Differentiated planetesimal impacts into a terrestrial magma ocean: Fate of the iron core

Jordan D. Kendall [a,*], H.J. Melosh [b,a]

[a] *Department of Physics and Astronomy, Purdue University, 525 Northwestern Ave., West Lafayette, IN 47907, United States*
[b] *Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, United States*

A B S T R A C T

The abundance of moderately siderophile elements ("iron-loving"; e.g. Co, Ni) in the Earth's mantle is 10 to 100 times larger than predicted by chemical equilibrium between silicate melt and iron at low pressure, but it does match expectation for equilibrium at high pressure and temperature. Recent studies of differentiated planetesimal impacts assume that planetesimal cores survive the impact intact as concentrated masses that passively settle from a zero initial velocity and undergo turbulent entrainment in a global magma ocean; under these conditions, cores greater than 10 km in diameter do not fully mix without a sufficiently deep magma ocean. We have performed hydrocode simulations that revise this assumption and yield a clearer picture of the impact process for differentiated planetesimals possessing iron cores with radius = 100 km that impact into magma oceans. The impact process strips away the silicate mantle of the planetesimal and then stretches the iron core, dispersing the liquid iron into a much larger volume of the underlying liquid silicate mantle. Lagrangian tracer particles track the initially intact iron core as the impact stretches and disperses the core. The final displacement distance of initially closest tracer pairs gives a metric of core stretching. The statistics of stretching imply mixing that separates the iron core into sheets, ligaments, and smaller fragments, on a scale of 10 km or less. The impact dispersed core fragments undergo further mixing through turbulent entrainment as the molten iron fragments rain through the magma ocean and settle deeper into the planet. Our results thus support the idea that iron in the cores of even large differentiated planetesimals can chemically equilibrate deep in a terrestrial magma ocean.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

The fate of metallic iron in planetesimals during planetary accretion is dictated by the physics of the impact process, the dispersion of metal within a growing planet, and the observed chemical abundances in the bulk silicate Earth. The observed abundance of moderately siderophile elements ("somewhat iron-loving"; e.g. Co, Ni, W, P) in the Earth's mantle is 10–100 times higher than expected if metallic iron had equilibrated with a silicate magma ocean at 1 bar (Capobianco et al., 1993; Ringwood, 1966). The original planetesimals were small and their internal pressures were low, implying initial chemical equilibria between metal and silicate consistent with these low pressures. However, the abundances of moderately siderophile elements in large planets, such as the Earth, imply that chemical re-equilibration between liq-

uid metal and liquid silicate must have occurred at high pressure and temperature (Murthy, 1991; Rubie et al., 2003). Current hypotheses, based on measured iron-silicate partition coefficients, propose chemical re-equilibration at the high temperatures and pressures found in a deep terrestrial magma ocean, typically around 2100–2400 K, at depths of 600 km to 1200 km, and pressures in the range of 25–30 GPa (Drake and Righter, 2002; Li and Agee, 2001; Righter et al., 1997).

Deep terrestrial magma oceans were likely to form during the final stages of Earth's accretion. The formation of magma oceans during the late stages of planetary accretion is attributed to large and energetic impacts of accreting planetary embryos (Melosh, 1990; Tonks and Melosh, 1993; Solomatov, 2007; Reese and Solomatov, 2006; Monteux et al., 2013; Srámek et al., 2010). The scale of the magma oceans is dependent upon the diameter and impact velocity of the accreting planetesimals, as well as the size of the target body. Because the slope of the size-frequency distribution of such accreting bodies is typically close to −2, the largest impacts add most of the mass. In the case of the Earth, the majority of its mass, including its metallic iron and siderophile elements, was

* Corresponding author. Current address: Department of Physics and Astronomy, Purdue University, 525 Northwestern Ave., West Lafayette, IN 47907, USA.
E-mail address: jordan.d.kendall@gmail.com (J.D. Kendall).

added through the impacts of 100 to 1000 km diameter planetesimals (Bottke et al., 2006; Chambers, 2004; Kokubo and Ida, 1998; Wasson, 1985).

Chemical equilibration of metal droplets falling through a liquid silicate magma ocean is controlled by the ratio between the rate of diffusion of chemical species and the time required for the droplets to fall through the magma ocean (Rubie et al., 2003; Stevenson, 1990). When the droplets are small enough that Stokes flow dominates, their sinking rate is proportional to their diameter: Smaller droplets of metal fall more slowly because their negative buoyancy scales with volume whereas the viscous drag force scales with area. When the droplets are large enough to enter the turbulent regime, their terminal velocity is proportional to the square root of diameter. To be effective, chemical re-equilibration must occur on a time scale shorter than that for the metal droplets to traverse the magma ocean. Equilibration thus requires that the metal disperse into small droplets, with diameters on the order of decimeters or less. Dispersion into smaller droplet sizes increases the fall time while also decreasing the time necessary for chemical diffusion (which scales as the inverse droplet size squared).

The metal in undifferentiated meteorites occurs as small blobs typically less than 1 mm in size. The chemical diffusion into droplets of this size in a silicate magma ocean occurs on a much shorter time scale than the time it takes for the droplets to pool at the base of the magma ocean. However, if the accreting planetesimals differentiate into metal cores and silicate mantles, the iron may fall through the magma ocean without completely equilibrating unless the iron core first disperses into smaller scale fragments before settling on the bottom of the magma ocean.

The surprisingly old ages of magmatic iron meteorites (Scherstén et al., 2006) implies that most large planetesimals differentiated very early in our solar system's history due to melting fueled by radiogenic heating, primarily from ^{26}Al (Baker et al., 2005; Bottke et al., 2006; Scherstén et al., 2006; Yoshino et al., 2003). The melting caused by heat released from ^{26}Al allowed the metal to separate from the silicate in planetesimals early, within 0.3 My of calcium–aluminum-rich inclusion (CAI) formation (Kruijer et al., 2014). This implies that nearly all planetesimals larger than a few 10 s of kilometers differentiated during the earliest stage of planetary accretion.

The inferred chemical re-equilibration of the Earth's mantle with iron at high pressure and temperature thus requires that the cores of these planetesimals were dispersed to decimeter sizes during accretion and further implies a two-stage equilibration process. Because the metal-silicate segregation within the original planetesimals took place at low pressure, the differentiated planetesimal cores would have scavenged most of the moderately siderophile elements from their mantles. The higher abundances of these elements observed in the present-day Earth's mantle arose from a second, later, stage of equilibration at high pressure and temperature as the dispersed iron cores of planetesimals equilibrated with molten silicate deep within the Earth's magma ocean.

Several recent studies (Dahl and Stevenson, 2010; Deguen et al., 2014; Samuel, 2012; Wacheul et al., 2014) conclude that planetesimal iron cores must be smaller than 10 km diameter to fully emulsify within a terrestrial magma ocean. Efficient emulsification of larger planetesimal iron cores requires a sufficiently deep magma ocean on order of 1000 km for a 100 km diameter core. Their models assume that the cores passively settled from zero initial velocity as a concentrated mass of metal. Cores smaller than 10 km disperse into centimeter scale fragments through turbulent entrainment and thus lead to rapid chemical equilibration with the liquid silicate in the magma ocean. These theoretical studies are supported by recent laboratory experiments in fluids with viscosity ratios similar to molten metal and silicate (Deguen et al., 2014, 2011; Wacheul et al., 2014). These studies provide a theoretical

and experimental framework for modeling the dispersion of iron masses passing through a liquid silicate magma ocean. However, under the assumption of zero initial velocity the required degree of dispersal cannot occur for cores greater than about 10 km in diameter without a deep magma ocean. This is a serious limitation, because hierarchical accretion models predict much larger bodies add the majority of the Earth's mass.

A complete assessment of the dispersion problem requires a more realistic treatment of the impact process during planetary accretion. In this work, we numerically simulate impacts of large differentiated planetesimals to revise the previous studies' assumption of a concentrated mass passively settling through a magma ocean. We show what happens when differentiated planetesimals strike a magma ocean on a nearly full-grown Earth. The impact strips away the planetesimals' silicate mantles and stretches their iron cores into thin filaments and ribbons which are much more liable to disperse than concentrated masses.

No modern numerical method (including ours) offers sufficient resolution to encompass both the size scale of the impact (100 s of km) and the size of metal fragments small enough to equilibrate chemically (decimeters). To address this limitation we use a large number of Lagrangian tracer particles to quantify the extent of stretching of the iron core during the impact (Danckwerts, 1952; Ottino, 1989). These tracers follow the positions of initially adjacent portions of the iron core during the impact. We assume conservation of volume as the tracers separate during the impact by the insinuation of silicate magma into the initially homogeneous iron mass. We infer the final size of the dispersed iron fragments from the amount of stretching (Danckwerts, 1952; Mohr et al., 1957). This technique permits us to infer fragment sizes at the sub-mesh scale, albeit by inference rather than by direct computation.

2. Methods

2.1. Hydrocode model

We simulated the impact and subsequent evolution of the crater in a purely hydrodynamic mode with the iSALE-2D shock physics code (Wünnemann et al., 2006; Ivanov et al., 1997; Melosh et al., 1992), which is an extension of the SALE hydrocode (Amsden et al., 1980). Also, we use the iSALE-3D shock physics code (Elbeshausen et al., 2009; Elbeshausen, 2012; Elbeshausen and Wünnemann, 2011; Hirt and Nichols, 1981). The iSALE model solves the Euler equations with extra terms to describe material rheology and strength with a finite-difference technique on a Eulerian mesh (the location of the mesh is fixed in space). Previous studies validated the iSALE code against laboratory experiments, cratering observations, and other hydrocodes (Pierazzo et al., 2008; Elbeshausen, 2012).

Equation of state tables derived using ANEOS represent the thermodynamic properties of the core and mantle of both projectile and target (Benz et al., 1989; Thompson, 1990). Dunite is similar in composition to the Earth's mantle and its equation of state is well characterized and available within the iSALE ANEOS library (Benz et al., 1989; Pierazzo et al., 1997). A spherical iron core surrounded by a dunite mantle represents the differentiated planetesimal. A half-space dunite target simulates the deep magma ocean with modern Earth gravity, 9.81 m/s^2 normal to the surface. We assume that the scale of the impact is small compared to the target body (i.e. curvature is negligible). The model assumes a purely hydrodynamic flow model with no strength or viscosity during the impact. This presumes that both the target and impactor were initially molten. An initially molten impactor and target is a first-order approximation, a future study is required for solid