The role of magma ocean material in determining the formation and evolution of liquid-metal diapirs with trailing conduits during differentiation of planets and large planetesimals

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The formation of planets in the early solar system involved violent impacts which partially or fully melted the planet’s surface materials, facilitating separation of iron metal from silicates. Among the mechanisms that have been proposed for this differentiation, metal-silicate plumes resulting from Rayleigh-Taylor instabilities of liquid-metal ponds at the bottom of magma oceans provide the fastest rates of delivery to cores of large planetesimals and proto-planets. These plumes consist of liquid-metal diapirs with trailing conduits of entrained silicate melt from magma oceans generated by large impacts. The physical properties of these magma oceans such as density, viscosity, or volume are unknown and may vary depending on the composition and properties of the impactors. Entrainment of this material behind a sinking metal plume may affect the time for core formation within differentiating bodies. Entrained material may also provide a locus for metal-silicate equilibration at depth, and thus affect lower layer composition, especially in the case of small metal drops that form a diapir made of a liquid emulsion or that descend in the wake of larger diapirs. We investigate the descent of liquid-metal drops using liquid gallium and dehydrated or diluted glucose and salt solutions. We scale our experiments through the use of low Reynolds numbers to characterize the Stokes flow regime and a non-dimensional length scale $\lambda$, defined as the ratio of conduit radius to conduit height that ranges from $\sim 0.05$ to $\sim 0.2$. We focus on low-Bond-number deformable metal drops with $Bo < 5$. We describe the density and viscosity conditions under which trailing conduits open behind metal drops, and the resulting conduit geometry and drop shapes. We find that the descent times of metal drops, morphology of plumes, and relaxation times of conduits in tri-fluid systems depend strongly on the density difference between the silicate melt and underlying material as well as the viscosity of the lower layers. We also find that for a given set of properties there is a characteristic ratio that determines the depth at which a conduit closes and return flow commences. We derive an expression for the descent speed of a metal-silicate plume with an open conduit, which differs measurably from the predicted Stokes flow for a two-fluid system. We show that the width of a conduit depends upon the surface tension between the drop and the surrounding fluid and that the rate of conduit collapse can be described with a mathematical expression for the shape of the conduit. Open conduits may entrain magma-ocean material to lower layers, with return flow occurring either via solitons that travel upward along the original conduit path, or more shallowly due to closure, or “pinching” of the conduit at a characteristic depth. Thus, in the case of high lower layer viscosities and low magma-ocean-to-mantle density differences, sinking metal drops will deliver iron rapidly to the cores of differentiating bodies such as large planetesimals and protoplanets while entraining trailing conduits of silicate melt and small metal droplets to regions at depth.