MULTI-STAGE CORE FORMATION IN PLANETESIMALS REVEALED BY NUMERICAL MODELING AND Hf-W CHRONOMETRY OF IRON METEORITES.

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Introduction: Magmatic iron meteorites are believed to sample metallic cores of planetesimals and each group represents a separate parent body. The IVB irons are extremely depleted in volatiles and enriched in refractory elements. The ^{182}W content[1] indicates that the metal-silicate separation occurred at ≈2.9 Ma after the formation of calcium-aluminium-rich inclusions (CAIs). Previous thermal models[1] that attempted reproducing the differentiation of IVB parent body consider heat conduction and fit the Hf-W age by assuming melt percolation at the Fe-Ni melting T≈1760 K. However, at 1760 K most of the silicates would be liquid, causing an earlier phase separation. For reasonable temperature and porosity dependent parameters, the Hf-W data is not reproduced for any formation time t_0 and parent body radius R. Intense heating and fast phase separation make an early accretion unlikely, while for a late accretion some melting and phase separation occurs, but the metal remains solid contradicting IVB meteorites being magmatic. Further processes, e.g. depletion of the interior in ^{26}Al and liquid-state convection need to be considered as they can prevent rapid heating for early accretion and delay the phase separation. We calculated the differentiation of the IVB parent body comparing its evolution to the Hf-W model ages and provide a best fit on its radius R and formation time t_0.

Model: The numerical model[2,3] solves energy balance in spherical symmetry considering heating by short- and long-lived radionuclides, temperature- and porosity-dependent parameters, compaction, melting and latent heat, metal-rock differentiation by Darcy flow, redistribution of radionuclides, and convection in a magma ocean and in the metallic liquid core. A typical ordinary chondritic composition is considered.

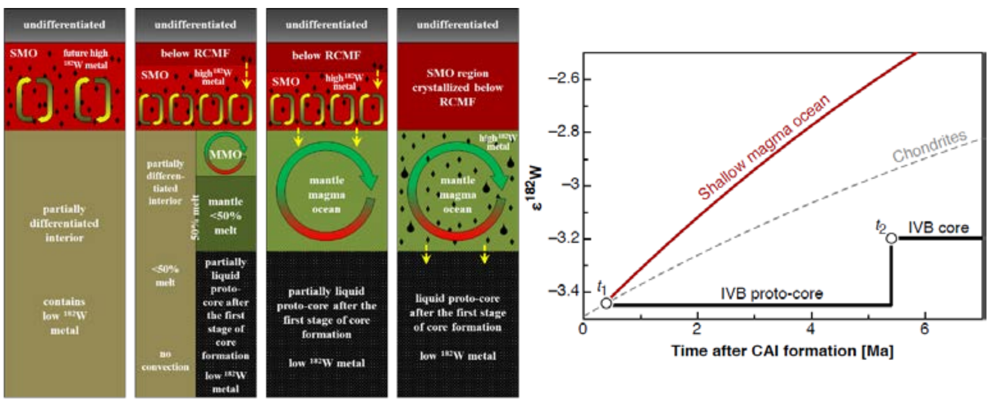

Figure 1. *Left*: Sequence of the metal segregation on IVB parent body (from left to right). Migration of partial silicate melt forms an SMO. Convection keeps some metal there while deeper a proto-core forms. The weakened convection in SMO allows the metal to sink. The proto-core has a small ^{182}W/^{184}W ratio while the metal in SMO has a high one; a mixture of the metal fractions yields the core ^{182}W/^{184}W ratio. *Right*: The evolution of ^{182}W in the core for the best-fit body.

Results: We calculated several models with different complexity, for R≤300 km and t_0≤5 Ma after CAIs. First estimates are provided by heat conduction and latent heat models. A variety of bodies produces enough melt for the differentiation, but only for R≥25 km and t_0≈1.2-1.3 Ma metal melting fits the Hf-W ages. A more realistic but extreme scenario includes differentiation, partitioning of ^{26}Al, and liquid-state convection[3], but melting and differentiation do not correlate with Hf-W ages for any R and t_0. An alternative is a "mixed" model with a quasi-instantaneous differentiation. The early partial melt is extracted via dikes[4] to the surface upon reaching T≈1570 K (a melt fraction of 10% containing 90% of ^{26}Al) without further differentiation. This melt extracts ^{26}Al, reducing the heating rate to 10%. The remaining nuclides provide a slow T increase while the depleted mantle has a higher melting T and remains solid. If no magma ocean forms, the lower mantle heats up without being cooled by liquid-state convection. This enables reaching the liquidus temperature of the metal of 1760 K at t≈2.9 Ma after CAIs (t_0≈0.1-0.2 Ma). While this is in agreement with the Hf-W core formation age of IVB, ^{182}Hf is extracted to the surface with the melt. This melt needs to be mixed with iron at 2.9 Ma in order for iron to equilibrate and drag ^{182}W into the core. This occurs in a complete differentiation model, with a self-consistent melting modeling and less effective diking (Fig. 1). Here, partial melt and ^{26}Al are removed from the interior into the sub-surface. Mixing of the melt at shallow depths with silicates and iron (present there from the initial composition) leads to a shallow magma ocean (SMO)[3]. The SMO heats the mantle inducing the formation of a mantle magma ocean and of a proto-core by Stokes settling of iron. This scenario is valid for a variety of R and t_0<0.4 Ma. However, the SMO crystallizes around 2.9 Ma only for R≈110 km. Iron particles contained there equilibrate, sink through the mantle within the second stage of the core formation and melt afterwards in the core.

Conclusions: Our calculations with the SMO model are consistent with an early accretion and a multistage late differentiation of the IVB parent body. While its size can differ slightly from the "best fit" R≈110 km, calculations with different radii lead to a similar interior evolution (for details see [5]).

References: [1] Kruijer et al. (2014) Science 344:1150-1154. [2] Neumann et al. (2012) A&A 545:A141. [3] Neumann et al. (2014) EPSL 395:267-280. [4] Wilson and Keil (2012) Chemie der Erde 72:289-321. [5] Neumann et al. (2018) JGR 123:421-444.