Revision 1

American Mineralogist Special Collection:

BUILDING PLANETS

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ABSTRACT

The Special Collection "Building Planets: The dynamics and geochemistry of core formation" aims to combine cutting edge experimental, analytical and modeling results with review articles defining the state of the science and current challenges to our understanding of the origin, geophysics and geochemistry of planetary cores. Our goal is to highlight novel and interdisciplinary approaches that address aspects of core formation and evolution at the atomic, grain, and planetary scales.

INTRODUCTION TO THE SPECIAL COLLECTION

A common attribute of the terrestrial planets is the existence of a metallic core surrounded by a silicate mantle. The segregation of metal from silicate in early, undifferentiated material is one of the most important steps in the evolution of terrestrial solar system bodies. The separation of Fe-rich metal from a magnesium silicate matrix imparted a strong geochemical signature on early silicate mantles due to the preferential incorporation of siderophile, (metal-loving), elements into the core. However, estimating the bulk silicate Earth (BSE) composition and that of other terrestrial bodies by way of candidate planetary bulk compositions requires not only an understanding of its timing and the associated geochemical ramifications, but the knowledge of the physical core forming process under different conditions (O'Neill & Palme, 1998, Yin et al., 2002; Rudge et al., 2010; Rubie, et al., 2007; 2011).

Core formation on Earth occurred simultaneously with the accretion process and was complete within about 30-100 million years of the beginning of the solar system (e.g. Lee and Halliday, 1997; Yin et al. 2002; Kleine et al. 2002). Some smaller bodies (<100km) may have formed their cores entirely through the percolation of metallic liquids through a solid silicate mantle, but planets as large as Earth likely experienced significant melting that aided efficient segregation of the core from the mantle (eg. Stevenson, 1990; Karato and Murthy, 1997; Solomatov, 2000; Rubie et al., 2003; Canup, 2008; Elkins-Tanton, 2012). Although some aspects of this process are well established, there are still important open questions regarding the details of core formation both geophysically and geochemically. The suggestion of an early magma ocean on Earth has persisted for decades (e.g. Stevenson, 1990; Abe and Matsui, 1986; Dahl and Stevenson, 2010; Rubie et al. 2011) and is supported by both geophysical and geochemical evidence. The heat supplied to Earth by a combination of impacts, radioactive decay by short lived isotopes such as ^{26}Al and ^{60}Fe, thermal blanketing effects of a dense atmosphere, and gravitational energy from metal segregation was sufficient to melt large portions of the Earth early in its history. In particular, the energy supplied by the large moon-forming impactor may have melted a substantial portion of the entire mantle (i.e. Tonks and Melosoh 1993; Canup, 2004; Halliday, 2004). Geochemical arguments for a terrestrial magma ocean are derived from the abundance of siderophile elements in the Earth's mantle, and their experimentally determined partition coefficients between molten silicate and liquid metal at high pressures and temperatures (e.g. Li and Agee, 1996, 2001; Righter et al. 1997; Righter and Drake, 1999; Chabot et al. 2005; Cottrell et al. 2009; Righter 2011; Siebert et al. 2012). Based on these two basic lines of evidence, a basic view of the magma ocean scenario for core formation evolved. In this simplest scenario, a significant portion of the accreting, chondritic, Earth is melted, creating a deep magma ocean with heat supplied from impacts, radioactive decay and metal infalling. New accreting material has a roughly chondritic composition, and is fully melted and incorporated into the deep magma ocean on impact. The metallic and silicate components in the magma ocean are emulsified, and small, immiscible droplets of metallic liquid "rain down" through the magma ocean, maintaining chemical equilibrium with the silicate as they fall. Upon hitting a rheological boundary, defined by the mantle liquidus and assuming a short liquidus/solidus interval, the metallic droplets pool together, forming a liquid metal pond, and record this as the pressure, temperature and *f*O2 conditions of their last equilibration with the mantle. Once a sufficient mass of liquid metal has ponded at the top of the solid mantle, due to a Rayleigh-Taylor instability it descends through the solid portion of the mantle as large diapirs. The diapirs settle into the core at a fast enough rate that they do not further equilibrate with the surrounding mantle, especially because equilibration would be rate limited by extremely slow diffusion within the solid silicate minerals.

Over the past several years, much effort has been put forth to model this magma ocean scenario from both a geochemical and geodynamic perspective, and results have indicated that the true process is likely much more complex than the proposed single-stage model described above. Recent high pressure/high temperature experiments on metal/silicate partitioning of some important siderophile elements such as Ni, Co (pressure dependent) and V (temperature dependent) tend to place the base of the magma ocean (or the mantle liquidus/solidus interval) at a pressure of between 25-60 GPa and temperatures ranging from 2000^{o}C to above 3800^{o}C with varying light element compositions of the core (e.g. Corgne et al. 2009; Siebert et al. 2011, Bouhifd and Jephcoat, 2011, Righter 2011; Ricolleau 2011). Satisfying the observed mantle abundances of *all* the siderophile elements with one set of P/T/fO_2 conditions has been problematic (i.e. Siebert et al. 2011), and some researchers have called upon additional inputs such as a late veneer (e.g. Holzheid et al. 2000; Brenan and McDonough, 2009) or variable oxidation conditions (Wood et al. 2006, Rubie et al. 2011) to help satisfy these constraints.

An additional impediment to the single stage magma ocean hypothesis arises from geodynamic arguments. Although the scenario described above implicitly assumes total equilibration of the silicate mantle with core forming melts, this may not have been the case. New models of accretion dynamics suggest that it is possible to produce the same siderophile and isotopic signatures in the mantle with as little as 36% equilibration of previously differentiated planetesimals contributing to the accretion of the Earth (e.g. Rudge et al. 2010, Dahl and Stevenson, 2010). Rudge et al. (2010) suggest that the cores of large pre-differentiated planetesimals may quickly join the Earth's protocore after impact, and minimally communicate with the surrounding mantle. Further complicating matters, they state that it is impossible to determine the degree of equilibration strictly from geochemical arguments.

Beyond the ambiguities introduced with regard to geochemical and dynamical constraints suggested above, new high pressure mineral physics data have also pointed away from the simple model of a single stage magma ocean. Andrault et al. (2010) present high pressure experimental data on the liquidus and solidus of chondritic mantle material at conditions up to the core mantle boundary during the stage of accretion and differentiation. They suggest that the majority of the mantle may have only been in a partially molten state during the period of core formation as the solidus-liquidus interval ranges from approximately 5GPa to 50 GPa along their proposed mantle geotherm. Having a partially molten mantle, corresponding to their model geotherm, would allow for a sustained, slowly cooling magma ocean with a reasonable surface temperature and could still explain most of the siderophile element abundances.

The presence of a partially molten magma ocean introduces complexity regarding the *physical mechanisms* of metal segregating from the silicate. The presence of a significant volume fraction of silicate solids within a magma ocean may impede the ability for metal to flow. There have been many experimental and theoretical studies aimed at understanding the fluid dynamics and physical mechanisms of metal segregation in scenario with a completely molten magma ocean followed by diapiric descent through a solid lower mantle (Solomatov 2000; H. Samuel and Tackley 2008; Golabek et al. 2008; Dahl and Stevenson 2010, Sramek et al. 2010). On the opposite end of the spectrum, there have also been several studies aimed at describing metallic liquid segregation through a completely solid silicate matrix (e.g. Minarik et al. 1996, Shannon and Agee, 1996; Bruhn et al. 2000; Yoshino et al. 2003, 2004; Terasaki et al. 2008; , Takafuji et al. 2004; Rushmer et al. 2005; Hustoft and Kohlstedt 2006, Groebner and Kohlstedt 2006, Roberts et al. 2007, Bagdassarov et al. 2009; Watson and Roberts 2011). However, there have been relatively few studies that address the behavior of core forming liquids in a partially molten silicate (e.g. Yoshino and Watson, 2005, Holzheid et al. 2000).

As mentioned above, dynamic models that aim to explain a variety of chemical and isotopic signatures on Earth, propose that early differentiation in *planetesimals* (up to Mars-sized impactors in size) have a critical role to play in controlling Earth's subsequent bulk composition. The accretion of these bodies to the early Earth created an environment where incomplete mixing and changes with time occurred as the cores of the smaller bodies were already formed (Halliday, 2004; Rudge et al., 2010; Rubie et al., 2011). In these models, impact of already differentiated planetesimals to the Earth's surface may be initially emulsified but as the impactors grow in size (along with the early Earth) their cores may not fully integrate with core formation processes occurring on the growing planet and may lead to a degree of chemical disequilibrium (Halliday, 2004; Rudge et al., 2010; Rubie et al., 2011).

Therefore the question of extent of core material equilibration with the silicate mantle is vital. Isotopic studies have now also provided additional timing constraints and have determined that the age of magmatic irons, which are considered to represent cores of planetesimals, appear virtually indistinguishable from the age of CAIs (Calcium Aluminium Inclusions) and of the solar system itself (Kleine et al., 2009; Carlson and Boyet, 2009). Core formation in these growing planetesimals must have occurred rapidly. These new data sets are requiring physical models that allow core fluid to migrate quickly. A complete understanding the physical mechanisms and rates of metal segregation and their geochemical consequences, remains one of our most outstanding questions in early terrestrial planet evolution.

Core formation scenarios in growing planetesimals include a variety of possible segregation mechanisms for separating metal from silicate, such as percolative flow (Balhaus and Ellis, 1996; Roberts et al., 2007 and Teraski et al., 2008; Rushmer and Petford, 2011), diapirism (Chen et al., 2009), and migration induced by deformation during high strain events (Bruhn et al., 2000; Rushmer et al, 2000; Groebner and Kohlstedt, 2006). Assessing and quantifying these different segregation mechanisms requires an understanding of metal-silicate separation at the granular level and a variety of experimental approaches have been taken to address metal liquid segregation, such as electrical conductivity (Yoshino et al., 2003, 2004), centrifuge (Bagdassarov et al, 2009) and, most recently, in situ x-ray tomography (Watson and Roberts, 2011; Todd et al., 2012). A current issue is that many early planetesimals may have undergone partially melting of the silicate matrix. Several numerical analyses of core formation in planetesimals conducted by calculating the heating of growing planetesimals by the decay of short-lived isotopes such as ^{26}Al and ^{60}Fe indicate that extensive melting may have occurred (Hevey & Sanders, 2006) even in small bodies. Hevey & Sanders (2006) modelled melting of growing, convecting, planetesimals by ^{26}Al decay and found that for planetesimals with radii of ~ 50km will melt up to 50% if they form within 1.5-

2 my of the solar system. In addition, isotopic studies of differentiated meteorites have shown geochemically that widespread silicate melting may have occurred and at the earliest stages of solar system formation (Baker, et al., 2005; Bizzaro et al., 2005). These results suggest that core formation in planetesimals not only occurs rapidly, but potentially in the presence of silicate melt. (In contrast to previous studies that suggested that small planetesimals never melted the silicate fraction, prompting studies of solid silicate/liquid metals pairs) The multi-faceted environment under which core formation occurs is clear, but the partially molten silicate matrix scenario has not had the same level of attention as the magma ocean model nor solid-silicate matrix systems in part due to the need to determine permeability and percolation processes in a more complex system with two fluid phases. Addressing metallic liquid in the presence of a silicate mush has thus far focused on surface energy changes observed texturally when silicate partial melting begins (eg. Rushmer et al., 2000; Yoshino and Watson, 2005).

In this Special Collection, we assemble a series of review articles and short contributions on the current issues and problems related to core formation on Earth and other planetary bodies that we are addressing today. It is our goal is to highlight novel and interdisciplinary approaches that address aspects of core formation and evolution at the atomic, grain, and planetary scales. Contributions to this volume broadly fall into one or more of the following emerging areas of research.

New Analytical Techniques:

New experimental technology (such as the large volume, high-pressure equipment, the advanced diamond anvil cells (DAC) capabilities combined with in-situ experiments using synchrotron high energy x-rays) has transformed the way we understand melting and melt migration in the metal-silicate system in both static and dynamic environments. This is particularly true of data collected in-situ, as the process can be captured in real time. The ability to directly sample the data under extreme pressure and temperature conditions by performing the experiments in the high-energy x-ray and then fully characterize the results with both traditional techniques, such as electron microprobe and laser ablation, and new techniques, such as electrical impedance and x-ray tomography has led to new results and developments in our understanding of core formation (eg. Siebert et al., 2012; Shi et al., 2013). Currently, the rise in synchrotron x-ray tomographic imaging has led to a significant increase in understanding of the distribution and nature of metal silicate systems. Three-dimensional datasets from synchrotron-based high-resolution hard x-ray microtomography have now provided access to information at the grain-scale at an unprecedented level. The datasets allow us the potential to answer fundamental questions, such as bulk strength in a metallic melt and silicate-bearing systems, as well as possibly discovering new mechanisms operating across different spatial scales, from the grain-size to the bulk material properties. Figure 1 is a 3D rendering of an ordinary chondrite (Kernouve) with FeNi and FeS highlighted. Virtual slices through the 3D object in any arbitrary direction can be visualized, or the full data set can be visualized by volume rendering. More importantly, automated image filtering and segmentation allows the extraction of boundaries between the various phases. The volumes, shapes, and distributions of each phase, and the connectivity between them, can then be quantitatively analysed, and these results can be compared to models. Recent results using this method have been shown by Rushmer et al., 2012; Todd et al., 2012; Shi et al., 2013.

Pushing the boundaries of P-T-composition space:

Core formation occurs under conditions that are inaccessible to traditional sample collection methods and only a few natural samples are available of the Earth's deep interior. As a result, experimental petrology has been the most widely applied technique to understand core formation and its impact on Earth's bulk silicate composition. As described above, over the last decade newly designed high-pressure apparatuses have revolutionized our ability to measure properties, in situ, at high pressures and temperatures and a new generation of experimental studies of metal liquid - silicate under deep-mantle conditions is emerging. This push to higher pressures and temperatures with the help of NSF-funded programs such as COMPRES, as also led to national synchrotron facilities being used for in-situ research. Developments in the area of DAC, coupled with intense synchrotron X-radiation, now permit the acquisition of X-ray diffraction data at extreme P–T conditions. Siebert et al. (2012) have continued their partitioning studies and now, through a series of laser-heated DAC experiments on Fe and Fe-Ni-Si with natural basalt or a well studied synthetic peridotite (KLB-1), have been able to extend our understanding of the partitioning of key elements Ni and Co, which are sensitive to fO_2. By combining their data with earlier work (Wade and Wood, 2005), the results help explain not only geochemical constraints on Ni and Co but also core density geophysical data. Our understanding of trace element behavior during core formation increases significantly with each of these state-of-the-art experimental studies.

Not only are the geochemical aspects being explored through these studies, but the physical nature of metal liquid in silicate can also be addressed. Recently, Shi et al. (2013) have used DAC to find that at high pressures (>50 GPa), percolation of liquid metal may be the dominant process for liquid metal migration in a silicate matrix at these high pressures. At lower pressures, melting of the silicate matrix is likely to be required for efficient core formation.

Meteorite studies

A major focus of meteoritics is to understand the range of materials present in the solar nebula and illustrate the processes that produce the solid bodies we observe today as planets, moons, asteroids and comets. Primitive achondrites are a broad class of meteorites that all have been partially melted to various degrees and they can provide insight into the early processes of core formation, although this application may be limited to the smaller bodies. An example is GRA 95209 which records metal silicate segregation and studies such as these can help us understand the earliest stages of core formation in asteroidal bodies. This lodranite preserves a complex texture and has physically, chemically and mineralogically complex metal-sulfide vein systems (McCoy et al., 2005). These meteoritical studies suggest that chemical disequilibrium is to be expected and chemical and isotopic homogenisation are likely only occur during large-scale melting events. Using natural material to study these processes provides an important link to experimental and numerical studies on core formation.

New (and complex) Modeling Ideas:

Currently, the main models of formation of the terrestrial planets are now becoming focused on the process of accretion. Models of accretion focus on the nature and number of collisions involving both small and large (Moon- to Mars-size) bodies. One clear consequence of the collisional accretion process is the energy released, which can cause large-scale melting and the formation of magma oceans. In the magma ocean scenario, liquid metal easily separates from silicate melt and can form the metallic cores of the planets, as described above, in addition to provided deformation which can trigger fracture and liquid metal migration. Core formation in terrestrial planets is now viewed as a multistage process and clearly closely linked to major collisions during accretion and ultimately determines the chemistry of bulk silicate Earth (eg Botke et al., 2006; Rubie et al., 2011)

Now, integrating astrophysical models of planetary accretion with meteoritics and geochemical models of planetary differentiation is likely the way forward to understanding the origin of the terrestrial planets.

BIG PICTURE THINKING (INTEGRATION OF GEOCHEMISTRY, GEODYNAMICS, AND GEOPHYSICS)

This Special Collection comes at a time when we need to synthesize the state of our understanding of the origin of Earth's core and the processes that have determined the bulk silicate Earth composition. To date, the view of core formation is becoming more complex and it is most likely a multi-stage process. If the later stages of core formation in the large terrestrial bodies can reset the geochemical signatures in the bulk silicate Earth, then we will need to further explore Earth's deep interior by a range of techniques. The integration of geochemistry, geodynamics and geophysics is required and several groups are beginning to do this. We plan several short contributions concerning the biggest questions the next 10 years.

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FIGURE CAPTIONS

Figure 1: This synchrotron image from Advanced Light Source beamline 8.3.2. is of an ordinary chondrite Kernouve with FeNi and FeS highlighted in yellow and orange respectively.

Figure 1