NUMERICAL MODELLING OF LIQUID METAL TRANSPORT IN PARTIALLY MOLTEN H5 ORDINARY CHONDRITE.

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Introduction: Although liquid iron-rich metal segregating from a molten silicate mantle (magma ocean) is a widely cited mechanism for segregating core forming material [1-2], the short times (< 30 Ma) required for core formation based on Hf-W isotope systematics [3] have reopened the debate on the role of magma oceans in core formation. In particular, the W-Hf data provide supporting evidence that the terrestrial planets and larger asteroids formed by rapid accretion of planetesimals that had already undergone early differentiation and contained proto-planetary cores. Recent experimental studies have investigated the physical efficiency of Fe-rich liquid segregation from a silicate matrix in both static and in actively deforming (dynamic) environments [4-6]. As shown by [4], under non-hydrostatic conditions, deformation mechanisms appear capable of providing high permeability pathways for metal segregation independent of surface tension effects. As a first step towards modelling Fe metal segregation in deforming planetesimals, we have devised a computation methodology that allows us to use actual rock texture as a basis for physics-based modelling of the segregation process.

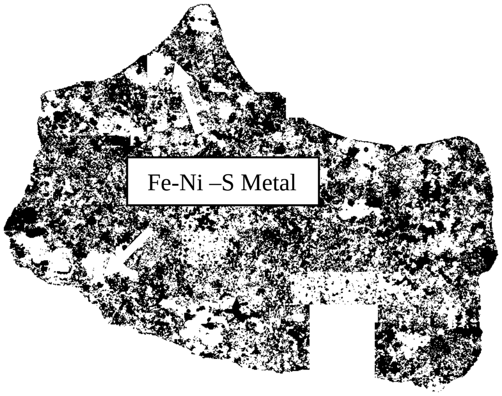

Fig. 1. Photomontage image of Kernouve H5 meteorite showing textural distribution of Fe-Ni-S metal. Silicate mineralogy is mostly pyroxene and olivine. Image scale approx 1 cm by 0.5 cm.

Experiments: Dynamic melting and deformation experiments were conducted on a partially molten ordinary H6 chondrite (Kernouve) using a solid-media rock deformation apparatus to investigate the mechanisms of metal-silicate under applied stress. Textural and chemical analyses confirm the mobility of Fe-Ni-S liquids under conditions where the silicate matrix remains subsolidus. Fig. 1. shows the distribution of metal in Kernouve H6 in the sample (to scale) after partial melting. (T = 900-1000ºC, P = 1 GPa). Subsequent experiments to investigate melt segregation during shear are described in [6].

Image analysis: In order to perform accurate (geometrically constrained) numerical modelling of liquid Fe-metal flow it was necessary to capture the texture and distribution of the metal phase in the sample. This was achieved using images obtained from optical microscopy (Fig. 1) and SEM backscatter (Fig. 2).

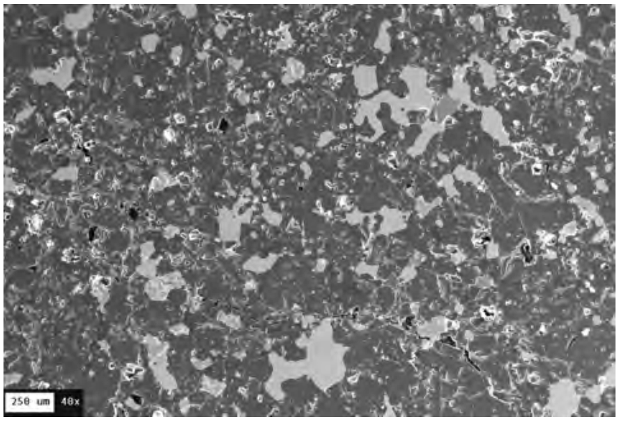

Fig. 2. SEM backscatter image of Kernouve H5 meteorite showing region used as basis for finite element (mesh) geometry and numerical flow modelling. Fe-Ni-S metal pockets shown as light grey.

The more detailed SEM image shown in Fig 2 was then image processed so that the regions of interest size (shape and distribution of the metal phase) could be segmented from the background matrix. The resulting greyscale image transform is shown in Fig. 3. The final stage in the imaging processes involved converting the greyscale texture image (Fig. 3) into a geometry object such that important elements of the original texture are preserved. The resultant geometry was then meshed ready to perform the finite element analysis and fluid flow modelling. The final pre-processing image is shown in Fig. 4. The finite element mesh consists of 32000 grid points and can be further refined for more detailed analysis. Fe-Ni-S melt pockets are shown in outline. Mesh density is highest around the melt pockets as these regions display the most complex flow behavior.

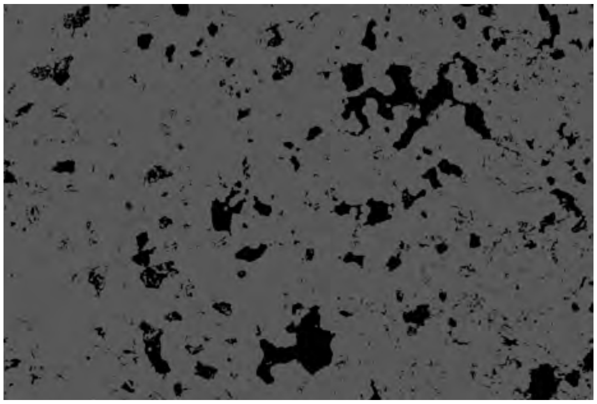

Fig. 3. Thresholded and negative (inverted) greyscale image of that shown in Fig. 2. Here the Fe-Ni-S metal phase is shown in black. Scale as in Fig. 2.

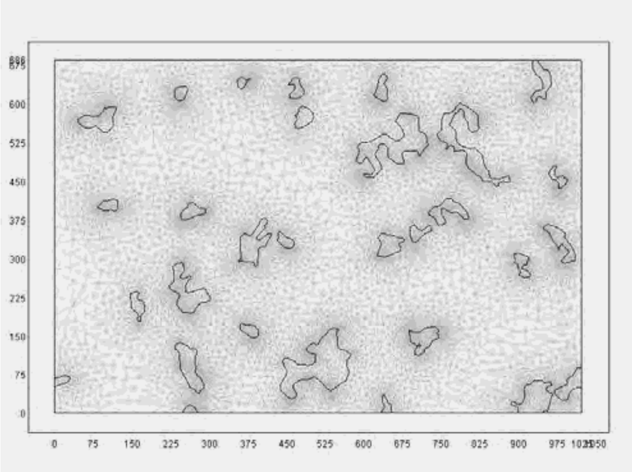

Fig. 4. Finite element mesh geometry derived from Fig 3. The mesh consists of 32000 grid pints. Fe-Ni-S melt pockets shown in outline. Mesh density is highest around the melt pockets as these regions develop complex flow fields.

Results: Fig 5 shows the results of a numerical solution applied to the digitized Kernouve H5 texture shown in Fig. 4. The analysis was performed using Comsol Multiphysics v.3.2 and solved assuming a Darcyan flux. The plot shows the 2D surface pressure gradient, fluid flow streamlines (red) and velocity field (yellow arrows). Fe-metal fluid flow is towards the existing pockets of Fe-Ni-S metal. In this simple model, metal fluid flow is driven in the porous matrix (blue) with fixed permeability of 10^{-11} m^2 [5] by a pressure gradient of c 10^3 Pa. Yellow arrows show the corresponding direction and magnitude of the melt velocity field. A key result is that porous flow of small melt fractions of Fe liquid metal takes place in the silicate matrix, where it is drawn to pre-existing 2D pools (in 3D these structures might be channels) which are sites of reduced pressure. In this way, small liquid fractions collect over a scale of several or more grains and concentrate in preferred sites (sinks) of liquid metal. Modelling microscale segregation may help understand macroscale core formation. The models also have potential to shed light on liquid metal transport across the CMB [e.g. 7].

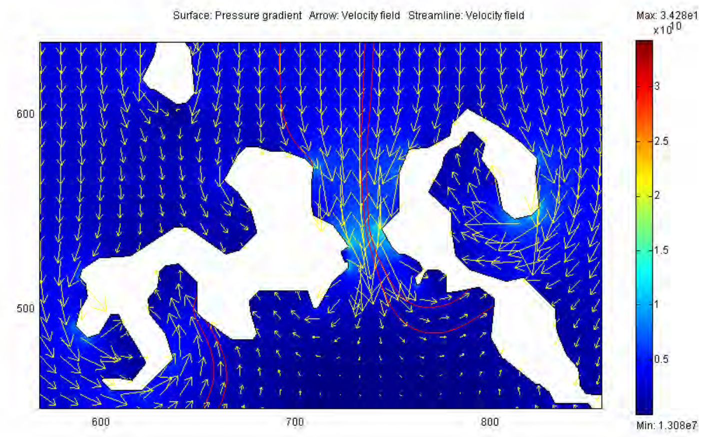

Fig 5. Numerical solution showing Fe metal flow velocity field (arrows) in Kernouve H5. Melt is attracted towards low pressure Fe-Ni-S melt pockets (while regions).

Discussion: The procedure outlined here offers a new way of modelling in detail grain-scale liquid metal segregation in natural samples. In the numerical model, constrained by true (2D) textural geometry, the pressure field, matrix permeability and Fe-Ni melt viscosity and density can be changed at will, allowing detailed sensitivity analysis of the transport process to be made. It is also possible to investigate thermal effects (e.g. temperature-dependent viscosity of the liquid metal), and in principle the electromagnetic effects of metallic liquid pore-scale flow. Future work will concentrate on highly detailed investigation of the microscale physics of Fe metal-silicate melt segregation as a precursor to planetary core formation through combined experimental and numerical study.

References: [1] Newsom, H. E. (1990) in *Origin of the Earth*, 273–288 Oxford Univ. Press, UK. [2] Stevenson, D., (1990) in: *Origin of the Earth*, 231-249, Oxford Univ. Press, UK. [3] Halliday, A. (2004) *Nature* **427**, 505–509. [4] Rushmer et al., (2000), in Origin of the Earth and Moon, LPI Arizona, 227-245. [5] Yoshino et al., (2003), *Nature*, *422* 154-157. [6] Rushmer et al., (2005), *EPSL*, **239**, 185-202. [7]. Petford et al., (2005), *EPS* **57**, 459-464.