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Silicate melts during Earth's core formation

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ABSTRACT

Accretion from primordial material and its subsequent differentiation into a planet with core and mantle are fundamental problems in terrestrial and solar system. Many of the questions about the processes, although well developed as model scenarios over the last few decades, are still open and much debated. In the early Earth, during its formation and differentiation into rocky mantle and iron-rich core, it is likely that silicate melts played an important part in shaping the Earth's main reservoirs as we know them today.

Here, we review several recent results in a deep magma ocean scenario that give tight constraints on the early evolution of our planet. These results include the behaviour of some siderophile elements (Ni and Fe), lithophile elements (Nb and Ta) and one volatile element (Helium) during Earth's core formation. We will also discuss the melting and crystallization of an early magma ocean, and the implications on the general feature of core-mantle separation and the depth of the magma ocean. The incorporation of Fe^{2+} and Fe^{3+} in bridgmanite during magma ocean crystallization is also discussed. All the examples presented here highlight the importance of the prevailing conditions during the earliest time of Earth's history in determining the composition and dynamic history of our planet.

1. Introduction

Silicate melts have played an important role in Earth's evolution from the core formation 4.5 billion years ago to present-day volcanic activity. Modern planetary formation models show that terrestrial planets likely formed through three modes of growth that were ordered in time in the protoplanetary disk. In step I, km-sized planetesimals formed by the coagulation of gas and dust in less than ~10^4 years. In step II, the collisional evolution of the planetesimals population led to the growth of Moon to Mars-sized planetary embryos formed by runaway growth through collisions among the planetesimals in <10^6 years. In step III, giant collisions among the planetary embryos resulted in the formation of a few terrestrial planets that swept up all the other bodies. This stage may have taken up to ~10^8 years (e.g. Chambers, 2004; Morbidelli et al., 2012). At least step II and step III were energetic enough to have likely melted a large fraction of the silicate Earth (e.g. Canup, 2012). Theory and observations point in fact to the occurrence of magma oceans in the early evolution of terrestrial planets and in many planetesimals (e.g. Greenwood et al., 2005; Elkins-Tanton, 2012). In addition a magma ocean scenario provides a favorable environment in which metal-silicate segregation can occur rapidly and efficiently (e.g. Stevenson, 1990).

It is now well established that for metal and silicate to segregate rapidly on a planetary scale requires that at least the metal is molten (Stevenson, 1990). On the other hand, when the silicate is also largely molten, liquid metal can segregate extremely efficiently (e.g. Rubie et al., 2003). The short time scale of Earth's core formation, ranging from 30 to 100 Ma after the beginning of solar system accretion (e.g. Kleine et al., 2009) can be also used as an indirect evidence for large scale melting during the first 100 Ma of Earth's history. There are three main sources of energy that can produce the melting that is required for core formation: (1) the decay of short-lived radioactive nuclides (^{26}Al and ^{60}Fe) during the first 1–3 Ma of the solar system evolution (Yoshino et al., 2003); (2) the energy delivered by impacts that can generate local or global melting especially during the late stages of Earth accretion (Tonks and Melosh, 1993); (3) the conversion of potential energy into heat via viscous dissipation during the segregation of the metallic phase that can increase the silicate temperature by 1000–3000° (Ke and Solomatov, 2009; Monteux et al., 2009; Samuel et al., 2010; more details can be found in the review paper by Rubie et al., 2015b).

Melting events are common in the first stages of Solar System history and start very rapidly after the beginning of solar nebula condensation, dated at 4.567–4.568 Ga, age of refractory inclusions, known as CAIs (see Amelin et al., 2002; Bouvier and Wadhwa, 2010; Connelly et al., 2012). Oldest ages measured in iron meteorites show that metal-silicate separation began on planetesimals within 1 to 1.5 Ma of the start of

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Solar System formation (Kruijer et al., 2012, 2014). The study of basaltic achondrites (angrites, eucrites) coming from different parent bodies shows that small planetesimals have experienced magma ocean stages during the first million years of their history (e.g. Brennecka and Wadhwa, 2012; Touboul et al., 2015). This chronology shows that the building blocks of forming planets implied mainly differentiated objects instead of primitive and undifferentiated materials. In planets, the last stages of accretion end with very large collisions. The most spectacular event for Earth corresponds to the Moon-forming giant impact event. The study of short-lived systematics in terrestrial samples gives evidence for successive magma-ocean stages on Earth. Noble gas systematics trace the mantle's degassing and the Xenon isotope signature is consistent with extensive loss of volatile elements within the first 100 Ma of Earth's existence (Allègre et al., 1983; Yokochi and Marty, 2005; Mukhopadhayay, 2012). The high ^{3}He/^{22}Ne fractionation observed in the Earth's mantle suggests at least two separate magma ocean steps during the Earth's accretion (Tucker and Mukhopadhyay, 2014). Excesses in ^{182}W (produced by the decay of ^{182}Hf) measured in 2.7 Ga-old komatiites are explained by a large-scale magmatic differentiation during the first 30 Ma of the Solar System's history (Touboul et al., 2012). Since the giant Moon-forming impact is dated between 40 and 200 Ma (Boyet et al., 2015 and references therein), this collision may not have induced a complete homogenization of the Earth's mantle. The combined measurements of ^{146,147}Sm-^{142,143}Nd systematics of undisturbed Eoarchean metabasalts (from the southwestern part of Greenland, Isua Supracrustal Belt) suggest differentiation of the mantle source at ~4.47 Ga (Rizo et al., 2011). Chemical fractionation would have occurred during the crystallization of a large magma ocean which extended down into the lower mantle. This chronology is consistent with the presence of zircon formed in a terrestrial crust at ~4.4 Ga (Wilde et al., 2001; Valley et al., 2014).

Concerning the Earth one of the most important events during the first 100 Ma is the segregation of the metallic core. Among the several uncertainties about the formation of the Earth and other planets, the physical conditions upon which Earth differentiated are important questions that remain much debated. Evidence on the earliest times on Earth comes mainly from two sources: (1) The concentrations of core-forming elements left behind in the silicate part provide a fingerprint on the conditions under which this segregation occurs. (2) The Moon is the second important source of evidence, it is believed to have formed after the Earth's core formation as a result of a giant impact between Earth and a Mars-size body (named Theia) (Hartmann and Davis, 1975; Tonks and Melosh, 1993). The magma oceans were reservoirs where partial to complete equilibrium and segregation of the metallic phase from the impactor and the silicate phase from the target were likely to occur (Rubie et al., 2003). The thermo-chemical exchanges that occurred in the magma oceans have strongly influenced the geochemical signature within the current deepest parts of the Earth. Hence they play a key role on how we constrain the differentiation processes in terms of characteristic timescales, P - T conditions or redox conditions. The metal silicate separation processes and especially the characteristic volumes that are involved (cm-droplets to km-diapirs) during the core formation govern the degree of chemical equilibration between the mantle and the core of the Earth (Samuel, 2012; Wacheul et al., 2014). During the latest stages of planetary accretions the large impactors were probably differentiated. After a collision, the impactor's core is assimilated into the partially to completely molten mantle leading to a first fragmentation due to the impact itself. This first fragmentation is poorly constrained but it is the starting point of the second fragmentation that is likely to occur within the turbulent magma ocean. During these two stages of fragmentation, the impactor's core was potentially fragmented down to cm-size droplets (Rubie et al., 2003). If the impactor's core was completely emulsified in droplets ("iron rain scenario"), the thermo-chemical exchanges between the metallic phase from the impactor and the silicates from the magma ocean were extremely efficient (Rubie et al., 2003). Many geochemical models are based on this "iron rain scenario". However, after a large impact, the emulsification of the impactor's core might be incomplete and large volumes of iron may sink without experiencing a complete equilibration with the mantle they are passing through (Dahl and Stevenson, 2010). In this case, a limited fraction of the mantle could equilibrate with the metallic phase. This could explain the relatively high abundance of highly siderophile elements of the terrestrial mantle that should have efficiently segregated into the core. Recently, laboratory experiments have constrained the mixing (Deguen et al., 2011, 2014) and the fragmentation dynamics (Wacheul et al., 2014) during the sinking of a metallic volume within a magma ocean. Wacheul et al. (2014) showed that there was a wide range of metallic droplet sizes and shapes as well as important interactions within the sinking metal cloud in which fragmentation and coalescence events are superimposed. For the first time, Wacheul et al. (2014) have estimated the influence of the viscosity contrast between liquid iron and the liquid silicates and showed that a large viscosity contrast favors large-scale diapirs. The characteristic size (that governs the sinking velocity) and the shape of the metallic droplets (that governs the exchange surface) are both key parameters to anticipate the degree of equilibration of any chemical element within a magma ocean (Rubie et al., 2003). This degree of equilibration is a strong function of the partition coefficient of each element considered (Deguen et al., 2014).

In summary, the Earth accreted over a period of at least 100 Ma with several magma ocean episodes. During this period the main part of core formation process occurred. In this paper we will review results involving exchanges between molten silicate and metal liquid during the first 100 Ma that give rise to strong constraints on the evolution of our planet. This review includes the conditions of the Earth's core formation determined from the behaviour of some siderophile elements (Ni and Fe) and lithophile elements (Nb and Ta). Recent results also show that the early core could have incorporated enough helium to supply deep-rooted plumes with high ^{3}He/^{4}He ratios throughout the age of the Earth. We will discuss the melting and crystallization of an early magma ocean, and the implications on the general feature of core-mantle separation and the depth of the magma ocean. We will also discuss the incorporation of Fe^{2+} and Fe^{3+} in bridgmanite during magma ocean crystallization.

2. Conditions during Earth's core formation

2.1. Constraints from siderophile elements

The knowledge of the pressure, temperature and oxygen fugacity (f_{O2}) conditions prevailing during Earth's core formation is derived mainly from the behaviour of the siderophile elements (iron loving elements) that are depleted in the mantle. In this context, the behaviour of Ni and Co has been considered to provide an important clue, both being refractory elements and present in the Earth's mantle in a near-chondritic Ni to Co ratio (Newsom, 1990). In addition, Ni and Co are almost identical to Fe in cosmochemical volatility (Grossman, 1972; O'Neill and Palme, 1998). By using all existing data of metal – silicate partitioning of Ni and Co the consensus at the present time is that metal-silicate equilibration at high pressures, in the range of 40–60 GPa (corresponding to depths of 1000–1500 km), was required to produce the observed Ni and Co depletions in the mantle (see: Bouhifd and Jephcoat, 2011; Righter, 2011; Fischer et al., 2015; Siebert et al., 2012; for the most recent studies). Similar conclusions were reached based on the metal-silicate partitioning of lithophile and weakly-siderophile elements (Mann et al., 2009; Siebert et al., 2011). One should note here that the conditions of Earth's core formation derived from metal-silicate partitioning of siderophile elements cannot be used as arguments for single-stage core formation as this is highly unlikely considering that Earth's core formation occurred during a series of large impact events (e.g. Canup, 2008; O'Brien et al., 2006; Morbidelli et al., 2012; Wetherill, 1985). Such impacts added Fe-rich