2D FOUR-PHASE NUMERICAL MODELLING OF PERCOLATION- AND RAINFALL-DRIVEN CORE FORMATION IN PLANETESIMALS. F. M. Bintang\textsuperscript{1}, T. Keller\textsuperscript{2,1} and L. Daly\textsuperscript{3,4} \textsuperscript{1}School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK. \textsuperscript{2}Department of Earth Sciences, Institute of Geochemistry and Petrology, ETH Zürich, Zürich, Switzerland \textsuperscript{3}Australian Centre for Microscopy and Microanalysis, The University of Sydney, Sydney, NSW, Australia. \textsuperscript{4}Department of Materials, University of Oxford, Oxford, UK

Background: The formation of the metal cores in the terrestrial planets of our Solar System was aided by the collision of planetesimals with pre-differentiated cores \footnote{1}. Planetesimal interiors likely differentiated from a primitive chondritic composition to compositionally distinct metal core and silicate mantle when the interior melted. The most significant heating source for early-formed planetesimals is the decay of short-lived radionuclides, most importantly \textsuperscript{26}Al [2], which melted mobilised, and differentiated into a chondritic body composed of a core, mantle and crust. The timescales, sequence, and extent of differentiation are dependent on the size, physical properties, and composition of the planetesimals, as well as the timing of planetesimal formation \footnote{3}.

Observations of \textsuperscript{129}Hf-\textsuperscript{129}W isotope ratios in meteorites, where the parent lithophile \textsuperscript{129}Hf decays to the siderophile \textsuperscript{129}W, is thought to constrain the timing of core formation in planetesimals to within 6 million years of the Solar System formation \footnote{4}. However, the mechanism for rapid metal-silicate partitioning is debated. Percolation of metal along grain boundaries at low melt fractions, as well as rainfall of metal droplets within a magma ocean have been proposed (Figure 1).

The earliest metal-silicate segregation can occur by porous flow at low melt fractions \footnote{5} when liquid metal melt forms interconnected networks between solid silicate grains, and flow towards the core. Static experiments and textural studies have quantified the percolation threshold for metal alloys through a permeable solid matrix to require \~5–15\% volume of liquid metal \footnote{5}. However, above 20\% melt fraction, the partial melt disaggregates into a mush, so percolation alone may not be a sufficient mechanism for rapid core formation \footnote{5, 6}.

Another mechanism for core-silicate segregation is by the rainfall of metal melt droplets through a soft, low, viscosity magma ocean. Sufficient heating from short-lived radionuclides may cause the whole interior of a planetesimal to melt into a global magma ocean (>50\% melt fraction), within which immiscible metal melt droplets and any residual refractory metal solids would rain down towards the forming core \footnote{7}. The segregation rate for an individual metal particle is given by the Stokes settling velocity:

\begin{equation}
\nu \Delta v = v_{Fe} - \bar{v} = \frac{2d^2(\rho_{Fe} - \bar{\rho})g}{9\bar{\eta}}
\end{equation}

Where \(v_{Fe}\) and \(\bar{v}\) are the metal and background velocities, \(d\) is the particle diameter, \(\rho_{Fe}\) is the particle density, \(\bar{\rho}\) is the bulk density, \(g\) is gravity and \(\bar{\eta}\) is the background viscosity. Numerical simulations have shown that heterogeneous distribution of metal particles can overcome buoyancy due to thermal convection, in a two-phase metal droplet-silicate melt system \footnote{7}. However, the rainfall mechanism when additional phases such as residual solid silicate and metals has not yet been explored.

Here we seek to investigate the rates of the proposed core formation mechanisms using numerical modelling to see how large-scale fluid mechanics contribute to the segregation of metal alloys and silicates in early-formed planetesimals.

![Conceptual model of the mechanisms of metal-silicate partitioning during different stages of planetesimal development.](image)

Model description: We are developing a 2-D, multi-phase, multi-component numerical model in a self-gravitating domain to quantify the timescales and mechanisms of core formation in planetesimals within a

framework relevant to igneous systems [8]. Our model will build upon a previous 1-D pilot model of a two-phase material of silicate solid and melt [3]. Our work expands the model to four phases, additionally including solid and molten metal alloys. We employ the enthalpy method [9] to calculate the melting of chondritic material into immiscible silicate and metal melts. Phase fractions at thermodynamic equilibrium are calculated using generic phase diagrams calibrated to represent silicate and Fe-FeS melting [Figure 2]. The rate and extent of melting is dependent on the size and formation time of a planetesimal, where larger and earlier-formed planetesimals contain more $^{26}$Al which will result in melting of the interior into a global magma ocean [3].

We simulate the fluid mechanics of the model depending on the melt fraction and stage of planetesimal development [Figure 1]. Early-stage percolation will be modelled by porous flow at low melt fractions (<50% melt) and later-stage particle/droplet settling by suspension flow at high melt fraction (>50% melt). Expanding the model to 2-D improves on the 1-D results by allowing us to include important dynamic and structural aspects to the model such as convection, mechanical and reactive flow channelling and gravitational stability of compositional layers. Figure 3 shows preliminary results of four-phase suspension flow model in an idealised 2-D domain, under uniform gravity. The percolation fluid mechanics and self-gravity are currently in-development.

![Figure 2. Example of a Fe-FeS phase diagram (top) and the equilibrium phase weight fractions (bottom) along the dotted line on the phase diagram which calculates in-situ melting. Note that this is poorly calibrated and is only for conceptual purposes. A separate silicate phase diagram is also needed to calculate silicate fractions.](image)

Model objectives: Our main objective is to quantify and compare the timescales of the two end-member mechanisms of percolation- and rainfall-driven mechanisms for core formation and whether the timescales comply with the HF-W isotope data. Model results will allow us to determine whether shear or reaction-driven flow localisation and channelling allows for rapid early-stage metal percolation, even from melt fractions below 5%. The suspension flow fluid mechanics will calculate the settling rate of particles of silicate crystals, metal solids and immiscible metals under a silicate magma ocean. The model will also show whether additional downwards buoyancy due to heterogeneous metal distribution can aid in the settling of metals into a core. We will continue to develop the model, ensuring rigorous benchmarking and verification. Phase diagrams will be finely calibrated by comparing with experimental studies and verified using the pMELTS software [10].

![Figure 3. Preliminary results for metal particle suspension flow in an idealized 2-D domain, showing the initial condition (top) and after 100 time steps (bottom). 100x100m domain, boundaries show a rigid, impermeable base and cap, and reflective sides. After 100 time steps, the iron accumulates at the bottom and depletes at the top. Dynamic time-stepping is calculated based on the maximum velocities.](image)