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# The feeding zones of terrestrial planets and insights into Moon formation

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ABSTRACT

The final stage of terrestrial planet formation consists of several hundred approximately lunar mass bodies accreting into a few terrestrial planets. This final stage is stochastic, making it hard to predict which parts of the original planetesimal disk contributed to each of our terrestrial planets. Here we present an extensive suite of terrestrial planet formation simulations that allows quantitative analysis of this process. Although there is a general correlation between a planet's location and the initial semi-major axes of its constituent planetesimals, we concur with previous studies that Venus, Earth, and Mars analogs have overlapping, stochastic feeding zones. We quantify the feeding zone width, $\Delta a$, as the mass-weighted standard deviation of the initial semi-major axes of the planetary embryos and planetesimals that make up the final planet. The size of a planet's feeding zone in our simulations does not correlate with its final mass or semi-major axis, suggesting there is no systematic trend between a planet's mass and its volatile inventory. Instead, we find that the feeding zone of any planet more massive than 0.1 $M_\oplus$ is roughly proportional to the radial extent of the initial disk from which it formed: $\Delta a \approx 0.25(a_{max} - a_{min})$, where $a_{min}$ and $a_{max}$ are the inner and outer edge of the initial planetesimal disk. These wide stochastic feeding zones have significant consequences for the origin of the Moon, since the canonical scenario predicts the Moon should be primarily composed of material from Earth's last major impactor (Theia), yet its isotopic composition is indistinguishable from Earth. In particular, we find that the feeding zones of Theia analogs are significantly more stochastic than the planetary analogs. Depending on our assumed initial distribution of oxygen isotopes within the planetesimal disk, we find a ~5% or less probability that the Earth and Theia will form with an isotopic difference equal to or smaller than the Earth and Moon's. In fact we predict that every planetary mass body should be expected to have a unique isotopic signature. In addition, we find paucities of massive Theia analogs and high velocity Moon-forming collisions, two recently proposed explanations for the Moon's isotopic composition. Our work suggests that there is still no scenario for the Moon's origin that explains its isotopic composition with a high probability event.



## 1. Introduction

An outstanding question in planetary science is the degree to which a planet's volatile inventory and isotopic composition is related to its size and location. In other words, how deterministic is terrestrial planet formation? In this paper we use ensembles of planet formation simulations to study the statistics of terrestrial planet feeding zones. Insofar as the initial planetesimal disks have radially non-uniform volatile content and isotopic composition, the width of feeding zones may be used as a proxy for the final water inventory and isotopes of planets.

The water inventory of rocky worlds is important: liquid water is the definition of habitability (Kasting et al., 1993), but planets with too much surface water will have no exposed continents, and hence will not benefit from the silicate weathering thermostat (Abbot et al., 2012). The combined effects of erosion, isostasy, and a substantial mantle water reservoir mean that planets with water mass fractions $<10^{-3}$ will not inundate their surface (Cowan and Abbot, 2014). Insofar as a terrestrial planet's water is delivered in the normal course of planet formation (Raymond et al., 2004), the statistics of planetary feeding zones affect the statistics of habitable planets.

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### 1.1. Theia and the Moon-forming impact

Furthermore, understanding the variance in isotopic composition predicted from terrestrial planet formation is key to deciphering the origin of our Moon. In the canonical giant impact hypothesis for the Moon's origin, a Mars-mass body (named Theia) strikes the proto-Earth in a glancing impact at the tail end of the giant impact phase of terrestrial planet formation (Hartmann and Davis, 1975; Cameron and Ward, 1976). This impact throws material into orbit around Earth, which eventually accretes into the Moon we have today. Using high-resolution smooth-particle hydrodynamic simulations, such a collision has been demonstrated to yield a lunar-mass satellite that is depleted in iron and also gives the Earth–Moon system approximately the angular momentum observed today (Canup and Asphaug, 2001). In such collisions, however, the Moon-forming accretion disk around the Earth is largely composed of material from the impactor rather than the proto-Earth (Canup, 2004). This presents a potential problem for the giant impact hypothesis because the oxygen isotope composition of lunar samples has been found to be virtually identical to terrestrial rocks ($\Delta^{17}$O$<$ 0.016‰) (Wiechert et al., 2001). In contrast, meteorites from Mars and Vesta are distinctly different from the Earth, with $\Delta^{17}$O values of 0.32‰ and −0.28‰, respectively (Franchi et al., 1999; Clayton and Mayeda, 1996). More recent work hints at a slight difference between the Moon and the Earth of $\Delta^{17}$O $\simeq$ 0.012‰, but the fact remains that the Moon is much more isotopically similar to Earth than samples from any other large object in the Solar System (Herwartz et al., 2014).

Because the formation of the Moon requires a relatively low-velocity impact between Theia and the proto-Earth, it had previously been argued that Theia likely resided in an orbit very similar to the proto-Earth and may have formed from a similar region of the planetesimal disk (Wiechert et al., 2001). If Theia and Earth formed from the same pool of planetesimals, they may have a similar composition, while Mars and Vesta have distinctly different oxygen signatures, owing to their different feeding zones in the planetesimal disk. However, the late stages of terrestrial planet formation are not a local process. Numerical studies of the final giant impact phase of terrestrial planet formation have conclusively demonstrated that the feeding zones of terrestrial planets are quite large and that most bodies undergo substantial and stochastic radial migration (Chambers, 2001; Raymond et al., 2004, 2005, 2006, 2009; O'Brien et al., 2006; Fischer and Ciesla, 2014). As a result, there is no reason to expect that Earth and its final impactor formed from the same zones of the protoplanetary disk. Hence, the identical composition of the Moon seems to rely on a potentially improbable coincidence.

In light of this, there have been recent searches for alternative scenarios to explain the similarities between lunar and terrestrial rocks. Instead of the canonical Mars-mass impactor, Canup (2012) explores the outcomes of collisions between a $\sim$0.5 $M_\oplus$ Theia and a $\sim$0.5 $M_\oplus$ proto-Earth. For certain impact velocities, the impactor makes nearly equal contributions to the Earth and the Moon-forming disk, resulting in an isotopically similar Earth and Moon. This scenario tends to give the Earth–Moon too much angular momentum, however. To alleviate this problem, Ćuk and Stewart (2012) suggest that the system's angular momentum could have decreased by up to a factor of 2 when it passed through a solar evection resonance; this allows for a higher impact velocity between the proto-Earth and Theia as well. If the proto-Earth had a rotation period of 2–3 h, Ćuk and Stewart (2012) show that high velocity impacts can yield a lunar composition dominated by the proto-Earth. Similarly, Reufer et al. (2012) finds that a hit-and-run collision at a slightly higher impact velocity can diminish Theia's contribution to the Moon's composition.

Another hypothesis for the isotopic similarities of the Earth and Moon is that they mixed immediately after the impact (Pahlevan and Stevenson, 2007). The energy from the Moon-forming impact would have vaporized portions of the outer Earth and generated a vapor accretion disk initially comprised of the impactor. The disk and outer Earth could have mixed and isotopically equilibrated in the $10^{2-3}$ years that the disk was in vapor form. During the time required for mixing, however, the outer portion of the disk would have already cooled and begun accreting into the Moon. In addition, in this scenario, one would expect refractory elements to exhibit stronger isotopic differences between the Earth and Moon since they would have condensed into solids faster, yet such a trend is not seen (Zhang et al., 2012; Armytage et al., 2012).

We may not need to abandon the canonical giant impact hypothesis, however. It is generally presumed that isotopically similar Theia and Earth are improbable outcomes of terrestrial planet formation, but the probability has not yet been quantified. While terrestrial planet formation simulations have recently been used to constrain the original orbit, timing, and collision statistics for Theia (Quarles and Lissauer, 2014; Jacobson et al., 2014; Jacobson and Morbidelli, 2014), few large statistical studies of the potential compositions and feeding zones of terrestrial planets (and their impactors) have been undertaken (Izidoro et al., 2013; Fischer and Ciesla, 2014). Because the feeding zones of terrestrial planets can be so large, it is intuitively plausible that Earth acquired the disk-averaged value of $\Delta^{17}$O due to the planet's high mass (Ozima et al., 2007). If this were the case, then Mars-mass bodies like Theia would likely possess similar $\Delta^{17}$O values, with Mars and Vesta simply being counter-examples; the unaltered canonical giant impact hypothesis could still be a viable explanation for the Moon's origin.

With this in mind, we have revisited the problem of late stage terrestrial planet formation. We have performed 150 different simulations modeling the formation of our terrestrial planets under different initial conditions. We use our simulations to make a statistical study of the relationship between a planet's final properties—mass and semimajor axis—and its accretion history and feeding zone. Such relationships can then help us discern how often, if ever, the accretion in our simulations results in isotopically similar Earth and Theia analogs, but still allows for an isotopically distinct Mars. This will enable us to estimate the probability that Theia had an Earth-like composition and will help assess the plausibility of the canonical giant impact hypothesis.

The large number of simulations we have performed also gives us new insights into the general process of the giant impact phase of terrestrial planet formation. In particular, we can statistically study the relationship between the final location of a planet and the location of its accretionary feeding zone within the original planetesimal disk. With 150 simulations, we will also be able to better quantify the level of stochasticity of these feeding zones and how this may affect the delivery of distant water-rich planetesimals to the terrestrial planets.

Our work is organized into the following sections: Section 2 describes the numerical methods and initial conditions employed in our simulations. Following this, we have five main sections of results. The first (Section 3.1) presents a general overview of the relationship between the final mass and orbit of a terrestrial planet and its feeding zone in the initial planetesimal disk; Section 3.2 specifically discusses the feeding zones for analogs of Solar System planets. Then in Section 3.3, we employ several different initial hypothetical distributions of $\Delta^{17}$O in our simulations, and we determine how often Earth-like Thieas are formed alongside isotopically distinct Mars analogs. With the work of Canup (2012) and Ćuk and Stewart (2012) in mind, we next use our simulations to quantify the mass and impact velocity distributions of Theia analogs in Section 3.4. In Section 3.5 we then make predictions