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Laboratory experiments on the breakup of liquid metal diapirs

Jean-Baptiste Wacheul [a,b], Michael Le Bars [a,c,*], Julien Monteux [d], Jonathan M. Aurnou [a]

[a] Department of Earth, Planetary and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA
[b] Ecole Normale Supérieure, Paris, France
[c] CNRS, Aix-Marseille Université, École Centrale Marseille, IRPHE UMR 7342, Marseille, France
[d] Laboratoire de Planétologie et de Géodynamique, LPG Nantes, CNRS UMR 6112, Université de Nantes, France

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ABSTRACT

The validity of the iron rain scenario, i.e. the widely accepted model for the dynamics of iron sedimentation through a magma ocean during the latest stage of the Earth's accretion, is explored via a suite of laboratory experiments. Liquid gallium and mixtures of water and glycerol are used as analogs of the iron and the molten silicate respectively. This allows us to investigate the effects of the viscosity ratio between iron and silicate and to reproduce the relevant effects of surface tension on the fragmentation dynamics. While the classical iron rain scenario considers a population of purely spherical drops with a single characteristic radius that fall towards the bottom of the magma ocean at a unique velocity without any further change, our experiments exhibit a variety of stable shapes for liquid metal drops, a large distribution of sizes and velocities, and an intense internal dynamics within the cloud with the superimposition of further fragmentations and merging events. Our results demonstrate that rich and complex dynamics occur in models of molten metal diapir physics. Further, we hypothesize that the inclusion of such flows into state of the art thermochemical equilibration models will generate a similarly broad array of complex, and likely novel, behaviors.

1. Introduction

Differentiation of Earth into a core and a mantle was likely completed within the first tens million years after its accretion (e.g. Stevenson, 1990; Boyet et al., 2003; Boyet and Carlson, 2005). Numerical simulations (Neumann et al., 2012) and geochemical data on meteorites (Yoshino et al., 2003) also show that small planetesimals could have differentiated even earlier when accounting for heating by decay of short-lived radionuclides. There is also strong evidence that the Earth's late accretion is due to collisions with large planetesimals (a tenth to a third of Earth mass), when both the impactor and the proto-Earth were already differentiated (Morbidelli et al., 2012). During accretion, the Earth and other planets in formation underwent several mechanisms of heating: 1) the decay of relatively abundant radioactive elements with short half-life (Merk et al., 2002; Walter and Tronnes, 2004), 2) the conversion of gravitational potential energy by viscous forces during differentiation (Rubie et al., 2007; Monteux et al., 2009; Samuel, 2012), 3) the collisions themselves with the conversion of huge amount of kinetic energy (Safronov, 1978; Kaula, 1979; Reese and Solomatov, 2006; Monteux et al., 2007), these impacts alone being able to generate a local melting resulting in a shallow magma ocean (Tonks and Melosh, 1992). In addition, the primitive atmosphere was certainly much more opaque to IR radiation, so the effect of thermal blanketing was highly efficient (Abe and Matsui, 1985). Thus, according to the simulations, Earth has probably had one or several episodes of global magma ocean, with depths possibly reaching thousands of kilometers (Tonks and Melosh, 1993). In this context, further impacts of differentiated planetesimals would require, in order for the cores of the Earth and the meteorites to merge, that the latter flows through the magma ocean (Fig. 1). This process can be seen as a secondary step of mixing between core and mantle, since it could lead to partial or complete thermo-chemical equilibration between the sinking metal and the molten surrounding silicates, depending on the characteristics of the flow of the core material through the mantle.

The importance of this exchange is an issue for the interpretation of numerous geochemical proxies, such as the tungsten 182 signal. Hafnium (^{182}Hf) disintegrates in tungsten (^{182}W) with a relatively short half-life of 9 My, comparable with the time scale of core differentiation. They are both refractory but tungsten is siderophile whereas hafnium is lithophile. This is why the

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[*] Corresponding author at: CNRS, Aix-Marseille Université, École Centrale Marseille, IRPHE UMR 7342, Marseille, France. Tel.: +33 4 13552020; fax: +33 4 13552001.
E-mail address: lebars@irphe.univ-mrs.fr (M. Le Bars).

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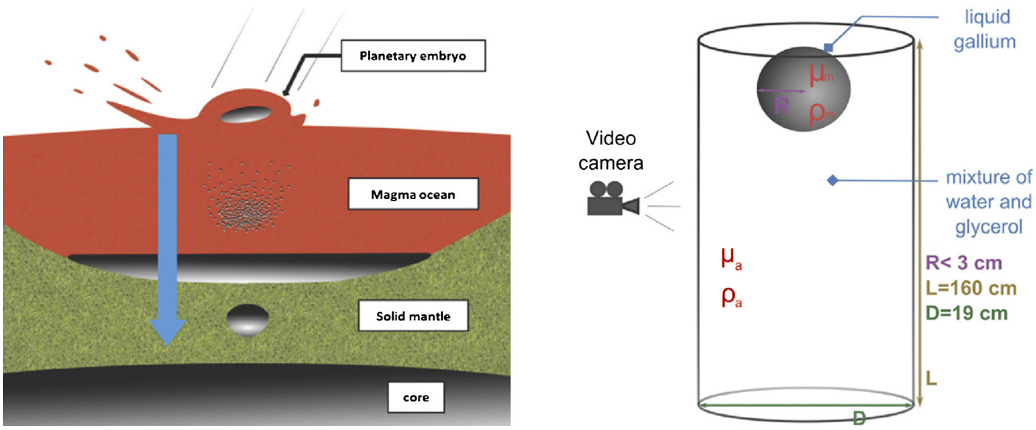

Fig. 1. Left: schematic of the metal/silicate separation after the impact of a differentiated planetesimal with the early Earth in reference to the work of Stevenson (1990). The equilibration by diffusion between the impactor's core and the magma ocean during the metal rainfall and later when sinking through the solid mantle as a large diapir is poorly constrained, and strongly depends on the fluid dynamics of the iron sedimentation. Right: schematic of our experiment.

^{182}Hf–^{182}W system has been used in multiple studies to approximate the age of terrestrial bodies' core (Lee and Halliday, 1996; Harper and Jacobsen, 1996; Kleine et al., 2004). However due to the late impacts and possible mixing that could occur, there are very poor constraints on which event – late impacts or core differentiation – is relevant for the interpretation of the ratio ^{182}W/^{184}W. Then the age given by this proxy could be any intermediary between the initial differentiation of the proto-Earth and the most recent giant impact that it endured, depending on how much ^{182}W has been absorbed by the asteroid's core during its passing through the mantle (Kleine et al., 2004). The same kind of interrogation can be held against interpretations of the U/Pb proxy, and for the coefficients of partition between metal and silicate, which strongly depend on the details of the small-scale processes at the iron–silicate interface during sedimentation. Actually, these interfacial dynamics influence every mechanism of equilibration by diffusion, such as diffusion of heat and diffusion of momentum by viscosity, both leading to indetermination on the initial thermal state of the mantle and the core, and on the repartition of the energy between these two (Monteux et al., 2009; Samuel et al., 2010). Thus, in order to model the evolution of both Earth's core and mantle, it is important to understand the fluid dynamics at the drop scale during the iron sedimentation (Solomatov, 2000). Towards this goal, we present here novel laboratory experiments investigating the fluid dynamics of sedimenting liquid metal droplets.

2. Parameters controlling the fluid dynamics of the iron sedimentation

The equilibration between the iron and molten silicate strongly depends on the typical size of the metal entities. Indeed, for a given volume of metal, a single large diapir would fall rapidly through the magma ocean with a relatively small surface of exchanges, while the fragmentation of the same volume of iron through a large number of small structures broadens the surface area of exchanges and slows down the falling velocity, hence extending the time during which iron and silicate equilibrate. Note that in the present paper, we generically use the term diapir to designate any large blob of fluid moving through an ambient fluid via the action of buoyancy forces.

Several approaches have been developed in order to give a physically coherent description of what happens when a liquid iron diapir falls through a magma ocean, and ultimately to provide a time scale for the equilibration. At first order, the shape of the falling diapir is dominated by two forces. The surface tension tends to stabilize a spherical shape, while the dynamic pressure deforms the diapir and tears it apart. Let us assume for instance, a typical diapir with a radius $R_0 = 10$ km falling at the inviscid, free fall Newtonian velocity V valid for a rigid sphere

$$V \simeq \sqrt{\frac{\Delta\rho}{\rho_a} g R_0}, \tag{1}$$

where ρ_a is the silicate density ("a" standing for "ambient"), $\Delta\rho$ is the density difference between iron and silicate, and g is the gravitational acceleration. Assuming an Earth with more than half its final mass, V is close to 1 km/s. The Re number for the flow in the mantle, which estimates the ratio of the inertial and viscous forces, is

$$Re_a = \frac{\rho_a V R_0}{\mu_a} \gtrsim 10^{10}, \tag{2}$$

where μ_a is the silicate dynamic viscosity. This large *Re* value provides an *a posteriori* validation of the inviscid velocity estimate provided by Eq. (1). It also implies that dynamic pressure scales as the inertia. On the other hand, the characteristic strength of surface tension is directly linked to the radius of curvature of the surface, so its order of magnitude roughly depends on the radius of the spheroid diapir R_0. A good estimation of the stability of a diapir is given by the Weber number, which is the ratio of the inertial and surface tension forces:

$$We_a = \frac{\rho_a V^2 R_0}{\sigma}, \tag{3}$$

where σ is the coefficient of surface tension. For $We \gg 1$, diapirs are unstable and break-up. Below some threshold of order 1 (e.g. $We_c = 6$ for rain drops, see Villermaux and Bossa, 2009), surface tension and inertia compensate, and the diapir is stable. This widely used breakup criterium (e.g. Tonks and Melosh, 1992; Rubie et al., 2003; Dahl and Stevenson, 2010; Deguen et al., 2011) allows a calculation of the maximal radius for stable diapirs, given some hypothesis regarding its falling speed. For the simple Newtonian velocity scaling given by (1), the maximal radius corresponds to

$$R_{cap} \simeq \sqrt{We_c \frac{\sigma}{\Delta\rho g}}, \tag{4}$$

which is about 1 to 2 cm for the Earth's iron–silicate system. Such a criterium is well known in the case of water drops in the air, for which it has been confirmed by experiments (Villermaux and Bossa, 2009). It has also been supported by a recent numerical study designed for the case of an iron diapir in molten