



In search of late-stage planetary building blocks



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ABSTRACT

Genetic contributions to the final stages of planetary growth, including materials associated with the giant Moon-forming impact, late accretion, and late heavy bombardment are examined using siderophile elements. Isotopic similarities between the Earth and Moon for both lithophile and siderophile elements collectively lead to the suggestion that the genetics of the building blocks for Earth, and the impactor involved in the Moon-forming event were broadly similar, and shared some strong genetic affinities with enstatite chondrites. The bulk genetic fingerprint of materials subsequently added to Earth by late accretion, defined as the addition of ~0.5 wt.% of Earth's mass to the mantle, following cessation of core formation, was characterized by $^{187}\text{Os}/^{188}\text{Os}$ and Pd/Ir ratios that were also similar to those in some enstatite chondrites. However, the integrated fingerprint of late accreted matter differs from enstatite chondrites in terms of the relative abundances of certain other HSE, most notably Ru/Ir. The final ≤ 0.05 wt.% addition of material to the Earth and Moon, believed by some to be part of a late heavy bombardment, included a component with much more fractionated relative HSE abundances than evidenced in the average late accretionary component. Heterogeneous $^{182}\text{W}/^{184}\text{W}$ isotopic compositions of some ancient terrestrial rocks suggest that some very early-formed mantle domains remained chemically distinct for long periods of time following primary planetary accretion. This evidence for sluggish mixing of the early mantle suggests that if late accretionary contributions to the mantle were genetically diverse, it may be possible to isotopically identify the disparate primordial components in the terrestrial rock record using the siderophile element tracers Ru and Mo.

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1. Introduction

The origins of the rocky planets, especially with regard to assembly processes and the chemical nature of their building blocks, have been the topic of intense interest and debate for decades. It is now generally agreed that the terrestrial planets were built as a result of a three stage process, initially consisting of the growth of planetesimals from dust,

followed by the collisions of bodies of increasingly greater mass to create planetary embryos, culminating in the collision and accretion of the embryos to form planets during a giant impact stage of growth (e.g., Kokuba and Uda, 1998; Raymond et al., 2006; Morbidelli et al., 2012; Raymond et al., 2013). The final stage of major growth for the Earth likely occurred with the giant impact of a body comprising 5 wt.% or more of the mass of the present Earth, leading to the formation of the Moon (Hartmann and Davis, 1975; Canup and Asphaug, 2001; Canup, 2012; Ćuk and Stewart, 2012; Reufer et al., 2012). Minor accretion amounting to ~0.5 wt.% of the present Earth's mass continued after this event (Kimura et al., 1974; Chou, 1978).

In addition to constraining the dynamical processes involved in the construction of the rocky planets, it is equally important to assess the origins and chemical nature of the materials from which the planets were built. Comparisons of the bulk compositions of the terrestrial planets have commonly been made on the basis of chemical models developed for these planetary bodies, most notably the Earth, Moon, and Mars; that is, bodies from which we are reasonably confident we have samples. Such models often require the assumption that the bodies were constructed from a combination of materials that were compositionally similar to the primitive meteorites present in our collections (Wänke and Dreibus, 1988; Wänke et al., 1994; McDonough and Sun, 1995; Wänke, 2001; Taylor et al., 2006). The bulk planetary concentrations of a number of poorly-constrained elements have been estimated by applying bootstrapping methods which assume that the ratios of these elements to relatively well-constrained, geochemically-comparable major elements, are similar to the ratios observed in primitive meteorites (e.g., McDonough and Sun, 1995). Models of the chemical composition of inaccessible planetary reservoirs, such as Earth's core, often require these types of general assumptions (McDonough, 2003). Of course, it is unlikely that our meteorite collections sample the full compositional range of primitive materials involved with planetary accretion. Thus, some limitations in bootstrapping methods must be recognized. To circumvent this problem when assessing the compositions of some elements in inaccessible planetary reservoirs, such as cores, abundances can also be estimated by reverse modeling, using known or assumed mantle concentrations, and applying appropriate metal–silicate distribution coefficients. Models of this type, however, must make assumptions about the conditions of progressive metal–silicate segregation in a growing body (e.g., Rubie et al., 2011).

The chemical and genetic makeup of the rocky planets can potentially be further constrained by isotopic comparisons to one another and to primitive meteorites. For example, planetary materials exhibit a large range in mass independent variations in $\Delta^{17}\text{O}$ (the *per mil* deviation in $^{17}\text{O}/^{16}\text{O}$ from the terrestrial fractionation line), which can be used as genetic fingerprints of precursor materials. It has been hypothesized that the heterogeneities in $\Delta^{17}\text{O}$ originated as a result of self-shielding effects in the photo-dissociation of CO by exposure to ultraviolet light within the solar nebula (e.g., Thiems and Heidenreich, 1983; Clayton, 2002; Lyons and Young, 2005). Variations in $\Delta^{17}\text{O}$ among differentiated bodies have, therefore, commonly been interpreted to reflect the formation of precursor materials at greater or lesser distances from the Sun, possibly coupled with time of formation (e.g., Yurimoto and Kuramoto, 2004). As an example of the application of O isotopes to issues of genetics, the similarity in the $\Delta^{17}\text{O}$ of the Earth and enstatite chondrites has commonly been interpreted to indicate that the major building blocks of the Earth formed in a region of the protoplanetary disk similar to where enstatite chondrites formed (Clayton et al., 1984; Javoy et al., 2010). Conversely, differences in the $\Delta^{17}\text{O}$ compositions of the Earth and Mars have been cited as evidence that the building blocks of these two bodies differed substantially (Franchi et al., 1999). Although there appears to be no perfect fit of all physical parameters between any types (or likely any combination of types) of primitive meteorites and the Earth, Moon or Mars, constraining the general categories of accretionary materials, nevertheless, remains an important objective of cosmochemistry.

Here, we focus mainly on the final ~10 to ~≤0.05 wt.% of Earth's accretion. Late stages of major terrestrial planetary accretion may have included the participation of materials that formed in different portions of the protoplanetary disk, and included water- and organic-rich materials (Weidenschilling et al., 1997; Chambers, 2001, 2004). Thus, although limited in mass, late stage planetary growth may have had a disproportionate effect on the volatile contents of the rocky planets (e.g., Kerridge, 1985; Balsiger et al., 1995; Eberhardt et al., 1995; Albarede et al., 2013; O'Brien et al., 2014; Rubie et al., 2015a). Further, late stage additions may have carried genetically distinct elemental and isotopic fingerprints. Here we use the term *genetic* to mean chemical and especially isotopic compositions of the primary nebular materials from which an object was built. Because of the comparatively limited mass contributed by these processes, elemental and isotopic tracers comprising major elements, such as O, are of limited value in constraining the nature of these final building blocks. Thus, we will instead explore the possibility of tracing the late-stages of planetary growth using insights gained from elemental and isotopic variability of so-called *siderophile*, or Fe-loving, elements.

In this overview, the elemental and isotopic fingerprints of late stage building blocks that may be recorded in mantle rocks from the Earth, as well as mantle-derived and impact generated rocks from Mars and the Moon, respectively, will be examined. In addition to considering the average elemental and isotopic characteristics of siderophile elements contained in the silicate portions of these bodies, we will also explore the possibility that the signals of individual building blocks might be identified through small differences in the isotopic compositions of the siderophile elements Ru and Mo, which varied among early solar system materials as a result of their incorporating differing proportions of diverse nucleosynthetic components. The basis for this optimism is the discovery that primordial mantle heterogeneities, recorded by lithophile, atmophile and siderophile short-lived radiogenic isotope systems, survived long enough to be preserved in the terrestrial rock record (Caro et al., 2003; Willbold et al., 2011; Mukhopadhyay, 2012; Touboul et al., 2012, 2014). If the interpretations of long-lived chemical/isotopic heterogeneity in the mantle presented by these studies are correct, isotopically distinct domains within the mantle, imparted during late stage accretion of genetically distinct materials, might also be preserved in the rock record.

2. Overview of siderophile elements

Siderophile elements are those elements that strongly partition into liquid metallic Fe relative to silicate melt, and are consequently concentrated, to greater or lesser extents, in the cores of the rocky planets (Goldschmidt, 1937). Because of this, their concentrations in silicate mantles and crusts are low compared to primitive meteorites, the compositions of which are presumed to be representative of the majority of the planetesimals involved in the final stages of rocky planet accretion (Anders and Grevesse, 1989). Siderophile trace elements are commonly divided into sub-groups based on the intensity of their siderophilic tendencies under the typical 1 atmosphere experimental conditions initially employed to characterize the nature of metal–silicate partitioning of these elements (e.g., Kimura et al., 1974; Borisov et al., 1994). The moderately siderophile elements (MSE), including W, Co, Ag, Ni, Ge, and Mo, are characterized by metal–silicate D values (concentration ratio of an element in liquid metal to liquid silicate) ranging from about 10 to 1000. The highly siderophile elements (HSE), including Re, Os, Ir, Ru, Pt, Rh, Au and Pd, are characterized by D values greater than 10,000.

One important characteristic of siderophile elements is that the intensity of their siderophilic behavior can shift considerably at increasingly higher temperatures and pressures (e.g., Ringwood, 1966; Murthy, 1991; Li and Agee, 1996, 2001; Holzheid et al., 2000). The general tendency of most, but not all, siderophile elements is towards lower D values, as pressure and temperature conditions increase (Righter and Drake, 1997; Mann et al., 2012). Their partitioning characteristics are

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