



# Accretion of the Earth—Missing Components?

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**Abstract** Primitive meteorites preserve the chemical and isotopic composition of the first aggregates that formed from dust and gas in the solar nebula during the earliest stages of solar system evolution. Gradual increase in the size of solid bodies from dust to aggregates and then to planetesimals finally led to the formation of planets within a few to tens of million years after the start of condensation. Thus the rocky planets of the inner solar system are likely the result of the accumulation of numerous smaller primitive as well as differentiated bodies. The chemically most primitive known meteorites are chondrites and they consist mostly of metal and silicates. Chondritic meteorites are derived from distinct primitive planetary bodies that experienced only limited element fractionation during formation and subsequent differentiation. Different chondrite classes show distinct chemical and isotopic characteristics, which may reflect heterogeneities in the solar nebula and the slightly different pathways of their formation. To a first approximation the chemical composition of the bulk Earth bears great similarities to primitive meteorites. However, for some elements there are striking and significant differences. The Earth shows a much stronger depletion of the moderate to highly volatile elements compared to chondrites. In addition, mixing trends of specific isotopes reveal that the Earth is most enriched in *s*-process isotopes compared to all other analysed bulk solar system materials. It is currently not possible to fully define and quantify the different chemical and isotopic materials that formed the Earth, because a major component seems missing in the extant collections of extraterrestrial samples. Variations in nucleosynthetic isotope compositions as well as the strong depletion of moderately and strongly volatile elements points towards a source in the inner solar system for this missing material. It is conceivable that Venus and Mercury contain a much larger fraction of this

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Role of Sample Return in Addressing Major Questions in Planetary Sciences

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missing component. Thus, for a complete reconstruction of the conditions that led to the formation of the inner solar system planets (Mercury to Mars) samples from the inner planets Venus and Mercury are of great interest and importance. High precision chemical and isotopic analyses in the laboratory of rocky material from inner solar system bodies could complete the knowledge on the chemical, isotopic and mineralogical make-up of the solar nebula just prior to planet formation and enhance our understanding of the evolution of the solar nebula in general and the formation of the rocky planets in particular.

**Keywords** Terrestrial planets · Accretion of Earth · Meteorites · Inner solar system

## 1 Introduction

The bulk composition of the Earth and that of the distinct terrestrial reservoirs is essential to understand and quantify the major differentiation processes that led to the present-day highly differentiated planet (e.g., McDonough and Sun 1995; Palme and O'Neill 2014). The bulk composition of the Earth is also required to reconstruct the formation of the Earth as a planet and to deduce the different processes that led to its specific chemical composition. Ultimately the material that formed the Earth originated from the solar nebula, which originally had the composition of the Sun. Starting from the solar nebula to the final accretion, the building material of the Earth underwent a variety of physical and chemical processes that led to the fractionation of elements. Key processes include condensation and evaporation of solids in the solar nebula, dust coagulation, evaporation of elements during collision of small bodies or during the magma ocean stage, accretion of solids to smaller bodies that grew to planetesimals and eventually to rocky planets like the Earth, and the late addition of bodies after the main phase of accretion (e.g., Chambers 2001; Day et al. 2012; Day 2015; Halliday 2014). Since solids formed at different distances from the Sun, different condensation histories and pathways of the building blocks have to be considered (e.g., Morbidelli et al. 2000; Ciesla 2010).

The asteroidal bodies that are the sources of most meteorites formed within the first few million years of the solar system; some were only minimally chemically modified after their formation (i.e. chondrite parent bodies), others differentiated significantly and segregated an iron core (i.e. achondrite parent bodies). The major groups of materials available for direct study in the laboratory are carbonaceous, ordinary and enstatite chondrites, iron meteorites, and achondrites such as eucrites or ureilites. A main constituent of the different chondrites are chondrules (e.g., Hewins 1997), which are sub-millimeter igneous spherules that can contain relict mineral grains that were not melted during chondrule formation. In addition to abundant chondrules that are surrounded by fine-grained matrix, some chondrites contain sulfides, metals as well as calcium–aluminum-rich inclusions (CAIs) and other refractory element enriched inclusions that formed as primary condensates from the solar nebula gas (e.g., Scott and Krot 2014; Yokoyama et al. 2017). The CAIs are particularly abundant in some carbonaceous chondrites (e.g., the CV group). The primitive chemical character has led to the idea that they could represent the building material of the terrestrial planets. The disparities in the chemical and isotopic composition of the rocky planets could reflect the different contributions of different known meteorite classes to their formation. Based on this assumption, it is possible to quantify the relative abundances of the different material that contributed to the growing Earth or other rocky planets whose bulk composition can be estimated (e.g., Sanloup et al. 1999; Lodders 2000; Fitoussi et al. 2016; Liebske and Khan 2019). However, as will be further shown in this contribution, a close investigation

of the currently available chemical and isotopic data on samples from the rocky planets Earth and Mars and the different meteorite classes shows that it is impossible to account for all chemical and isotopic characteristics, particularly of the Earth, by combining different proportions of known materials from the solar system. In some respects, the Earth seems to be an apparent end member for many geochemical parameters among the rocky materials in the solar system studied so far (e.g., Wänke and Dreibus 1988; Dauphas et al. 2004; Burkhardt et al. 2011; Akram et al. 2013, 2015; Akram and Schönбächler 2016; Fischer-Gödde et al. 2015; Liebske and Khan 2019).

This contribution explores the chemical and isotope characteristics of different meteorites classes and their temporal evolution in order to evaluate their potential contributions to the formation of the Earth. Isotopes, element abundances and age constraints are used to evaluate, which known components contributed to the Earth and which terrestrial building blocks might be missing in the extant collection of extra-terrestrial materials. Particular questions addressed are: What are the characteristics of this potentially missing component and where might it be found within the solar system? Is the Earth possibly an end member in its chemical composition or does the Earth sample a common component of the inner solar system that is dominantly present in the inner solar system planets like Venus and Mercury? What is the timing of formation for planetesimals and planets, and is there a relationship with their nucleosynthetic compositions?

## 2 Compositional Constraints on the Building Blocks of Earth

Estimates for the abundances of the elements in bulk Earth and its different geochemical reservoirs (core, mantle, crust, hydro- and atmosphere) have been obtained using a variety of approaches (e.g., Allègre et al. 1995; McDonough and Sun 1995; Palme and O'Neill 2014). These estimates show that the Earth is a chemically highly differentiated planet that was accreted from heterogeneous and on average volatile element depleted (i.e. compared to the solar composition) materials with distinct isotopic and chemical compositions. These materials were added to the growing planet during different stages, while the planet was internally differentiating (e.g., Rubie et al. 2011). Chemical and isotopic diversity is also obvious in meteorites and their components that derive from primitive bodies of the solar system.

Due to the abundance of chondrites in the extant meteorite collection, their relatively primitive composition and first order similarities with estimates for the bulk Earth composition, chondrites have been traditionally used as a proxy for the material from which the Earth and the other rocky planets of the inner solar system formed (e.g., Wänke and Dreibus 1988; Schönбächler et al. 2010; Rubie et al. 2011; Fitoussi et al. 2016; Liebske and Khan 2019). However, chondrites may not be the only materials that contributed to the formation of the terrestrial planets. With the exception of CI chondrites, chondrites contain once molten materials, now preserved as spherical objects, i.e. chondrules, embedded in a fine-grained matrix. The chemically primitive chondrites, which represent a collection of materials from before or during before planet formation, may have played a key role in the early stages of planet formation. Most importantly, they are accessible for laboratory studies. In the global collection of meteorites, chondrites constitute the majority of samples with around 80% of all collected specimens (e.g., Bischoff and Geiger 1995; Gattacceca et al. 2019).

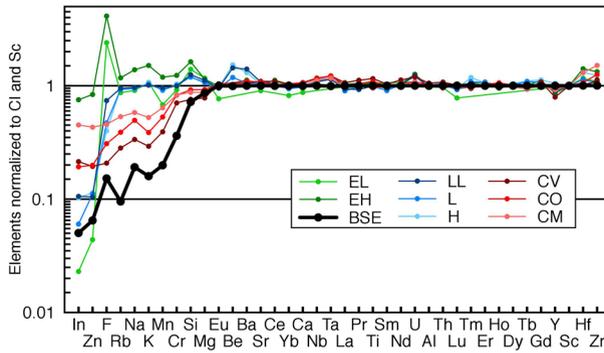
The chronology of primitive and differentiated materials from the early solar system has changed this traditional view (e.g., Kleine et al. 2005). The composition of the chondrites must reflect the composition of the reservoirs from which they accreted and because they

accreted relatively late compared to some achondrite parent bodies, it is possible that these reservoirs were already modified by planetary formation and/or chondrule formation. It is therefore unlikely that the Earth formed by direct accretion of dust with a homogeneous composition from the solar nebula, but rather by the addition of smaller chemically distinct differentiated bodies that had element abundances different from the bulk solar system composition. These planetesimals were already differentiated into core, mantle and crust (e.g., Kleine et al. 2005; Kruijer et al. 2014). Some of these planetary crusts were also rapidly re-processed by impact melting producing further elemental fractionation (Frossard et al. 2019). An alternative planet formation scenario provides the relatively recently proposed mechanism of pebble accretion (see Johansen and Lambrechts 2017 for a review). In a protoplanetary gas disk, a planetary embryo can grow very quickly through accretion of small pebbles that formed further away from the Sun than the protoplanet and were captured by the protoplanet on their way towards the Sun.

Meteorites that are available for direct mineralogical, chemical and isotopic studies reveal a breadth of different materials that could potentially represent the building blocks for the Earth (e.g., Wasson 1985; Day 2015). Some meteorite bodies have compositions that are similar to the elemental composition of the Sun, like the rare CI meteorites, others are highly fractionated like iron meteorites that represent the cores of differentiated planetesimals. All these materials have in common that they are depleted to some degree in moderately to highly volatile elements. To a first approximation the degrees of depletion of the chemical elements in different primitive meteorite classes follow the respective condensation temperatures of the elements when condensing from a cooling solar gas (Lodders 2003; Wood et al. 2019) (Fig. 1). All materials from the solar system so far studied show various degrees of depletion for elements with 50% condensation temperatures below ca. 1300 K (e.g., Palme and O'Neill 2014). The different depletion patterns are characteristic for each meteorite class and by inferences their respective parent bodies (Fig. 1). The least depleted material is represented by the rare CI chondrites. They have lost atmophile elements, but are otherwise similar in composition to the Sun (e.g., Anders and Grevesse 1989; Asplund et al. 2009; Palme et al. 2014) and thus the primary solar nebula. For this reason, they are commonly used as a reference to which other materials are compared. Together with CI chondrites, the least differentiated materials are the carbonaceous, enstatite and ordinary chondrites. Their relative abundances of refractory elements are similar to the solar abundances for elements with a 50% condensation temperature above ca. 1300 K (Fig. 1), but they show different extents of depletion for the volatile elements (e.g., Palme and O'Neill 2014).

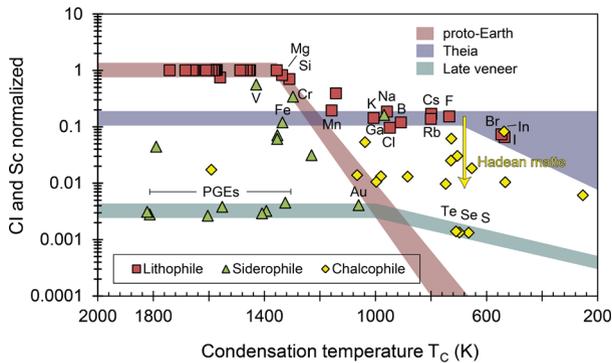
In order to reconstruct the quantity and composition of the possible components that formed the Earth from known materials, as represented by meteorites, it is essential to estimate the bulk Earth composition (BE) or at least the bulk silicate Earth composition (BSE). For this reason, several efforts have been made to obtain robust estimates for the abundances of the chemical elements in the Earth as a whole or in the silicate mantle, the volumetrically dominant chemical reservoir of the Earth (e.g., McDonough and Sun 1995; Allègre et al. 1999; Palme and Jones 2003; Palme and O'Neill 2014). These estimates can be compared with bulk analyses made to obtain the absolute element abundance for each meteorite class (e.g., Wasson and Kallemeyn 1988; Miyamoto et al. 2016; Clay et al. 2017; Braukmüller et al. 2018, 2019) (Fig. 1).

A comparison of the element abundances in different chondrite classes with the bulk composition of the Earth reveals general agreement among the refractory element ratios. All rocky materials known from the solar system have very similar relative abundances for refractory elements. However, there are striking differences in the moderately to highly volatile element abundances for different meteorite classes that show various degrees of depletion. These depletions start with the highly abundant elements Mg, Fe and Si and follow



**Fig. 1** Element abundances in different chondrites (carbonaceous chondrites: CM, CO, CV; ordinary chondrites: H, L, LL; enstatite chondrites: EH, EL) and the bulk silicate Earth (BSE). Compared to the different chondrites the Earth shows the strongest depletion in moderately to highly volatile elements. Elements (McDonough and Sun 1995; Wasson and Kallemeyn 1988) normalized to CI abundances (Anders and Grevesse 1989) and sorted according to their condensation temperature ( $T_{c50}$ ) ( $10^{-4}$  bar total pressure) (Lodders 2003)

the 50% condensation temperatures and thus reflect different thermal regimes in the feeding zones of the solids that subsequently accreted in different parent bodies (e.g., Palme and O'Neill 2014). This continuous and regular trend attests to a thermal cause for the depletion and may represent different places in the nascent solar system where these materials formed from a cooling and condensing nebula. Striking is the extreme depletion of volatile elements in the Earth; and compared to primitive meteorites, the Earth forms a compositional end member (Fig. 1). The chemical differences among the chondrites and the strong depletion of Earth in the more volatile elements are evidence that the Earth must have a major component that is more depleted than any known chondrite class (Wänke and Dreibus 1988; O'Neill and Palme 1998; Drake and Righter 2002; Schönbächler et al. 2010; Palme and O'Neill 2014; Palme and Zipfel 2016). Thus, for the formation of Earth, primitive but strongly volatile depleted material is needed to account for the observed missing volatile elements. The presence of such a depleted component in the Earth is supported by evidence from radiogenic isotope systems (e.g., Rb–Sr, U–Pb, Ag–Pd) that are sensitive to volatility related processes (e.g., Albarède 2009; Schönbächler et al. 2010; Peslier et al. 2017). It has been suggested that this strongly depleted material may be represented by achondrites, particularly angrites (e.g., Fitoussi et al. 2016). Although their abundances of moderately volatile lithophile elements make them a suitable component, the abundance pattern for the other moderately volatile lithophile elements does not show this depletion (e.g., Warren and Kallemeyn 1995). The volatile budget of the Earth must be a primary signature and cannot be the result of volatile loss by evaporation during accretion, because this would result in a step-function in the element depletion trend with a strong depletion below a certain threshold temperature and essentially no depletion above, which is not observed. The Earth shows a depletion in moderately volatile elements by a factor around 10 compared to the refractory elements (McDonough and Sun 1995; Fig. 1, 2). If this depletion occurred during condensation of the solids that formed the Earth or by evaporation during accretion into planetesimals that later formed the Earth, this should result in detectable stable isotope variations of these depleted elements. Such effects between the terrestrial planets are analytically barely resolvable (e.g., Nebel et al. 2011; Paniello et al. 2012). This depleted component was also most likely strongly reduced to account for the depletion of moderately siderophile elements in



**Fig. 2** Element abundances in bulk silicate Earth (BSE). Lithophile element abundances in the Earth can be modelled by a mixture of a ca. 85% of a component that was volatile element depleted (proto-Earth) and 15% of a component that was less volatile element depleted and oxidized (Theia). Siderophile and chalcophile elements are depleted in BSE due to metal core formation and segregation of a sulphide melt (Hadean matte; O’Neill 1991). Abundance of the platinum group elements (PGEs) is due to the addition of a late veneer after completion of core formation. Elements sorted according to their condensation temperature ( $T_{c50}$ ) ( $10^{-4}$  bar total pressure) (Lodders 2003). Modified after Maltese and Mezger (2020)

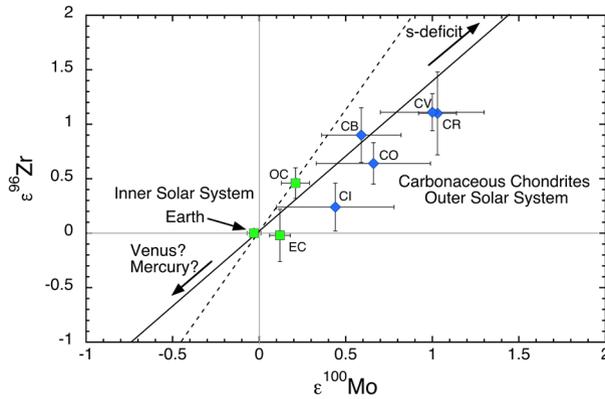
Earth’s mantle, particularly Cr, which would otherwise be lithophile and not enter the metal melt during core formation (Wänke and Dreibus 1988). Such material has not been found in the meteorite collection yet. It may bear some similarities to enstatite or ordinary chondrites, however the latter have isotope compositions distinct from the bulk Earth (e.g., Warren 2011; Kruijjer et al. 2019).

The similarity in the chemical and in isotopic composition of Earth and Moon has led to the suggestion that a giant impact is responsible for the formation of the Moon and at the same time completed the major accretion of Earth (e.g., Hartmann and Davis 1975; Benz et al. 1986; Wiechert et al. 2001; Canup and Asphaug 2001). This model implies that the present-day Earth consists of two major components that could have distinct compositions. Figure 2 shows the chondrite-normalized element abundances in bulk silicate Earth. Striking features of this element distribution in the silicate Earth are the relative chondritic abundances of the refractory lithophile elements and the less abundant moderately volatile lithophile elements, which are also present in relative chondritic abundances. The least abundant elements are the platinum group elements that also occur in relative chondritic abundances. Based on this observation, Wänke and Dreibus (1988) suggested that the Earth consists of two major chemically distinct components. The dominant component was strongly volatile depleted and highly reduced and the second was less volatile depleted and oxidized with nearly chondritic abundances of the volatile elements (e.g., Braukmüller et al. 2018, 2019). This model was further refined and modified (O’Neill 1991; Albarède 2009; Schönbächler et al. 2010; Albarède et al. 2013; Ballhaus et al. 2013) and is consistent with the following scenario: in a first stage highly reduced and volatile element depleted accreted to form proto-Earth, followed by a major chemical differentiation of the body into a metallic core and a silicate mantle. Subsequently an oxidized component was added to this proto-Earth (e.g., Ballhaus et al. 2013) followed by the segregation of a sulfide melt (“Hadean matte”, O’Neill 1991). In a final stage a small amount of primitive material was added creating the late veneer and resulting in the relative chondritic abundances of the platinum group elements (e.g., Chou 1978). The two major components can be ascribed to a depleted proto-Earth that makes up ca. 85% of the present-day BSE and about 15% of a volatile richer

component (e.g., O'Neill 1991). In terms of bulk composition of the Earth, the ratio of the two bodies is ca. 90:10, making the smaller body equivalent in size to Theia, the proposed body that impacted proto-Earth and led to the formation of the Moon (e.g., Canup and Asphaug 2001). A further implication of this accretion model is that proto-Earth was more volatile element depleted than known primitive meteorites and also more highly reduced. This may indicate that the material had a strong similarity to Mercury (Nittler et al. 2019), making this planet a prime target for a sample return mission to improve our understanding of the chemical and isotopic composition of the inner solar system during its early evolution (e.g., van der Kaaden et al. 2019).

### 3 Nucleosynthetic Isotope Constraints on Terrestrial Building Blocks

The missing volatile-depleted and reduced component indicated based on elemental concentrations can be further constrained by nucleosynthetic anomalies. Over the past decade, distinct nucleosynthetic anomalies in a variety of elements (Ca, Ti, Cr, Ni, Zr, Mo, Ru, Pd, Ba, Nd etc.) have been well characterised for the different meteorite parent bodies, Mars, and Earth. The only two major bodies with virtually identical mass-independent isotope compositions are Earth and Moon. These nucleosynthetic variations are powerful tools for provenance studies of planetary building blocks. The isotope variations stem from the heterogeneous distribution of presolar grains in the protoplanetary disc from which the planets formed. Primitive meteorites still today contain nm- to  $\mu\text{m}$ -sized presolar grains. These grains can possess extreme isotope compositions that were established in distinct stellar environments (e.g., AGB stars, novae) before the solar system formed (e.g., Zinner 2014; Hoppe et al. 2017). These presolar grains were gradually destroyed during parent body heating and are thus most abundant in very primitive meteorites of low metamorphic grade (e.g., Huss et al. 2003; Davidson et al. 2014). Some of the abundance variations in primitive meteorites and those between planetary bodies, however, result from incomplete homogenisation of this presolar dust in the solar nebula (Burkhardt and Schönbächler 2015). This heterogeneous distribution of presolar grains can account for the unique nucleosynthetic isotope compositions for many elements in the different meteorite parent bodies, Mars and the Earth (e.g., Cr, Ti, Mo, Zr; Dauphas et al. 2004; Trinquier et al. 2007, 2009; Leya et al. 2008; Qin et al. 2010; Burkhardt et al. 2011; Akram et al. 2015) (Figs. 3, 4). A preferred explanation for the origin of nucleosynthetic variations is selective thermal destruction of less robust presolar carriers (e.g., silicates), which occurred when dust was transported to hotter regions in the solar protoplanetary disc (Trinquier et al. 2009; Akram et al. 2015). Alternatively, it has been suggested that this isotope variability is a remnant of a heterogeneous distribution of this dust in the molecular cloud from which the solar system formed (Nanne et al. 2019). A recent study attributes these variations to mixing of dust that formed in the local interstellar medium with a second less abundant dust fraction (stardust) mainly consisting of presolar grains that formed around AGB-stars (Ek et al. 2019). This scenario also provides an explanation as to why *s*-process variations are generally smaller in heavy elements (e.g., Nd, W) compared to those in the mass region of Zr and Mo. Presolar grains only survive a limited time in the interstellar medium (Heck et al. 2020) and, therefore, were generally formed around higher metallicity stars than the remaining interstellar matter that on average has been synthesised over the whole galactic chemical evolution. Moreover, higher metallicity stars produce higher amounts of elements in the mass region of Zr and Mo compared to the heavy elements (e.g., Nd, W, Pt). This signal is imprinted in the presolar stardust component and thus leads to smaller anomalies in the heavy elements in the solar system bodies (Ek et al. 2019).



**Fig. 3** Nucleosynthetic Zr and Mo isotope data for bulk meteorites and Earth are correlated despite their different geochemical properties (Zr: lithophile and Mo: moderately siderophile). The Earth shows the most extreme isotope composition closest to the *s*-process end member. Venus and Mercury may display even more extreme isotope compositions. Carbonaceous chondrites originating from further out in the solar system constitute the other end of the mixing array. Non-carbonaceous bodies are shown in green. Also shown are the mixing lines calculated for the addition of *s*-process Zr and Mo predicted from Arlandini et al. (1999) (dashed line, classical model) and Bisterzo et al. (2011) (black solid line) to a terrestrial composition. CI, CB, CO, CV, CR: different groups of carbonaceous chondrites, OC: ordinary chondrites, EC: enstatite chondrites. Figure updated from Akram et al. (2015). Zr data are from Akram et al. (2015), and Mo data are from Burkhardt et al. (2011) and Render et al. (2017)

However, independent of their exact origin, nucleosynthetic isotope variations are powerful tools to determine (i) genetic relationships of building blocks and planetary objects and (ii) the physio-chemical processes that influenced the planetary materials on their path from dust to planets. Several studies (e.g., Dauphas et al. 2004; Akram et al. 2015; Akram and Schönbächler 2016; Fitoussi et al. 2016; Render et al. 2017; Schiller et al. 2018; Liebcke and Khan 2019) used nucleosynthetic isotope variations to trace the building blocks of the Earth. This is generally done by comparing the terrestrial isotope composition to those of meteorites, preferentially chondrites. It is important to note that depending on the geochemical behaviour of an element, its abundance in the silicate part of Earth (i.e. BSE) can be dominated by material delivered during different phases of accretion. Highly siderophile elements (HSEs), such as the platinum group elements, record the latest accretion history of Earth after core formation ceased. This is because previously delivered HSEs were stripped from the mantle into the Earth's core with high efficiency. With decreasing siderophile behaviour, the BSE composition reflects the integration of material accreted over larger parts of Earth's late accretion history (e.g., Mo isotopes; Dauphas 2017), while lithophile elements remained in the silicate part and reflect the average composition of the material delivered over the whole accretion history. Despite these distinct characteristics, elements with different geochemical behaviour in the mass region of Zr, Mo, Ru and Pd (Akram et al. 2013, 2015; Akram and Schönbächler 2016; Burkhardt et al. 2011; Dauphas et al. 2004; Fischer-Gödde et al. 2015; Ek et al. 2019) show correlated isotope effects indicating a two-component mixture with *s*-process material as one end member (Fig. 3). This implies that the average isotopic composition of accreted materials did not drastically change over time, although minor deviations are likely (e.g., for Mo isotopes; Budde et al. 2019). Strikingly, the Earth possesses the most *s*-process enriched composition for these elements and no mixture of known meteoritic materials can build the Earth. The known materials most similar to Earth are enstatite chondrites with isotopic compositions identical or very close to

the Earth, when considering nucleosynthetic isotope variations and O isotopes (e.g., Akram et al. 2015; Akram and Schönbachler 2016; Bouvier and Boyet 2016; Burkhardt et al. 2016; Fukai and Yokoyama 2017; Dauphas 2017; Render et al. 2017; Boyet et al. 2018). Since enstatite chondrites are generally considered to originate from the inner solar system, this suggests that the Earth is mainly built from material of the inner solar system. However, while this meteorite group fits well in terms of isotopic composition, the group significantly differs from Earth in its bulk elemental abundances (see Sect. 2). Dynamical considerations and numerical models (e.g., O'Brien et al. 2006; Hansen 2009; Brasser 2013) also indicate that terrestrial planets mainly accreted material from their own local annulus. In dynamical simulations, materials from further away from the Sun (= volatile-rich material) are generally acquired in the later accretion stages (e.g., Morbidelli et al. 2000; O'Brien et al. 2014).

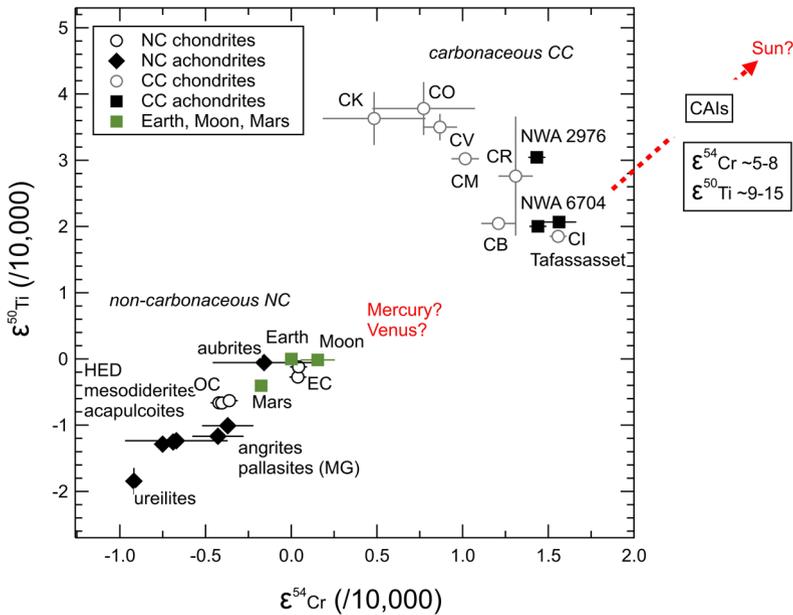
The observation that the Earth has the most *s*-process enriched composition so far identified for bulk planetary material, while members of the volatile-rich carbonaceous chondrite group belong to the most *s*-process depleted, severely limits the amount of carbonaceous chondrites that can be added to the Earth. Average estimates are around 10% (Fitoussi et al. 2016; Dauphas 2017; Budde et al. 2019), in good agreement with evidence from radiogenic isotopes for volatile element addition (up to 40%, Schönbachler et al. 2010). This volatile-rich carbonaceous chondrite material is added late during the main accretion history of the Earth to a more reduced composition likely typical for the inner solar system (Fig. 2). It hints to the so far elusive, reduced reservoir in the inner solar system (see Sect. 2).

However, it is possible that the observed trend of increasing *s*-process enriched compositions for bodies closer to the Sun (Fig. 3) continues further with Venus and Mercury. If so, material from inside the Earth's orbit can counterbalance volatile-rich, oxidised material from the outer solar system and therefore allows for much larger contributions of these materials. The most likely hosts with a significant portion of this volatile depleted and reduced component could be the inner solar system planets Mercury and Venus. They might contain larger amounts of this elusive material, if the solar nebula was indeed chemically zoned with stronger volatile depleted and *s*-process enriched material that formed closer to the Sun. These inner planets could preserve the missing link that is needed to form the Earth from materials that are derived from different regions of the solar system. Characterising this material would allow a better quantification of the accretion models for Earth that can describe the amount of different materials accreted in combination with concomitant differentiation of the growing planet. This illustrates that samples from Venus or Mercury play a fundamental role in answering the question of the building blocks of the Earth.

### 3.1 Evidence from the Dichotomy

The conclusions drawn from volatile elements concentrations and *s*-process anomalies are also supported by mass-independent variations in the O (mostly caused by irradiation processes, i.e. photo dissociation), Cr and Ti isotope compositions (nucleosynthetic anomalies) of different meteorites and the Earth. For O isotope analyses, samples from Venus and Mercury would help to address the O isotope homogeneity the inner solar system reservoir and compare this to Mars and the outer solar system, potentially tracing a signal of water in the disk (Krot et al. 2015).

In contrast to the expressed *s*-process anomalies (at first order produced by AGB stars) in the mass region of Zr, the nucleosynthetic Cr and Ti isotope compositions are generated by the heterogeneous distribution of dust formed in a supernovae environment (again at first order, less dominant contribution of other sources such as the *s*-process are likely;



**Fig. 4**  $\epsilon^{54}\text{Cr}$  vs.  $\epsilon^{50}\text{Ti}$  mass-independent isotope data in epsilon (parts per 10,000 deviation of the ratio from the respective terrestrial standards) of whole-rock chondrites and achondrites from the so-called carbonaceous and non-carbonaceous reservoirs (e.g., Warren 2011; Kruijjer et al. 2019 for further details on their significance, originally discovered by Trinquier et al. 2007 and Leya et al. 2008), and Earth's mantle, lunar Apollo samples and Martian meteorites for Earth, Moon and Mars bulk compositions, respectively. Possible locations of Venus, Mercury, and the Sun are indicated but have not been measured yet. CAIs = calcium, aluminium-rich inclusions have reported  $\epsilon^{54}\text{Cr}$  and  $\epsilon^{50}\text{Ti}$  anomalies that range from  $\sim 5$ –8 and  $\sim 9$ –15, respectively (Larsen et al. 2018; Leya et al. 2009; Trinquier et al. 2009), and are thus represented, with the potential location of the Sun, off the chart. CC = carbonaceous chondrites and related groups, EC = enstatite chondrites (EH and EL groups), OC = ordinary chondrites (H, L and LL). Data sources from Trinquier et al. (2007), Leya et al. (2008, 2009), Göpel et al. (2015), Sanborn et al. (2019)

Schönbächler et al. 2011). Strikingly for all these elements (Ca, Ti, Cr and Ni), the Earth is not an endmember in the solar system, but falls at the end of the trend defined by Earth, Mars and non-carbonaceous (NC) meteorites (e.g., Steele et al. 2012; Schiller et al. 2018) (Fig. 4). This is often called the NC reservoir as compared to the carbonaceous chondrite (CC) reservoir, defined by CC. The two reservoirs are also referred to as solar system dichotomy and may have been separated by the early formation of Jupiter (Olsen et al. 2016; Kruijjer et al. 2017; 2019; Alibert et al. 2018) or a ringed structure in the protoplanetary disc (Brasser and Mojzsis 2020). The CI chondrites fall on the extension of the trend of the NC material together with the Earth as the closest body to the NC reservoir (Fig. 4). Based on this observation, it was proposed that the Earth might have accreted significant amounts of CI materials through pebble accretion (Schiller et al. 2018). On the other hand, the data are also consistent with adding carbonaceous chondrite material to the Earth in the later history of Earth's main accretion phase through planetesimal accretion. The location of Mercury and Venus in Fig. 3 and 4 can potentially help to distinguish between the two scenarios (planetesimal accretion versus pebble accretion). For example, if the Cr and Ti isotope compositions of Mercury and Venus fall to the right of the Earth in Fig. 4, the addition of more CI-like material to Mercury and Venus can account for the Cr–Ti trend. If so, then the two planets must also fall between Earth and CI chondrites in the Zr–Mo graph (right to

the Earth) (Fig. 3). If they fall to the left of the Earth, as indicated in Fig. 3, this does not allow for the accretion of more CI material and thus favours planetesimal accretion, where the material is not limited to CI chondrites. Instead, it would again indicate that Mercury and Venus have accreted material from an inner solar system reservoir that is enriched in the enigmatic strongly volatile depleted material from which also the Earth mainly accreted and from which no identified material is available in our meteorite collection.

### 3.2 Moon Formation

The similarity of Earth and the Moon in nucleosynthetic isotope compositions can be exploited to constrain the origin of the hypothetical impactor Theia that collided with the Earth to form the Moon. Recently, a new variation of the giant impactor scenario has been proposed, in which the Moon formed from an originally completely vaporized accretion disk that fully equilibrated with the silicate Earth (Synestia; Lock et al. 2018). In such a scenario, tracing of the impactor material using nucleosynthetic isotope anomalies is not possible. However, it is debated whether full equilibration indeed occurred. If it was not achieved, comparison of elemental and isotopic measurements of the Earth and Moon today allows predicting the isotopic composition of the lunar impactor Theia using mass balance calculations. It requires the combination of isotopic data with the results of dynamic simulations that constrain the proportions of the impactor material that merged with the proto-Earth or mixed with terrestrial material to form the Moon. The prediction for the isotopic composition of the impactor can then be compared to data from solar system bodies to identify its origin (Akram and Schönbachler 2016). Such considerations yield that Theia most likely had a composition very similar to the Earth and, hence, must have formed in a similar orbit as the Earth (Dauphas et al. 2014; Meier et al. 2014; Melosh 2014; Akram and Schönbachler 2016). To fully exploit these models, however, knowledge of the compositions of Venus or Mercury to characterize the material that formed inside the Earth's orbit in the protoplanetary disk would be essential.

## 4 Constraints on the Reservoirs and Timescales of Formation for the Terrestrial Planets from Radiogenic Isotopes

### 4.1 Timescales of Planetary Accretion and Differentiation

The timescales of planet formation can be resolved with a precision of tens of thousands of years for processes that occurred 4.5 billion years ago using the daughter products of short-lived and now extinct radionuclides. Among the short-lived radionuclide isotope systems, 16 parent-daughter pairs have been used so far in cosmochemistry as high-resolution chronometers (Davis and McKeegan 2014). The parent isotopes were freshly synthesized within different stellar environments and injected shortly before or after the collapse of the solar nebula (e.g., Lugaro et al. 2014). They can be identified by finding a correlation of mass-independent isotopic variations of the radiogenic daughter products with the parent/daughter elemental ratio (e.g., Lee et al. 1976). Short-lived radioactive isotopes such as  $^{26}\text{Al}$  ( $T_{1/2} \approx 0.71$  Ma),  $^{53}\text{Mn}$  ( $T_{1/2} \approx 3.7$  Ma),  $^{107}\text{Pd}$  ( $T_{1/2} \approx 6.5$  Ma),  $^{182}\text{Hf}$  ( $T_{1/2} \approx 8.9$  Ma),  $^{92}\text{Nb}$  ( $T_{1/2} \approx 37$  Ma), and  $^{146}\text{Sm}$  ( $T_{1/2} \approx 103$  Ma) are principally used as high-resolution chronometers (down to a few 1,000 yr) and tracers for early planetary processes (e.g., Bizzarro et al. 2005; Kleine et al. 2009; Wadhwa et al. 2009; Boyet et al. 2010; Schönbachler et al. 2010; Bouvier et al. 2011; Iizuka et al. 2016; Pape et al. 2019). These isotope systems

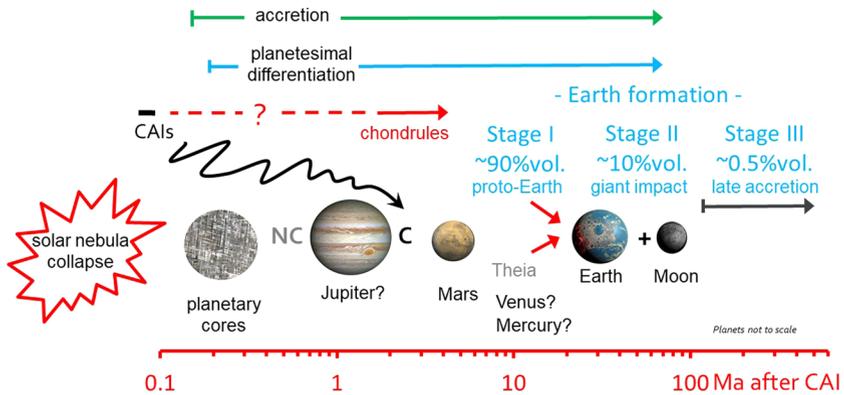
provide relative age information that can be placed on an absolute timescale using high-precision ages obtained from the long-lived U–Pb isotope system. For the latter a precision of 300,000 yr is now achievable. The decay products of short-lived radionuclides can be measured with high-precision and for some systems also with high spatial resolution by mass spectrometry (e.g., secondary ion mass spectrometry, SIMS; thermo-ionization MS, TIMS, multi-collector inductively coupled plasma MS, MC-ICPMS). They can be used as isotopic tracers and chronometers for the dynamic evolution of the nebula, if the parent isotopes were homogeneously distributed (e.g., Nyquist et al. 2009). Several short-lived radionuclides are also of interest to interpret isotopic anomalies identified in meteorites within a chronological context. This is the case of the decay of  $^{247}\text{Cm}$  to  $^{235}\text{U}$  ( $T_{1/2} \approx 15.6$  Ma), which affects accurate  $^{207}\text{Pb}$ – $^{206}\text{Pb}$  age determinations of early solar system objects and processes (Brennecka and Wadhwa 2012; Tissot et al. 2016) relevant to planetary formation.

Chondrites come from asteroids that did not fully melt because these bodies formed relatively late (few Myr after CAIs) in the history of the solar system or derive from relatively small parent bodies. Most chondrules identified in chondrites (beside metal-rich CBs and large single OC, CR and CV chondrules dated by Pb–Pb; Bollard et al. 2017) formed 2–4 Myr after CAIs (e.g., Kita et al. 2013; Kita and Ushikubo 2012; Bollard et al. 2017; Pape et al. 2019) and therefore relatively late during the accretion period (Fig. 5) compared to the parent bodies of many achondrites. There is growing evidence of a variety of planetesimals that formed and differentiated within a short time interval after the condensation started, i.e. as little as 0.1 to 0.3 million years after the formation of CAIs based on iron meteorites (Kruijer et al. 2014). This time period is also within less than 2 Ma for silicate achondrite parent bodies (Barrat et al. 2015) and thus before the formation of most chondrules and the accretion of chondrite parent bodies (e.g., Hunt et al. 2018). Widespread mafic magmas formed on various parent bodies within the first 3 to 5 Myr (Fig. 5) as shown by old U–Pb and Al–Mg ages of basaltic meteorites from angrites, eucrites, diogenites, ureilites, primitive achondrites, or ungrouped meteorites (e.g., Goodrich et al. 2010; Bouvier et al. 2011; Srinivasan et al. 2018).

## 4.2 Timing of Formation of the Terrestrial Planets

Constraints from the Hf–W system indicate that 95% of the accretion of Mars took place within 5 Ma after the beginning of the solar system, contemporaneously with the formation of planetesimals and chondrules (e.g., Kleine et al. 2009; Dauphas and Pourmand 2011; Pape et al. 2019). The formation of the Earth was more protracted and can be divided into three main intervals (Fig. 5) with (i) the main accretion sequence from dust to oligarchic growth from planetesimals to planetary embryos merging into planets bringing the Earth to about 85 to 90% of its current volume over 30 to 100 Ma (e.g., Kleine et al. 2009), (ii) the Moon-formation event likely bringing about 10% of the Earth’s mass between 60 to 100 Ma after the formation of the Solar System (Barboni et al. 2017; Kruijer et al. 2017; Maltese and Mezger 2020), and (iii) late accretion by impacts over 200 to 500 Ma after Earth’s core formation bringing about 0.5% of its final mass (e.g., Day et al. 2016). The highly siderophile elements in the silicate Earth were added during this period forming the “late veneer” (Walker 2009; Bottke et al. 2010; Dauphas 2017).

The origin of materials, which may have been involved during this late stage, can be assessed through the measurements of highly siderophile elements in terrestrial and meteorite samples. The group of IAB irons uniquely share their Mo, Ru and Pd isotopic compositions with the silicate Earth (Burkhardt et al. 2011; Fischer-Gödde et al. 2015; Worsham et al. 2017; Ek et al. 2019). The only specimen of EL3 enstatite chondrite that has been measured



**Fig. 5** Summary of timescales for the accretion and differentiation of planetary materials and their connection to Earth's formation (split here into 3 main stages, see also Fig. 2). After the collapse of the solar nebula, the oldest materials dated so far are CAIs, which mark the start of condensation, before their transportation and accretion within the carbonaceous chondrite parent body (C) within the outer regions of the protoplanetary disk. Accretion must start within 0.1 to 0.3 Ma and subsequent differentiation within 1 Ma after CAIs to explain the Hf–W systematics of iron meteorites (Kruijer et al. 2014; Hunt et al. 2018). The isolation of non-carbonaceous (NC) and carbonaceous (C) chondrite reservoirs with distinct isotopic signatures over 2–4 Ma has been linked to the formation of Jupiter within 1–2 Ma (Kruijer et al. 2017, 2019; Alibert et al. 2018). Although such a complete isolation based on Jupiter can be challenged (Brasser and Mojzsis 2020), Jupiter potentially provides a good barrier for at least CAI-sized particles (Desch et al. 2018)

so far is also identical in Ru isotopes to Earth's modern mantle (Fischer-Gödde et al. 2015). These results contrast with most carbonaceous chondrites, which have a range of compositions that limit their contribution to the late silicate Earth's HSE budget (Fischer-Gödde et al. 2015). They imply that carbonaceous chondrites, as strong candidates for the source of volatiles, would have to be involved in the earlier phase of the Earth's making process (i.e. Stage I to II in Fig. 5).

When combined with elemental and isotopic systematics, the chronology of solar system materials provides critical information about the evolution of isotopic reservoirs in space and time. It is thus important to obtain detailed chronological records with high time resolution for planetary processes, which took place within a few  $10^4$  to  $10^7$  years after the formation of CAIs, the oldest materials dated in the Solar System (e.g., Bouvier and Wadhwa 2010).

### 4.3 Constraints on Planetary Building Blocks from Radiogenic Isotope Systems

Due to their close similarities in major element abundances (e.g., Mg/Si, Al/Si) with the Earth's mantle, the carbonaceous chondrites have long been thought to represent the main components that make up the Earth (e.g., Jagoutz et al. 1979; Allègre et al. 1995). The refractory elements in carbonaceous, ordinary and enstatite chondrites have similar normalized abundances (Fig. 1). For this reason, the term Chondrite Uniform Reservoir was coined (CHUR) to represent the Bulk Earth's composition (DePaolo and Wasserburg 1976). Amongst several radio-isotopic systems used to trace and date planetary processes, the  $^{176}\text{Lu}$ – $^{176}\text{Hf}$  and  $^{147,146}\text{Sm}$ – $^{143,142}\text{Nd}$  systems have become extremely powerful because they are both composed of two refractory and lithophile elements with similar condensation temperatures and geochemical behaviour during igneous processes. The initial isotopic compositions of the terrestrial planets (e.g., Earth, Mars) have to be constrained to compare

and interpret the isotope measurements obtained on Earth and planetary samples. The ratios of the refractory Sm–Nd and Lu–Hf systems are relatively homogeneous, with only a  $\sim 4\%$  variation within unequilibrated chondrites (e.g., Bouvier et al. 2008). Variations in certain groups or metamorphic types of chondrites can be explained by secondary processes such as thermal metamorphism, or are due to the presence of exogenic components such as CAIs (Patchett et al. 2004; Bouvier et al. 2008; Martin et al. 2013; Debaille et al. 2017). There is no discernible difference in compositions for the long-lived systems  $^{176}\text{Lu}$ – $^{176}\text{Hf}$  and  $^{147}\text{Sm}$ – $^{143}\text{Nd}$  between the CHUR parameters and Earth’s mantle array (Bouvier et al. 2008). However, when looking at the short-lived  $^{146}\text{Sm}$ – $^{142}\text{Nd}$  system, variations in initial  $^{142}\text{Nd}$  abundances have been found between chondrite groups and the Earth’s modern mantle composition. A  $\sim 20$  part per million (ppm) difference in  $^{142}\text{Nd}$  abundance was originally detected between chondrites and the Earth’s mantle compositions (Boyet and Carlson 2005). It was interpreted as an early episode of global differentiation within the Earth (Boyet and Carlson 2005). However, additional measurements of stable and radiogenic Nd isotopes in a variety of chondrite groups and metamorphic types showed that the difference in the initial  $^{142}\text{Nd}$  abundance of chondrites and the Earth is related to variable amounts of nucleosynthetic *s*-process isotopes, originally carried by dust grains within the disc, and not, as initially thought, due to Sm/Nd fractionation and radioactive decay (Bouvier and Boyet 2016; Burkhardt et al. 2016). Amongst the chondrite groups, the average composition of enstatite chondrites is closest to that of Earth with a small  $^{142}\text{Nd}$  deficit of  $-10 \pm 12$  ppm (2SD), and even closer with  $-3 \pm 5$  ppm (2SD) when only considering the EL3 sub-type (Bouvier and Boyet 2016; Burkhardt et al. 2016; Boyet et al. 2018). A  $\sim 10$  ppm  $^{142}\text{Nd}$  gap between EC and BSE, if caused solely by  $^{146}\text{Sm}$  decay, would correspond to a maximum of 3% fractionation of the parent/daughter isotope ratios during condensation and accretion of planetary bodies. Enstatite chondrites comprise several sub-groups, possibly originating from different parent bodies (Weyrauch et al. 2018). Amongst these, the rare EL3 chondrites best match the Earth’s Nd composition. They may sample a different parent body compared to the other types of enstatite chondrites, which have been more commonly analysed for other isotopic systems. Nevertheless, it is likely that the different types of enstatite chondrites are genetically linked to each other (Boyet et al. 2018). The ordinary and carbonaceous chondrites are clearly distinct from Earth with anomalies of  $-16 \pm 9$  ppm (2SD) and  $-33 \pm 13$  ppm (2SD) in  $\epsilon^{142}\text{Nd}$ , respectively (Boyet et al. 2018). Such variations have two potential implications: (1) the Earth formed from material(s) isotopically similar to enstatite chondrites, whereas ordinary and carbonaceous chondrites were only minor contributors, or (2) Earth accreted a larger variety of chondritic materials, which would require the contribution of a missing enriched composition with excesses in initial  $^{142}\text{Nd}$ , a component that is currently missing from our collections (Burkhardt et al. 2016). This second implication is identical to that drawn from other isotopes that show larger *s*-process isotope anomalies (Zr, Mo, Ru and Pd, see above) than Nd.

In addition to the Earth, materials from other known planetary bodies have been also analysed for their  $^{146}\text{Sm}$ – $^{142}\text{Nd}$  systematics, including samples from the Moon (returned from Apollo and Luna missions and meteorites), meteorites from Mars, Vesta, and other unknown planetary bodies (e.g., angrites and mesosiderites) (e.g., Stewart et al. 1994; Foley et al. 2005; Boyet et al. 2010; Sanborn et al. 2015). The Moon has mass-dependent and mass-independent isotope compositions for many elements (e.g., O, Cr, Ti, Ca, Zr) that are identical within analytical precision or nearly indistinguishable from the Earth within a few tens of parts per million (e.g., Wiechert et al. 2001; Spicuzza et al. 2007; Hallis et al. 2010; Akram and Schönbachler 2016; Young et al. 2016; Greenwood et al. 2018) (Fig. 3). The Moon also appears to have a  $^{146}\text{Sm}$ – $^{142}\text{Nd}$  evolution identical to the Earth’s mantle

(Sprung et al. 2013). Such identical isotopic compositions suggest that the proto-Earth and Theia, the impactor in the giant impact scenario that led to the formation of the Moon, may have formed from chemically similar building blocks or the material from both bodies was homogenized during the impact (e.g., Young et al. 2016; Akram and Schönbachler 2016). This interpretation is also supported by the similarity of nucleosynthetic elements in the two bodies. When considering giant impact scenarios and analytical precision for different isotopic system, some variations in composition for the impactor from the Earth are nevertheless allowed (e.g., Akram and Schönbachler 2016). Even further complexity arises from signatures from late accretion (stage III in Fig. 5) for O and W isotopes (e.g., Kruijjer et al. 2014; Greenwood et al. 2018).

Mars formed before the Earth and the Moon (Fig. 5), with about 50% of its mass accreted within only 2 Myr after CAIs based on its  $^{182}\text{Hf}$ – $^{182}\text{W}$  and  $^{60}\text{Fe}$ – $^{60}\text{Ni}$  systematics (Dauphas and Pourmand 2011; Tang and Dauphas 2014; Barrat et al. 2015). It has generally closer isotopic similarities with ordinary chondrites (Trinquier et al. 2009; Warren 2011; Brasser et al. 2018) than Earth, and a positive  $\Delta^{17}\text{O}$  of  $0.318 \pm 0.016\text{‰}$  (Ali et al. 2016). From stable isotopic relationships, its initial  $^{142}\text{Nd}$  abundance was deduced to be about  $-15$  ppm compared to Earth, which would place Mars between enstatite and ordinary chondrite compositions, with a minor contribution from carbonaceous chondrites (Burkhardt et al. 2017a, 2017b).

The Howardite–Eucrites–Diogenite (HED) meteorite suite, sampling Vesta-type asteroids, is the most common group of achondrites with over 1200 eucrites alone available in the meteorite collections to this date. The HEDs are enriched in  $^{16}\text{O}$  with a  $\Delta^{17}\text{O}$  of  $-0.240 \pm 0.014\text{‰}$  (Greenwood et al. 2017) and depleted in  $^{54}\text{Cr}$  and  $^{50}\text{Ti}$  compared to Earth and Mars (Trinquier et al. 2007, 2009), suggesting accretion from materials that formed within the inner solar system, with lower contributions from carbonaceous chondrite materials. The initial  $^{142}\text{Nd}$  abundance for Vesta was estimated from internal mineral isochrons of basaltic and cumulative eucrites (Boyet et al. 2010 and references therein). These meteorites have a similar isotopic evolution as angrites and in particular mesosiderites, which is also reflected in the similarity of U–Pb ages of zircons separated from these meteorites (Haba et al. 2019). Their  $^{146}\text{Sm}$ – $^{142}\text{Nd}$  evolution, when compared with the crystallization ages, is most consistent with a source that had a composition similar to ordinary chondrites (Gannoun et al. 2011). Thus, the comparison of the  $^{146}\text{Sm}$ – $^{142}\text{Nd}$  systematics in different materials from the solar system indicates that the Earth has an end member composition and cannot be the end product of mixing of known components. This result is in agreement with the constraints provided by the bulk chemical composition and the variations of nucleosynthetic isotope variation for Earth and extant meteorites.

In the search for planetary building blocks of the Earth, the chronology of planetary accretion and differentiation puts the focus on the investigation of achondrite meteorites to track the composition of precursors and early planetary formation reservoirs. In this search, many new and previously unknown types of primitive and differentiated achondrites have been recovered, primarily from the hot deserts. Some of these have the potential to represent the Earth's original main building material. Based on their mineralogical-geochemical characteristics and/or O-isotope compositions, many of these meteorites have been categorized as “ungrouped”, because they do not appear to belong to any previously recognized achondrite types within the meteorite classification nomenclature. These include Northwest Africa (NWA) 7325 and paired meteorites, which were proposed to potentially originate from Mercury based on their elemental compositions. However, this is unlikely because their ancient age of 4563 Ma (within only 4–5 Myr after CAIs) suggests that they originated by re-melting of an early planetary crust that formed within 1.7 Myr of CAIs (Koefoed et al.

2016). Moreover, this crust had to be anorthositic in composition to explain the unique elemental composition of pyroxenes in NWA 7325 and paired meteorites (e.g., NWA 8486) (Frossard et al. 2019). Meteorite sample NWA 11119, an ungrouped achondrite, may be related to NWA 7325 based on its O isotopic composition (Srinivasan et al. 2018). It contains ~20 vol.% of silica polymorphs mostly as tridymite. Such a high abundance of silica is generally found only in differentiated, evolved, crustal rocks on terrestrial planets. Its  $^{26}\text{Al}$ – $^{26}\text{Mg}$  age is the oldest of any silicate-rich achondrite:  $4564.8 \pm 0.3$  Ma (Srinivasan et al. 2018). Silica-rich magmatism was thus taking place within ~3 Ma after CAI formation. Both the NWA 7325 and NWA 11119 have O–Cr–Ti anomalies which would place them closer to the acapulcoite and ureilite formation reservoirs (Goodrich et al. 2017; Srinivasan et al. 2018), and therefore away from the innermost part of the protoplanetary disc where Mercury would be expected to be located (Fig. 4). Other ungrouped enstatite-rich achondrites also yielded identical O isotope compositions to Earth (e.g., Itqiy, NWA 5400), but differ in nucleosynthetic anomalies (Burkhardt et al. 2017a, 2017b). These meteorites may represent the crust and mantle of planetesimals and planets that formed in a similar accretion region as Earth before planetesimals were scattered by for example planet migration (e.g., the Grand tack, Raymond and Morbidelli 2014). As such, they may be remnants of Theia or the proto-Earth before the Moon-formation event took place. At present no connection between these meteorites and potential parent asteroids has been identified.

#### 4.3.1 Conclusions

Bulk Earth has an extreme composition, when considering its element abundances as well as radiogenic initial and nucleosynthetic isotope compositions and comparing them with known materials from the solar system available for direct analysis in the form of meteorites. The carbonaceous and ordinary chondrite groups are clearly distinct from Earth's isotopic composition, while enstatite chondrites are the closest to Earth's mass-independent isotopic inventory (Figs. 2 and 3). However, due to their high Si abundance (Jagoutz et al. 1979), the composition of enstatite chondrites are quite distinct in their major element composition from that of Earth and thus cannot represent main precursors of the Earth's total mass. Possible condensation or vapour loss fractionation effects during accretion have been suggested to explain such discrepancies in the Si, Mg and Fe mass-dependent isotope compositions between Earth and chondrite compositions (Dauphas et al. 2015; Hin et al. 2017).

Currently, no mixing model can account for the observed composition of the Earth using known materials. The distinct nucleosynthetic variations observed in different meteorite classes or their components indicate that different regions in the early solar system had unique characteristic compositions. These differences in the isotopic compositions can be used as tracers for the region of origin within the disc for these meteorites and their parent bodies, before being transported and trapped within the asteroid belt (Akram et al. 2015; Akram and Schönbachler 2016; Bouvier and Boyet 2016; Burkhardt et al. 2016; Boyet et al. 2018). However, it is not well constrained where exactly each specific region was located in the protoplanetary disk. These regions can have varied in time and space. The chemical and isotopic diversity of known solar system materials and their difference to the Earth strongly points to a major missing component that possibly formed in the innermost regions of the solar system.

Most meteorites available for study are derived from the asteroid belt. Thus, only the regions beyond the Earth's orbit may be well represented in the meteorite collection. The CAIs are the earliest extant condensates of the solar nebula in our collection. They are considered to have formed close to the young Sun before being transported to the carbonaceous

chondrite forming region (e.g., Nanne et al. 2019). Some CAIs share similar  $^{142}\text{Nd}$  abundances to the Earth (Bouvier and Boyet 2016) suggesting a closer relationship to the inner solar system in terms of formation reservoirs compared to the accretion region of the carbonaceous chondrites, which may have been located beyond Jupiter (Kruijjer et al. 2019). However, other isotope systematics are clearly distinct between the Earth and CAIs (e.g.,  $\Delta^{17}\text{O}$ ,  $^{50}\text{Ti}$ ,  $^{54}\text{Cr}$ ,  $^{96}\text{Zr}$ ; e.g., Clayton 2003; Leya et al. 2009; Trinquier et al. 2009; Akram et al. 2013) suggesting different carriers or formation mechanisms for these isotope effects.

Based on O-isotope abundances, meteorites sample only ca. 110 parent bodies (Greenwood et al. 2017) and many new objects from other reservoirs need to be studied to achieve further breakthroughs about the formation of Earth and the planets in the solar system. So far, no known group of chondrites satisfies the Earth's elemental and isotopic composition and it is likely the Earth formed from a variety of different materials. Based on their stable isotopic compositions achondrites (e.g., ureilites, HED meteorites) are remnants of distinct parent bodies, but they have not substantially contributed to the Earth. Materials that may constitute building blocks of the terrestrial planets likely formed within a short time interval of a few million years, but must also satisfy both elemental abundance and isotopic constraints.

In order to explain the particular isotopic composition of the Earth–Moon system with robust mixing models, samples from the innermost and outer solar system regions are needed to measure the range of chemical and isotopic variations within the solar system as a function of heliocentric distance. In search for the place and composition of the “missing component” that makes up the bulk of planet Earth, a sample return mission that provides material from inside the Earth's orbit would fill a current gap and help constrain models for the formation of rocky planets in general and the habitable Earth in particular. This illustrates that samples from Venus or Mercury can play a fundamental role in answering the question of the building blocks of the Earth. Models for the formation of the Earth would tremendously benefit from the knowledge of the compositions of Venus or Mercury to define the nature of the material that formed inside the Earth's orbit in the protoplanetary disk. This will lead to deeper understanding of the accretion of rocky planets and may help to understand how to build a habitable world.

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## References

- W. Akram, M. Schönбächler, Zirconium isotope constraints on the composition of Theia and current Moon-forming theories. *Earth Planet. Sci. Lett.* **449**, 302–310 (2016)
- W. Akram, M. Schönбächler, P. Sprung, N. Vogel, Zirconium–hafnium isotope evidence from meteorites for the decoupled synthesis of light and heavy neutron-rich nuclei. *Astrophys. J.* **777**, 169–181 (2013)

- W. Akram, M. Schönbachler, S. Bisterzo, R. Gallino, Zirconium isotope evidence for the heterogeneous distribution of *s*-process materials in the solar system. *Geochim. Cosmochim. Acta* **165**, 484–500 (2015)
- F. Albarède, Volatile accretion history of the terrestrial planets and dynamic implications. *Nature* **461**, 1227 (2009)
- F. Albarède, C. Ballhaus, J. Blichert-Toft, C-T. Lee, B. Marty, F. Moynier, Q-Z. Yin, Asteroidal impacts and the origin of terrestrial and lunar volatiles. *Icarus* **222**, 44–52 (2013)
- A. Ali, I. Jabeen, D. Gregory, R. Verish, N.R. Banerjee, New triple oxygen isotope data of bulk and separated fractions from SNC meteorites: evidence for mantle homogeneity of Mars. *Meteorit. Planet. Sci.* **51**, 981–995 (2016)
- Y. Alibert, J. Venturini, R. Helled, S. Ataiee, R. Burn, L. Senecal, W. Benz, L. Mayer, C. Mordasini, S.P. Quanz, M. Schönbachler, The formation of Jupiter by hybrid pebble–planetesimal accretion. *Nat. Astron.* **2**(11), 873 (2018)
- C.J. Allègre, J.P. Poirier, E. Humler, A.W. Hofmann, The chemical composition of the Earth. *Earth Planet. Sci. Lett.* **134**(3–4), 515–526 (1995)
- C. Allègre, G. Manhès, E. Lewin, Chemical composition of the Earth and the volatility control on planetary genetics. *Earth Planet. Sci. Lett.* **185**, 49–69 (1999)
- E. Anders, N. Grevesse, Abundances of the elements: meteoritic and solar. *Geochim. Cosmochim. Acta* **53**, 197–214 (1989)
- C. Arlandini, F. Käppeler, K. Wisshak, R. Gallino, M. Lugaro, M. Busso, O. Straniero, Neutron capture in low-mass asymptotic giant branch stars: cross sections and abundance signatures. *Astrophys. J.* **525**, 886–900 (1999)
- M. Asplund, N. Grevesse, A.J. Sauval, P. Scott, The chemical composition of the Sun. *Annu. Rev. Astron. Astrophys.* **47**, 481–522 (2009)
- C. Ballhaus, V. Laurenz, C. Münker, R.O.C. Fonseca, F. Albarède, A. Rohrbach, M. Lagos, M.W. Schmidt, K-P. Jochum, B. Stoll, U. Weis, H.M. Helmy, The U/Pb ratio of the Earth’s mantle—a signature of late volatile addition. *Earth Planet. Sci. Lett.* **362**, 237–245 (2013)
- M. Barboni, P. Boehnke, B. Keller, I.E. Kohl, B. Schoene, E.D. Young, K.D. McKeegan, Early formation of the Moon 4.51 billion years ago. *Sci. Adv.* **3**, e1602365 (2017)
- J.A. Barrat, R.C. Greenwood, A.B. Verchovsky, P. Gillet, C. Bollinger, J.A. Langlade, C. Liorzou, I.A. Franchi, Crustal differentiation in the early solar system: clues from the unique achondrite Northwest Africa 7325 (NWA 7325). *Geochim. Cosmochim. Acta* **168**, 280–292 (2015)
- W. Benz, W.L. Slattery, A.G.W. Cameron, Origin of the Moon and the single-impact hypothesis I. *Icarus* **66**, 515–535 (1986)
- A. Bischoff, T. Geiger, Meteorites for the Sahara: find locations, shock classification, degree of weathering and pairing. *Meteorit. Planet. Sci.* **30**, 113–122 (1995)
- S. Bisterzo, R. Gallino, O. Straniero, S. Cristallo, F. Käppeler, The *s*-process in low-metallicity stars—II. Interpretation of high-resolution spectroscopic observations with asymptotic giant branch models. *Mon. Not. R. Astron. Soc.* **418**, 284–319 (2011)
- M. Bizzarro, J.A. Baker, H. Haack, K.L. Lundgaard, Rapid timescales for accretion and melting of differentiated planetesimals inferred from <sup>26</sup>Al–<sup>26</sup>Mg chronometry. *Astrophys. J.* **632**, L41–L44 (2005)
- J. Bollard, J.N. Connelly, M.J. Whitehouse, E.A. Pringle, L. Bonal, J.K. Jørgensen, Å. Nordlund, F. Moynier, M. Bizzarro, Early formation of planetary building blocks inferred from Pb isotopic ages of chondrules. *Sci. Adv.* **3**(8), e1700407 (2017)
- W.F. Bottke, R.J. Walker, J.M.D. Day, D. Nesvorný, L. Elkins-Tanton, Stochastic late accretion to Earth, the Moon, and Mars. *Science* **330**, 1527–1530 (2010)
- A. Bouvier, M. Boyet, Primitive Solar System materials and Earth share a common initial <sup>142</sup>Nd abundance. *Nature* **537**, 399–402 (2016)
- A. Bouvier, M. Wadhwa, The age of the Solar System redefined by the oldest Pb–Pb age of a meteoritic inclusion. *Nat. Geosci.* **3**, 637–641 (2010)
- A. Bouvier, J.D. Vervoort, P.J. Patchett, The Lu–Hf and Sm–Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth Planet. Sci. Lett.* **273**, 48–57 (2008)
- A. Bouvier, L.J. Spivak-Birndorf, G.A. Brennecka, M. Wadhwa, New constraints on early Solar System chronology from Al–Mg and U–Pb isotope systematics in the unique basaltic achondrite Northwest Africa 2976. *Geochim. Cosmochim. Acta* **75**, 5310–5323 (2011)
- M. Boyet, R.W. Carlson, <sup>142</sup>Nd evidence for early (>4.53 Ga) global differentiation of the silicate Earth. *Science* **309**, 576–581 (2005)
- M. Boyet, R.W. Carlson, M. Horan, Old Sm–Nd ages for cumulate eucrites and redetermination of the solar system initial <sup>146</sup>Sm/<sup>144</sup>Sm ratio. *Earth Planet. Sci. Lett.* **291**, 172–181 (2010)

- M. Boyet, A. Bouvier, P. Frossard, T. Hammouda, M. Garçon, A. Gannoun, Enstatite chondrites EL3 as building blocks for the Earth: the debate over the  $^{146}\text{Sm}$ – $^{142}\text{Nd}$  systematics. *Earth Planet. Sci. Lett.* **488**, 68–78 (2018)
- R. Brasser, The formation of Mars: building blocks and accretion time scale. *Space Sci. Rev.* **174**, 11–25 (2013)
- R. Brasser, S.J. Mojzsis, The partitioning of the inner and outer Solar System by a structured protoplanetary disk. *Nat. Astron.* (2020). <https://doi.org/10.1038/s41550-019-0978-6>
- R. Brasser, N. Dauphas, S.J. Mojzsis, Jupiter's influence on the building blocks of Mars and Earth. *Geophys. Res. Lett.* **45**, 5908–5917 (2018)
- N. Braukmüller, F. Wombacher, D.C. Hezel, R. Escoube, C. Münker, The chemical composition of carbonaceous chondrites: implications for volatile element depletion, complementarity and alteration. *Geochim. Cosmochim. Acta* **239**, 17–48 (2018)
- N. Braukmüller, F. Wombacher, C. Funk, C. Münker, Earth's volatile element depletion pattern inherited from a carbonaceous chondrite-like source. *Nat. Geosci.* **12**, 564–568 (2019)
- G.A. Brennecka, M. Wadhwa, Uranium isotope compositions of the basaltic angrite meteorites and the chronological implications for the early Solar System. *Proc. Natl. Acad. Sci.* **109**, 9299–9303 (2012)
- G. Budde, C. Burkhardt, T. Kleine, Molybdenum isotopic evidence for the late accretion of outer Solar System material to Earth. *Nat. Astron.* **3**, 736–741 (2019)
- C. Burkhardt, M. Schönbächler, Intrinsic W nucleosynthetic isotope variations in carbonaceous chondrites: Implications for W nucleosynthesis and nebular vs. parent body processing of presolar materials. *Geochim. Cosmochim. Acta* **165**, 361–375 (2015)
- C. Burkhardt, T. Kleine, F. Oberli, A. Pack, B. Bourdon, R. Wieler, Molybdenum isotope anomalies in meteorites: constraints on solar nebula evolution and origin of the Earth. *Earth Planet. Sci. Lett.* **312**, 390–400 (2011)
- C. Burkhardt, L.E. Borg, G.A. Brennecka, Q.R. Shollenberger, N. Dauphas, T. Kleine, A nucleosynthetic origin for the Earth's anomalous  $^{142}\text{Nd}$  composition. *Nature* **537**, 394–398 (2016)
- C. Burkhardt, N. Dauphas, H. Tang, M. Fischer-Gödde, L. Qin, J.H. Chen, S.S. Rout, A. Pack, P.R. Heck, D.A. Papanastassiou, In search of the Earth-forming reservoir: mineralogical, chemical, and isotopic characterizations of the ungrouped achondrite NWA 5363/NWA 5400 and selected chondrites. *Meteorit. Planet. Sci.* **52**, 807–826 (2017a)
- C. Burkhardt, T. Kruijjer, L. Borg, T. Kleine, Nucleosynthetic heritage and origin of Mars, In: *Goldschmidt Abstracts* (2017b), p. 507
- R.M. Canup, E. Asphaug, Origin of the Moon in a giant impact near the end of the Earth's formation. *Nature* **412**, 708–712 (2001)
- J. Chambers, Making more terrestrial planets. *Icarus* **152**, 205–224 (2001)
- C.L. Chou, Fractionation of siderophile elements in the Earth's upper mantle, in *Lunar and Planetary Science Conference Proceedings*, vol. 9 (1978), pp. 219–230
- F.J. Ciesla, Radial transport in the solar nebula: implications for moderately volatile element depletions in chondritic meteorites. *Meteorit. Planet. Sci.* **43**, 639–655 (2010)
- P.L. Clay, R. Burgess, H. Busemann, L. Ruzié-Hamilton, B. Joachim, J.M.D. Day, C.J. Ballentine, Halogens in chondritic meteorites and terrestrial accretion. *Nature* **551**, 614–618 (2017)
- R.N. Clayton, Oxygen isotopes in the solar system. *Space Sci. Rev.* **106**, 19–32 (2003)
- N. Dauphas, The isotopic nature of the Earth's accreting material through time. *Nature* **541**(7638), 521–524 (2017)
- N. Dauphas, A. Pourmand, Hf-W-Th evidence for rapid growth of Mars and its status as a planetary embryo. *Nature* **473**, 489–492 (2011)
- N. Dauphas, A.M. Davis, B. Marty, L. Reisberg, The cosmic molybdenum–ruthenium isotope correlation. *Earth Planet. Sci. Lett.* **226**(3–4), 465–475 (2004)
- N. Dauphas, J.H. Chen, J. Zhang, D.A. Papanastassiou, A.M. Davis, C. Travaglio, Calcium-48 isotopic anomalies in bulk chondrites and achondrites: evidence for a uniform isotopic reservoir in the inner protoplanetary disk. *Earth Planet. Sci. Lett.* **407**, 96–108 (2014)
- N. Dauphas, F. Poitrasson, C. Burkhardt, H. Kobayashi, K. Kurosawa, Planetary and meteoritic Mg/Si and  $\delta^{30}\text{Si}$  variations inherited from solar nebula chemistry. *Earth Planet. Sci. Lett.* **427**, 236–248 (2015)
- J. Davidson, H. Busemann, L.R. Nittler, C.M.D. Alexander, F.R. Orthous-Daunay, I.A. Franchi, P. Hoppe, Abundances of presolar silicon carbide grains in primitive meteorites determined by NanoSIMS. *Geochim. Cosmochim. Acta* **139**, 248–266 (2014)
- A. Davis, K. McKeegan, Short-lived radionuclides and early solar system chronology, in *Meteorites and Cosmochemical Processes*. Treatise on Geochemistry, vol. 1 (2014), pp. 361–395
- J.M. Day, Planet formation processes revealed by meteorites. *Geol. Today* **31**, 12–20 (2015)
- J.M.D. Day, R.J. Walker, L. Qin, D. Rumble III., Late accretion as a natural consequence of planetary growth. *Nat. Geosci.* **5**, 614–617 (2012)

- J.M.D. Day, A.D. Brandon, R.J. Walker, Highly siderophile elements in Earth, Mars, the Moon, and asteroids. *Rev. Mineral. Geochem.* **81**, 161–238 (2016)
- V. Debaille, J. Van Orman, Q.-Z. Yin, Y. Amelin, The role of phosphates for the Lu–Hf chronology of meteorites. *Earth Planet. Sci. Lett.* **473**, 52–61 (2017)
- D. DePaolo, G. Wasserburg, Nd isotopic variations and petrogenetic models. *Geophys. Res. Lett.* **3**, 249–252 (1976)
- S.J. Desch, A. Kalyaan, C.M.D. Alexander, The effect of Jupiter’s formation on the distribution of refractory elements and inclusions in meteorites. *Astrophys. J. Suppl. Ser.* **238**(1), 11 (2018)
- M. Drake, K. Righter, Determining the composition of the Earth. *Nature* **416**, 39–44 (2002)
- M. Ek, A.C. Hunt, M. Lugaro, M. Schönbächler, The origin of s-process isotope heterogeneity in the solar protoplanetary disk. *Nat. Astron.* (2019). <https://doi.org/10.1038/s41550-019-0948-z>
- M. Fischer-Gödde, C. Burkhardt, T.S. Kruijjer, T. Kleine, Ru isotope heterogeneity in the solar protoplanetary disk. *Geochim. Cosmochim. Acta* **168**, 151–171 (2015)
- C. Fitoussi, B. Bourdon, X. Wang, The building blocks of Earth and Mars: a close genetic link. *Earth Planet. Sci. Lett.* **434**, 151–160 (2016)
- C.N. Foley, M. Wadhwa, L.E. Borg, P.E. Janney, R. Hines, T.L. Grove, The early differentiation history of Mars from  $^{182}\text{W}$ - $^{142}\text{Nd}$  isotope systematics in the SNC meteorites. *Geochim. Cosmochim. Acta* **69**, 4557–4571 (2005)
- P. Frossard, M. Boyet, A. Bouvier, T. Hammouda, J. Monteux, Evidence for anorthositic crust formed on an inner solar system planetesimal. *Geochem. Perspect. Lett.* **11**, 28–32 (2019)
- R. Fukai, T. Yokoyama, Neodymium isotope heterogeneity of ordinary and carbonaceous chondrites and the origin of non-chondritic  $^{142}\text{Nd}$  compositions in the Earth. *Earth Planet. Sci. Lett.* **474**, 206–214 (2017)
- A. Gannoun, M. Boyet, H. Rizo, A. El Goresy,  $^{146}\text{Sm}$ – $^{142}\text{Nd}$  systematics measured in enstatite chondrites reveals a heterogeneous distribution of  $^{142}\text{Nd}$  in the solar nebula. *Proc. Natl. Acad. Sci.* **108**, 7693–7697 (2011)
- J. Gattacceca, A. Bouvier, J. Grossman, K. Metzler, M. Uehara, The meteoritical bulletin, No. 106. *Meteorit. Planet. Sci.* **54**, 469–471 (2019)
- C.A. Goodrich, I.D. Hutcheon, N.T. Kita, G.R. Huss, B.A. Cohen, K. Keil,  $^{53}\text{Mn}$ – $^{53}\text{Cr}$  and  $^{26}\text{Al}$ – $^{26}\text{Mg}$  ages of a feldspathic lithology in polymict ureilites. *Earth Planet. Sci. Lett.* **295**, 531–540 (2010)
- C.A. Goodrich, N.T. Kita, Q.-Z. Yin, M.E. Sanborn, C.D. Williams, D. Nakashima, S. Boyle, Petrogenesis and provenance of ungrouped achondrite Northwest Africa 7325 from petrology, trace elements, oxygen, chromium and titanium isotopes, and mid-IR spectroscopy. *Geochim. Cosmochim. Acta* **203**, 381–403 (2017)
- C. Göpel, J.-L. Birck, A. Galy, J.-A. Barrat, B. Zanda, Mn–Cr systematics in primitive meteorites: insights from mineral separation and partial dissolution. *Geochim. Cosmochim. Acta* **156**, 1–24 (2015)
- R.C. Greenwood, T.H. Burbine, M.F. Miller, I.A. Franchi, Melting and differentiation of early-formed asteroids: the perspective from high precision oxygen isotope studies. *Chem. Erde* **77**(1), 1–43 (2017)
- R.C. Greenwood, J.-A. Barrat, M.F. Miller, M. Anand, N. Dauphas, I.A. Franchi, P. Sillard, N.A. Starkey, Oxygen isotopic evidence for accretion of Earth’s water before a high-energy Moon-forming giant impact. *Sci. Adv.* **4**, eaao5928 (2018)
- M.K. Haba, J.F. Wotzlaw, Y.J. Lai, A. Yamaguchi, M. Schönbächler, Mesosiderite formation on asteroid 4 Vesta by a hit-and-run collision. *Nat. Geosci.* **12**, 510–515 (2019)
- A.N. Halliday, The origin and earliest history of the Earth, in *Treatise on Geochemistry*, vol. 2, ed. by A.M. Davis, second edn. (Elsevier, Amsterdam, 2014), pp. 509–557
- L.J. Hallis, M. Anand, R.C. Greenwood, M.F. Miller, I.A. Franchi, S.S. Russell, The oxygen isotope composition, petrology and geochemistry of mare basalts: evidence for large-scale compositional variation in the lunar mantle. *Geochim. Cosmochim. Acta* **74**, 6885–6899 (2010)
- B.M. Hansen, Formation of the terrestrial planets from a narrow annulus. *Astrophys. J.* **703**, 1131 (2009)
- W.K. Hartmann, D.R. Davis, Satellite-sized planetesimals and lunar origin. *Icarus* **24**, 504–515 (1975)
- P.R. Heck, J. Greer, L. Kööp, R. Trappitsch, F. Gyngard, H. Busemann, C. Maden, J.N. Ávila, A.M. Davis, R. Wieler, Lifetimes of interstellar dust from cosmic ray exposure ages of presolar silicon carbide. *Proc. Natl. Acad. Sci.* **117**(4), 1884–1889 (2020)
- R.H. Hewins, Chondrules. *Annu. Rev. Earth Planet. Sci.* **25**, 61–83 (1997)
- R.C. Hin, C.D. Coath, P.J. Carter, F. Nimmo, Y.-J. Lai, P.A.P. von Strandmann, M. Willbold, Z.M. Leinhardt, M.J. Walter, T. Elliott, Magnesium isotope evidence that accretional vapour loss shapes planetary compositions. *Nature* **549**, 511 (2017)
- P. Hoppe, J. Leitner, J. Kodolányi, The stardust abundance in the local interstellar cloud at the birth of the solar system. *Nat. Astron.* **1**(9), 617 (2017)
- A.C. Hunt, D.L. Cook, T. Lichtenberg, P.M. Reger, M. Ek, G.J. Golabek, M. Schönbächler, Late metal–silicate separation on the IAB parent asteroid: constraints from combined W and Pt isotopes and thermal modelling. *Earth Planet. Sci. Lett.* **482**, 490–500 (2018)

- G.R. Huss, A.P. Meshik, J.B. Smith, C.M. Hohenberg, Presolar diamond, silicon carbide, and graphite in carbonaceous chondrites: implications for thermal processing in the solar nebula. *Geochim. Cosmochim. Acta* **67**, 4823–4848 (2003)
- T. Iizuka, Y.-J. Lai, A. Akram, Y. Amelin, M. Schönbachler, The initial abundance and distribution of  $^{92}\text{Nb}$  in the Solar System. *Earth Planet. Sci. Lett.* **439**, 172–181 (2016)
- E. Jagoutz, H. Palme, H. Baddenhausen, K. Blum, M. Cendales, D. Dreibus, B. Spettel, V. Lorenz, H. Wänke, 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.*, vol. 10 (1979), pp. 2031–2050
- A. Johansen, M. Lambrechts, Forming planets via pebble accretion. *Annu. Rev. Earth Planet. Sci.* **45**, 359–387 (2017)
- N.T. Kita, T. Ushikubo, Evolution of protoplanetary disk inferred from  $^{26}\text{Al}$  chronology of individual chondrules. *Meteorit. Planet. Sci.* **47**, 1108–1119 (2012)
- N.T. Kita, Q.-Z. Yin, G.J. MacPherson, T. Ushikubo, B. Jacobsen, K. Nagashima, E. Kurahashi, A.N. Krot, S.B. Jacobsen,  $^{26}\text{Al}$ - $^{26}\text{Mg}$  isotope systematics of the first solids in the early solar system. *Meteorit. Planet. Sci.* **48**, 1383–1400 (2013)
- T. Kleine, K. Mezger, H. Palme, E.E. Scherer, C. Münker, Early core formation in asteroids and late accretion of chondrite parent bodies: evidence from  $^{182}\text{Hf}$ - $^{182}\text{W}$  in CAIs, metal-rich chondrites, and iron meteorites. *Geochim. Cosmochim. Acta* **69**, 5805–5818 (2005)
- T. Kleine, M. Touboul, B. Bourdon, F. Nimmo, K. Mezger, H. Palme, S.B. Jacobsen, Q.-Z. Yin, A.N. Halliday, Hf–W chronology of the accretion and early evolution of asteroids and terrestrial planets. *Geochim. Cosmochim. Acta* **73**, 5150–5188 (2009)
- P. Koefoed, Y. Amelin, Q.-Z. Yin, J. Wimpenny, M.E. Sanborn, T. Iizuka, A.J. Irving, U–Pb and Al–Mg systematics of the ungrouped achondrite Northwest Africa 7325. *Geochim. Cosmochim. Acta* **183**, 31–45 (2016)
- A.N. Krot, K. Nagashima, C.M.O.D. Alexander, F.J. Ciesla, W. Fujiya, L. Bonal, Sources of water and aqueous activity on the chondrite parent asteroids, in *Asteroids IV* (2015), pp. 635–660
- T.S. Kruijjer, M. Touboul, M. Fischer-Gödde, K.R. Bermingham, R.J. Walker, T. Kleine, Protracted core formation and rapid accretion of protoplanets. *Science* **344**, 1150–1154 (2014)
- T.S. Kruijjer, C. Burkhardt, G. Budde, T. Kleine, Age of Jupiter inferred from the distinct genetics and formation times of meteorites. *Proc. Natl. Acad. Sci.* **114**, 6712–6716 (2017)
- T.S. Kruijjer, T. Kleine, L.E. Borg, The great isotopic dichotomy of the early Solar System. *Nat. Astron.* (2019). <https://doi.org/10.1038/s41550-019-0959-9>
- K.K. Larsen, D. Wielandt, M. Bizzarro, Multi-element ion-exchange chromatography and high-precision MC-ICP-MS isotope analysis of Mg and Ti from sub-mm-sized meteorite inclusions. *J. Anal. At. Spectrom.* **33**, 613–628 (2018)
- T. Lee, D.A. Papanastassiou, G.J. Wasserburg, Demonstration of  $^{26}\text{Mg}$  excess in Allende and evidence for  $^{26}\text{Al}$ . *Geophys. Res. Lett.* **3**, 109–112 (1976)
- I. Leya, M. Schönbachler, U. Wiechert, U. Krähenbühl, A.N. Halliday, Titanium isotopes and the radial heterogeneity of the solar system. *Earth Planet. Sci. Lett.* **266**, 233–244 (2008)
- I. Leya, M. Schönbachler, U. Krähenbühl, A.N. Halliday, New Titanium isotopes data for Allende and Efremovka CAIs. *Astrophys. J.* **702**, 1118–1126 (2009)
- C. Liebske, A. Khan, On the principal building blocks of Earth and Mars. *Icarus* **322**, 121–134 (2019)
- S.J. Lock, S.T. Stewart, M.I. Petaev, Z. Leinhardt, M.T. Mace, S.B. Jacobsen, M. Cuk, The origin of the Moon within a terrestrial synestia. *J. Geophys. Res., Planets* **123**(4), 910–951 (2018)
- K. Lodders, An oxygen isotope mixing model for the accretion and composition of rocky planets, in *From Dust to Terrestrial Planets* (Springer, Dordrecht, 2000), pp. 341–354
- K. Lodders, Solar system abundances and condensation temperatures of the elements. *Astrophys. J.* **591**, 1220–1247 (2003)
- M. Lugaro, A. Heger, D. Osrin, S. Goriely, K. Zuber, A.I. Karakas, B.K. Gibson, C.L. Doherty, J.C. Lattanzio, U. Ott, Stellar origin of the  $^{182}\text{Hf}$  cosmochronometer and the presolar history of solar system matter. *Science* **345**, 650–653 (2014)
- A. Maltese, K. Mezger, The Pb isotope evolution of Bulk Silicate Earth: constraints from its accretion and early differentiation history. *Geochim. Cosmochim. Acta* **271**, 179–193 (2020)
- C. Martin, V. Debaille, P. Lanari, S. Goderis, I. Vandendael, F. Vanhaecke, O. Vidal, P. Claeys, REE and Hf distribution among mineral phases in the CV–CK clan: A way to explain present-day Hf isotopic variations in chondrites. *Geochim. Cosmochim. Acta* **120**, 496–513 (2013)
- W.F. McDonough, S.-S. Sun, The composition of the Earth. *Chem. Geol.* **120**, 223–253 (1995)
- M.M. Meier, A. Reufer, R. Wieler, On the origin and composition of Theia: constraints from new models of the Giant Impact. *Icarus* **242**, 316–328 (2014)
- H. Melosh, New approaches to the Moon's isotopic crisis. *Philos. Trans. R. Soc., Math. Phys. Eng. Sci.* **372**, 20130168 (2014)

- H. Miyamoto, T. Niihara, T. Kuritani, P. Hong, J. Dohm, S. Sugita, Cluster analysis on the bulk elemental compositions of Antarctic stony meteorites. *Meteorit. Planet. Sci.* **51**, 906–919 (2016)
- A. Morbidelli, J.E. Chambers, J.I. Lunine, J.M. Petit, F. Robert, G.B. Valsecchi, K.E. Cyr, Source regions and timescales for the delivery of water on Earth. *Meteorit. Planet. Sci.* **35**, 1309–1320 (2000)
- J.A. Nanne, F. Nimmo, J.N. Cuzzi, T. Kleine, Origin of the non-carbonaceous–carbonaceous meteorite dichotomy. *Earth Planet. Sci. Lett.* **511**, 44–54 (2019)
- O. Nebel, K. Mezger, W. van Westrenen, Rubidium isotopes in primitive chondrites: constraints on Earth's volatile element depletion and lead isotope evolution. *Earth Planet. Sci. Lett.* **lan305**, 309–316 (2011)
- L. Nittler, N.L. Chabot, T.L. Grove, P.N. Peplowski, The chemical composition of Mercury, in *Mercury: The View After MESSENGER*, ed. by S.C. Solomon, L.R. Nittler, B.J. Anderson (Cambridge University Press, Cambridge, 2019), pp. 30–51
- L.E. Nyquist, T. Kleine, C.Y. Shih, Y.D. Reese, The distribution of short-lived radioisotopes in the early solar system and the chronology of asteroid accretion, differentiation, and secondary mineralization. *Geochim. Cosmochim. Acta* **73**, 5115–5136 (2009)
- D.P. O'Brien, A. Morbidelli, H.F. Levison, Terrestrial planet formation with strong dynamical friction. *Icarus* **184**(1), 39–58 (2006)
- D.P. O'Brien, K.J. Walsh, A. Morbidelli, S.N. Raymond, A.M. Mandell, Water delivery and giant impacts in the 'Grand Tack' scenario. *Icarus* **239**, 74–84 (2014)
- M.B. Olsen, D. Wielandt, M. Schiller, E.M. Van Kooten, M. Bizzarro, Magnesium and  $^{54}\text{Cr}$  isotope compositions of carbonaceous chondrite chondrules—insights into early disk processes. *Geochim. Cosmochim. Acta* **191**, 118–138 (2016)
- H.S.C. O'Neill, The origin of the Moon and the early history of the Earth—a chemical model. Part 2: the Earth. *Geochim. Cosmochim. Acta* **55**, 1159–1172 (1991)
- H.St.C. O'Neill, H. Palme, Composition of the silicate Earth: implications for accretion and core formation, in *The Earth's Mantle: Structure, Composition and Evolution—the Ringwood Volume*, ed. by I. Jackson (Cambridge University Press, Cambridge, 1998), pp. 3–126
- H. Palme, A. Jones, Solar system abundances of the elements, in *Treatise on Geochemistry* (2003), pp. 41–61
- H. Palme, H. O'Neill, Cosmochemical estimates of mantle composition, in *Treatise on Geochemistry*, vol. 3 (2014), pp. 1–38
- H. Palme, J. Zipfel, The Earth contains a large fraction of material not represented by meteorites, in *47th Lunar and Planetary Science Conference* (2016), p. 2252
- H. Palme, K. Lodders, A. Jones, Solar system abundances of the elements, in *Treatise on Geochemistry*, vol. 2, ed. by H.D. Holland, K.K. Turekian, second edn. (Elsevier, Oxford, 2014), pp. 15–36
- R.C. Paniello, J.M. Day, F. Moynier, Zinc isotopic evidence for the origin of the Moon. *Nature* **490**, 376 (2012)
- J. Pape, K. Mezger, A.-S. Bouvier, L. Baumgartner, Time and duration of chondrule formation: constraints from  $^{26}\text{Al}$ – $^{26}\text{Mg}$  ages of individual chondrules. *Geochim. Cosmochim. Acta* **244**, 416–436 (2019)
- P.J. Patchett, J.D. Vervoort, U. Soderlund, V.J.M. Salters, Lu–Hf and Sm–Nd isotopic systematics in chondrites and their constraints on the Lu–Hf properties of the Earth. *Earth Planet. Sci. Lett.* **222**, 29–41 (2004)
- A.H. Peslier, M. Schönbächler, H. Busemann, S.I. Karato, Water in the Earth's interior: distribution and origin. *Space Sci. Rev.* **122**, 743–810 (2017)
- L. Qin, C.M.O.D. Alexander, R.W. Carlson, M.F. Horan, T. Yokoyama, Contributors to chromium isotope variation of meteorites. *Geochim. Cosmochim. Acta* **74**, 1122–1145 (2010)
- R.A. Raymond, A. Morbidelli, The Grand Tack model: a critical review, in *Proceedings of the International Astronomical Union*, vol. 9 (2014), pp. 194–203
- J. Render, M. Fischer-Gödde, C. Burkhardt, T. Kleine, The cosmic molybdenum–neodymium isotope correlation and the building material of the Earth. *Geochim. Perspect. Lett.* **3**, 170–178 (2017)
- D.C. Rubie, D.J. Frost, U. Mann, Y. Asahara, T. Nimmo, T. Kyusei, P. Kegler, A. Holzheid, H. Palme, Heterogeneous accretion, composition and core-mantle differentiation of the Earth. *Earth Planet. Sci. Lett.* **301**, 31–42 (2011)
- M.E. Sanborn, R.W. Carlson, M. Wadhwa,  $^{147,146}\text{Sm}$ – $^{143,142}\text{Nd}$ ,  $^{176}\text{Lu}$ – $^{176}\text{Hf}$ , and  $^{87}\text{Rb}$ – $^{87}\text{Sr}$  systematics in the angrites: implications for chronology and processes on the angrite parent body. *Geochim. Cosmochim. Acta* **171**, 80–99 (2015)
- M.E. Sanborn, J. Wimpenny, C.D. Williams, A. Yamakawa, Y. Amelin, A.J. Irving, Q.-Z. Yin, Carbonaceous achondrites Northwest Africa 6704/6693: milestones for early Solar System chronology and genealogy. *Geochim. Cosmochim. Acta* **245**, 577–596 (2019)
- C. Sanloup, A. Jambon, P. Gillet, A simple chondritic model of Mars. *Phys. Earth Planet. Inter.* **112**, 43–54 (1999)
- M. Schiller, M. Bizzarro, V.A. Fernandes, Isotopic evolution of the protoplanetary disk and the building blocks of Earth and the Moon. *Nature* **555**(7697), 507–510 (2018)

- M. Schönbachler, R.W. Carlson, M.F. Horan, T.D. Mock, E.H. Hauri, Heterogeneous accretion and the moderately volatile element budget of Earth. *Science* **328**, 884–887 (2010)
- M. Schönbachler, W.M. Akram, N.H. Williams, I. Leya, Nucleosynthetic heterogeneities of neutron-rich isotopes in calcium aluminum-rich inclusions and bulk solar system materials, in *Workshop on Formation of the First Solids in the Solar System*, vol. 1639 (2011), p. 9085
- E.R.D. Scott, A. Krot, Chondrites and their components, in *Planets, Asteroids, Comets and the Solar System*, ed. by A.M. Davis, second edn. Treatise on Geochemistry, vol. 2 (Elsevier, Amsterdam, 2014), pp. 143–200
- M.J. Spicuzza, J.M.D. Day, L.A. Taylor, J.W. Valley, Oxygen isotope constraints on the origin and differentiation of the Moon. *Earth Planet. Sci. Lett.* **253**, 254–265 (2007)
- P. Sprung, T. Kleine, E.E. Scherer, Isotopic evidence for chondritic Lu/Hf and Sm/Nd of the Moon. *Earth Planet. Sci. Lett.* **380**, 77–87 (2013)
- P. Srinivasan, D.R. Dunlap, C.B. Agee, M. Wadhwa, D. Coleff, K. Ziegler, R. Zeigler, F.M. McCubbin, Silica-rich volcanism in the early solar system dated at 4.565 Ga. *Nat. Commun.* **9**, 3036 (2018)
- R.C. Steele, C.D. Coath, M. Regelous, S. Russell, T. Elliott, Neutron-poor nickel isotope anomalies in meteorites. *Astrophys. J.* **758**(1), 59–70 (2012)
- B.W. Stewart, D.A. Papanastassiou, G.J. Wasserburg, Sm–Nd chronology and petrogenesis of mesosiderites. *Geochim. Cosmochim. Acta* **58**, 3487–3509 (1994)
- H. Tang, N. Dauphas,  $^{60}\text{Fe}$ – $^{60}\text{Ni}$  chronology of core formation in Mars. *Earth Planet. Sci. Lett.* **390**, 264–274 (2014)
- F.L.H. Tissot, N. Dauphas, L. Grossman, Origin of uranium isotope variations in early solar nebula condensates. *Sci. Adv.* **2**(3), e1501400 (2016)
- A. Trinquier, J.L. Bircok, C.J. Allègre, Widespread  $^{54}\text{Cr}$  heterogeneity in the inner solar system. *Astrophys. J.* **655**, 1179–1185 (2007)
- A. Trinquier, T. Elliott, D. Ulfbeck, C. Coath, A.N. Krot, M. Bizzarro, Origin of nucleosynthetic isotope heterogeneity in the solar protoplanetary disk. *Science* **324**, 374–376 (2009)
- K.E. van der Kaaden, F.M. McCubbin, P.K. Byrne, N.L. Chabot, C.M. Ernst, C.L. Johnson, M.S. Thompson, Revolutionizing our understanding of the Solar System via sample return from Mercury. *Space Sci. Rev.* **215**, 49 (2019)
- M. Wadhwa, Y. Amelin, O. Bogdanovski, A. Shukolyukov, G.W. Lugmair, P.E. Janney, Ancient relative and absolute ages for a basaltic meteorite: implications for timescales of planetesimal accretion and differentiation. *Geochim. Cosmochim. Acta* **73**, 5189–5201 (2009)
- R.J. Walker, Highly siderophile elements in the Earth, Moon and Mars: update and implications for planetary accretion and differentiation. *Chem. Erde* **69**, 101–125 (2009)
- H. Wänke, G. Dreibus, Chemical composition and accretion history of terrestrial planets. *Philos. Trans. R. Soc., Math. Phys. Eng. Sci.* **325**, 545–557 (1988)
- P.H. Warren, Stable-isotopic anomalies and the accretionary assemblage of the Earth and Mars: a subordinate role for carbonaceous chondrites. *Earth Planet. Sci. Lett.* **311**, 93–100 (2011)
- P.H. Warren, G.W. Kallemeyn, Angrites: a volatile-rich variety of asteroidal basalt (except for alkalis and gallium!). *Meteoritics* **30**, 593 (1995)
- J.T. Wasson, *Meteorites: Their Record of Early Solar-System History* (WH Freeman and Co., New York, 1985), 274 pp.
- J.T. Wasson, G.W. Kallemeyn, Compositions of chondrites. *Philos. Trans. R. Soc., Math. Phys. Eng. Sci.* **325**, 535–544 (1988)
- M. Weyrauch, M. Horstmann, A. Bischoff, Chemical variations of sulfides and metal in enstatite chondrites—introduction of a new classification scheme. *Meteorit. Planet. Sci.* **53**, 394–415 (2018)
- U. Wiechert, A.N. Halliday, D.C. Lee, G.A. Snyder, L.A. Taylor, D. Rumble, Oxygen isotopes and the Moon-forming giant impact. *Science* **294**, 345–348 (2001)
- B.J. Wood, D.J. Smythe, T. Harrison, The condensation temperatures of the elements: a reappraisal. *Am. Mineral.* **104**, 844–856 (2019)
- E.A. Worsham, K.R. Bermingham, R.J. Walker, Characterizing cosmochemical materials with genetic affinities to the Earth: genetic and chronological diversity within the IAB iron meteorite complex. *Earth Planet. Sci. Lett.* **467**, 157–166 (2017)
- K. Yokoyama, Y. Kimura, C. Kaito, Experiments on condensation of calcium sulfide grains to demarcate environments for the formation of enstatite chondrites. *ACS Earth Space Chem.* **1**, 601–607 (2017)

- E.D. Young, I.E. Kohl, P.H. Warren, D.C. Rubie, S.A. Jacobson, A. Morbidelli, Oxygen isotopic evidence for vigorous mixing during the Moon-forming giant impact. *Science* **351**, 493–496 (2016)
- E. Zinner, 1.4—Presolar grains, in *Treatise on Geochemistry*, ed. by H.D. Holland, K.K. Turekian, second edn. (Elsevier, Oxford, 2014), pp. 181–213