The effects of shear deformation on planetesimal core segregation: Results from in-situ X-ray micro-tomography

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ABSTRACT

It is well accepted that the Earth formed by the accretion and collision of small (10–100 km), rocky bodies called planetesimals. W-Hf isotopic evidence from meteorites suggest that the cores of many planetesimals formed within a relatively short time frame of ~3 My. While a very hot, deep magma ocean is generally thought to have been the driving mechanism for core formation in large planetary bodies, it inadequately explains differentiation and core formation in small planetesimals due to temperatures potentially being insufficient for wide-scale silicate melting to occur. In order for these planetesimals to differentiate within such a relatively short time without a magma ocean, a critical melt volume of the metallic (core-forming) phase and sufficient melt connectivity and grain size must have existed to attain the required permeability and lead to efficient core formation. Shear deformation may increase the connectedness of melt and the permeability, and thus could have been a major contributing factor in the formation of planetesimal cores. This deformation may have been caused by large impacts and collisions experienced by the planetesimals in the early solar system. The purpose of this work is to test the hypothesis that shear deformation enhances the connectivity and permeability of Fe-S melt within a solid silicate (olivine) matrix, such that rapid core formation is plausible. A rotational Drickamer apparatus (RDA) was used to heat and torsionally deform a sample of solid olivine + FeS liquid through six steps of large-strain shear deformation. After each deformation step, X-ray microtomographs were collected in the RDA to obtain in situ three-dimensional images of the sample. The resulting permeabilities of the sample at various steps of deformation are the same within uncertainty and do not exhibit a change with increasing deformation. Additionally, the migration velocity calculated from the permeability of the sample is not high enough for segregation to take place within the time frame of ~3 My. In addition to further constraining the mechanism of core formation in planetesimals, the image processing techniques developed in this study will be of great benefit to future studies utilizing similar methods.

Keywords: Core formation, microtomography, permeability, lattice Boltzmann

INTRODUCTION

Core formation is a significant, yet not completely understood process in the formation of the terrestrial planets and other small, rocky bodies such as large asteroids and satellites. Hafnium-tungsten isotopic studies of the Earth’s mantle and several meteorites indicate that the Earth’s core likely formed in ~30–100 My after the formation of the proto-Earth, while the parent bodies of iron meteorites differentiated much faster (~1–5 My) (Kleine et al. 2002, 2009; Schersten et al. 2006; Rubie et al. 2007; Burkhart et al. 2008) and perhaps even before 1 My (Kruijer et al. 2014). This short timescale of 1–5 My for core formation is in agreement with the theoretical model that accretion in the early solar system took place relatively rapidly (Alexander et al. 2001; Wood et al. 2006; Rubie et al. 2007). The mechanism by which core formation took place in planetesimals largely depends upon the thermal history of the body (Rubie et al. 2007). Heat generated from 26Al decay would have melted the core forming alloy in planetesimals 10–100 km in diameter (Yoshino et al. 2003; Walter and Trønnes 2004; Bizzarro et al. 2005), but may not have melted the silicate to a significant degree. In the absence of widespread silicate melting, the mechanism by which metal and silicate might have segregated in planetesimals is limited to inter-granular percolation of metallic melt through a solid silicate matrix (Yoshino et al. 2003; Watson and Roberts 2011).

In order for core formation to take place efficiently in an equilibrium setting, the metallic melt must be fully connected within the solid silicate (e.g., Roberts et al. 2007; Watson and Roberts 2011). Whether or not connectivity is achieved depends on the dihedral (wetting) angle between the liquid and solid