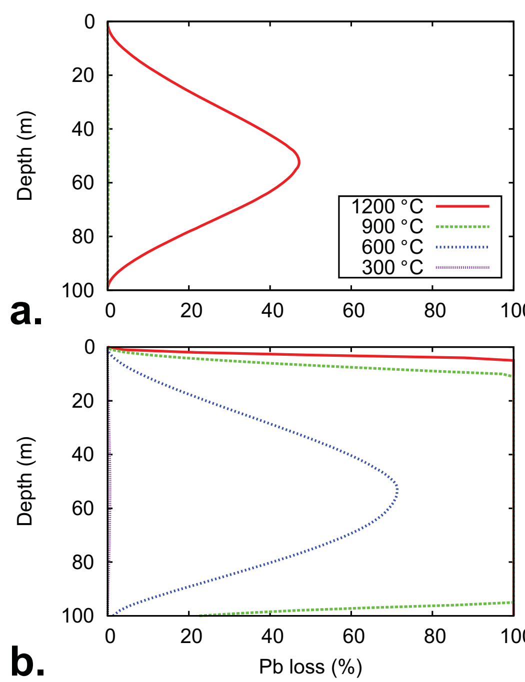

Figure 2. Percentage of Pb-loss in 50-µm zircon grains within a 100-m thick impact ejecta blanket of various temperatures. a) Normal zircon grain. b) Shock-damaged zircon grain.

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