THE FATE OF IMPACTOR CORES IN LARGE TERRESTRIAL COLLISIONS. R. M. Canup[1], S. Marchi[1], and R. J. Walker[2], [1]Southwest Research Institute, 1050 Walnut St., Ste. 300, Boulder, CO 80302; robin@boulder.swri.edu, [2]Dept. of Geology, University of MD, College Park, MD 20742.

Introduction: After the Moon-forming giant impact, subsequent collisions with the Earth were likely characterized by a waning impactor flux, punctuated by large collisions. The mass delivered during this so-called *late accretion* stage is estimated to be ~ 0.5% of Earth's mass ($M_\oplus$), based on highly siderophile element (HSE) concentrations in the mantle [1]. This estimate assumes that the entire HSE content of the late impacting mass was dispersed into and retained within the Earth's mantle, which appears valid for impactors up to several hundred km in diameter [2].

However recent works [3-4] suggest that most of the late mass was delivered by large planetesimals, 1000-3000 km in diameter (0.0003-0.01$M_\oplus$ for a density of 3000 kg m^{-3}). Such impactors may have been differentiated. Simulations of Moon-forming impacts and fluid mixing models suggest that substantial portions of a large impactor's core may descend directly to the Earth's core in only hours [5-6]. In high-velocity and/or highly oblique impacts, much of a large impactor may escape the Earth entirely.

The fate of impactor material in collisions relevant to the late accretion stage remains poorly understood. This is key to understanding the efficiency of HSE delivery to the early Earth, and to assess whether such collisions may have left behind any trace, e.g., through terrestrial isotopic anomalies. Here we use simulations of large impacts to begin to address both issues.

Impact simulations: For large impacts, the target's shape and the self-gravity of the impactor and target as they are distorted by the collision are important, and a numerical treatment that includes both is required. We simulate large impacts into Earth using smooth particle hydrodynamic (SPH). Our code [7] implements the equation of state ANEOS [8]. The energy budget is determined by shock dissipation, and work done by compressional heating and expansional cooling; explicit self-gravity is included and strength is ignored.

Each simulation considers between 2×10^5 to 10^6 SPH particles, so that the impactor core is resolved by ~ 10^3 particles. Particle smoothing lengths within the target and impactor are $h \sim 10^2$ km. While SPH may aptly track the overall dynamical outcome of a large impact, as well as flow regions described by many particles, fluid behavior at scales smaller than h is not treated by SPH. Even in large collisions, small-scale behavior may be important on short timescales due to, e.g., shearing flows that could disperse material into smaller component sizes, which cannot be resolved with SPH [2].

We consider differentiated impactors with silicate mantles and iron cores (30% by mass), and impactor masses between 0.001 to 0.03$M_\oplus$. We assume all of an impactor's HSEs are contained within its core.

Fate of the Impactor: Fig. 1 shows example outputs from SPH simulations at about 20 hr. A common outcome is that a portion of the impactor's core descends quickly through the mantle and settles in proximity to Earth's core, often in a single well-resolved clump, consistent with expectations [5-6]. For this material, chemical equilibration with the mantle may be very limited [6]. A fraction of the impactor's core also escapes the system. Both processes reduce the impactor HSEs delivered to the Earth's mantle.

Results: A range of outcomes emerge from our simulations that suggest that for large impacts, the delivery of HSEs to the Earth's mantle may be disproportionate with the overall delivery of mass. To quantify this effect, we define 3 outcomes for the impactor's core material: 1) core particles that have descended to overlap with the target's core particles ("core"); 2) core particles that remain within the target's mantle or that are outside the planet but gravitationally bound ("mantle"); and 3) core particles that escape the system ("ejected").

Figure 2 shows results as a function of impactor mass for two impact angles, $\xi = 30°$ and 45° (where $\xi = 0°$ is a head-on impact). For impacts with $\xi \leq 45°$, between ~20% to ~80% of the impactor's core may merge directly with the Earth's core and not contribute to the terrestrial mantle HSEs. For highly oblique impacts with $\xi = 60°$, most of the impactor core escapes for moderate impact speeds. An implication is that the late accreted mass inferred from terrestrial HSE abundances may be a substantial underestimate.

Large impacts could also potentially result in isotopic perturbations. We define a *delta*-mass parameter (δm_t):

$$\delta m_t\,(\%) = ((M'_s/M'_c)/(M_s/M_c) - 1) \times 100$$

where M'_s and M'_c are the impactor silicate and core mass delivered to the Earth's mantle, respectively, while M_s and M_c are the impactor silicate and core mass, with $M_s/M_c = 2.3$. Thus δm_t is the fractional enrichment of silicate/metal material deposited to the silicate Earth; $\delta m_t = 0$ would indicate that the impactor addition to the silicate Earth maintains the (assumed chondritic) silicate/metal proportion of the impactor. Values of δm_t > 0 or < 0 would indicate a disproportional addition of silicate or metal, respectively. For the simulations reported in Fig. 2, we find δm_t ranging from ~10% to ~ 200%, implying substantial compositional variations in the accreted mass. Such variations could produce initially localized domains in Earth's mantle with distinct, mass independent isotopic signatures, given the isotopic variability resulting from nucleosynthetic heterogeneities among genetically diverse meteorites [9]. In general we find that larger, low angle collisions would be more likely to produce initial "pockets" of anomalous composition material. Retention of isotopically diverse genetic signatures in siderophile elements, such as Ru and Mo, would be a function of the impactor mass and whether the accreted mass is ultimately well-mixed in the silicate Earth or retained more locally. Long-term preservation of ^{182}W isotopic heterogeneity in the terrestrial rock record, resulting from radioactive decay [e.g., 10], suggests that genetic isotopic variations resulting from late accretion might also be preserved.

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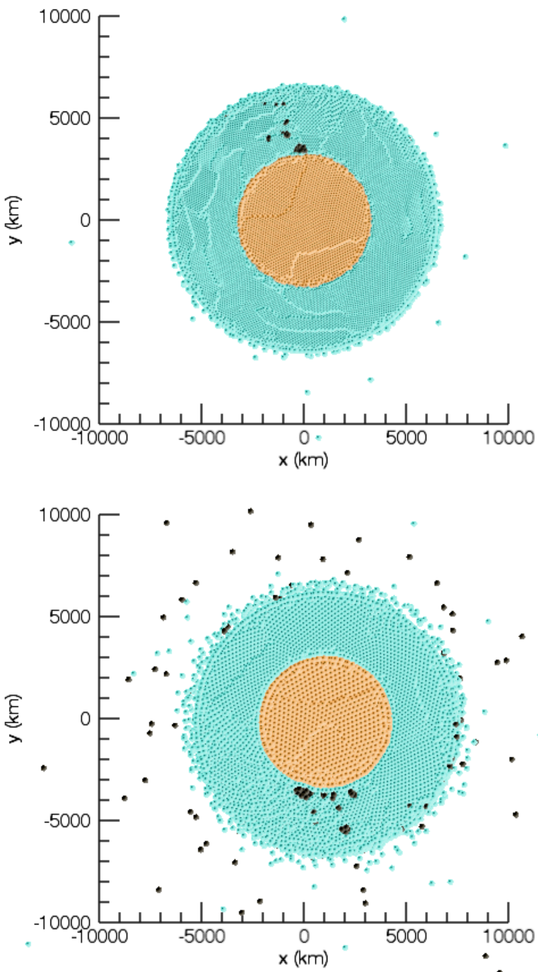

Fig. 1: Impactor's core fate. Panels show final time step in two SPH simulations. Cyan particles represent silicate material (Earth + impactor), brown particles indicate Earth's core, and black particles indicate the impactor' core. The impactor masses are $M_i = 0.001 M_\oplus$ (top) and $0.01 M_\oplus$ (bottom). In both cases, the impact speed ($v_i \sim 19$ km s^{-1}) was 1.7 times the escape velocity (v_e), and the impact angle was $\xi = 45°$.

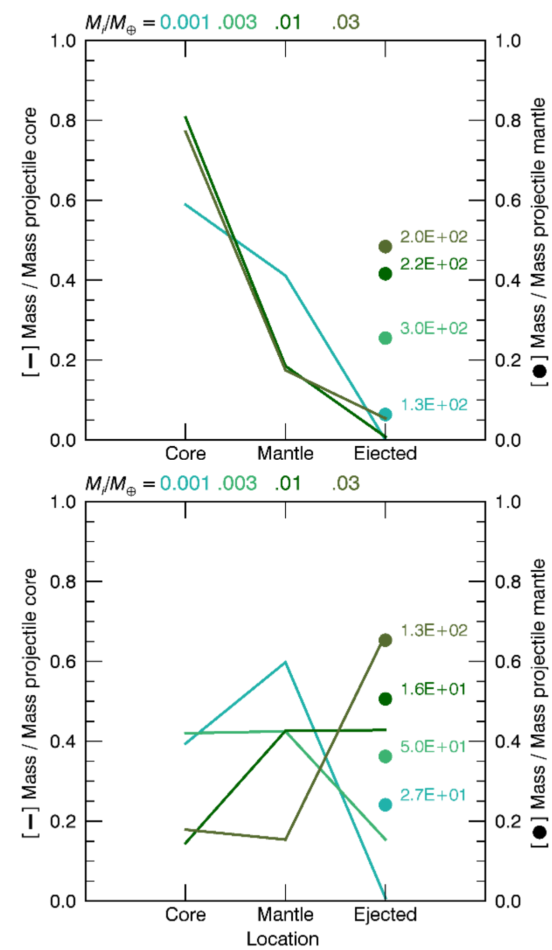

Fig. 2: Post-impact distribution of impactor material. The top figure shows cases with $\xi = 30°$, while the bottom shows cases with $\xi = 45°$. All have $v_i/v_e = 1.7$. The x-axis shows the location of impactor material at the end of the SPH simulations (see text). The left-hand y-axis indicates the normalized mass of the impactor's core in each location. Impactor mantle is assumed to be mixed with the Earth's mantle unless it is ejected from the system; the latter is indicated by the large dots and the right-hand y-axis. The numbers next to the dots show δm_t (see text).