

CORE FORMATION BY PERCOLATION OF IRON-RICH LIQUIDS. Catherine A. Hier-Majumder¹, Justin W. Hustoft², and Sean C. Solomon¹. ¹Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015, catherine@dtm.ciw.edu, scs@dtm.ciw.edu; ²Department of Geology and Geophysics, University of Minnesota, 310 Pillsbury Drive, SE, Minneapolis, MN 55455, hust0059@umn.edu.

Introduction: There is strong isotopic evidence that core formation is a rapid process, occurring within the first few million years for asteroids [1] and the first few tens of millions of years for terrestrial planets [2]. Iron and silicates can separate easily by the raining of heavier liquid-iron droplets through a liquid-silicate magma ocean [3]. In previous models it has been assumed that such liquid-liquid separation would result in an iron-rich layer at the base of the magma ocean [4, 5]. To complete core formation, the liquid iron must move downward through the underlying solid silicate-rich material beneath the magma ocean. Typically invoked is a diapiric mechanism [4, 5], which for a terrestrial planet requires the accumulation of a liquid iron-rich layer tens of kilometers thick. It is difficult to achieve such a layer thickness, however, because a magma ocean will have a mushy region at its base [6]. Since the liquid iron will settle into the crystal mush, it is not likely to form a distinct layer. A mechanism other than diapirs is therefore needed to move the iron to the planet's center. The diapiric mechanism also cannot be invoked after solidification of magma oceans and on satellites lacking magma oceans (e.g., Ganymede and Europa). We suggest an alternative mechanism, percolation of iron-rich liquid through a solid silicate matrix, which does not have the drawbacks of the diapiric mechanism.

Experimental evidence of iron percolation: It was earlier thought, on the basis of experiments, that it is not possible to move iron-rich liquids through solid silicates by percolation. The experiments on which this inference was made, however, were conducted in static situations; whereas in planetary bodies silicates are likely to be deforming through solid-state convection. Because the permeability of systems can vary greatly with deformation [7], the static experiments gave an incomplete picture of the process.

The early studies of the microstructure of silicate with metallic melt aggregates were performed under hydrostatic conditions. The results of these studies led to the conclusion that porous flow of metallic melts through silicate matrices was prohibited by the large melt-solid and solid-solid interfacial energy ratio, manifested as high dihedral angles (*i.e.*, $> 60^\circ$) of the metallic melt in contact with silicate grains [8-10].

The application of differential stress, however, strongly affects the distribution of melts [7, 11]. Sim-

ple-shear deformation experiments on olivine plus Fe-S aggregates have demonstrated that metallic melts can develop melt-preferred orientations (MPOs) that allow segregation by porous flow [7, 12, 13] (Fig. 1). The metallic melt-rich bands that form in samples deformed ductilely in simple shear have melt fractions exceeding 0.3, while the melt-depleted regions of the same samples have melt fractions of 0.01-0.02 [12]. These results indicate that Fe-rich melts will be able to percolate through a deforming solid silicate matrix along the melt-rich bands.

Core formation by compaction: The overall permeabilities of deformed samples with melt-rich bands can be described as [12]:

$$K = \frac{d^m \phi^n}{C} \quad (1)$$

where d is the grain size, ϕ is the porosity, m is the grain size exponent, n is the melt fraction exponent, and C is a geometric factor. For the geometry formed by the band network in the sheared samples, $n = 2$, $m = 2$, and $C = 8\pi$ [12]. These values give a permeability of about $4 \times 10^{-10} \text{ m}^2$ for a grain size of 1 mm and a porosity of 0.1. Such a permeability is sufficiently high to allow melts to percolate through planetary interiors well within the time constraints indicated by short-lived isotopes.

As Fe-rich melt percolates through the silicate mantle to the center of the planet, it will push away the overlying silicates to enlarge the liquid Fe-rich core at the planet's center. This process is described by the compaction equations [14]. We solved these equations for a one-dimensional Cartesian system using a silicate matrix of density 3300 kg/m^3 and effective viscosity 10^{18} Pa-s , along with an Fe-rich melt of density 4500 kg/m^3 and viscosity 0.04 Pa-s . We considered the case of a Moon-sized body with a gravitational acceleration of about 2 m/s^2 . For a silicate matrix of thickness 1000 km with an Fe-rich-melt-filled porosity of about 0.1, it took only 35 years to expel 90% of the melt from the matrix (Fig. 2). During this time, the size of the liquid core grew by 90 km and the silicate matrix was compacted from 1000 km to 910 km.

Concluding Discussion: Percolation of Fe-rich melt through solid silicates provides a plausible mechanism for core formation. It does not require the formation of an iron-rich layer at the base of a magma ocean, as is required for the diapiric mechanism. This

mechanism for core formation could have been especially important during the stage when the accreting planets were growing from about Moon size to Mars size. Accretional energy was not likely to be sufficiently large to melt the entire body [5]. There would be a layer of crystal mush mixed with the iron at the base of the magma oceans rather than a sharp boundary between liquid iron and solid silicate. Because the melting temperatures of iron sulfides increase less with increasing depth than those of silicates [15], an iron-sulfide-rich melt could remain molten and percolate through the underlying solid silicates to the growing core. Since Moon to Mars sized bodies likely formed within the first million years of solar system formation [16], the short-lived isotopes ^{26}Al and ^{60}Fe could have provided the heat needed both to keep the iron sulfides molten and to allow convective deformation in the silicate interior [17, 18].

The percolation mechanism would also have been active during any late-veneer stage of planetary accretion [13]. In particular, not all siderophile material added to the Earth during a late-veneer stage would have remained trapped in the mantle. Because the percolation process is not completely efficient, however, a few percent of the siderophile material from a late veneer would have remained in the Earth's mantle.

Finally, the percolation mechanism could have been important for core formation on the Galilean satellites Ganymede and Europa [19, 20]. The interior of these bodies would have been heated to around 1500 K by long-lived radionuclides [19], a temperature sufficient to melt iron sulfides but not silicates.

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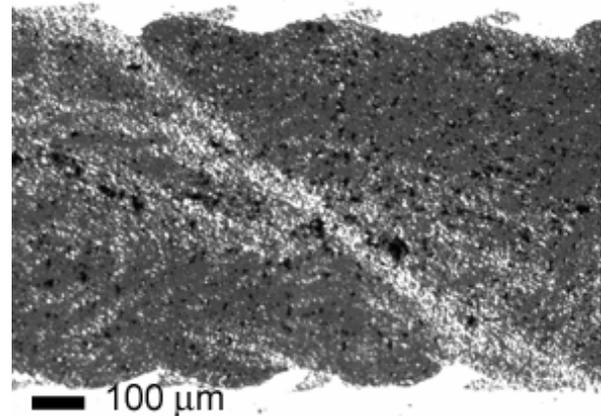


Fig. 1. Reflected light micrograph of a sample of olivine plus 9 vol % Fe-S deformed dextrally in simple shear to $\gamma = 2.5$.

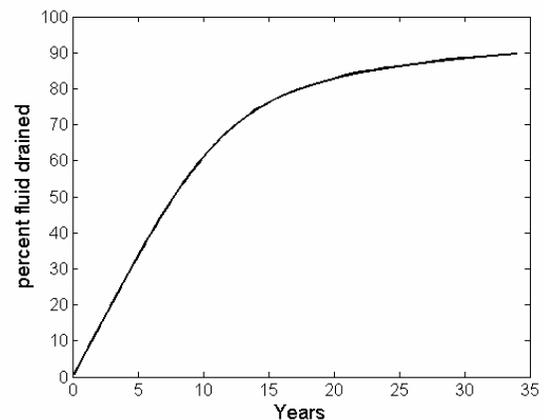


Fig. 2. Percent of the original Fe-rich fluid that has been drained from an upward compacting matrix and added to the fluid core versus time for a matrix that is initially 1000 km thick and has an initial fluid content of 10 vol %.