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Radial mixing and Ru–Mo isotope systematics under different accretion scenarios

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Abstract

The Ru–Mo isotopic compositions of inner Solar System bodies may reflect the provenance of accreted material and how it evolved with time, both of which are controlled by the accretion scenario these bodies experienced. Here we use a total of 116 *N*-body simulations of terrestrial planet accretion, run in the Eccentric Jupiter and Saturn (EJS), Circular Jupiter and Saturn (CJS), and Grand Tack scenarios, to model the Ru–Mo anomalies of Earth, Mars, and Theia analogues. This model starts by applying an initial step function in Ru–Mo isotopic composition, with compositions reflecting those in meteorites, and traces compositional evolution as planets accrete. The mass-weighted provenance of the resulting planets reveals more radial mixing in Grand Tack simulations than in EJS/CJS simulations, and more efficient mixing among late-accreted material than during the main phase of accretion in EJS/CJS simulations. We find that an extensive homogenous inner disk region is required to reproduce Earth's observed Ru–Mo composition. EJS/CJS simulations require a homogeneous reservoir in the inner disk extending to 3–4 AU (74–98% of initial mass) to reproduce Earth's composition, while Grand Tack simulations require a homogeneous reservoir extending to 3–10 AU (97–99% of initial mass), and likely to 6–10 AU. In the Grand Tack model, Jupiter's initial location (the most likely location for a discontinuity in isotopic composition) is ~3.5 AU; however, this step location has only a 33% likelihood of producing an Earth with the correct Ru–Mo isotopic signature for the most plausible model conditions. Our results give the testable predictions that Mars has zero Ru anomaly and small or zero Mo anomaly, and the Moon has zero Mo anomaly. These predictions are insensitive to wide variations in parameter choices.

Keywords

Ru–Mo isotopes; feeding zones; accretion; Mars; Moon; Theia

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1. Introduction

The bulk chemical and isotopic compositions of the terrestrial planets are largely controlled by the original location of material from which these planets accreted (their provenance). Different proposed accretion scenarios (which differ primarily by the behavior of Jupiter and Saturn during terrestrial planet accretion) produce different degrees of radial mixing and predict different provenance histories. A body's ruthenium–molybdenum isotopic signature can act as a fingerprint of its source material and how that source evolved, due to correlated nucleosynthetic variations in Ru and Mo stable isotopes. These variations are likely caused by variable addition of s-process material in different regions of the initial disk (e.g., Dauphas et al., 2004; Chen et al., 2010; Fischer-Gödde and Kleine, 2017).

Siderophile (“iron loving”) elements partition preferentially into iron-rich metal more than into silicates. Highly siderophile elements (including Ru) in Earth's mantle are thought to have been delivered in a “late veneer,” since they should have been stripped from the mantle during core formation (e.g., Kimura et al., 1974). Therefore, the mantle Ru isotopic composition is sensitive only to the last accreted material. On the other hand, Mo is moderately siderophile, so the mantle Mo isotopic composition is dominated by the main phase of accretion (Dauphas, 2017). Comparing mass-independent Ru and Mo isotopic variations can thus inform our knowledge of the feeding zones of the Earth and other terrestrial planets and their changes with time (Dauphas et al., 2004). However, the initial distribution of Ru–Mo isotopes in the disk is unknown.

Ru and Mo isotopic anomalies are often reported as:

$$\begin{aligned}\epsilon^{100}\text{Ru} &= \left[\frac{\left(\frac{^{100}\text{Ru}}{^{101}\text{Ru}} \right)_{\text{sample}}}{\left(\frac{^{100}\text{Ru}}{^{101}\text{Ru}} \right)_{\text{standard}}} - 1 \right] * 10,000 \quad (1) \\ \epsilon^{92}\text{Mo} &= \left[\frac{\left(\frac{^{92}\text{Mo}}{^{96}\text{Mo}} \right)_{\text{sample}}}{\left(\frac{^{92}\text{Mo}}{^{96}\text{Mo}} \right)_{\text{standard}}} - 1 \right] * 10,000\end{aligned}$$

The Earth's mantle has $\epsilon^{100}\text{Ru} = \epsilon^{92}\text{Mo} = 0$. Meteorite groups form a linear trend with negative $\epsilon^{100}\text{Ru}$ and positive $\epsilon^{92}\text{Mo}$, with the Earth as one endmember (Dauphas et al., 2004, 2014a; Fischer-Gödde et al., 2015; Walker et al., 2015; Dauphas and Schauble, 2016; Fischer-Gödde and Kleine, 2017). There are subtle variations in trend slope between carbonaceous and non-carbonaceous material (Budde et al., 2016). Since ruthenium and molybdenum isotopes sample different temporal phases of accretion, in principle the bulk Earth need not fall on this cosmic trend. But it does, implying that material accreted by the Earth at different times came from the same isotopic reservoir (Dauphas et al., 2004; Dauphas, 2017). Two martian crustal samples have been analyzed for mass-independent Mo isotopic variations (Burkhardt et al., 2011), but not for Ru. These analyses indicate consistency with zero $\epsilon^{92}\text{Mo}$ anomaly, though at least one of the two samples may have experienced terrestrial weathering (Burkhardt et al., 2014).

The Moon has an identical or very similar isotopic composition to the Earth for many elements (e.g., Dauphas and Schauble, 2016, and references therein), which is striking considering the range in isotopic compositions exhibited by meteorites. Theories to explain this phenomenon include: 1) isotopic equilibration between the Earth and Moon via the proto-lunar disk (Pahlevan and Stevenson, 2007), which may not explain isotopic similarities in refractory elements; 2) collisions that result in the Earth and Moon containing similar fractions of the proto-Earth and the Moon-forming impactor, “Theia” (e.g., Canup, 2012; uk and Stewart, 2012), which require specific dynamical conditions; or 3) the proto-Earth and Theia having identical isotopic compositions, which either requires them to have similar provenance/location (e.g., Quarles and Lissauer, 2015; Kortenkamp and Hartmann, 2016) or requires isotopic homogeneity in the inner disk (e.g., Dauphas et al., 2002a, 2014a, 2014b). However, the latter theory does not explain the nearly-identical lunar and terrestrial ^{182}W isotopic anomalies as these anomalies are sensitive to differentiation timescales (Dauphas and Schauble, 2016; Dauphas et al., 2014a; Nimmo and Kleine, 2015).

Previous studies have used various isotopic systems to probe heterogeneity and mixing in the disk and address this Earth–Moon isotopic conundrum. Kaib and Cowan (2015a) and Mastrobuono-Battisti et al. (2015) used N -body simulations of terrestrial planet accretion to assess the probability of the proto-Earth and Theia having the same oxygen isotopic composition. Kaib and Cowan (2015a) concluded that no initial isotopic distribution succeeds and so there remains no probable explanation for the Moon’s oxygen isotopic composition, in agreement with earlier work by Pahlevan and Stevenson (2007). Mastrobuono-Battisti et al. (2015) found success at producing isotopically similar proto-Earths and Theias with a 20–40% probability, or 5–18% in a follow-up study (Mastrobuono-Battisti and Perets, 2017) (but see also Kaib and Cowan, 2015b). The model of Young et al. (2016) favors mixing during the giant impact to produce an Earth and Moon with identical oxygen isotopes. Alexander et al. (2012) used H, N, and O isotopes to constrain the source regions of Earth’s volatiles, arguing against an outer disk origin. Differences between $^{142}\text{Nd}/^{144}\text{Nd}$ of Earth and chondrites may be of nucleosynthetic origin (Burkhardt et al., 2016), with the Earth as one endmember in terms of Sm–Nd isotopes. The similarity in isotopic composition of the Earth and enstatite meteorites, and its difference from other meteorites, has also been used to argue for isotopic homogeneity in the inner disk (e.g., Dauphas et al., 2002a, 2014b).

The goal of this study is to evaluate and quantify the homogeneity of the inner disk by analyzing the provenance of terrestrial planets formed in N -body simulations, and using Ru and Mo isotopes as specific tracers of mixing to model the isotopic evolution of Earth, Mars, and Theia analogues. Unlike oxygen isotopes, the Ru–Mo system is sensitive to temporal changes in source material provenance because Ru was predominantly delivered in the late veneer. Using these methods, the degree of homogeneity required to match observational constraints for the Earth can be assessed, and testable predictions can be made for the Ru–Mo isotopic compositions of Mars and the Moon. A homogeneous isotopic reservoir has previously been proposed (e.g., Dauphas et al., 2002a, 2014b) but not constrained quantitatively using dynamics.

After discussing methods in the following section, Section 3 focuses on extracting and quantifying planetary provenance and mixing in the disk from N -body simulations. Section 4 presents isotopic modeling calculations, beginning with one example case (Section 4.1) where the two compositional endmembers are the Earth and the most anomalous composition reported in meteorites. Then, we discuss what happens when we let one endmember composition vary (Section 4.2), then both (Section 4.3). Section 4.4 shows a full exploration of parameter space, including compositions with positive $\epsilon^{100}\text{Ru}$ and negative $\epsilon^{92}\text{Mo}$ that are not present in the meteorite record. Finally, Section 5 discusses the limitations and complications of the model, followed by conclusions (Section 6).

2. Methods

2.1. N -body simulations

This study utilizes two pre-existing suites of N -body simulations. Fischer and Ciesla (2014) ran fifty simulations with Jupiter and Saturn on slightly eccentric orbits (Eccentric Jupiter and Saturn, EJS) and fifty with the giant planets on non-eccentric orbits (Circular Jupiter and Saturn, CJS) predicted by the Nice model (e.g., Tsiganis et al., 2005). O'Brien et al. (2014) ran sixteen simulations extending previous models of the proposed Grand Tack event (Walsh et al., 2011), in which the giant planets migrate inward and then outward to truncate the disk of embryos (larger bodies) and planetesimals (smaller bodies). For more details, see the Supplemental Text.

Earth and Mars analogues were defined by their final semimajor axes only (Earth: 0.75–1.25 AU, Mars: 1.25–2 AU) (similar to Raymond et al., 2009), and must have late veneers to calculate their Ru–Mo anomalies. Planetary mass was not considered in the definition because no single simulation reproduces all Solar System properties, and here the focus is not on the simulations' success but rather their implications for radial mixing. Theia analogues were defined as the last large body (containing at least one embryo) to hit an Earth analogue (e.g., Mastrobuono-Battisti et al., 2015). Any planetesimals accreted to the Earth after the collision with Theia are considered to comprise the late veneer, regardless of mass. It is critical to use a large number of simulations for statistical analyses due to stochastic variations in accretion that can transform the resulting planetary chemistry (e.g., Fischer et al., 2017). Here the provenance of surviving bodies was quantified using their mass-weighted average semimajor axis:

$$\text{MWSMA} = \frac{\sum_i m_i a_i}{\sum_i m_i} \quad (2)$$

where m_i and a_i are the mass and initial semimajor axis of each accreted body i (e.g., Kaib and Cowan, 2015a).

The “canonical” (EJS/CJS) simulations begin with all mass inside of ~ 4 AU, divided evenly between embryos and planetesimals. Grand Tack simulations contain 97% of initial mass inside of ~ 3 AU, again divided evenly between embryos and planetesimals. The remaining 3% of initial mass is in planetesimals spanning ~ 3 –13 AU (Figure 1a). This difference in

initial mass distribution, with the Grand Tack resulting in inwards scattering of outer disk material and subsequent incorporation into terrestrial planets, drives many of the findings discussed below. In the Grand Tack model, there is a proposed discontinuity in initial composition at ~3.5 AU, the location of the ice line and Jupiter's initial orbit, causing much compositional variability in the asteroid belt (Walsh et al., 2011). The existence of two different isotopic classes of meteorites (Warren, 2011) might be due to initial differences between materials formed inside and outside of Jupiter's initial orbit (Kruijer et al., 2017) at ~3.5 AU.

2.2. Isotopic calculations

In the post-processing of the N -body simulations, an initial distribution of $\epsilon^{100}\text{Ru}$ and $\epsilon^{92}\text{Mo}$ was prescribed, with $\epsilon^{100}\text{Ru}$ and $\epsilon^{92}\text{Mo}$ always related by the cosmic trend defined by meteorites. The results shown here used a step function, with an inner disk with near zero anomaly and an outer disk with variable anomaly. The inner disk cannot have negative $\epsilon^{100}\text{Ru}$ and positive $\epsilon^{92}\text{Mo}$ to form Earth with zero anomaly; here values of zero (Sections 4.1–4.2) as well as positive $\epsilon^{100}\text{Ru}$ and negative $\epsilon^{92}\text{Mo}$ (Sections 4.3–4.4) were tested. A more complex distribution than a step function is difficult to justify, although a few linear gradients were tested (Section 5). There is some evidence for two populations of Mo compositions (Budde et al., 2016), and a step function in $\epsilon^{100}\text{Ru}$ and $\epsilon^{92}\text{Mo}$ is consistent with a well-mixed, isotopically homogeneous inner disk (e.g., Dauphas et al., 2014b). Allowing a small amount of Gaussian scatter in the initial compositions does not have significant effects (Supplemental Text).

Each body was assigned initial $\epsilon^{100}\text{Ru}$ and $\epsilon^{92}\text{Mo}$ based on its starting location. Stepping through the simulations, Ru and Mo isotopes in each body were tracked using a mass balance. Mantle ruthenium was assumed to only originate from the late veneer, after the last giant impact. Two different models for Mo were tested. For most planets, mantle $\epsilon^{92}\text{Mo}$ was calculated using a mass balance and evolved proportionally to impactor mass, resulting in a flat probability density function for Mo delivery (i.e., the entire planet's history is recorded in its mantle Mo isotopic composition). For Earth analogues, we also tested a model in which mantle Mo originates only from the last ~12% of accreted material (Dauphas, 2017), with earlier-accreted Mo drawn into the core by subsequent impacts. This model follows a power-law cumulative distribution function:

$$\text{CDF}(x) = x^{\mathcal{K} + 1} \quad (3)$$

where x is the fraction of Earth's final mass and $\mathcal{K} = 24$ for Mo (Dauphas, 2017). This model is not applicable to Mars or Theia analogues because it is based on core formation conditions for the Earth; for Mars and Theia the narrower pressure-temperature range would result in a situation closer to the flat probability distribution (Section 5). In EJS/CJS simulations, the two models produce equivalent results for Earth (Supplemental Figure S1), so only the model with a flat probability density function for Mo delivery was used. Grand Tack results are more sensitive to the choice of Mo model (Figure S1), so the power-law

model (a more realistic case) was used; however, even in the Grand Tack case, the choice of model does not generally affect our major conclusions.

The adjustable variables in our model are the location of the step in composition within the disk and the compositions of the inner and outer disk. A planet's Ru–Mo anomaly is considered “negligible” if it is within 0.1 epsilon units of the origin in $\epsilon^{100}\text{Ru}$ – $\epsilon^{92}\text{Mo}$ space:

$$\sqrt{(\epsilon^{100}\text{Ru})^2 + (\epsilon^{92}\text{Mo})^2} \leq 0.1 \quad (4)$$

This limit is comparable to variability in the Earth's Mo isotopic composition (e.g., Willbold and Elliott, 2017) and the uncertainty on the Mo anomalies of most meteorite groups (e.g., Dauphas and Schauble, 2016).

3. Provenance of the terrestrial planets

Modeling of Ru–Mo isotopes (Section 4) can be better understood by first assessing the provenance of the terrestrial planets (expressed here as the MWSMA, Eq. 2) and its temporal changes (Figure 1b–c). For bulk planets at the end of simulations (Figure 1b), the MWSMA is typically larger than the actual final semimajor axis (though less so farther from the Sun), reflecting a net inward transport of material. In canonical simulations, the bulk MWSMA and semimajor axis are correlated (cf. Kaib and Cowan, 2015a), with a greater semimajor axis typically corresponding to a greater bulk MWSMA (correlation coefficients of 0.78 and 0.87 for EJS and CJS simulations, respectively). Therefore, radial mixing in canonical simulations is only moderately efficient (Chambers, 2001; Wetherill, 1994). EJS and CJS simulations have the same average MWSMA (Table 1) and show increased spread at greater semimajor axes (tails in the likelihood distribution toward higher MWSMA, Figure 1b). Mean feeding zone widths were calculated as mass-weighted standard deviations of the semimajor axes of accreted bodies (cf. Brasser et al., 2017; Kaib and Cowan, 2015a), though a planet's effective feeding zone is a factor of two wider (a similar result is achieved by calculating the width of a 68% two-sided region). Mean feeding zone widths in EJS and CJS simulations are 0.46 and 0.68 AU, respectively, and are independent of semimajor axis, in agreement with Kaib and Cowan (2015a) (Table 1). Grand Tack planets exhibit a flat distribution of bulk MWSMA (Brasser et al., 2017; Kaib and Cowan, 2015a), indicating very efficient radial mixing and corresponding to a peaked likelihood distribution (Figure 1b); the bulk MWSMA of a Grand Tack planet that forms inside of ~1.4 AU is independent of its semimajor axis (correlation coefficient of 0.15), with more scatter and a higher average bulk MWSMA outside of that (Brasser et al., 2017). The mean feeding zone width in Grand Tack simulations is 0.79 AU (Table 1) (higher than that reported for the “annulus” simulations of Kaib and Cowan (2015a), because their initial mass only spanned 0.7–1 AU). Therefore, there is much more radial mixing and homogenization in Grand Tack simulations than in canonical simulations.

In EJS/CJS simulations, the late veneer MWSMA of these same planets are less dependent on final semimajor axis than their bulk MWSMA are, indicating more efficient radial mixing among late-accreted material (Figure 1c). Average late veneer and bulk feeding zone widths

are very similar to each other in canonical simulations; in Grand Tack simulations, late veneer feeding zones are ~50% wider than bulk feeding zones (Table 1). A planet's late veneer MWSMA is typically higher than its semimajor axis (Table 1), though this trend diminishes at larger semimajor axes (Figure 1c). The MWSMA of late veneers imply that they originate in the inner disk, consistent with the results of Fischer-Gödde and Kleine (2017). In CJS and Grand Tack simulations, the average late veneer MWSMA is significantly higher than that of the bulk planets, while this temporal change in provenance is not observed in EJS simulations (Table 1). CJS simulations exhibit higher average late veneer MWSMA than EJS simulations (Table 1), probably due to Jupiter and Saturn more efficiently ejecting outer disk bodies from the Solar System or driving them into the Sun via gravitational scattering in EJS simulations.

The average late veneer mass fraction for Earth analogues is large compared to the observed value of 0.1–0.5% (Dauphas and Marty, 2002) (Table 1); 13/57 Earth analogues have a late veneer of <1% by mass in both EJS and CJS simulations. Restricting the analysis to simulated planets with a late veneer of <1% results in no statistically significant differences in any calculated parameters in canonical cases (Supplemental Table S1). The Grand Tack simulations only produced one Earth analogue and one Mars analogue with a late veneer of <1%, preventing a similar analysis.

Theia often has a higher MWSMA than Earth in canonical simulations (Table 1, Supplemental Figure S2), with Theia and Earth exhibiting a significant (>0.1 AU) difference in MWSMA in 84% and 93% of EJS and CJS simulations, respectively. Therefore, one would expect Theia and Earth to have different isotopic signatures, in agreement with Pahlevan and Stevenson (2007), Kaib and Cowan (2015a), and Mastrobuono-Battisti et al. (2015), unless the inner disk is isotopically homogeneous. In Grand Tack simulations, Earth and Theia have only slightly more similar MWSMA (significant difference in 77% of simulations) (Table 1, Supplemental Figure S2). There is more variability in the bulk MWSMA of Theia than of the Earth, in agreement with Kaib and Cowan (2015a), but feeding zones of Theia are narrower than of Earth (Table 1). Mars analogues typically have slightly higher MWSMA than Earth analogues (Table 1), in subtle contrast with the results of Brasser et al. (2017).

4. Ru–Mo isotopic modeling results

4.1. One example case

We begin by fixing the inner and outer disk compositions and varying the step location in different accretion scenarios, and later investigate the effects of changing the inner and outer disk compositions (Sections 4.2–4.4). Initially the inner disk has $\epsilon^{100}\text{Ru} = \epsilon^{92}\text{Mo} = 0$ and the outer disk has $\epsilon^{100}\text{Ru} = -3.35$, $\epsilon^{92}\text{Mo} = 6.09$. These values were chosen because they are endmembers encompassing the full range of observed compositions, with Earth's composition in the inner disk and that of CM chondrites in the outer disk (Dauphas et al., 2014a; there is variation in anomalies reported for CM chondrites, cf. Dauphas and Schauble, 2016), with a small correction to the CM $\epsilon^{92}\text{Mo}$ to fall on the cosmic Ru–Mo trend. In this model, since there is no material with positive $\epsilon^{100}\text{Ru}$ or negative $\epsilon^{92}\text{Mo}$, the Earth must be made almost entirely of inner disk material. The step location required to

match Earth's zero anomaly was determined, then the compositions of Mars and Theia were calculated.

In canonical scenarios, most Earth analogue planets lie below the cosmic trend line, because late addition of small amounts of outer disk material reduces $\epsilon^{100}\text{Ru}$ but not $\epsilon^{92}\text{Mo}$ (Figure 2a), since mantle Ru is delivered only in the late veneer while mantle Mo is also delivered near the end of the main stage of accretion. A step location of 2 AU fails to reproduce Earth's composition, while using more distant step locations increases the probability (based on stochastic variations from simulation to simulation) (Figure 2b, left panel). The median value of Earth's Ru–Mo anomaly becomes negligible for a step at 3 AU (74% initial mass in inner disk), and zero for a step at 3.5 AU (87% initial mass) (Supplemental Figure S3a). In the Grand Tack case, a few Earth analogues have a near-zero anomaly for a step at 7 AU (97.6% initial mass in inner disk) (Figure 2b, right panel); the median anomaly becomes almost negligible for a step at 8 AU (97.8% initial mass), and nearly reaches zero at 10 AU (99.2% initial mass) (Supplemental Figure S3b). Such a large inner disk is consistent with recent work suggesting that the late veneer is comprised of inner disk material (Fischer-Gödde and Kleine, 2017). Grand Tack simulations initially have mass extending out to ~13 AU (Figure 1a), with Jupiter and Neptune at original positions of ~3.5 AU and ~8 AU. The range of step locations that best reproduce the Earth's Ru–Mo composition are different from the ice line and original orbit of Jupiter (~3.5 AU) proposed to represent a compositional change in the model of Walsh et al. (2011). Therefore the Grand Tack model may be more consistent with Earth's Ru–Mo composition if Jupiter's initial orbit is revised outwards, though this would also imply moving the ice line. In this model, the step location is a proxy for the extent of a homogeneous isotopic reservoir in the inner disk. Meteorites with intermediate compositions must have formed near the step location and incorporated material from both sides of the step to explain their variable Ru–Mo compositions (e.g., Figure 2a). In the Grand Tack case this may be problematic for matching other isotopic constraints, such as D/H ratios (e.g., Alexander et al., 2012), unless the distributions of different isotopic systems are decoupled.

Mars analogues often have larger $\epsilon^{92}\text{Mo}$ than Earth analogues but comparable $\epsilon^{100}\text{Ru}$ (compare Figures 2a and S4a). This indicates that material accreted by Mars analogues during the main phase of accretion (but not the late veneer) originated farther out in the disk, consistent with the MWSMA of these planets (Table 1). In canonical scenarios, the median anomaly (Eq. 4) for Mars is 0.4 with a step at 3 AU and negligible with a step at 3.5 AU (Supplemental Figure S5a). In the Grand Tack case, the median anomaly for Mars is negligible for a step at 6 AU (Supplemental Figure S5b). Therefore, for step locations that consistently reproduce Earth's zero anomaly, Mars is also likely to have a small or zero anomaly (Figure 3, left panel) with Mo more likely to be anomalous than Ru. This finding is consistent with early measurements of Mars's Mo isotopic composition (Burkhardt et al., 2011).

To assess the probability of the Moon being isotopically similar to the Earth, the Mo isotopic composition of Earth and Theia analogues can be compared. (The Ru isotopic composition of Theia was not calculated, since lunar late veneer delivery is not included in these *N*-body simulations.) In canonical simulations, step locations that reproduce Earth's zero anomaly

are equally likely to produce a negligible anomaly in the Moon. In the Grand Tack case, Theia is more likely than the Earth to have a negligible anomaly (Figure 3, right panel). Therefore, for any mix of Theia and proto-Earth material in the Moon, the Moon is likely to have zero Mo anomaly. The Mo anomalies of Earth and Theia are uncorrelated in this example case.

4.2. Varying outer disk compositions

The next step in increasing complexity of the model is to fix the inner disk as $\epsilon^{100}\text{Ru} = \epsilon^{92}\text{Mo} = 0$ and vary the outer disk composition and step location. Three example outer disk compositions were used, which span the full range of possible compositions in the meteorite record. A composition of $\epsilon^{100}\text{Ru} = -3.5$, $\epsilon^{92}\text{Mo} = 6.36$ encompasses the full range of reported meteorite compositions (Dauphas et al., 2014a), defining the most anomalous case. Adopting $\epsilon^{100}\text{Ru} = -0.7$, $\epsilon^{92}\text{Mo} = 1.27$ is likely problematic because the inner and outer disk compositions do not encompass the full range of meteorites (e.g., Dauphas et al., 2014a), but these results are shown as an example case with very low anomaly. An intermediate composition of $\epsilon^{100}\text{Ru} = -1.15$, $\epsilon^{92}\text{Mo} = 2.09$ is similar to endmember meteorite compositions (typically carbonaceous chondrites and IVB irons) reported in many studies (Fischer-Gödde and Kleine, 2017; Fischer-Gödde et al., 2015; Walker et al., 2015; Bermingham et al., 2016; Dauphas and Schauble, 2016; Mayer et al., 2016), representing perhaps the most realistic case.

In canonical simulations, Earth and Mars are slightly more likely to have negligible anomalies for outer disk compositions closer to zero (Figure 4a, upper panel). In all cases, a step near 3–4 AU makes it probable to reproduce Earth's composition. Appealing to more moderate outer disk compositions does not greatly boost Earth's likelihood of negligible anomaly, because its isotopic composition is sensitive to even a small amount of outer disk material. As before, step locations that produce a negligible Earth anomaly typically give Mars a small to zero anomaly (Figure 4a, upper panel), with Mo more likely to be anomalous than Ru. When the outer disk composition is farther from zero, the difference in probability curves between Earth and Mars lessens (Figure 4a, upper panel).

In Grand Tack simulations, there is a stronger correlation between the probability of no anomaly and the outer disk composition (Figure 4b, upper panel). For the intermediate (most likely) outer disk composition, a step at 6 AU ensures reproduction of Earth's zero anomaly. Mars is typically more likely than Earth to have negligible Ru–Mo anomaly (Figure 4b, upper panel), supporting the conclusions reached in Section 4.1 for a sample case.

4.3. Varying inner and outer disk compositions

It is possible that the inner disk had positive $\epsilon^{100}\text{Ru}$ and negative $\epsilon^{92}\text{Mo}$, and that a mixture of inner and outer disk materials created Earth's zero anomaly. There is new evidence that slightly positive $\epsilon^{100}\text{Ru}$ and/or negative $\epsilon^{92}\text{Mo}$ may be represented in known meteorites (Bermingham et al., 2016; Mayer et al., 2016), providing constraints for the compositions tested here. For slightly non-zero inner disk compositions (e.g., $\epsilon^{100}\text{Ru} = 0.05$, $\epsilon^{92}\text{Mo} = -0.09$), the range of plausible step locations is comparable to the case of zero anomaly

(Figure 4), since it is governed by the initial mass distribution in the N -body simulations (Figure 1a), but the shape of the distribution is quite different (Figure 4, lower panels). Qualitatively, when the step is too close or far from the Sun, the probability of planets having negligible Ru–Mo anomaly drops to zero (e.g., Figure 4, lower panels). For intermediate step locations, EJS/CJS Earth analogues reach ~50% probability of a negligible Ru–Mo anomaly in this example, for the appropriate balance of inner and outer disk material accreted. Probabilities never reach 100%, unlike the case of the inner disk having zero anomaly, even with the small inner disk anomaly used here. Mars is about half as likely as the Earth to have a negligible anomaly, but the maxima in their probability distributions coincide, so it remains possible (~25–40% chance) for Mars to have negligible Ru–Mo anomaly (Figure 4a, lower panel). Again, Mars is more likely to have anomalous Mo than Ru.

For these inner and outer disk compositions, Earth and Mars analogues are more likely to have negligible Ru–Mo anomalies in Grand Tack simulations than in canonical scenarios (Figure 4b, lower panel). Mars is less likely than the Earth to have negligible anomaly, but it remains possible. However, a Grand Tack scenario still requires a step at greater heliocentric distances (~4.5–8 AU versus ~2.5–3.5 AU) and more initial mass inside the step (97–98% vs 62–87%; Figure 1a), implying a larger inner disk homogeneous reservoir. For the Grand Tack, the expectation is that material beyond Jupiter’s initial position (~3.5 AU) would be isotopically distinct (Section 2.1); in contrast, our results would be more consistent with a step location at a greater distance.

4.4. A fuller exploration of parameter space

Results from a wider range of inner and outer disk compositions are shown in Figures 5 and 6 for canonical and Grand Tack scenarios, respectively. In canonical simulations, the inner disk composition is substantially more tightly constrained than the outer disk composition. Earth’s zero Ru–Mo anomaly is most likely to be reproduced for an inner disk composition of $\epsilon^{100}\text{Ru} = \epsilon^{92}\text{Mo} = 0$, with this probability falling to ~40% for $\epsilon^{100}\text{Ru} = 0.05$, $\epsilon^{92}\text{Mo} = -0.09$, and <10% for $\epsilon^{100}\text{Ru} = 0.2$, $\epsilon^{92}\text{Mo} = -0.36$ (Figure 5a). Higher probabilities exist if the outer disk has a very small anomaly (e.g., $\epsilon^{100}\text{Ru} = -0.5$, $\epsilon^{92}\text{Mo} = 0.91$), but this is unrealistic, since most meteorites have larger anomalies than this (Figure 2). A more anomalous inner disk composition is not supported by the meteorite record, and no matches to the Earth would be expected. Qualitatively, Earth accreting a small amount of material with slightly positive $\epsilon^{100}\text{Ru}$ and negative $\epsilon^{92}\text{Mo}$ is permitted because the bulk composition is not highly sensitive to this small anomaly. But if inner disk material has a larger anomaly, the probability of reproducing the Earth plummets, because a precise ratio of inner to outer disk material is required to produce zero bulk anomaly, and there is considerable stochastic variability in provenance (Figure 1b–c). Larger inner disk anomalies are possible, but highly unlikely; for example, an inner disk with $\epsilon^{100}\text{Ru} = 0.3$, $\epsilon^{92}\text{Mo} = -0.55$ has a 4–8% chance of matching Earth’s zero anomaly. For probable, moderate outer disk compositions (approximately $\epsilon^{100}\text{Ru} = -1$, $\epsilon^{92}\text{Mo} = 1.82$ to $\epsilon^{100}\text{Ru} = -2$, $\epsilon^{92}\text{Mo} = 3.64$; Section 4.2), Earth’s zero anomaly is reproduced with >50% probability for steps at ~2.5–4 AU (Figure 5a). The probability of Mars having negligible Ru–Mo anomaly is slightly smaller than for

the Earth but peaks at comparable step locations (Figure 5b), again indicating that Mars likely has a small to zero Ru–Mo anomaly.

To examine whether Theia and the Earth have the same isotopic composition, the probability of Theia having negligible Mo anomaly was calculated at the step locations that minimized Earth's Ru–Mo anomaly (Figure 5a). The Mo anomalies of Earth and Theia are uncorrelated in canonical and Grand Tack scenarios, so these probabilities are independent from the likelihood of Earth having negligible Mo anomaly. The probability distribution for Theia having negligible Mo anomaly (Figure 5c) is slightly higher than for the Earth having negligible Ru–Mo anomaly (Figure 5a). Therefore, Theia probably also had no Mo anomaly. Regardless of the ratio of proto-Earth and Theia material incorporated into the Moon, the Moon likely also has no Mo anomaly.

In Grand Tack simulations, a wider range of parameter space reproduces Earth's negligible Ru–Mo anomaly than in canonical simulations (Figure 6a), likely due to the narrower range of MWSMA exhibited in Grand Tack Earth analogues (Figure 1b; Table 1). Inner disk compositions near zero anomaly are most likely to match the Earth, but anomalies up to approximately $\epsilon^{100}\text{Ru} = 0.16$, $\epsilon^{92}\text{Mo} = -0.29$ have a >50% probability of reproducing Earth's composition for moderate outer disk compositions (Section 4.2). Steps at ~3–10 AU are required, while steps at ~6–10 AU are most likely to match the Earth (Figure 6a). These step locations from Grand Tack simulations fall at greater heliocentric distances and greater cumulative mass fractions than those from canonical simulations (97% at 3 AU in the Grand Tack case, compared to 74% at 3 AU in EJS/CJS cases; Figure 1a), requiring more extensive Ru–Mo isotopic homogeneity. A Grand Tack scenario in which the step was located at the initial location of Jupiter (~3.5 AU) would be somewhat unlikely to reproduce Earth's zero anomaly (Figure 6a): for an inner disk composition of $\epsilon^{100}\text{Ru} = \epsilon^{92}\text{Mo} = 0$ and an outer disk composition of $\epsilon^{100}\text{Ru} = -1.15$, $\epsilon^{92}\text{Mo} = 2.09$, this probability is only 33%. A solution with >50% probability and a step at ~3.5 AU is only possible for specific ranges of positive $\epsilon^{100}\text{Ru}$ and negative $\epsilon^{92}\text{Mo}$ inner disk anomalies ($\epsilon^{100}\text{Ru}$ of 0.09 to 0.16, $\epsilon^{92}\text{Mo}$ of -0.16 to -0.29), which have only been preliminarily reported to exist in the meteorite record (Bermingham et al., 2016; Mayer et al., 2016).

For most parameter choices, Mars is less likely to have a negligible Ru–Mo anomaly than Earth (Figure 6b). For inner disk compositions of $\epsilon^{100}\text{Ru} = 0.05$, $\epsilon^{92}\text{Mo} = -0.09$ to $\epsilon^{100}\text{Ru} = 0.15$, $\epsilon^{92}\text{Mo} = -0.27$, Earth has a >50% chance of negligible Ru–Mo anomaly but Mars has a <50% chance of a negligible anomaly; for smaller inner disk anomalies most likely to match the Earth, Mars has a >50% chance of a negligible anomaly. The picture for Theia is intermediate between that of Mars and Earth (Figure 6c). Theia is likely to have negligible Mo anomaly for inner disk compositions of $\epsilon^{92}\text{Mo} = 0$ to $\epsilon^{92}\text{Mo} = -0.14$, using the same step locations that minimize Earth's anomaly (Figure 6a).

5. Limitations, complications, and additional variables

It is important to recognize the limitations and simplifications inherent in this modeling. When using a flat probability density function or a power-law model for Mo accumulation gives different results for the Earth, the power-law model is favored here because it accounts

for realistic changes in mantle molybdenum during accretion (Section 2). However, this effect is not included for Mars and Theia, because the power-law model from Dauphas (2017) only applies to the Earth. Pressures and temperatures inside the Earth are much greater than in smaller bodies, so assuming a flat probability density function model is less problematic for Mars or Theia because their range of core formation conditions is much narrower. For example, extrapolating experimental measurements of Mo partitioning (e.g., Wade et al., 2012), D_{Mo} varies by ~4 orders of magnitude over conditions (e.g., Fischer et al., 2017) of Earth's core formation and ~1 order of magnitude over core formation conditions (e.g., Rubie et al., 2015) in Mars or similar sized bodies like Theia. Therefore, using a flat probability density model for Mars and Theia is likely an acceptable approximation, but future work could address this effect by explicitly modeling the physics and chemistry of core formation in all planets.

Recent experiments (Laurenz et al., 2016) show that Ru becomes less siderophile with increasing sulfur concentrations, pressure, and temperature. Thus it is possible that not all mantle Ru was delivered in a late veneer, as was assumed here. A model based on Laurenz et al. (2016), including a “Hadean matte” stripping iron sulfide and highly siderophile elements from Earth's mantle, predicts that ~2/3 of mantle Ru came from the late veneer; the remainder came from the latter half of the main phase of accretion (Rubie et al., 2016). Incorporating some Ru from the main phase of accretion should not affect results from EJS simulations, since the average MWSMA of bulk Earth analogues and their late veneers are very similar (Table 1). In CJS and Grand Tack cases, Ru from the main phase of accretion originates at smaller heliocentric distances on average (Table 1), which should produce smaller Ru anomalies in Earth analogues. However, this is unlikely to change any conclusions regarding required step locations because constraints from molybdenum are not affected by the model of Rubie et al. (2016).

In this study, a step function is used to describe the initial Ru–Mo isotopic distribution, based on the isotopically homogeneous inner disk suggested for other elements (e.g., Dauphas et al., 2014b). For completeness, a linear variation in Ru–Mo isotopes was also tested between 0 and 4 AU in canonical simulations, with an inner composition of $\epsilon^{100}\text{Ru} = 0.2$, $\epsilon^{92}\text{Mo} = -0.36$ (the most extreme positive $\epsilon^{100}\text{Ru}$ /negative $\epsilon^{92}\text{Mo}$ compositions reported in meteorites; Bermingham et al., 2016; Mayer et al., 2016) and an outer composition of $\epsilon^{100}\text{Ru} = -1.15$, $\epsilon^{92}\text{Mo} = 2.09$ (the likely composition of meteorites with the largest negative $\epsilon^{100}\text{Ru}$ /positive $\epsilon^{92}\text{Mo}$ anomalies; Fischer-Gödde et al., 2015; Walker et al., 2015; Dauphas and Schauble, 2016; Mayer et al., 2016). This model produces no terrestrial planets with a negligible Ru–Mo anomaly (Supplemental Figure S6). To succeed, the inner disk composition would have to be much more anomalous, for which there is no evidence in meteorite collections, and/or the outer composition would have to be much less anomalous, in which case some meteorite compositions could not be explained. More complicated initial distributions of Ru–Mo isotopes would require arbitrary assumptions that cannot be justified by existing data.

The inner and outer disk may not have been perfectly homogeneous. To consider possible heterogeneity, some models were run with both inner and outer disk compositions described by Gaussian distributions centered around nominal values. This variability in initial

composition had virtually no effect on the results or conclusions reached here (Supplemental Text; Supplemental Figures S7–S8).

This work focuses on the EJS, CJS, and Grand Tack cases, but other accretion scenarios are possible. It is possible that Mars formed via a different dynamical pathway (e.g., Brasser et al., 2017). Additionally, it has recently been proposed that the terrestrial planets could have initially grown by “pebble accretion” (e.g., Levison et al., 2015). This hypothesis implies a continual inward drift of material from greater semimajor axes; consequences for the resulting isotopic signatures of the final planets are unexplored and are an important topic for future work.

In this work, isotopic reservoirs are treated as being separated solely in space, but they could be separated in time (for example, due to Mo partitioning) or by volatility/temperature. Even in a well-mixed disk, distinct isotopic signatures could result. Finally, we note that isotopic reservoirs of different elements do not necessarily coincide with one another spatially, so the lateral extent of the Ru–Mo homogeneous inner disk reservoir may not be related to that of oxygen isotopes, for example. On the other hand, this approach can be used to predict variations in nucleosynthetic isotopic systems that have been less thoroughly investigated, such as Nd (Burkhardt et al., 2016) or V (Nielsen et al., 2017).

6. Conclusions

We successfully replicated the Earth’s zero Ru–Mo anomaly using a step function to describe initial variations in isotopic composition, encompassing the range of observed meteorite anomalies. This model reproduces the Earth’s composition for a wide range of outer disk anomalies, but constrains the initial inner disk anomaly to near $\epsilon^{100}\text{Ru} = \epsilon^{92}\text{Mo} = 0$.

Canonical (EJS/CJS) simulations require homogeneous Ru–Mo isotopes in the inner disk to smaller radial distances (~3–4 AU) and total initial mass fractions (74–98%) compared to Grand Tack simulations (~3–10 AU and 97–99%, more likely ~6–10 AU). In both cases, homogenization to greater heliocentric distances increases probabilities of reproducing Earth’s composition. In a canonical scenario, the asteroid belt may have formed in situ, incorporating variable amounts of isotopically distinct inner and outer disk material to create the observed array of meteorite compositions (e.g., Dauphas and Schauble, 2016). We find that the Grand Tack model is more consistent with a step in composition at >6–10 AU, with material scattered inwards from beyond Jupiter’s original location contributing to the isotopic and spectral diversity of the present-day asteroid belt. The more distant original location for some present-day main belt asteroids suggested by our findings may be problematic in explaining their D/H ratios (e.g., Alexander et al., 2012). While the Earth might simply be a lower probability outcome (33%; Section 4.4), these findings raise the possibility that Jupiter’s initial location was more distant than the ~3.5 AU originally proposed.

Model parameters that reproduce Earth’s zero Ru–Mo anomaly lead to a Mars anomaly that is either small (and dominated by Mo) or zero. A non-zero Mars anomaly would provide a

tighter constraint on the step location (Figure 4). Early Mo measurements on two Martian meteorites suggest consistency with zero anomaly (Burkhardt et al., 2011); additional analyses (on less weathered samples) will provide further tests of our model. We also predict that Mars has negligible $\epsilon^{100}\text{Ru}$ (not yet measured), possibly yielding a Ru–Mo composition for Mars close to that of the Earth. Model parameters that reproduce Earth’s zero Ru–Mo anomaly typically result in an expected Theia Mo anomaly of zero. The predicted Mo isotopic similarity of the Earth and Moon thus appears to be a consequence of the broad, isotopically homogeneous inner disk originally advocated by Dauphas et al. (2002a, 2014a, 2014b).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

a) Examples of initial mass distributions (embryos + planetesimals) used in canonical (EJS/CJS) simulations of Fischer and Ciesla (2014) and in Grand Tack simulations of O'Brien et al. (2014) and Walsh et al. (2011), prior to the migration of Jupiter and Saturn. Both canonical and Grand Tack scenarios have most mass interior to 3–4 AU, but the Grand Tack simulations also include mass extending out to ~13 AU. b) Left panel: relationship between the final bulk mass-weighted semimajor axes (MWSMA, Eq. 2) of terrestrial planets and their final semimajor axes. Each point represents one planet that survived its simulation. Symbol size is proportional to planetary mass. Dot-dashed line is a 1:1 line, indicating no mixing; a planet plotting on this line is comprised, on average, of material from its final

location. Planets above (below) this line are made, on average, of material from greater (smaller) heliocentric distances than their final locations. A positive linear trend is seen in canonical simulations, while a flat trend is seen in Grand Tack simulations, implying more radial mixing in the Grand Tack scenario. Right panel: Likelihood distribution of bulk MWSMA. c) Same as part (b), but only considering the late veneers of the planets. Symbol shading is proportional to late veneer mass fraction. Canonical simulations have a flat trend, indicating more radial mixing in their late veneer material than in their bulk composition. Statistics are shown in Table 1. Bulk MWSMA for Theia analogues are shown in Supplemental Figure S2.

Figure 2.

Calculated $\epsilon^{92}\text{Mo}$ – $\epsilon^{100}\text{Ru}$ anomaly for Earth analogues that form in N -body simulations, for an initial inner disk composition of $\epsilon^{100}\text{Ru} = \epsilon^{92}\text{Mo} = 0$, outer disk composition of $\epsilon^{100}\text{Ru} = -3.35$, $\epsilon^{92}\text{Mo} = 6.09$, and variable step location. Each point is the final composition of one Earth analogue for one step location. a) Full range of compositions produced in canonical (EJS/CJS) cases, compared to observations of meteorite compositions (filled black triangles; compilation from Dauphas and Schauble, 2016; data from Dauphas et al., 2002a, 2002b, 2004; Chen et al., 2010; Burkhardt et al., 2011; Fischer-Gödde et al., 2015). Other symbol colors (step locations) and sizes (planetary mass) are from the left panel of part (b). Labels indicate meteorite groups. b) Left panel: enlarged view of the area indicated by a black

rectangle in part (a). Right panel: same as left panel, but showing calculated Ru–Mo anomaly of Earth analogues from Grand Tack simulations. Note that different step locations were used in the two panels, and that many data plot at the origin. These data are plotted in terms of distance from the origin in Supplemental Figure S3, and similar results for Mars analogues are shown in Supplemental Figures S4–S5.

Figure 3.

Results of Ru–Mo modeling for Earth, Mars, and Theia for different step locations and accretion scenarios, for an initial inner disk composition of $\epsilon^{100}\text{Ru} = \epsilon^{92}\text{Mo} = 0$ and outer disk composition of $\epsilon^{100}\text{Ru} = -3.35$, $\epsilon^{92}\text{Mo} = 6.09$. Dashed lines: canonical (EJS/CJS) simulations. Solid lines: Grand Tack simulations. Left panel: Probabilities of Earth and Mars having negligible Ru–Mo anomaly. Right panel: Probabilities of Earth and Theia having negligible Mo anomaly. Model conditions that reproduce Earth’s zero anomaly often produce Mars and especially Theia analogues with negligible anomalies.

Figure 4.

Results of Ru-Mo modeling for Earth and Mars for different step locations, different accretion scenarios, and varying inner and outer disk compositions. a) Results from canonical (EJS/CJS) accretion simulations. Upper panel: The case of an inner disk composition of $\epsilon^{100}\text{Ru} = \epsilon^{92}\text{Mo} = 0$ and variable outer disk composition as indicated by the line types. Solid lines: $\epsilon^{100}\text{Ru} = -0.7$, $\epsilon^{92}\text{Mo} = 1.27$. Dashed lines: $\epsilon^{100}\text{Ru} = -1.15$, $\epsilon^{92}\text{Mo} = 2.09$. Dotted lines: $\epsilon^{100}\text{Ru} = -3.5$, $\epsilon^{92}\text{Mo} = 6.36$. Blue: Earth analogues; orange: Mars analogues. Lower panel: A different example case, with an inner disk composition of $\epsilon^{100}\text{Ru} = 0.05$, $\epsilon^{92}\text{Mo} = -0.09$ and outer disk composition of $\epsilon^{100}\text{Ru} = -1.15$, $\epsilon^{92}\text{Mo} = 2.09$. Note difference in vertical scale between upper and lower panels. b) Analogous to part (a), but showing results from Grand Tack simulations.

Figure 5a

Figure 5b

Figure 5c

Figure 5.

Tradeoffs between inner and outer disk Ru–Mo compositions, step locations that produce the highest likelihood of zero anomaly for Earth and Mars (black line contours and labels), and those maximum likelihoods (color shading) in canonical (EJS/CJS) simulations. Vertical axes indicate the inner disk composition ($\epsilon^{100}\text{Ru}$ and $\epsilon^{92}\text{Mo}$, related by the trend defined by meteorites); horizontal axes indicate the outer disk compositions. a) Step locations and maximum probabilities for Earth analogues to have negligible Ru–Mo anomaly. b) Similar to part (a), but for Mars analogues. c) The probability of Theia analogues having negligible Mo anomaly for the step locations that are most likely to reproduce the Earth's zero anomaly (from part (a)). An inner disk composition between $\epsilon^{100}\text{Ru} = \epsilon^{92}\text{Mo} = 0$ and $\epsilon^{100}\text{Ru} = 0.05$, $\epsilon^{92}\text{Mo} = -0.09$ is most likely to reproduce the Earth's zero Ru–Mo anomaly, which is also likely to produce Mars and Theia analogues with small or zero anomaly.

Figure 6a

Figure 6b

Figure 6c

Figure 6.

Analogous to Figure 5, but showing results from Grand Tack simulations.

Table 1

Mean values of mass-weighted semimajor axes, feeding zone widths, and other parameters. Terrestrial planets: formed inside of 2 AU and have a late veneer. Earth analogues: formed within 0.75–1.25 AU and have a late veneer. Mars analogues: formed within 1.25–2 AU and have a late veneer. Theia analogues: last body containing at least one embryo to hit an Earth analogue. Uncertainties are 1σ variations. Feeding zone widths are one mass-weighted standard deviation of the semimajor axes of all bodies accreted by a planet.

	Accretion scenario	Bulk MWSMA (AU)	Late veneer MWSMA (AU)	Bulk feeding zone width (AU)	Late veneer feeding zone width (AU)	Final semimajor axis (AU)	Number of planets	Mass ($M_{\oplus}$)	Late veneer mass fraction
All terrestrial planets	EJS	1.3 ± 0.4	1.4 ± 0.2	0.46 ± 0.13	0.47 ± 0.12	1.0 ± 0.4	164	0.7 ± 0.4	$(9 \pm 11)\%$
	CJS	1.5 ± 0.5	2.0 ± 0.3	0.68 ± 0.16	0.73 ± 0.12	1.1 ± 0.5	167	0.9 ± 0.3	$(7 \pm 8)\%$
	Grand Tack	1.5 ± 0.3	1.9 ± 0.6	0.79 ± 0.14	1.2 ± 0.4	1.0 ± 0.4	65	0.4 ± 0.3	$(23 \pm 18)\%$
Earth analogues	EJS	1.3 ± 0.3	1.4 ± 0.2	0.47 ± 0.12	0.44 ± 0.13	0.97 ± 0.13	57	0.8 ± 0.4	$(6 \pm 8)\%$
	CJS	1.4 ± 0.2	2.0 ± 0.3	0.68 ± 0.16	0.74 ± 0.11	0.97 ± 0.15	57	1.0 ± 0.3	$(5 \pm 7)\%$
	Grand Tack	1.40 ± 0.07	1.73 ± 0.15	0.79 ± 0.06	1.1 ± 0.2	1.01 ± 0.14	27	0.6 ± 0.3	$(26 \pm 20)\%$
Mars analogues	EJS	1.6 ± 0.3	1.5 ± 0.2	0.50 ± 0.14	0.49 ± 0.15	1.6 ± 0.2	48	0.6 ± 0.3	$(5 \pm 8)\%$
	CJS	2.0 ± 0.4	2.1 ± 0.3	0.74 ± 0.14	0.70 ± 0.13	1.6 ± 0.2	56	0.9 ± 0.4	$(3 \pm 4)\%$
	Grand Tack	1.9 ± 0.4	2.3 ± 1.1	0.7 ± 0.2	1.2 ± 0.6	1.5 ± 0.2	17	0.10 ± 0.11	$(22 \pm 16)\%$
Theia analogues	EJS	1.6 ± 0.5	—	0.33 ± 0.18	—	—	55	0.10 ± 0.10	—
	CJS	2.1 ± 0.8	—	0.38 ± 0.19	—	—	57	0.15 ± 0.15	—
	Grand Tack	1.4 ± 0.5	—	0.59 ± 0.19	—	—	28	0.09 ± 0.05	—