TIMESCALES OF PERCOLATIVE CORE FORMATION IN PLANETESIMALS. M. A. Hesse[1], S. Ghanbarzadeh[2], and J. S. Jordan[1], [1]Department of Geological Sciences, The University of Texas at Austin, 2Unconventional Reservoir Technology, BP America Inc.

Introduction: The metal-silicate differentiation that leads to the formation of planetary cores is one of the most significant processes in the evolution of planetary bodies. Meteoritic evidence shows that many asteroids had metallic cores and geochemical and geophysical evidence requires rapid core formation [1,2]. While some planetesimals may have undergone complete melting, evidence from primitive achondrites [3] and recent space craft observations [4] suggests that others only experienced partial melting and incomplete differentiation.

Metal-silicate differentiation in such partially molten bodies requires grain-scale melt percolation and segregation by porous flow. Experimental studies of the microtexture of core forming melts suggest that they are not mobile in a solid silicate matrix at the relatively low pressures in planetesimals [5,6,7]. This has long been thought to hinder percolative core formation in planetesimals. However, recent pore-scale computations of texturally equilibrated melt networks have shown strong hysteresis in melt network connectivity [8]. They suggest that the melt remains connected once it overcomes the percolation threshold and can drain to very low melt fractions. This potentially resolves the physical mechanism that allows metal mobility partially molten primitive achondrites and incompletely differentiated asteroids.

Most previous workers assume that core formation by metal percolation is fast, efficient or even instantaneous [9,10], if the melt is connected. However, the timescales required for percolative core formation are poorly constrained. Understanding these timescales is important to determine if metal percolation can form cores at the rapid timescales of less that 3 Ma required by geochemical and geophysical evidence [1,2].

Determining these timescales requires estimates of the melt network permeabilities as function of porosity and must take into account the dramatic changes in porosity/permeability and the driving buoyancy forces during metal/silicate differentiation. In addition the process is closely coupled to the thermal evolution and latent heat changes during melting and freezing. Therefore, we have developed a numerical model of the thermal evolution and melt migration within a planetesimal.

Percolative Core Formation Model: Our model assumes a three phase planetesimal comprisng, silicate, solid metal and liquid metal. The planetesimal is heated by the decay of ^{26}Al and the melting of the metal phase occurs at the Fe-FeS eutectic temperature. Our model assumes that the silicate phase does not melt and hence cannot model the mass and energy redistribution due to migration of the silicate melt. The model assumes that melt migration is by porous flow once the melt fraction exceeds the percolation threshold [8]. The rate of melt segregation is limited by the compaction of the highly viscous solid matrix. The dynamics of compaction are described by the standard viscous compaction model used in magma dynamics [11]. The model assumes radial spherical geometry. The governing equations are discretized using a finite volume method and solved sequentially coupled.

Melt Network Permeability: The permeability of melt network as function of porosity is an important control on the timescales of melt segregation. Permeabilities have been obtain by Lattice Boltzmann Simulations on texturally equilibrated melt networks with a metal-silicate dihedral angle of 90° [8].

Results: Simulations have been used to explore the timescales of percolative core formation in planetesimals with radii from 20 to 100 km and acretion times between 0 and 5 Ma since the formation of Calcuim Aluminum Inclusions (CAIs). All simulations assume a uniform inital composition with 20% metal, which is sufficient to exceed the percolation threshold. The results are summarized in Figure 1.

Figure 1*a* shows the timing of core formation for a planetesimal with a radius of 50 km as function of accretion time. Due to the rapid decay of ^{26}Al the timing is strongly dependent on the accretion time. Planetesimals accreted after 1.5 Ma may experience metal melting and limited melt migration, but do not form a metallic core with more than 90% metal. In general, there is a delay between the onset of melting at the center of the planetesimal and core growth of al least 300 ka. This delay is not insignificant given the short timescale inferred from geochemical and geophysical evidence [1,2]. The delay in core formation is due to the time required for the melt fraction to exceed the percolation threshold and the time required to migrate towards the center in a low gravity environment.

However, once core formation commences the initial core growth is rapid, so that approximately 50% for the core from within 100 ka. After that core formation slows significantly and completion of core formation requires 2 to 3 Ma. The duration of core formation in planetesimals that accrete after 1 Ma decreases, because the core is small and requires less material transport.

Figure 1*b* shows the effect of planetesimal radius on core formation timescales. Only planetesimals that exceed a critical radius form a core that exceeds 90%

metal. This critical radius increases from 20 km to 60 km as accretion time increase from 0 to 2 Ma.

The time required to complete core formation decreases with planetesimal radius, because the increase in graviational driving force exceeds the increase in migration distance. Planetesimals that accrete before 1 Ma with radii larger than 70 km can complete core formation within the required 3 Ma. In smaller planetesimals or those accreting later, the completion of core formation may require as much as 9 Ma.

Discussion: We have investigated the timescales of percolative core formation in planetesimals. Our model results show that percolative core formation is far from instantaneous. In general, core growth only begins a few hundred thousand years after the onset of melting, because the melt must accumulate to exceed the percolation threshold and the gravitational driving force is weak. Initially the growth of the core is fast, but then slows down significantly as compaction of the silicate mantle increasingly reduces the porosity and permeability and slows the segregation of the metallic melt. The time scale to complete core formation therefore exceeds 1Ma in all cases and may require up to 9Ma in small planetesimals that accrete late.

Therefore, only planetesimals in the top left corner of Figure 1*b* allow percolative core formation in the timescale of less than 3 Ma inferred meteorite observations [1,2]. However, these conditions also lead to temperatures that significantly exceed the silicate solidus, so that the model used here neglects important physical processes. Most importantly the redistribution of heat producing ^{26}Al, which partitions into the silicate melt. It may therefore seem that percolation is not efficient enough to produce metal core within the observational constraints. To determine this several questions should be adressed.

The most obvious mechanism to accelerate melt transport is the formations of fractures, either due to volume increase during melting, the overpressure in the melt, or impacts. Melt filled fractures in an otherwise porous matrix have been observed in primitive achondrites [3]. Fractures can accelerate the melt transport by orders of magnitude. The critical question is the spacing of the fractures that is required, such that melt segregation is not limited by the perclative flow towards the fracture.

The effect of silicate melting on the metal segregation is not clear. On the one hand, the outward transport of the heat source will heat the outer shells of the planetesimal more rapidly, which likely decreases the time for core formation. One the other hand, the existance of two pore fluids may reduce the effective permeability of the metallic melt and therefore increase time

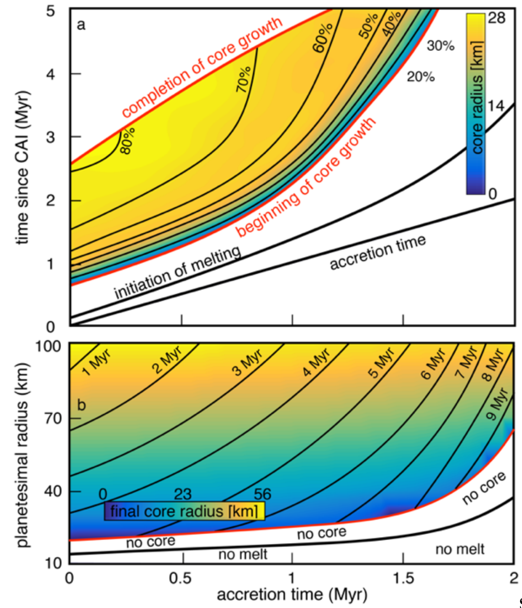

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Figure 1: *a*) Numerical simulation results for core formation in a planetesimal with radius 50 km as function of accretion time. *b*) Time to complete core formation as function of planetesimal radius and accretion time.

core formation. Further study of the mechanisms of coupled silicate and metal melt percolation is therefor required.

Finally, it is worth considering if the observations from meteorties require the completion of core fromation, or pertain only to the onset of core formation. In the latter case, the time constraints would be much less stringent and percolation as modeled here would be sufficient.

Conclusion: Despite the limitations of the model presented here, we can conclude that percolative core formation in planetesimals cannot be assumed to be instantaneous. Therefore, models that describe the complex multi-phase flows that occur during planetesimal evolution should be developed to determine if percolative processes are consistent with time constraints of geochemical and geophysical observations.

References: [1] Baker J. et al. (2005) *Nature,* 436, 1127-1131. [2] Weiss B.P. et al. (2008) *Science*, 322, 713-716. [3] McCoy T.J. et al. (1997) *Geochim Cosmochim Ac,* 61, 639-650. [4] Sierks H. et al. (2011) *Science,* 334, 487-490. [5] Ballhaus C. et al. (1996) *Earth Planet Sci Lett,* 143, 137-145. [6] Minarik W.G., et al. (1996) *Science,* 272, 530-533. [7] Shannon M. C. and Agee C. B. (1998) *Science,* 280*,* 1059–1062. [8] Ghanbarzadeh S. et al. (2016) LPS 47, Abstract #2664. [9] Qin L. et al. (2008) *Earth Planet Sci Lett,* 273, 94-102. [10] Terasaki H et al. (2008) *Earth Planet Sci Lett*, 273, 132-137. [11] McKenzie D. (1984) *J Petrol*, 25, 713-765.