Earth Planet. Sci. Lett. 659 (2025) 119337

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Porphyritic olivine chondrules with enstatite chondrite isotopic composition as a main building block of Earth

Yves Marrocchi [a,*], Tahar Hammouda [b], Maud Boyet [b], Guillaume Avice [c], Alessandro Morbidelli [d,e]

[a] Université de Lorraine, CNRS, CRPG, F-54000 Nancy, France
[b] CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, Université Clermont Auvergne, 63000 Clermont-Ferrand, France
[c] Institut de physique du globe de Paris, CNRS, Université de Paris, Paris 75005, France
[d] Laboratoire Lagrange, Centre National de la Recherche Scientifique, Observatoire de la Côte d'Azur, Université Côte d'Azur, 06304 Nice, France
[e] Collège de France, Centre National de la Recherche Scientifique, Université Paris Sciences et Lettres, Sorbonne Université, 75014 Paris, France

A R T I C L E I N F O

Keywords:
Earth
Enstatite chondrites
Chondrules
Building blocks
Protoplanetary disk

A B S T R A C T

The nature and origin of the Earth's building blocks remain intensely debated. While enstatite chondrites (ECs) were formed from a reservoir with an isotopic composition of major elements similar to that of the Earth, they nevertheless exhibit significant chemical differences. Specifically, the Earth is enriched in refractory elements and depleted in moderately volatile elements compared to ECs. By reevaluating the budget of rare earth elements in enstatite chondrites, we show that EC chondrule precursors correspond to early condensates formed in the inner protoplanetary disk. Taking condensation models into account, we propose that these condensates consist primarily of olivine, which was subsequently transformed into enstatite due to gas-melt interactions during chondrule formation. We show that the accretion of the Earth from olivine-rich EC chondrules, which underwent shorter gas-melt interactions compared to those present in ECs, satisfactorily reproduces its chemical ratios (i.e., Mg/Si, Al/Si, Na/Si, Ti/Si, Ca/Si) and oxygen isotopic composition. This difference in the duration of gas-melt interactions in the protoplanetary disk had thus major consequences on the chemical composition of the planetesimals accreted by planetary embryos. Our approach thus addresses the chemical divergence between Earth and ECs without altering their isotopic compositions, while also supporting planet formation models involving large embryos formed in the inner protoplanetary disk.

1. Introduction

Mass-independent isotopic variations of moderately volatile and refractory elements (the so-called nucleosynthetic anomalies) represent fingerprints of the building blocks of planets because they are conserved through planetary magmatic differentiation processes (Burkhardt et al., 2021). Previous studies have shown that the Earth, the Moon, and enstatite chondrites (ECs) have indistinguishable compositions at the ppm-ppb level for many elements (i.e., oxygen, titanium, calcium, and molybdenum; Burkhardt et al., 2021; Dauphas, 2017) whereas outer solar system materials thought to be sampled by carbonaceous chondrites (CCs) have isotopic signatures differing by tens to hundreds of ppm (Warren, 2011). Despite these isotopic similarities, the Earth and ECs strongly differ in their chemical ratios (e.g., Mg/Si, Al/Si, Na/Si; Jagoutz et al., 1979; Palme and O'Neill, 2014), with Earth being enriched in refractory elements and depleted in moderately volatile elements relative to ECs (Fig. 1, Jagoutz et al., 1979; Morbidelli et al., 2020). It has been proposed that this chemical-isotopic conundrum could result from (i) the building blocks of the Earth possessing isotopic compositions similar to those of ECs but different chemical ratios (Dauphas, 2017; Frossard et al., 2022), (ii) Earth's accretion involving chondritic, chemically-fractionated components (e.g., refractory inclusions, chondrules) rather than bulk chondrites (Alexander, 2022; Morbidelli et al., 2020; Yoshizaki and McDonough, 2021), or (iii) the formation of the Earth from a mixture of different meteorite types, some of which may not be represented in our current collections (Drake and Righter, 2002; Mezger et al., 2020; Burkhardt et al., 2021). The linear correlations observed between different s-process elements (e.g., Nd and Mo) among chondrites with Earth as an end-member partly support the latter hypothesis (Frossard et al., 2021; Burkhardt et al., 2021).

* Corresponding author.
E-mail address: yves.marrocchi@univ-lorraine.fr (Y. Marrocchi).

https://doi.org/10.1016/j.epsl.2025.119337
Received 4 December 2024; Received in revised form 14 February 2025; Accepted 25 March 2025
Available online 30 March 2025

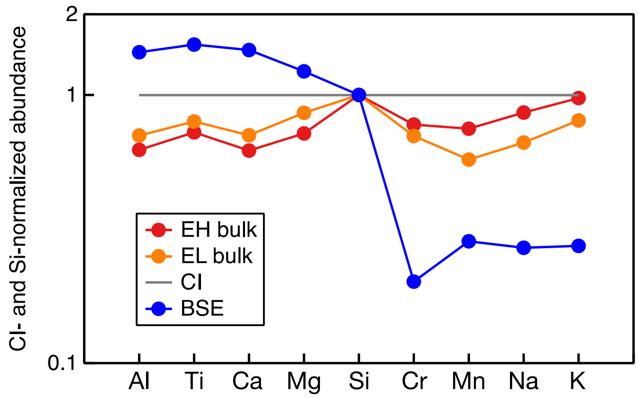

Fig. 1. Lithophile element abundance in the bulk silicate Earth (BSE) and bulk EH and EL chondrites. Elemental abundances are normalized to CI chondrite composition and Si. Elements are arranged by their 50 % nebular condensation temperatures. Data for EH and EL chondrites from Wasson and Kallemeyn (1988). Data for BSE from McDonough and Sun (1995).

Several post-accretion processes have also been proposed to account for the large chemical divergence between the Earth and ECs. This includes the preferential incorporation of Si into Earth's core in a reduced environment, but to reconcile the Mg/Si and Al/Si ratios between the Earth and ECs, the core would have to contain up to 30 % Si, which is highly unlikely (Javoy et al., 2010). It has also been suggested that collisional erosion processes would raise the Earth's Mg/Si ratio to its current values by removing early-formed proto-crusts (Boujibar et al., 2015). However, this process requires complex and poorly constrained processes, including (i) loss of volatile lithophile elements and recondensation of refractory lithophile elements after the impacts (Boujibar et al., 2015) and (ii) changes in refractory element ratios that remain difficult to discern in estimates of the Bulk Silicate Earth (BSE) chemical composition (Palme and O'Neill, 2014).

Alternatively, it has been proposed that ECs were depleted in an early-condensed forsterite component enriched in refractory elements (Dauphas et al., 2015). This component could have been accreted by a first generation of planetesimals (Morbidelli et al., 2020), leaving behind a residual condensate at the origin of ECs. In such a scenario, the Earth formed through the accretion of ~ 40 % of the first-generation refractory-rich planetesimals together with ~ 60 % of material with solar-like composition down to condensation temperatures of ~900 K (Morbidelli et al., 2020). Although appealing, this scenario appears difficult to reconcile with the peculiar O isotopic composition of early condensates (i.e., $\Delta^{17}O = \delta^{17}O - 0.52 \times \delta^{18}O \sim -23$ ‰, (Krot, 2019) compared to the BSE composition ($\Delta^{17}O = 0$ ‰; Eiler, 2001). Additionally, these models do not consider the magmatic formation of EC chondrules, which result from complex processes involving chondrule precursor recycling and gas-melt interactions (Tissandier et al., 2002; Piani et al., 2016; Marrocchi et al., 2018). Alternative planetary growth models proposed that Earth formed *via* accretion of chondrule-sized pebbles (Johansen et al., 2015). However, the claim that these pebbles correspond to chondrules similar to those observed in carbonaceous chondrites (CCs; Alexander, 2022; Yoshizaki and McDonough, 2021) is difficult to reconcile considering the numerous constraints now imposed by multi-isotopic systems and astrophysical modeling (Burkhardt et al., 2021; Mah et al., 2022; Nimmo et al., 2024; Morbidelli et al., 2025). Furthermore, these models treat chondrules as black boxes, without accounting for their different petrographic types within each chondrite class (Jones, 2012; Marrocchi et al., 2024).

Altogether, the nature of Earth's building blocks and the origin of the Earth–ECs chemical divergence remain unexplained. In this study, we first reevaluate the budget and distribution of Rare Earth Elements (REEs) in ECs. We then use this new approach to constrain (i) the evolution of dust in the EC reservoir and (ii) the nature of the Earth's building blocks. This leads us to revisit the hypothesis of the Earth's formation from early condensates (Morbidelli et al., 2020), taking into account constraints on chondrule formation (Marrocchi et al., 2024). We thus show that the Earth–EC chemical divergence can be solved by considering Earth's accretion from olivine-rich chondrules that are not sampled by enstatite chondrites. We propose that these chondrules were incorporated into early Earth and derive from early refractory condensates but experienced shorter gas-melt interactions than the pyroxene-rich chondrules predominantly observed in ECs. Finally, we explore the implications of this model for planet formation conditions in the inner protoplanetary disk.

2. Reevaluating the distribution of rare earth elements in ECs

Rare earth elements (REEs) are a group of 17 metallic elements (15 lanthanides + scandium and yttrium) that are powerful tracers of various geological processes (e.g., melting-crystallization, evaporation-condensation; Barrat et al., 2021, Hu et al., 2021). Although bulk ECs exhibit CI-like REE compositions (Fig. 2), their constituent minerals display variably fractionated REE patterns (Hammouda et al., 2022). In particular, oldhamite –a rare type of calcium sulfide with minor amount of Fe, Mg and Mn (hereafter CaS)– mostly occurring within complex metal-sulfide nodules located between chondrules, are characterized by REE abundances reaching up to 100 times the CI value, representing up to half the REE budget of ECs (Fig. 2; Crozaz and Lundberg, 1995; Gannoun et al., 2011; Hammouda et al., 2022). As REEs are highly refractory elements and larger REE ions can substitute for Ca in condensates (Ingrao et al., 2019; Lodders, 1996), CaS is generally interpreted as being formed by condensation under reducing conditions (i.e., C/O ratio > 0.9; Lodders and Fegley, 1993). Under these conditions, thermodynamical calculations predict CaS REE patterns characterized by negative Eu and Yb anomalies due to their lower condensation temperatures relative to the other REEs (Lodders and Fegley, 1993). Instead, oldhamites in unequilibrated ECs from the EH subgroup show systematic Eu- and Yb-enrichments compared to other REEs (Fig. 2; Gannoun et al., 2011; Hammouda et al., 2022). This peculiar REE signature implies that EC CaS condensed from a residual gas whose initial composition was already fractionated relative to the solar composition by primordial condensates (Hammouda et al., 2022). EC from the EL subgroups are not considered in this contribution, as they recorded a more complex

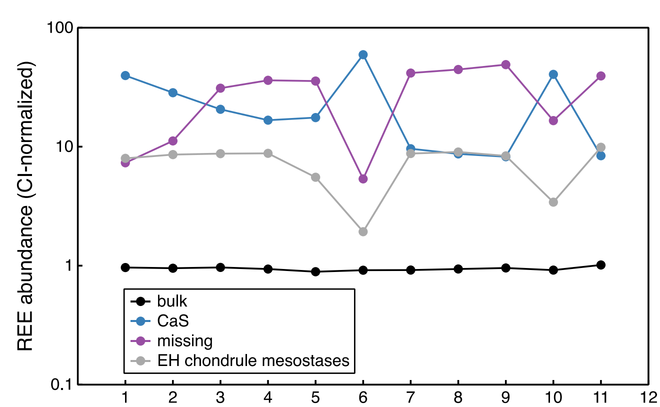

Fig. 2. CI-normalized REE patterns of the bulk EH3 Sahara 97,158 (paired with Sahara 97,096), together with EC chondrule mesostasis, CaS, and the reconstructed pattern of the missing component, which corresponds to the mismatch between the whole-rock and the reconstructed compositions based on the constituent minerals of Sahara 97,158. It should be noted that the rare-earth pattern of the missing component has also been normalized to the amount of matrix, which has been tentatively proposed as a potential carrier for this component. EH chondrule mesostasis data from Jacquet et al. (2015), EH3 data from Hammouda et al. (2022), and CI values from Barrat et al. (2012).

magmatic history, with their CaS exhibiting fractionated REE pattern driven by volatility loss, similar those measured in aubrites (Hammouda et al., 2022).

The nature of these Eu-Yb-depleted primordial condensates remains uncertain. Hammouda et al. (2022) proposed that this component (referred to as the "missing" component; Fig. 2) could correspond to sulfide aggregates or isolated grains in the EC but also noted similarities with some chondrule mesostasis analyzed in the EH3 Sahara 97,096 (Fig. 2; Jacquet et al., 2015). To explore this further, we recalculated the REE spectra of the chondrules from the EH3 Sahara 97096, as this chondrite is one of the least altered ECs by both asteroidal processes and terrestrial weathering. In addition, this meteorite has been studied in detail in the past, and we have precise estimates of the modal abundance and REE signatures of silicates and glassy mesostasis (Jacquet et al., 2015). Our calculations show that the bulk EC chondrules, as recalculated, have both negative Eu and Yb anomalies (Fig. 3) and thus likely correspond to the missing component previously ascribed to the EC matrix. We emphasize that the mismatch for the light REE La and Ce likely results from terrestrial alteration, as commonly reported in meteorites from hot deserts (Crozaz et al., 2003). In any case, this result demonstrates that the precursors of EC chondrules were primordial condensates containing an Eu- and Yb-depleted phase, which likely corresponds to a first generation of CaS (see §3 below).

We note that the condensation of EC chondrule precursors should have occurred after the isotopic composition of the inner disk had shifted from ^{50}Ti-^{54}Cr-rich compositions –sampled by refractory inclusions in carbonaceous chondrites (CC)– to ^{50}Ti-^{54}Cr-poor compositions as recorded in non-carbonaceous chondrites (NC; Burkhardt et al., 2021; Ebert et al., 2018). This important constraint arises from the lack of ^{54}Cr excess reported in bulk ECs and in all (but two) separated EC chondrules ($n = 12$; Burkhardt et al., 2021; Schneider et al., 2020; Zhu et al., 2020). Our finding also implies that condensation processes continued in the inner disk after the early-formed ^{50}Ti-^{54}Cr-rich calcium-aluminum-rich inclusions (CAIs) and ameboid olivine aggregates (AOAs) were transferred to the outer disk by viscous spreading or disk winds (Jansen et al., 2024; Morbidelli et al., 2024). We note that similar conclusions were reached based on the existence of (i) CC CAIs with NC Mo isotopic compositions (Brennecka et al., 2020) and (ii) rare CAIs without ^{50}Ti-excess in ordinary chondrites (Ebert et al., 2017). Importantly, EC CAIs have similar ^{16}O-rich compositions to those of CC CAIs (Guan et al., 2000), implying that EC chondrule precursors were ^{50}Ti-^{54}Cr-poor but ^{16}O-rich. This ^{16}O-rich signature may seem counterintuitive to the Earth's isotopic composition, but as detailed in the next section, it results from the conditions of dust evolution in the EC/Earth reservoir.

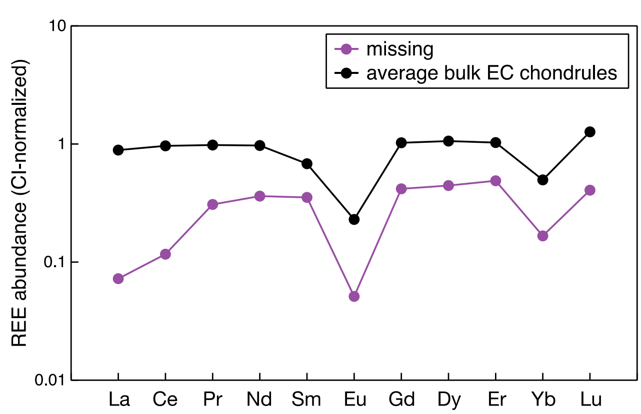

Fig. 3. Average reconstructed CI-normalized REE patterns of chondrules from the EH3 Sahara 97,096 based on the modal abundance of each chondrule phase and their respective REE concentrations (data from Jacquet et al., 2015). This reconstructed REE pattern mimics that of the missing component.

3. Nature of EC chondrule precursors and dust evolution in the EC reservoir

Thermodynamic calculations show that condensates are dominated by oxides, silicates and metal for C/O ratios 〈 0.95, whereas oldhamite starts to condense at C/O 〉 0.9 (Ebel, 2006; Larimer, 1975). It thus appears that EC chondrule precursors could have condensed at $0.95 > C/O > 0.9$ and were composed of oxides (e.g., $MgAl_2O_4$), Fe-Ni metal, and silicates, the latter being dominated by Mg-rich olivine (i.e., forsterite, Mg_2SiO_4; Ebel, 2006; Morbidelli et al., 2020). Mineralogically speaking, they could thus be considered as CaS-bearing, AOA-like condensates akin to those supposedly accreted in a first generation of planetesimals and proposed to represent ~40 % of the Earth's building blocks (Morbidelli et al., 2020). As detailed in the introduction, this model would produce a highly ^{16}O-rich planet, at odds with the BSE O-isotopic composition ($\Delta^{17}O = 0$ ‰).

To explore this issue, we first emphasize that EC chondrules are systematically dominated by low-Ca pyroxene (i.e., $MgSiO_3$) rather than Mg-rich olivine, as predicted by condensation modelling (Ebel, 2006; Morbidelli et al., 2020). However, Mg-rich olivine is commonly present in EC chondrules as rounded grains enclosed in low-Ca pyroxene (Piani et al., 2016; Weisberg et al., 2021). In addition, the modal abundance of Mg-rich olivine in EC chondrules has also been shown to be underestimated due to a 2D-3D sectioning effect (Barosch et al., 2020). This suggests that Mg-rich olivine was a major constituent of EC chondrule precursors, in agreement with its mineralogy inferred from condensation modeling (Ebel, 2006). The overabundance of low-Ca pyroxene at the expense of Mg-rich olivine in EC chondrules has been interpreted as resulting from protracted gas-melt interactions under high $PSiO_{(g)}$ (Piani et al., 2016), according to the following reactions:

$$SiO_{(gas)} + 1/2O_{2(gas)} = SiO_{2(melt)} \tag{1}$$

$$Mg_2SiO_4 + SiO_{2(melt)} = 2MgSiO_3 \tag{2}$$

In this scenario, porphyritic pyroxene (PP) –as predominantly sampled by ECs– experienced a longer duration of gas-melt interactions than porphyritic olivine pyroxene (POP) chondrules, which themselves resulted from a longer duration than porphyritic olivine (PO) chondrules (Tissandier et al., 2002). We stress that the key point of this model is that PO–POP–PP chondrules correspond to an evolutionary sequence of increasing duration of gas-melt interactions, in line with the observation that the abundance of PO chondrules decreases as that of PP increases (Jones, 2012; Tissandier et al., 2002). In addition, ~50 % of EC chondrules show mineralogical zoning with olivine cores surrounded by low-Ca pyroxene rims (Barosch et al., 2020). Therefore, the absence of PO chondrules in ECs (Jones, 2012) does not mean that they did not exist in the EC-forming reservoir, but that they fully transformed into POP and then into PP chondrules (Piani et al., 2016). In this sense, ECs are indeed depleted in a forsterite component, but this results from longer exposure of their constituent chondrules to the surrounding gas. We emphasize that such a model is thought to have been operative in all chondrite types, whether belonging to the NC or CC superclans (Marrocchi et al., 2024). The difference in PO, POP and PP modal abundances between each chondritic type therefore results from the variable duration of gas-melt interaction processes during chondrule formation in each sub-reservoir (Piralla et al., 2021; Marrocchi et al., 2022, 2024).

One can see that the change in chondrule mineralogy as gas-melt interactions progress strongly affects their bulk chemical compositions. This is illustrated in Fig. 4 for ordinary chondrites (OCs) in which PO, POP, and PP chondrules have drastically different Mg/Si, Al/Si and Na/Si ratios. Once again, PO chondrules *sensu stricto* (i.e., olivine content > 90 %) have never been reported in ECs as they experience protracted gas-melt interactions that transform them into POP and PP chondrules (Piani et al., 2016). Nevertheless, a significant chemical difference is visible between EC POP and PP chondrules (Fig. 4). We also

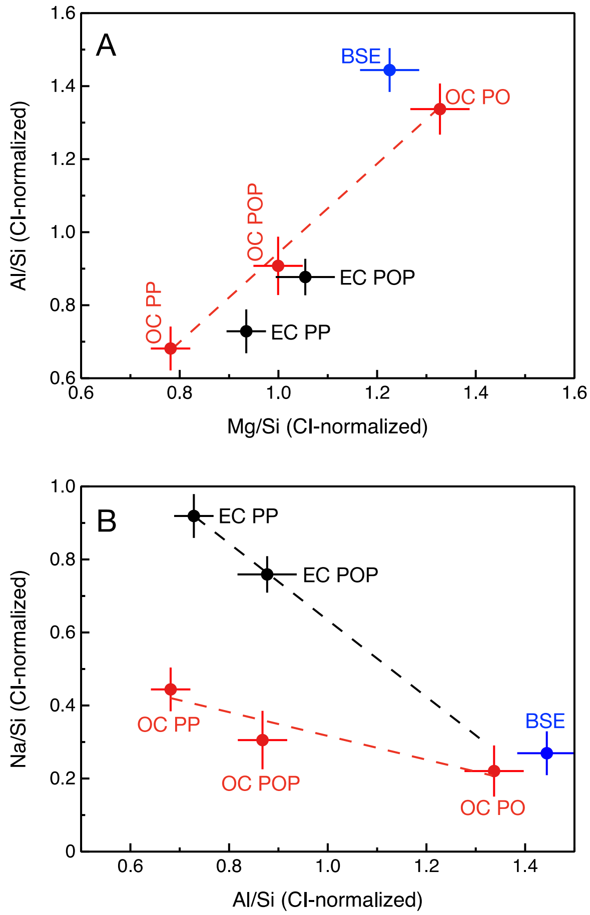

Fig. 4. Average Mg/Si and Al/Si ratios of PO, POP, and PP chondrules in ordinary chondrites (OC) as well as POP and PP chondrules in enstatite chondrites (EC). The ratios of the Bulk Silicate Earth (BSE) are also shown. Chondrule data from Alexander et al. (2008); Grossman et al. (1985); Jones (1996, 1994, 1990); Jones and Scott (1989); Tachibana et al. (2003). BSE data from McDonough and Sun (1995).

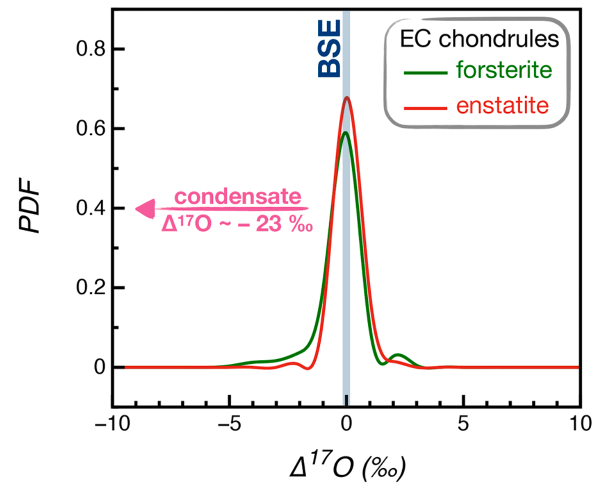

Fig. 5. Probability density function of the oxygen isotopic compositions (expressed as Δ^{17}O) of olivines and low-Ca pyroxenes in EC chondrules (data from Weisberg et al., 2021). The Δ^{17}O values of the BSE and refractory inclusions are shown for comparison (data from Eiler, 2001; Krot, 2019; Marrocchi et al., 2019b).

note that in a Mg/Si vs. Na/Si diagram (Fig. 4, bottom), the EC POP and PP chondrules define a line that intersects the trend defined by the OC PO-POP-PP chondrules near the OC PO chondrule/bulk Earth point. Combined with petrographic observations (Piani et al., 2016; Barosch et al., 2020), these chemical evolutions suggest that EC PO chondrules had chemical compositions close to their PO counterparts in ordinary chondrites, which can therefore be used to understand the dynamics of dust evolution in the disk reservoir that gave rise to ECs and the Earth.

Although having experienced varying durations of gas-melt interactions, PO, POP and PP chondrules are, however, characterized by olivines and low-Ca pyroxenes with similar Δ^{17}O values (Tenner et al., 2018). This is because they crystallized from melts whose compositions were buffered by gas-melt interaction processes as attested by the similar oxygen isotopic composition of olivine and low-Ca pyroxene crystals (Rudraswami et al., 2011). The only exception is the relict ^{16}O-rich olivine grains commonly found in PO chondrules and inherited from the early-condensed precursors from which they derive (Marrocchi et al., 2019a, 2024). In any case, their rarity in PO chondrules does not affect the bulk isotopic composition of chondrules. Focusing on EC chondrules, it is important to note that their constitutive olivines and pyroxenes have the same oxygen isotopic composition as the BSE (Fig. 5; Eiler, 2001; Weisberg et al., 2021). We note here that although CC, EC, and OC olivine-rich chondrules result from similar process (precursor recycling and gas-melt interactions; Marrocchi et al., 2024), they can be characterized by different Δ^{17}O values. This likely results from gas-melt interactions under different conditions, such as dust/gas ratios. The slight difference in Δ^{17}O observed between EC and OC chondrules (Marrocchi et al., 2024) should not be seen as a weakness of our model. We do not claim that olivine-rich EC chondrules were isotopically similar to olivine-rich OC chondrules but had identical mineralogy and chemical ratios, despite small variations in the conditions of gas-melt interactions they experienced.

Due to their refractory nature, REEs are less prone being affected by gas-melt interactions although Eu can experience evaporation (Hammouda et al., 2022). Nevertheless, the peculiar REE feature of EH chondrules (Fig. 3) suggests that they retained the initial REE signature of primordial condensates from which they derive and that the putative EC PO chondrules should have the same REE patterns as EC POP–PP chondrules (Fig. 3, Jacquet et al., 2015).

4. The slightly different nature of Earth's and EC building blocks

No comprehensive model has so far succeeded in mitigating the chemical divergence between Earth and ECs, without breaking their isotopic similarities. This implies that the Earth's building blocks neither correspond to ECs *sensu stricto* (Javoy et al., 2010) nor early-formed planetesimals composed of refractory inclusions and/or chondrules (e.g., Garai et al., 2025). The key observations detailed above allow us to draw the following scenario:

1- EC chondrule precursors correspond to ^{16}O-rich early condensates, and EC chondrules deriving from these condensates underwent protracted gas-melt interactions that drove their Δ^{17}O values toward the BSE composition (Δ^{17}O = 0 ‰). This implies that Earth's building blocks may correspond to a specific type of chondrules instead of bulk chondrites.
2- In addition to O-isotopic compositions, the interactions with the surrounding gas strongly modified the bulk chemical compositions of chondrules, leading to a decrease of the Mg/Si and Al/Si ratios and an increase of the Na/Si ratio, respectively (Fig. 4). This shows that the bulk chemical compositions of chondrules are strongly dependent on their petrological types (i.e., PO, POP and PP), a parameter that is largely ignored in attempts to model the Earth's building blocks (e.g., Garai et al., 2025, Yoshizaki and McDonough, 2021).
3- By considering the chondrule petrological type, we show that (i) OC PO chondrules have Mg/Si, Al/Si, and Na/Si ratios plotting close to those of the BSE and (ii) EC POP and PP chondrules define lines that

cross those produced by OC PO–POP–PP chondrules near the BSE compositions in both Mg/Si vs. Al/Si and Mg/Si vs. Na/Si diagrams (Fig. 4). This suggests that the olivine-rich chondrules unsampled in ECs had bulk chemical compositions close to OC PO chondrules and thus near-similar to that of the BSE (Fig. 4).

Based on these observations, we test a model where the Earth formed *via* the accretion of a first generation of planetesimals composed of varying amounts of refractory inclusions and EC PO chondrules (Fig. 6). To do so, we used the chemical compositions of (i) AOAs as a representative example of condensates formed in the inner disk (Morbidelli et al., 2020; Ruzicka et al., 2012) and (ii) OC PO chondrules, as they represent a good proxy for the composition of the olivine-rich chondrules unsampled by ECs (Fig. 4). Our results show that planetesimals composed solely of the "missing" EC PO chondrules have Mg/Si, Al/Si, Na/Si, Ti/Si and Ca/Si ratios similar, within errors, to those of the BSE (Fig. 7). As a test of the robustness of our model, we calculated the chi-squared for planetesimals formed from varying amounts of AOAs and PO chondrules (Fig. 8). It appears that the minimum value is obtained by considering planetesimals composed of 100 % of PO chondrules (Fig. 8), thus supporting our model derived from petrographic and chemical constraints. We stress that a major strength of this model is that it produces planetesimals with Earth-like O-isotopic compositions (Fig. 5). It therefore appears that the Earth is made up of material (i) unsampled in ECs (and thus not present in our collections) and (ii) slightly different than that accreted to form the EC parent bodies (i.e., EC POP and PP chondrules). This difference has a drastic impact on the chemical composition of the planetesimals formed and offers a solution to the chemical divergence observed between Earth and ECs, without affecting their respective isotopic compositions. The EC parent bodies result from the accretion of (i) chondrules having experienced longer durations of gas-melt interactions (POP and PP chondrules) and (ii) Eu-Yb-rich CaS condensed from the residual gas fractionated by the condensation of EC chondrule precursors (Figs. 3& 6).

We acknowledge that building the Earth from PO chondrules with EC isotopic composition would provide too-limited iron content to produce the terrestrial core. However, condensing EC chondrule precursors under the proposed C/O ratio of ∼ 0.9 also produces Fe-Ni metal in abundance large enough (∼ 37.5 wt%, Morbidelli et al., 2020) to account for the high Fe/Si and Fe/Mg of the Earth (Yoshizaki and McDonough, 2021).`

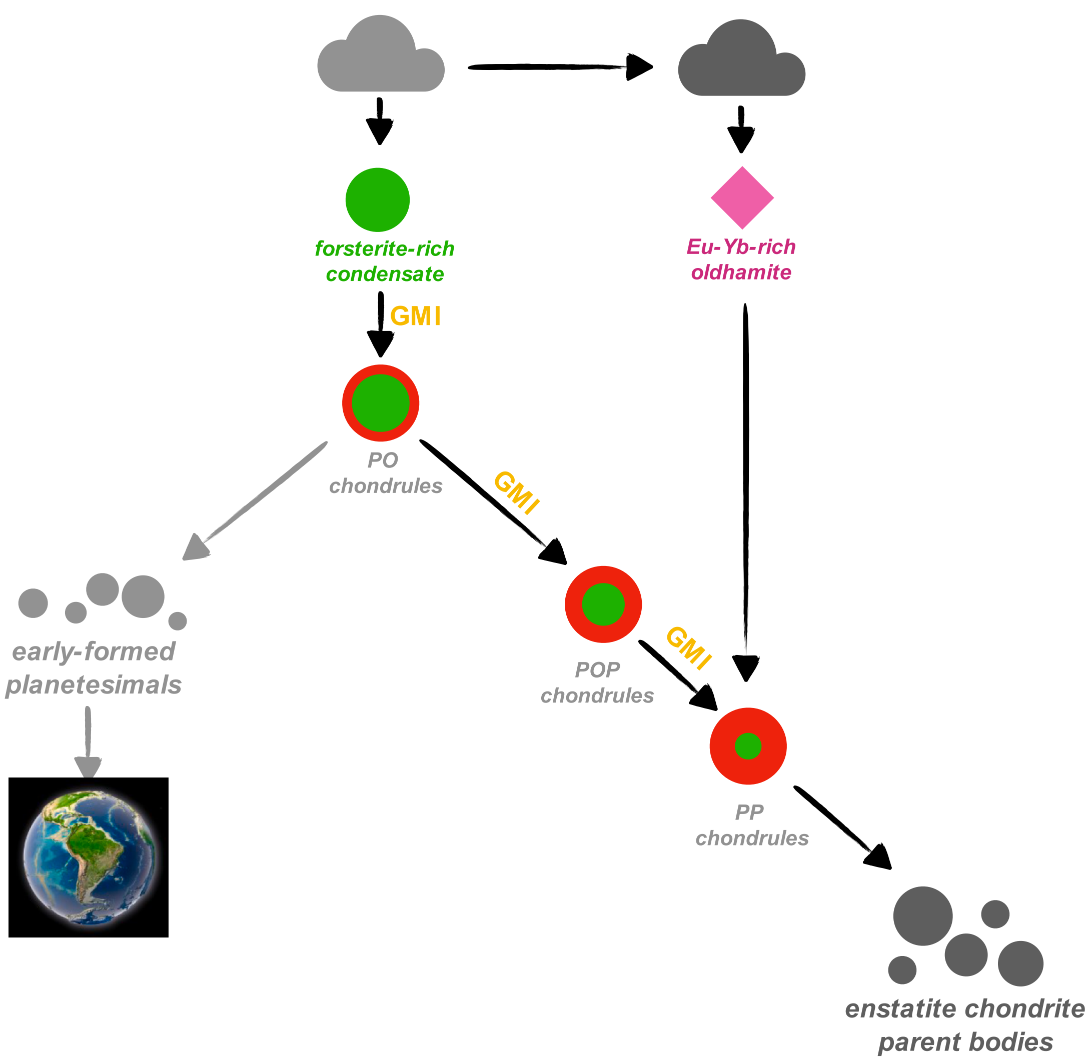

Fig. 6. Schematic representation of the model proposed in this work. In this scenario, early-condensed refractory inclusions produce a residual gas from which Eu-Yb-rich oldhamite will eventually condense. The early condensates then experience gas-melt interactions of varying durations, leading to the formation of PO, POP, and PP chondrules as the duration increases. We propose that the planetesimals that formed the Earth were mostly composed of PO chondrules, whereas EC parent bodies accreted POP and PP chondrules, which experienced longer durations of gas-melt interactions.

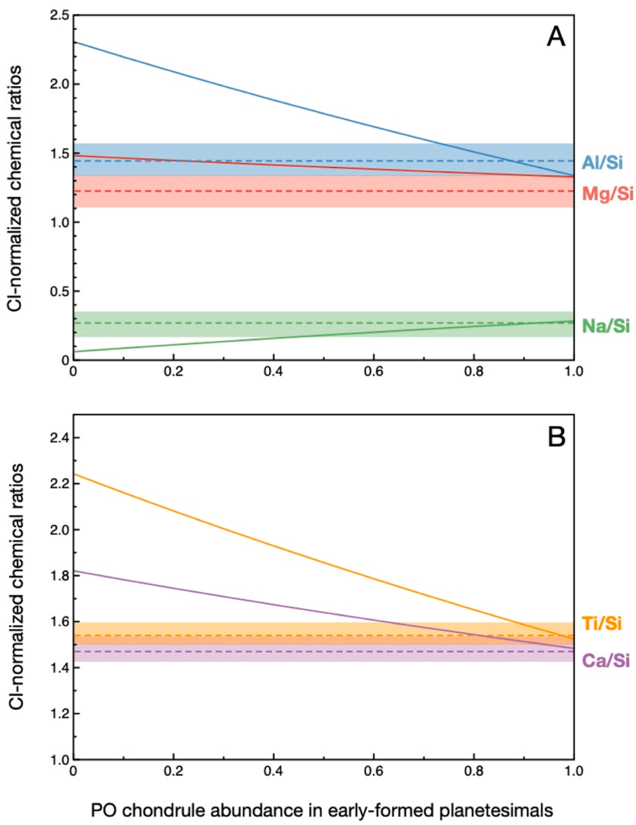

Fig. 7. (A) The Mg/Si (red), Al/Si (blue), and Na/Si (green) ratios as a function of the mass fraction of refractory inclusions (referred to as AOAs, Ruzicka et al., 2012) and the missing EC PO chondrules. The dashed lines represent the estimated bulk ratios of the BSE, and the horizontal bands correspond to their respective uncertainties. (B) Same diagram for Ti/Si (purple) and Ca/Si (orange) ratios.

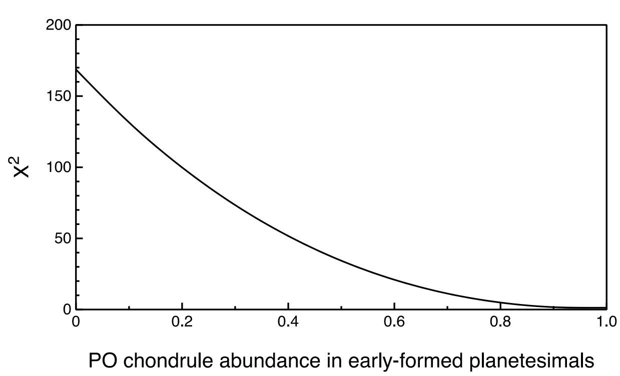

Fig. 8. Chi-squared values calculated for a mixing between AOAs and OC PO chondrules, considering the five chemical ratios tested in our models (i.e., Mg/Si, Al/Si, Na/Si, Ti/Si, and Ca/Si).

5. Astrophysical implications and concluding remarks

Most elements have the same isotopic compositions in ECs and Earth, whereas other chondritic meteorites show significant differences (Dauphas, 2017). However, small nucleosynthetic anomalies for ECs relative to Earth have been reported for the s-process elements Mo, Ru, and Nd (Burkhardt et al., 2021; Frossard et al., 2022, 2021). For this reason, the Earth must have accreted a component isotopically different from ECs.

In this contribution, we propose a scenario that explains the chemical divergence between the Earth and ECs, without breaking their isotopic similarities for most elements, by considering the complex magmatic process at the origin of chondrules of various petrological types. It thus appears that the Earth and ECs formed from planetesimals composed of chondrules that experienced different evolutionary paths driven by gas-melt interactions (Fig. 6). This implies that, compared to ECs, the planetesimals that formed the Earth accreted (i) earlier in the disk's history (i.e., at least 1 Myr after CAIs in order to produce chondrules, Piralla et al., 2023) or (ii) in a sub-reservoir where chondrules underwent shorter gas-melt interaction processes. In any case, this suggests that Earth's embryos accreted within few Myr, i.e., before the dissipation of the nebular gas. This is in line with (i) the rapid formation of Mars' embryos inferred from Hf–W–Th evidence (Dauphas and Pourmand, 2011) and (ii) the presence of solar neon in Earth's mantle (Yokochi and Marty, 2004).

The formation conditions of telluric planets have been a long-standing debate, with two main processes being dynamically possible during the evolution of the protoplanetary disk: oligarchic growth and pebble accretion (Raymond and Morbidelli, 2022). The classical model of oligarchic growth corresponds to the early accretion of Moon- to Mars-sized embryos in the protoplanetary disk followed –after gas removal– by mutual collisions that led to the formation of rocky planets (Chambers and Wetherill, 1998). Oligarchic growth produces telluric planets dominated by embryos formed in the inner solar system, with only a minor contribution inherited from outer solar system bodies (Raymond and Morbidelli, 2022).

A more recent and alternative model suggests planet growth *via* the accretion of pebbles (i.e., mm- to cm-size grains) formed in the outer solar system and drifting sunward due to gas drag (Lambrechts and Johansen, 2014). In contrast to oligarchic growth, the pebble model suggests that the Earth and Mars would be composed of 30 to 50 % of solar system material originally volatile-rich (Johansen et al., 2021), requiring a specific process to remove those volatile elements during accretion (Johansen et al., 2023). Deciphering which process was operative in forming telluric planets and determining how quickly planets can form are of fundamental importance to understand the dynamical evolution of the solar system, as well as the source and timing of delivery of volatile elements in the inner disk, especially on Earth (Johansen et al., 2021; Piani et al., 2020).

Our conclusions –that Earth is made of PO chondrules with EC isotopic composition– do not support a pebble accretion origin of the Earth but are rather consistent with collisional growth from early-formed inner solar system embryos (Brasser et al., 2018; Carlson et al., 2018; Brasser and Mojzsis, 2020). However, in this standard scenario of planet formation, the building blocks of planets are kilometer-sized planetesimals made of solids whose nature is generally referred to by the vague term "dust" (e.g., Kokubo and Ida, 2002). Our approach shows that this dust component corresponds to olivine-rich PO EC chondrules that are missing in ECs due to the protracted gas-melt interactions their constitutive chondrules underwent. Importantly, our model implies that early-condensates must survive long enough in the inner disk to be recycled into chondrules. This point is critical for both EC parent bodies and Earth's embryos as solids tend to migrate towards the Sun (Morbidelli et al., 2024). We however note that EC parent bodies appear to have formed earlier than all other chondritic types (i.e., ~1.8 Myr after CAIs, Sugiura and Fujiya, 2014), implying that Earth's embryos should have formed even earlier in our scenario. The lower limit for the formation of Earth's embryos is 1.5 Myr after CAIs, a timing constraint set by shift recorded in the isotopic composition of several elements (Nd, Mo, Zr) in early formed embryos (Frossard et al., 2021). This is also in line with the (i) recent revaluation of chondrules ^{26}Al-^{26}Mg systematics, which suggest their formation are 1 Myr older than previously thought (Piralla et al., 2023) and (ii) presence of relict chondrules in NC primitive achondrites, whose formation predate that of EC parent bodies (Schrader et al., 2017; Sugiura and Fujiya, 2014). Overall, this suggests that the embryos at the origin of the Earth were composed of chondrules formed early in the disk's history.

CRediT authorship contribution statement

Yves Marrocchi: Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Tahar Hammouda:** Writing – original draft, Methodology. **Maud Boyet:** Writing – original draft, Methodology. **Guillaume Avice:** Writing – original draft, Methodology, Conceptualization. **Alessandro Morbidelli:** Writing – original draft, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Christoph Burkhardt, Ramon Brasser, Emmanuel Jacquet and Laurette Piani for scientific discussions and feedbacks. Steve Mojzsis and an anonymous reviewer are thanked for helpful reviews. We thank Olivier Mousis for editorial handling. Alessandro Morbidelli acknowledges support the funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement No 101019380-HolyEarth). This work was supported by Programme National de Planétologie of CNRS-INSU, by the French Government Laboratory of Excellence initiative ANR-10-LABX-0006, the Région Auvergne, and the European Regional Development Fund. This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant Agreement No 682778—ISOREE). This is CRPG contribution #2865 and contribution #693 of the ClerVolc program of the International Research Center for Disaster Sciences and Sustainable Development of the University of Clermont Auvergne.

Data availability

Data will be made available on request.

References

Alexander, C.M.O'D, 2022. An exploration of whether Earth can be built from chondritic components, not bulk chondrites. Geochim. Cosmochim. Acta 318, 428–451. https://doi.org/10.1016/j.gca.2021.12.012.

Alexander, C.M.O'D., Grossman, J.N., Ebel, D.S., Ciesla, F.J., 2008. The formation conditions of chondrules and chondrites. Science (1979) 320, 1617–1619. https://doi.org/10.1126/science.1156561.

Barosch, J., Hezel, D.C., Sawatzki, L., Halbauer, L., Marrocchi, Y., 2020. Sectioning effects of porphyritic chondrules: implications for the PP/POP/PO classification and correcting modal abundances of mineralogically zoned chondrules. Meteorit Planet Sci maps, 13476. https://doi.org/10.1111/maps.13476.

Barrat, J.-A., Chaussidon, M., Yamaguchi, A., Beck, P., Villeneuve, J., Byrne, D.J., Broadley, M.W., Marty, B., 2021. A 4565-my-old andesite from an extinct chondritic protoplanet. Proc Natl Acad Sci USA 118, e2026129118. https://doi.org/10.1073/pnas.2026129118.

Barrat, J.A., Zanda, B., Moynier, F., Bollinger, C., Liorzou, C., Bayon, G., 2012. Geochemistry of CI chondrites: major and trace elements, and Cu and Zn isotopes. Geochim. Cosmochim. Acta 83, 79–92. https://doi.org/10.1016/j.gca.2011.12.011.

Boujibar, A., Andrault, D., Bolfan-Casanova, N., Bouhifd, M.A., Monteux, J., 2015. Cosmochemical fractionation by collisional erosion during the Earth's accretion. Nat. Commun. 6, 8295. https://doi.org/10.1038/ncomms9295.

Brasser, R., Dauphas, N., Mojzsis, S.J., 2018. Jupiter's influence on the building blocks of Mars and Earth. Geophys. Res. Lett. 45, 5908–5917. https://doi.org/10.1029/2018GL078011.

Brasser, R., Mojzsis, S.J., 2020. The partitioning of the inner and outer Solar System by a structured protoplanetary disk. Nat. Astron. 4, 492–499. https://doi.org/10.1038/s41550-019-0978-6.

Brennecka, G.A., Burkhardt, C., Budde, G., Kruijer, T.S., Nimmo, F., Kleine, T., 2020. Astronomical context of Solar System formation from molybdenum isotopes in meteorite inclusions. Science (1979) 370, 837–840. https://doi.org/10.1126/science.aaz8482.

Burkhardt, C., Spitzer, F., Morbidelli, A., Budde, G., Render, J.H., Kruijer, T.S., Kleine, T., 2021. Terrestrial planet formation from lost inner solar system material. Sci. Adv. 7, eabj7601. https://doi.org/10.1126/sciadv.abj7601.

Chambers, J.E., Wetherill, G.W., 1998. Making the terrestrial planets: n-body integrations of planetary embryos in three dimensions. Icarus 136, 304–327. https://doi.org/10.1006/icar.1998.6007.

Carlson, R.W., Brasser, R., Yin, Q., Fischer-Gödde, M., Qin, L., 2018. Feedstocks of the terrestrial planets. Space Sci. Rev. 214, 121. https://doi.org/10.1007/s11214-018-0554-x.

Crozaz, G., Floss, C., Wadhwa, M., 2003. Chemical alteration and REE mobilization in meteorites from hot and cold deserts. Geochim. Cosmochim. Acta 67, 4727–4741. https://doi.org/10.1016/j.gca.2003.08.008.

Crozaz, G., Lundberg, L.L., 1995. The origin of oldhamite in unequilibrated enstatite chondrites. Geochim. Cosmochim. Acta 59, 3817–3831. https://doi.org/10.1016/0016-7037(95)00268-5.

Dauphas, N., 2017. The isotopic nature of the Earth's accreting material through time. Nature 541, 521–524. https://doi.org/10.1038/nature20830.

Dauphas, N., Poitrasson, F., Burkhardt, C., Kobayashi, H., Kurosawa, K., 2015. Planetary and meteoritic Mg/Si and δ30Si variations inherited from solar nebula chemistry. Earth Planet. Sci. Lett. 427, 236–248. https://doi.org/10.1016/j.epsl.2015.07.008.

Dauphas, N., Pourmand, A., 2011. Hf-W-Th evidence for rapid growth of Mars and its status as a planetary embryo. Nature 473, 489–492. https://doi.org/10.1038/nature10077.

Drake, M.J., Righter, K., 2002. Determining the composition of the Earth. Nature 416, 39–44. https://doi.org/10.1038/416039a.

Ebel, D.S., 2006. Condensation of rocky material in astrophysical environments. Meteorites and the early solar system II 253, 277.

Ebert, S., Render, J., Brennecka, G.A., Bischoff, A., Burkhardt, C., Kleine, T., 2017. ^{50}Ti isotope excesses in CAIs from ordinary and Rumuruti chondrites. In: 80th Annual meeting of the Meteoritical Society, p. 6250.

Ebert, S., Render, J., Brennecka, G.A., Burkhardt, C., Bischoff, A., Gerber, S., Kleine, T., 2018. Ti isotopic evidence for a non-CAI refractory component in the inner Solar System. Earth Planet. Sci. Lett. 498, 257–265. https://doi.org/10.1016/j.epsl.2018.06.040.

Eiler, J.M., 2001. Oxygen isotope variations of basaltic Lavas and Upper Mantle Rocks. Rev. Mineral. Geochem. 43, 319–364. https://doi.org/10.2138/gsrmg.43.1.319.

Frossard, P., Guo, Z., Spencer, M., Boyet, M., Bouvier, A., 2021. Evidence from achondrites for a temporal change in Nd nucleosynthetic anomalies within the first 1.5 million years of the inner solar system formation. Earth Planet. Sci. Lett. 566, 116968. https://doi.org/10.1016/j.epsl.2021.116968.

Frossard, P., Israel, C., Bouvier, A., Boyet, M., 2022. Earth's composition was modified by collisional erosion. Science (1979) 377, 1529–1532. https://doi.org/10.1126/science.abq7351.

Gannoun, A., Boyet, M., El Goresy, A., Devouard, B., 2011. REE and actinide microdistribution in Sahara 97072 and ALHA77295 EH3 chondrites: a combined cosmochemical and petrologic investigation. Geochim. Cosmochim. Acta 75, 3269–3289. https://doi.org/10.1016/j.gca.2011.03.017.

Garai, S., Olson, P.L., Sharp, Z.D., 2025. Building Earth with pebbles made of chondritic components. Geochim. Cosmochim. Acta 390, 86–104. https://doi.org/10.1016/j.gca.2024.11.021.

Grossman, J.N., Rubin, A.E., Rambaldi, E.R., Rajan, R.S., Wasson, J.T., 1985. Chondrules in the Qingzhen type-3 enstatite chondrite: possible precursor components and comparison to ordinary chondrite chondrules. Geochim. Cosmochim. Acta 49, 1781–1795. https://doi.org/10.1016/0016-7037(85)90149-8.

Guan, Y., McKeegan, K.D., MacPherson, G.J., 2000. Oxygen isotopes in calcium–aluminum-rich inclusions from enstatite chondrites: new evidence for a single CAI source in the solar nebula. Earth Planet. Sci. Lett. 181, 271–277. https://doi.org/10.1016/S0012-821X(00)00218-1.

Hammouda, T., Boyet, M., Frossard, P., Cartier, C., 2022. The message of oldhamites from enstatite chondrites. Prog. Earth. Planet. Sci. 9, 13. https://doi.org/10.1186/s40645-022-00471-w.

Hu, J.Y., Dauphas, N., Tissot, F.L.H., Yokochi, R., Ireland, T.J., Zhang, Z., Davis, A.M., Ciesla, F.J., Grossman, L., Charlier, B.L.A., Roskosz, M., Alp, E.E., Hu, M.Y., Zhao, J., 2021. Heating events in the nascent solar system recorded by rare earth element isotopic fractionation in refractory inclusions. Sci. Adv. 7, eabc2962. https://doi.org/10.1126/sciadv.abc2962.

Ingrao, N.J., Hammouda, T., Boyet, M., Gaborieau, M., Moine, B.N., Vlastelic, I., Bouhifd, M.A., Devidal, J.-L., Mathon, O., Testemale, D., Hazemann, J.-L., Proux, O., 2019. Rare Earth elements partitioning between sulphides and melt: evidence for Yb^{2+} and Sm^{2+} in EH chondrites. Geochim. Cosmochim. Acta 265, 182–197.

Jacquet, E., Alard, O., Gounelle, M., 2015. The formation conditions of enstatite chondrites: insights from trace element geochemistry of olivine-bearing chondrules in Sahara 97096 (EH3). Meteorit Planet. Sci. 50, 1624–1642. https://doi.org/10.1111/maps.12481.

Jagoutz, E., Palme, H., Baddenhausen, H., Blum, K., Cendales, M., Dreibus, G., Spettel, B., Lorenz, V., Wänke, H., 1979. The abundances of major, minor and trace elements in the earth's mantle as derived from primitive ultramafic nodules. In: Proc. Lunar Planet. Sci. Conf, pp. 2031–2050.

Jansen, C.A., Burkhardt, C., Marrocchi, Y., Schneider, J.M., Wölfer, E., Kleine, T., 2024. Condensate evolution in the solar nebula inferred from combined Cr, Ti, and O isotope analyses of amoeboid olivine aggregates. Earth Planet. Sci. Lett. 627, 118567. https://doi.org/10.1016/j.epsl.2024.118567.

Javoy, M., Kaminski, E., Guyot, F., Andrault, D., Sanloup, C., Moreira, M., Labrosse, S., Jambon, A., Agrinier, P., Davaille, A., Jaupart, C., 2010. The chemical composition of the Earth: enstatite chondrite models. Earth Planet. Sci. Lett. 1–10. https://doi.org/10.1016/j.epsl.2010.02.033.

Johansen, A., Low, M.M.M., Lacerda, P., Bizzarro, M., 2015. Growth of asteroids, planetary embryos, and Kuiper belt objects by chondrule accretion. Sci. Adv. 1. https://doi.org/10.1126/sciadv.1500109 e1500109–e1500109.

Johansen, A., Ronnet, T., Bizzarro, M., Schiller, M., Lambrechts, M., Nordlund, Å., Lammer, H., 2021. A pebble accretion model for the formation of the terrestrial planets in the Solar System. Sci. Adv. 7, eabc0444. https://doi.org/10.1126/sciadv.abc0444.

Johansen, A., Ronnet, T., Schiller, M., Deng, Z., Bizzarro, M., 2023. Anatomy of rocky planets formed by rapid pebble accretion: III. Partitioning of volatiles between planetary core, mantle, and atmosphere. A&A 671, A76. https://doi.org/10.1051/0004-6361/202142143.

Jones, R.H., 2012. Petrographic constraints on the diversity of chondrule reservoirs in the protoplanetary disk. Meteorit. Planet. Sci. 47, 1176–1190. https://doi.org/10.1111/j.1945-5100.2011.01327.x.

Jones, R.H., 1996. FeO-rich, porphyritic pyroxene chondrules in unequilibrated ordinary chondrites. Geochim. Cosmochim. Acta 60, 3115–3138. https://doi.org/10.1016/0016-7037(96)00152-4.

Jones, R.H., 1994. Petrology of FeO-poor, porphyritic pyroxene chondrules in the Semarkona chondrite. Geochim. Cosmochim. Acta 58, 5325–5340. https://doi.org/10.1016/0016-7037(94)90316-6.

Jones, R.H., 1990. Petrology and mineralogy of type II, FeO-rich chondrules in Semarkona (LL3.0): origin by closed-system fractional crystallization, with evidence for supercooling. Geochim. Cosmochim. Acta 54, 1785–1802. https://doi.org/10.1016/0016-7037(90)90408-D.

Jones, R.H., Scott, E., 1989. Petrology and thermal history of type IA chondrules in the Semarkona (LL3.0) chondrite. Lunar and Planetary Science 19, 523–536.

Kokubo, E., Ida, S., 2002. Formation of Protoplanet Systems and diversity of Planetary Systems. ApJ 581, 666–680. https://doi.org/10.1086/344105.

Krot, A.N., 2019. Refractory inclusions in carbonaceous chondrites: records of early solar system processes. Meteorit. Planet. Sci. 54, 1647–1691. https://doi.org/10.1111/maps.13350.

Lambrechts, M., Johansen, A., 2014. Forming the cores of giant planets from the radial pebble flux in protoplanetary discs. A&A 572, A107. https://doi.org/10.1051/0004-6361/201424343.

Larimer, J.W., 1975. The effect of ratio on the condensation of planetary material. Geochim. Cosmochim. Acta 39, 389–392. https://doi.org/10.1016/0016-7037(75)90204-5.

Lodders, K., 1996. An experimental and theoretical study of rare-earth-element partitioning between sulfides (FeS, CaS) and silicate and applications to enstatite achondrites. Meteorit. Planet. Sci. 31, 749–766.

Lodders, K., Fegley, B., 1993. Lanthanide and actinide chemistry at highCO/ratios in the solar nebula. Earth Planet. Sci. Lett. 117, 125–145. https://doi.org/10.1016/0012-821X(93)90122-P.

Mah, J., Brasser, R., Bouvier, A., Mojzsis, S.J., 2022. Effects of pebble accretion on the growth and composition of planetesimals in the inner solar system. Mon. Not. R. Astron. Soc. 511, 158–175. https://doi.org/10.1093/mnras/stab3766.

Marrocchi, Y., Euverte, R., Villeneuve, J., Batanova, V., Welsch, B., Ferrière, L., Jacquet, E., 2019a. Formation of CV chondrules by recycling of amoeboid olivine aggregate-like precursors. Geochim. Cosmochim. Acta 247, 121–141. https://doi.org/10.1016/j.gca.2018.12.038.

Marrocchi, Y., Jones, R., Russell, S., Hezel, D., Barosch, J., Kuznetsova, A., 2024. Chondrule properties and formation conditions. Space Sci. Rev. 220, 69. https://doi.org/10.1007/s11214-024-01102-0.

Marrocchi, Y., Piralla, M., Regnault, M., Batanova, V., Villeneuve, J., Jacquet, E., 2022. Isotopic evidence for two chondrule generations in CR chondrites and their relationships to other carbonaceous chondrites. Earth Planet. Sci. Lett. 593, 117683. https://doi.org/10.1016/j.epsl.2022.117683.

Marrocchi, Y., Villeneuve, J., Batanova, V., Piani, L., Jacquet, E., 2018. Oxygen isotopic diversity of chondrule precursors and the nebular origin of chondrules. Earth Planet. Sci. Lett. 496, 132–141. https://doi.org/10.1016/j.epsl.2018.05.042.

Marrocchi, Y., Villeneuve, J., Jacquet, E., Piralla, M., Chaussidon, M., 2019b. Rapid condensation of the first Solar System solids. Proc. Natl. Acad. Sci. U.S.A. 116, 23461–23466. https://doi.org/10.1073/pnas.1912479116.

McDonough, W.F., Sun, S.-s., 1995. The composition of the Earth. Chem. Geol. 120, 223–253. https://doi.org/10.1016/0009-2541(94)00140-4.

Mezger, K., Schönbächler, M., Bouvier, A., 2020. Accretion of the Earth—Missing components? Space Sci. Rev. 216, 27. https://doi.org/10.1007/s11214-020-00649-y.

Morbidelli, A., Libourel, G., Palme, H., Jacobson, S.A., Rubie, D.C., 2020. Subsolar Al/Si and Mg/Si ratios of non-carbonaceous chondrites reveal planetesimal formation during early condensation in the protoplanetary disk. Earth Planet. Sci. Lett. 538, 116220. https://doi.org/10.1016/j.epsl.2020.116220.

Morbidelli, A., Kleine, T., Nimmo, F., 2025. Did the terrestrial planets of the solar system form by pebble accretion? Earth Planet. Sci. Lett. 650, 119120. https://doi.org/10.1016/j.epsl.2024.119120.

Morbidelli, A., Marrocchi, Y., Ali Ahmad, A., Bhandare, A., Charnoz, S., Commerçon, B., Dullemond, C.P., Guillot, T., Hennebelle, P., Lee, Y.-N., Lovascio, F., Marschall, R., Marty, B., Maury, A., Tamami, O., 2024. Formation and evolution of a protoplanetary disk: combining observations, simulations, and cosmochemical constraints. A&A 691, A147. https://doi.org/10.1051/0004-6361/202451388.

Nimmo, F., Kleine, T., Morbidelli, A., Nesvorny, D., 2024. Mechanisms and timing of carbonaceous chondrite delivery to the Earth. Earth Planet. Sci. Lett. 648, 119112. https://doi.org/10.1016/j.epsl.2024.119112.

Palme, H., O'Neill, H.St.C., 2014. Cosmochemical estimates of mantle composition. Treatise On Geochemistry. Elsevier, pp. 1–39. https://doi.org/10.1016/B978-0-08-095975-7.00201-1.

Piani, L., Marrocchi, Y., Libourel, G., Tissandier, L., 2016. Magmatic sulfides in the porphyritic chondrules of EH enstatite chondrites. Geochim. Cosmochim. Acta 195, 84–99. https://doi.org/10.1016/j.gca.2016.09.010.

Piani, L., Marrocchi, Y., Rigaudier, T., Vacher, L.G., Thomassin, D., Marty, B., 2020. Earth's water may have been inherited from material similar to enstatite chondrite meteorites. Science (1979) 369, 1110–1113. https://doi.org/10.1126/science.aba1948.

Piralla, M., Villeneuve, J., Batanova, V., Jacquet, E., Marrocchi, Y., 2021. Conditions of chondrule formation in ordinary chondrites. Geochim. Cosmochim. Acta 313, 295–312. https://doi.org/10.1016/j.gca.2021.08.007.

Piralla, M., Villeneuve, J., Schnuriger, N., Bekaert, D.V., Marrocchi, Y., 2023. A unified chronology of dust formation in the early solar system. Icarus 394, 115427. https://doi.org/10.1016/j.icarus.2023.115427.

Raymond, S.N., Morbidelli, A., 2022. Planet formation: key mechanisms and global models. In: Biazzo, K., Bozza, V., Mancini, L., Sozzetti, A. (Eds.), Demographics of Exoplanetary Systems. Astrophysics and Space Science Library, Demographics of Exoplanetary Systems. Astrophysics and Space Science Library, 466. Springer, Cham. https://doi.org/10.1007/978-3-030-88124-5_1.

Rudraswami, N.G., Ushikubo, T., Nakashima, D., Kita, N.T., 2011. Oxygen isotope systematics of chondrules in the Allende CV3 chondrite: high precision ion microprobe studies. Geochim. Cosmochim. Acta 75, 7596–7611. https://doi.org/10.1016/j.gca.2011.09.035.

Ruzicka, A., Floss, C., Hutson, M., 2012. Amoeboid olivine aggregates (AOAs) in the Efremovka, Leoville and Vigarano (CV3) chondrites: a record of condensate evolution in the solar nebula. Geochim. Cosmochim. Acta 79, 79–105. https://doi.org/10.1016/j.gca.2011.11.043.

Schneider, J.M., Burkhardt, C., Marrocchi, Y., Brennecka, G.A., Kleine, T., 2020. Early evolution of the solar accretion disk inferred from Cr-Ti-O isotopes in individual chondrules. Earth Planet. Sci. Lett. 551, 116585. https://doi.org/10.1016/j.epsl.2020.116585.

Schrader, D.L., McCoy, T.J., Gardner-Vandy, K., 2017. Relict chondrules in primitive achondrites: remnants from their precursor parent bodies. Geochim. Cosmochim. Acta 205, 295–312. https://doi.org/10.1016/j.gca.2017.02.012.

Sugiura, N., Fujiya, W., 2014. Correlated accretion ages and ε 54Cr of meteorite parent bodies and the evolution of the solar nebula. Meteorit Planet. Sci. 49, 772–787. https://doi.org/10.1111/maps.12292.

Tachibana, S., Nagahara, H., Mostefaoui, S., Kita, N.T., 2003. Correlation between relative ages inferred from 26 Al and bulk compositions of ferromagnesian chondrules in least equilibrated ordinary chondrites. Meteorit & Planetary Scien 38, 939–962. https://doi.org/10.1111/j.1945-5100.2003.tb00289.x.

Tenner, T.J., Ushikubo, T., Nakashima, D., Schrader, D.L., Weisberg, M.K., Kimura, M., Kita, N.T., 2018. Chondrules, In: Oxygen Isotope Characterisitics of Chondrules from Recent Studies by Secondary Ion Mass Spectrometry. Cambridge University Press, pp. 196–246.

Tissandier, L., Libourel, G., Robert, F., 2002. Gas-melt interactions and their bearing on chondrule formation. Meteorit. Planet. Sci. 37, 1377–1389. https://doi.org/10.1111/j.1945-5100.2002.tb01035.x.

Warren, P.H., 2011. Stable-isotopic anomalies and the accretionnary assemblage of the Earth and Mars: A subordinate role for carbonaceous chondrites. Earth Planet. Sci. Lett. 311, 93–100.doi. https://doi.org/10.1016/j.epsl.2011.08.047.

Wasson, J.T., Kallemeyn, G.W., 1988. Compositions of Chondrites. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 325, 535–544. https://doi.org/10.1098/rsta.1988.0066.

Weisberg, M.K., Kita, N.T., Fukuda, K., Siron, G., Ebel, D.S., 2021. Micro-distribution of oxygen isotopes in unequilibrated enstatite chondrites. Geochim. Cosmochim. Acta 300, 279–295. https://doi.org/10.1016/j.gca.2021.02.027.

Yokochi, R., Marty, B., 2004. A determination of the neon isotopic composition of the deep mantle. Earth Planet. Sci. Lett. 225, 77–88. https://doi.org/10.1016/j.epsl.2004.06.010.

Yoshizaki, T., McDonough, W.F., 2021. Earth and Mars–Distinct inner solar system products. Geochemistry 81, 125746. https://doi.org/10.1016/j.chemer.2021.125746.

Zhu, K., Moynier, F., Schiller, M., Bizzarro, M., 2020. Dating and tracing the origin of enstatite chondrite chondrules with Cr isotopes. ApJ 894, L26. https://doi.org/10.3847/2041-8213/ab8dca.