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A two-stage scenario for the formation of the Earth's mantle and core

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ABSTRACT

Various geophysical constraints on the deep Earth point to a chemically heterogeneous mantle. Based on such constraints, Bulk Earth compositions inferred from Enstatite chondrites (E-Earth composition) predict that, whereas the Primitive Upper mantle (PUM) had a pyrolitic composition, the Primitive Lower mantle (PLoM) was enriched in Fe and Si. In E-Earth formalism, this chemical heterogeneity is related to the formation and differentiation of the Early Earth, and mantle Si and Fe variations reflect variations in the efficiency of Si and FeO dissolution in the metal phase during core formation. In the simplest scenario of homogeneous accretion, we calculate by mass balance the composition and the mass fraction of the metallic extract in equilibrium with a pyrolite. The O, Si and Ni contents of this metal extract correspond to a silicate-metal equilibrium at high pressure (50 ± 5 GPa) and high temperature (3500 ± 500 °C), in line with a giant impact scenario. Mass balance calculations then yield the composition of the proto-core and the proto-mantle prior to the giant impact. We obtain that the core of the proto-Earth was almost devoid of oxygen, hence formed under lower pressure and temperature conditions, in agreement with an early differentiation of planetesimals in the early solar system. In such a two-stage scenario of Earth's core formation, no massive silicate differentiation is required to create a pristine mantle heterogeneity. The concentration of lithophile elements in the Primitive Lower mantle can then be constrained using RLE ratios in E-chondrites and in the upper mantle.

1. Introduction

The bulk composition of the Earth, which is related to the conditions of its accretion and differentiation, bears major consequences for its early and present dynamics (e.g., Tackley, 2012). In particular, the existence of a primitive chemical heterogeneity between the upper and lower mantle will exert a strong control on the thermal evolution of the planet and the efficiency of reservoir-mixing through thermo-chemical convection (e.g., Davaille, 1999; McNamara and van Keken, 2000; Tan and Gurnis, 2007; Deschamps et al., 2011).

The composition of the Primitive Upper mantle (PUM) can be inferred solely from the composition of basalts and peridotites (Ringwood, 1975), and eventually be improved by the use of constraints brought by primitive chondrites, such as the ratio of refractory lithophile elements (RLE) (e.g., Jagoutz et al., 1979; Hart and Zindler, 1986; McDonough and Sun, 1995; Lyubetskaya and Korenaga, 2007). The resulting composition defines a theoretical rock, the pyrolite, which allows a reasonable fit of the geophysical constraints of PREM (Preliminary Reference Earth Model, Dziewonski and Anderson, 1981) to a maximum depth of about 400 km (Cammarano and Romanowicz, 2007). Seismic properties of the pyrolite at higher pressure and temperature would match the PREM velocity profiles only for a *super*-adiabatic geotherm (Matas et al., 2007). However, a chemically homogeneous convective system heated from within has a slightly *sub*-adiabatic thermal profile (Parmentier et al., 1994; Sotin and Labrosse, 1999). Since density and sound velocity experimentally determined in pyrolite at high pressure and high temperature do not match PREM, the composition of the mantle at depth may be significantly different from a pyrolite (Ricolleau et al., 2009; Murakami et al., 2012).

Geophysical methods, particularly seismic tomography, can be used to confirm the existence of chemical heterogeneities in the mantle, and even to give their gross repartition (e.g., Li and Romanowicz, 1996; Ishii and Tromp, 1999; Trampert et al., 2004; Lekic et al., 2012). Recycled MORB (Mid-Oceanic Ridge Basalts) can form stable reservoirs at the base of the mantle (e.g., Samuel and Farnetani, 2003; Xie and Tackley, 2004), but the recent modeling of Deschamps et al. (2012) indicates that they cannot explain low shear-wave velocity provinces. Furthermore, Samuel and Tosi (2012) have shown that the presence of "weak" post-perovskite (ppv) significantly increases mixing efficiency in thermo-chemical convection. Since ppv may appear only in the cold lithospheric plates in

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the D″ layer (Grocholski et al., 2012) and not in the surrounding mantle, this effect may render the MORB reservoir less stable. Noble gases also confirm the presence of an undegassed primitive reservoir at depth (e.g., Moreira et al., 2001; Marty, 2012; Mukhopadhyay, 2012). The existence of a primitive reservoir, enriched in Fe and SiO_2, is then a good way to consistently account for the present day seismic characteristics of the lower mantle (e.g., Kaminsky, 2012; Deschamps et al., 2012; Murakami et al., 2012). However, geophysical methods by themselves are not sufficient to quantify thoroughly the composition of the lower mantle, because of the entangled influence of temperature and composition (Fe, Si content) on seismic properties (Deschamps and Trampert, 2004; Deschamps et al., 2007), or the limited impact on them of some elements (Al, Ca) (Matas et al., 2007).

The "E-Earth" geochemical model of Earth composition of Javoy (1995) and Javoy et al. (2010) proposes that the Earth composition is similar to the bulk composition of a sulfur-free Enstatite chondrite (E-chondrite), based on the isotopic similarities between E-chondrites and the Earth's mantle (e.g., Regelous et al., 2008; Trinquier et al., 2009; Moynier et al., 2010; Gannoun et al., 2011; Warren, 2011). This model uses a pyrolitic composition for the Primitive Upper mantle (PUM) only, and includes additional geophysical constraints on the amount of light elements in the core as well as the results of the ab initio calculations of Alfè et al. (2002). It provides, by mass balance, the composition of the Primitive Lower mantle (PLoM). The composition of the PLoM is characterized by an increase of Fe and Si at depth, as required by seismic data (Deschamps et al., 2012), together with a decrease of Mg, Ca and Al. The resulting decrease of the Mg/Si ratio in the lower mantle is consistent with the PREM inversion performed by Matas et al. (2007).

E-Earth models provide a stringent framework to model the formation and differentiation of the Earth. Javoy (1995) described a simple way to generate the Primitive Upper/Lower mantle differentiation from a single bulk composition, and established the equation governing that differentiation. However, the lack of reliable experimental data at that time on the solubility of key light elements (Si, O, S) in Fe–Ni alloys at very high temperature and pressure did not allow then a definitive test of the model predictions in terms of accretion and differentiation scenarios for the Earth. Such data are now available (Asahara et al., 2007; Corgne et al., 2008; Bouhifd and Jephcoat, 2011; Siebert et al., 2012) and can be incorporated into a complete model of E-Earth formation (e.g., Wade and Wood, 2005). The output of the model can then be confronted to various scenarios which have been proposed for the differentiation of the Earth, such as a chemical evolution of the accreting material in the course of accretion (e.g., Wänke and Dreibus, 1988), or some petrological differentiation between the upper and lower mantle (e.g., Liebske et al., 2005). The aim of this paper is to show that, within the framework of E-chondrite model, it is possible to form the Earth with an accreted material of constant composition, while producing a chemical contrast between the lower and upper mantles through a variation of P,T conditions of metal extraction during the formation of the core. A two-stage scenario, first with a proto-core formed at relatively low pressure and temperature, then a pyrolitic upper mantle resulting from a HP–HT giant impact episode, is shown to be able to account for all the chemical characteristics of the E-Earth.

2. Formation of a pyrolitic upper mantle from an "E-chondrite" bulk Earth

2.1. A model for metal–silicate separation in the E-Earth

The baseline of the E-Earth model is that the bulk composition of its building material corresponds to the composition of a sulfur-free Enstatite chondrite. This means in particular that there is no (or little) oxidized Fe in the material falling on Earth during accretion, and that an internal iron-oxidation mechanism is required to produce the present day iron content of the Bulk Silicate Earth (Javoy, 1995).

A sulfur-free Earth material composition can be derived from E-chondrite composition by a moderate temperature increase, leading to reactions such as (Javoy et al., 2010)

$$3MgSiO_3 + CaS + 0.5O_2 \rightarrow CaMgSi_2O_6 + Mg_2SiO_4 + 0.5S_2, \quad (1)$$

$$FeS \rightarrow Fe + 0.5S_2. \quad (2)$$

Table 1 gives the sulfur-free bulk composition of the Earth's Building Blocks (EBB) obtained from Javoy et al. (2010), as well as their metal and silicate fractions compared to those of the Primitive Upper mantle (PUM). As noted in Javoy et al. (2010), the model composition of the sulfur-free E-chondrite corresponding to the Earth composition is intermediate between EH chondrites (high Fe content) and EL chondrites (relatively high Mg content). The composition of the EBB silicate phase is different from both the primitive upper (PUM) and lower (PLoM) mantles of Javoy et al. (2010), notably because it is devoid of FeO and too rich in Silica. Hence, the pyrolitic Primitive Upper mantle shall result from the FeO enrichment of the EBB silicate phase through silica reduction by metal Fe and dissolution of the resulting Si into the metal (hereafter metal extract).

Following the approach of Javoy (1995), we consider that the differentiation of the E-Earth can be modeled as the fractionation of the different elements between a silicate phase and a sinking metal extract. An incoming mass flow rate of EBB $(1+f)\,dm/dt$ splits into a fraction $f\,dm/dt$ of sinking metal and a fraction dm/dt of "floating" silicate. The equation of Javoy is written as

$$\frac{d(mC)}{dt} = C_0(1+f)\frac{dm}{dt} - KCf\frac{dm}{dt}, \quad (3)$$

where C is the concentration of an element in the silicate, C_0 its concentration in the EBB, and K the "effective" silicate/metal partition coefficient of the element. For lithophile elements (Mg, Ca, Al) $K=0$, whereas, for the elements partitioned between metal and silicate (Fe, Ni, Si, O), K will reflect the P,T conditions of metal extraction.

The simplest solution of that differential "filtration" equation is the time-independent steady state solution written as

$$C_\infty = \frac{C_0(1+f)}{1+Kf}, \quad (4)$$

where C_∞ is the concentration of the element in the silicate phase at steady state. In the following, we make the hypothesis that the Primitive Upper mantle results from such a steady state metal extraction, hence, that the concentration C_∞ is the concentration of the element in the pyrolite. Because we do not want to fix a priori the P,T conditions that prevailed during this stage, we apply the minimum a priori constraints on K for Fe, Ni, Si and O: for Ni, Si and Fe, we consider about twice the range of variation allowed

Table 1
Composition (wt%) of the Primitive Upper mantle (PUM) and of the Earth's Building Blocks (EBB) and their metal and silicate phases (from Javoy et al., 2010). The metal phase represents 34.8 ± 0.51% of the Bulk Earth.

Element	PUM	EBB bulk	EBB silicate	EBB metal
Mg	23.8 ± 0.68	14.7 ± 0.32	23.0 ± 0.54	–
Al	1.90 ± 0.32	0.87 ± 0.19	1.33 ± 0.30	–
Si	21.4 ± 0.51	18.2 ± 0.30	26.5 ± 0.49	1.91 ± 0.83
Ca	2.03 ± 0.34	0.92 ± 0.20	1.42 ± 0.30	–
Fe	6.31 ± 0.41	32.5 ± 0.36	0.44 ± 0.45	92.7 ± 1.08
Ni	0.20 ± 0.02	1.87 ± 0.26	–	5.39 ± 0.74
O	44.4 ± 0.20	30.82 ± 0.24	47.3 ± 0.21	1.99 ± 0.46