COLLISION FRAGMENTS AS A CHEMICALLY SIMILAR SOURCE FOR LATE ACCRETION.

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Introduction: The impacts that occur during planet formation play a fundamental role in setting the compositions of planets. Giant impacts, in particular, can deliver large amounts of mass to a growing planet, and may allow extensive equilibration between a terrestrial planet's mantle and the incoming metallic core. Metal-silicate equilibration as a result of giant impacts is expected to remove highly siderophile elements from the mantle of the growing Earth. Earth's inventory of highly siderophile elements must then be delivered after the final giant impact in a stage of 'late accretion.' There is substantial debate about the nature of this late accreted material and the sizes of the bodies that delivered it.

There is a long held expectation that late accretion delivers Earth's volatiles, via bodies similar to carbonaceous chondrites [e.g. 1]. This view is challenged by the lack of a major carbonaceous-chondrite-like isotopic signature in the Earth. Earth, instead, appears isotopically most similar to the enstatite chondrite family, and it has been shown that late accretion was likely also dominated by enstatite-like material [2].

The origin of late accreted bodies is unknown. The source has been assumed to be primordial because the highly siderophile elements are in chondritic proportions. The lack of a substantial outer solar system chemical signature for the Earth suggests that most late-accreted mass originated in the inner disk. Here we examine the compositions of one likely source of late accretion: planetesimals 'left over' from the main period of growth of the terrestrial planets.

In planet formation simulations, a number of planetesimal impacts occur at late times, after the final embryo-embryo impacts. In N-body simulations these planetesimals are typically primordial, and their properties have not been examined closely. We use high-resolution, fully interacting, collisional simulations that allow us to follow the evolution and production (via fragmentation) of these small bodies.

Numerical method: N-body simulations of terrestrial planet growth were carried out using a modified version of the parallelized code PKDGRAV [3]. These simulations track many thousands of bodies and calculate the gravitational acceleration for each body in the simulation, including the planetesimals. These simulations include a state-of-the-art collision model to predict the outcomes of collisions at all velocities and impact angles [4, 5]. Debris smaller than a specified resolution limit is placed in annular bins in the corresponding location throughout the disk. The debris is reaccreted by planetesimals and embryos as they pass through these annuli. In this manner, a portion of the mass in resolved bodies is processed through small-scale ejecta, but the mass of unresolved debris at any given time is small.

All bodies have a composition based on the initial radial location of the mass they contain, corresponding to the same 0.1 au wide annuli as the debris bins. These compositions evolve any time a body experiences a collision or accretes debris. Unlike in most other N-body simulations, in our work planetesimals can accrete both via collisions with other resolved bodies and via unresolved debris. Remnants and fragments of collisions are updated to have the mass-weighted average composition of the impactors.

We carried out two types of simulations: a set covering only the terrestrial planet region with no perturbation from giant planets, and a set based on the Grand Tack model [6] in which Jupiter migrates inward and then outward through the inner disk. Simulations began with a range of planetesimal sizes with the majority having radii of $\sim$200 km. All planetesimals were assumed to have differentiated to form an iron core and silicate mantle at the start of the simulations. These planetesimals experienced aerodynamic drag from the nebular gas. After $\sim$2 Myr (the time corresponding to giant planet migration), the nebula dispersed with an e-folding timescale of 0.1 Myr. Further details of these simulations can be found in Carter et al. [7].

We extracted the composition histograms for all bodies at regular intervals throughout the simulations. The compositions of the metallic cores of these differentiated bodies were also extracted. These compositions can be compared by cross correlating the histograms of any pair of bodies. We thus determine how similar any planetesimal is to each embryo as a function of time.

Results: The dynamically excited Grand Tack simulations produce Earth-like planets with a mixture of material from across the inner solar system. This is a result of Jupiter's inward migration 'pushing' planetesimals from more distant parts of the inner disk into the Earth-forming region. There are several embryos remaining at the end of these simulations, many of which have fairly similar compositions. These final bodies include smaller embryos that are very similar in composition to the Earth-sized planets, suggesting that Theia – the Moon-forming impactor – may have had a similar composition to the proto-Earth.

The simulations also end with many planetesimals that share similar compositions to the Earth-sized planets (Fig. 1). In many cases these 'planetesimals' are silicate-rich fragments ejected from the larger embryos during their accretion. Some of these planetesimal-sized fragments then survive to the end of the simulation period. At the end of this simulation only approximately 25% of the planetesimals are primitive bodies that have not undergone any collisional processing.

The time evolution of body compositions allows us to examine when bodies become similar in composition. The most-similar planetesimals to the planet highlighted in Fig. 1 mostly acquire these compositions at the time they form, indicating they are fragments ejected from a near-fully-grown planet. In the example shown here, these surviving planetesimals remain in the system for 10 Myr or more as the planets continue growing.

Embryos and planetesimals become compositionally similar early (in the first few Myr), as a result of collisions caused by the inward migration of Jupiter. There are thus many intermediate bodies (planetesimals and embryos) with similar compositions interior to the tack point early in the giant impact phase (see Fig. 1), and well before the Moon-forming impact. One of these embryos could represent a Theia with isotopic composition similar to the proto-Earth. The final planets can have similar compositions to several intermediate embryos, and planetesimals could be ejected from any of these embryos.

We assume that all bodies in these simulations are differentiated and remain differentiated throughout. Since these bodies can undergo imperfect collisions, the compositions of core and mantle can diverge. While this has a negligible effect on massive embryos, the planetesimals can develop substantial differences. In some cases the leftover planetesimals can have metallic cores similar to an embryo's composition, while the silicate mantle (or bulk composition) does not match.

The 'leftover' planetesimals are expected to eventually be accreted by the terrestrial planets over the following billion years of evolution, or ejected from the solar system via dynamical interactions. A small fraction are likely scattered into the asteroid belt (Fig. 1), as has been suggested for iron-rich bodies [8], possibly becoming enstatite-like achondrites. However, we expect these 'planet fragments' to represent a small fraction of the total mass in the asteroid belt.

Our results suggest that a fraction of late accreted mass came from fragments of intermediate planetary embryos ejected earlier in the history of the solar system. These bodies naturally have similar compositions to the planets. This leads us to a possible solution to the confounding origin of late accreted mass: it is leftover material that already matches the Earth in composition.

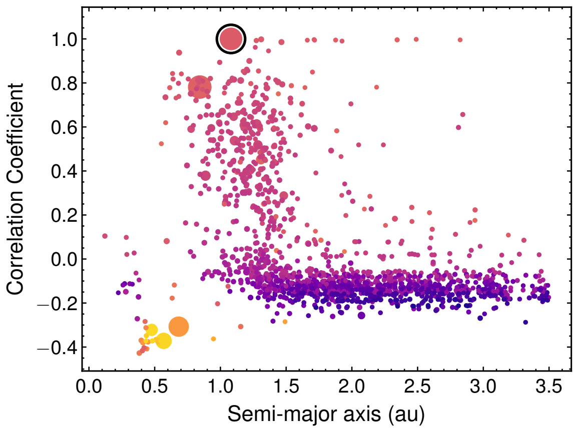

Figure 1: Correlation of embryo and planetesimal composition histograms to that of planet B (circled in black) at the end of an example Grand Tack simulation. In this simulation Jupiter migrated inward to 1.5 au before migrating outward. A correlation coefficient of +1 indicates a perfect match, −1 indicates that the bodies are totally unlike each other. The size and color of each body represent their mass and average composition. Some bodies have similar compositions to the planet, and a small number of planetesimal-sized bodies have near-perfect-matching compositions, while most bodies show little similarity.

Conclusions: Dynamically excited planet formation can result in a region with terrestrial planets and embryos with similar compositions. Commonly, planetesimals with similar compositions to the Earth-like planets are left at the end of the main period of accretion. This outcome is in contrast to 'cold accretion', which does not result in such highly similar compositions. We have shown that compositional evolution can occur in small bodies, and thus care must be taken associating meteorites with single processes or locations in the disk during planet formation. Many of the chemically-similar leftover planetesimals are fragments of proto-planets ejected millions of years earlier. If these planetesimals are later accreted by the planets, they would represent late accreted mass with compositions that naturally match the planet.

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References: **[1]** F. Albarède. (2009), *Nature* ***461***, 1227–1233. **[2]** N. Dauphas. (2017), *Nature* ***541***, 521–524. **[3]** D. C. Richardson et al. (2000), *Icarus* ***143***, 45–59. **[4]** Z. M. Leinhardt and S. T. Stewart. (2012), *ApJ* ***745***, 79. **[5]** Z. M. Leinhardt et al. (2015), *ApJ* ***806***, 23. **[6]** K. J. Walsh et al. (2011), *Nature* ***475***, 206–209. **[7]** P. J. Carter et al. (2015), *ApJ* ***813***, 72. **[8]** W. F. Bottke et al. (2006), *Nature* ***439***, 821–824.