FLUID MIGRATION IN EARLY-ACCRETING PLANETESIMALS. R. R. Fu[1], E. D. Young[2], R. C. Greenwood[3], L. T. Elkins-Tanton[4]. [1]Dept. of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA (rogerfu@mit.edu). [2]Department of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, MA, USA. [3]Planetary and Space Sciences, The Open University, Milton Keynes MK7 6AA, UK. [4]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.

Introduction: The parent bodies of primitive meteorites and asteroids of the outer main belt accreted with a significant complement of volatiles such as H_2O, CO_2, and Cl [1]. The potential migration of these volatiles strongly influences the subsequent chemical and physical evolution of the body. Upon progressive interior heating due to the presence of short-lived radioisotopes such as ^{26}Al, water ice melts and reacts with surrounding anhydrous silicate and metal phases. Migration of aqueous fluids during these reactions potentially leads to unique signatures in the elemental and isotopic composition of chondritic material [2, 3]. The efficiency of fluid transport also strongly impacts the thermal evolution of volatile-rich bodies such as the asteroid Ceres, imminent target of the NASA Dawn mission [4, 5].

If the interior temperature reaches the silicate solidus, the concentration of retained volatiles is a critical factor in the buoyancy of the resulting silicate melts and the likelihood of their upward migration [6]. The ascent of silicate melts strongly affects the thermal evolution of the planetesimal and its surface composition. Magmas with a high volatile content may also lead to pyroclastic volcanism [7].

Despite the important implications of aqueous fluid migration in early-accreting planetesimals, broad uncertainty exists as to the extant of fluid mobility. Early studies argued that fractures would enhance the permeability of chondritic material and permit the flow of water in parent bodies with diameter greater than 120 km [4, 8]. However, theoretical calculations based on the estimated characteristic grain size of chondritic matrices suggest that such planetesimals were essentially impermeable and that fluid flow did not occur on scales of greater than 100 μm [9].

Here we consider the likelihood of aqueous fluid migration in the parent bodies of several chondrite groups. We evaluate the likely permeability of bulk, fractured chondrite material and examine vaporization of interior fluids as a driver of fracturing on early-accreting parent bodies.

Global permeability of chondritic parent bodies: The capacity for aqueous fluids to migrate through their parent bodies depends on a balance between driving forces, predominantly gravity, and the permeability of the host material. In the case of single pass ascent via density-driven Darcy flow [6], the very low density and viscosity of high-temperature fluids permit migration on the ~100 km scale in 10^5 years given permeabilities of 10^{-16} m^2 (Fig 1). Thermal convection of pore space fluids, because of the smaller density contrasts and higher viscosities at the modeled temperatures, may require higher permeabilities of 10^{-13} m^2 on a 100 km sized body [8].

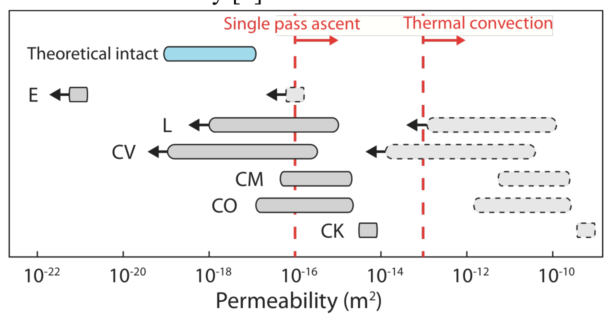

Fig. 1. Summary of laboratory (dark gray; [10, 11]) and theoretical (blue; [9]) permeabilities for chondrites. Light gray values with dashed outlines represent laboratory permeabilities augmented by 10^5 to account for the effects of fractures and scale (see text). Black arrows indicate meteorite groups that have at least one sample with permeability below the detection threshold of the experimental setup.

Direct measurements of the permeability of chondritic hand samples have found that most primitive ordinary and carbonaceous chondrites have permeabilities in the range between 10^{-17} and 10^{-15} m^2 (Fig. 1; [10, 11]). However, some CV, L, and enstatite chondrite hand samples have extremely low permeabilities between 10^{-18} and $<10^{-21}$ m^2. These permeabilities are consistent with theoretical calculations based on characteristic matrix grain sizes estimated from a TEM section of Acfer 094 [9]. Micro-fractures or a diversity of grain sizes in the matrix may account for the higher measured permeabilities of most chondrites.

However, the presence of fractures has a dramatic effect on the bulk permeability. Laboratory experiments on terrestrial rocks indicate that throughgoing fractures in a rock mass increases the permeability by between two and nine orders of magnitude [12, 13]. Furthermore, comparison of laboratory and field measurements of fractured rocks shows that permeabilities at the km and larger scale are higher than those of hand samples by approximately three orders of magnitude [14]. This effect is due to the sampling of a wider range of local permeabilities at the larger scales, which results in concentration of flow in the most permeable zones. Given these constraints, the bulk permeability of fractured chondritic parent bodies at the global scale was likely at least five orders of magnitude higher than values based on intact hand samples (Fig. 1).

Among the meteorite classes with measured permeabilities, fractured parent bodies with L, CV, CM, CO, and CK compositions are expected to have sufficiently high global permeabilities to permit both thermal convection and single pass ascent of pore space fluids. In contrast, enstatite chondrite parent bodies may not permit flow at all given their low fracture and scale-corrected permeabilities of $<10^{-16}$ m^2.

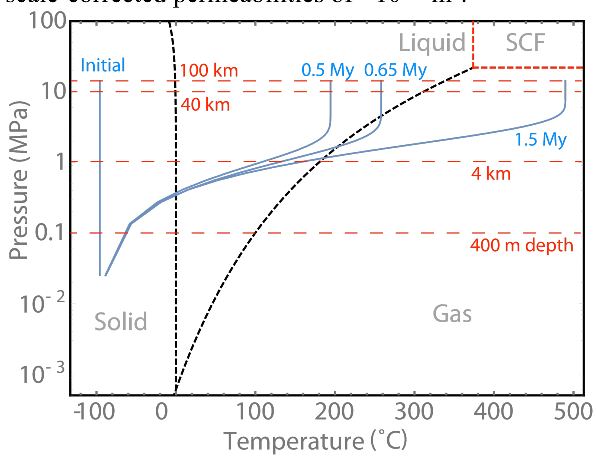

Fig. 2. Evolution of the interior temperatures of a 200 km diameter planetesimal accreted 1.3 My after CAIs overlaid on the water phase diagram. Blue curves indicate the temperature profiles at the specified times. Although we assume only conductive cooling in a body with uniform thermal diffusivity, pore fluid convection may occur in the near-surface zone of large temperature gradients given sufficiently high permeability [8].

Fracturing on early-forming planetesimals: The extent of aqueous fluid migration in chondritic planetesimals is therefore a strong function of the degree of fracturing. For planetesimals that undergo significant interior heating, the production of water vapor may cause pervasive fracturing [4, 8]. Under the simplifying assumption of pure water composition for the fluids, gas is generated at all depths of a 200 km diameter planetesimal upon heating to ~300˚C (Fig. 2).

The tensile strength of primitive, poorly consolidated chondritic material is of order 0.01 MPa [15]. Meanwhile, although no detailed study has been performed on the tensile strength of lithified chondrites, typical compressive strengths of intact ordinary chondrites are between 100 and 300 MPa [16]. Intact terrestrial basalts, which have a similar range of compressive strengths, exhibit tensile strengths between 10 and 20 MPa. However, this value drops to ~1 MPa with even a minimal density of pre-existing fractures [17].

Overpressures much greater than 1 MPa are readily produced during the vaporization of pore fluids. For example, in an interior zone with confining pressure of 10 MPa (40 km depth in a d=200 km planetesimal; Fig. 2), the slope of the vaporization curve is such that superheating of only 8˚C is required to generate 1 MPa of excess pore pressure, exceeding the likely tensile strength of the surrounding material. Superheating of 60˚C would lead to fracturing of even intact chondrite.

Conclusions: Chondritic parent bodies with CK, CO, and CM compositions had high intact permeabilities that permitted the buoyant ascent of aqueous fluids. In the case of early-accreting L and CV parent bodies, progressive heating and the production of vapor would have allowed the rapid ascent of aqueous fluids via fractures despite their lower intact permeabilities.

Therefore, for chondritic parent bodies (apart from E chondrites) internally heated to above ~300˚C, aqueous fluids ascended efficiently, potentially producing oxygen isotopic signatures of down-temperature flow and elemental abundances consistent with solubility trends [2, 3]. Further evidence of fluid migration includes the Allende CV chondrite, which experienced extensive metasomatism [18] but is now essentially dry and so requires fluid loss at greater than the sample (meter) scale.

The size scale of fracture networks, which is likely much larger than the hand sample scale [14], remains to be investigated. Finally, detailed modeling of elemental solubilities taking into account upstream equilibration of pore fluids ascending from the interior is necessary to assess whether the observed elemental depletion patterns in chondrites are consistent with the migration of aqueous fluids.

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