From chondrules to planets – tracking the recycling of solids in an evolving protoplanetary disk

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The most abundant constituent of chondrites are chondrules, mm-sized spherules formed by transient heating events. High-resolution uranium-corrected Pb-Pb dates indicate that chondrule formation started contemporaneously with the Solar System first solids, CAIs, and lasted ~3 Myr [1]. Further, numerical simulations show that the main growth of asteroids results from gas-drag-assisted accretion of chondrules, leading to the formation of planetary embryos <3 Myr [2]. Thus, chondrules dominate the precursor material of most asteroids and, by extension, inner Solar System planets.

We report U-corrected Pb-Pb ages and $^{54}Cr/^{52}Cr$ compositions ($\mu^{54}Cr$) of indivudual chondrules from the pristine ordinary chondrite NWA5697 (L3.10) to better understand the history and nature of the material that accreted to form the inner Solar System planets. A total of 13 chondrules, including 8 with measured $^{238}U/^{235}U$, record Pb-Pb ages ranging from 4567.6±0.5 to 4563.6±0.5 Myr. These chondrules record $\mu^{54}Cr$ values typical of inner Solar System asteroids and planets, namely ranging from -90 to +25 ppm relative ot Earth. Collectively, these data require that genetically-unrelated chondrules formed in different regions of the inner disk and were thereafter transported to the accretion region of the NWA5697 parent body. Moreover, the ~3 Myr age variability recorded by chondrules from the same parent body entails storage or/and recycling of chondrules via multiple chondrule forming-events. It is well established that the chondrule-forming process increases the U/Pb ratio via Pb devolatization. Therefore, continous recycling of chondrules will lead to a secular increase in the U/Pb ratio of younger chondrules and, thus, more evolved initial Pb isotope compositions with time. Our data reveals a linear relationship between the chondrule ages and initial Pb compositions with younger chondrules systematically recording more evolved compositions. These observations suggest that recycling and, hence, outward transport of chondrules is intrinsincally linked to the chondrule forming process. If chondrule accretion is the main growth mechanism leading to planetary embryos, our data imply that the precursor material to the inner Solar System planets was effectively devolatized. Thus, Earth's volatile inventory must reflect a post accretion feature, perhaps through late delivery of volatile-rich bodies.

[1] J.N. Connelly *et al.* (2012) *Science* **338**, 651 [2] A. Johansen *et al.* (2015) *Sci. Adv.* **1**, e1500109.