THE POSSIBLE ROLE OF WATER IN THE EARLY THERMAL EVOLUTION OF THE MOON. A. J. Evans[1] and M. T. Zuber[1] ([1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, xan@mit.edu)

Introduction: Past lunar studies to investigate the Moon's formation and its chemical and thermal evolution have focused on a bulk moon with minimal volatile content and free of water [1]. However, recent analyses of very-low-Ti glasses and lunar melt inclusions present compelling evidence that water content concentrations of at least 260 ppm were present in the deep lunar interior prior to 3 Ga [2, 3]. Though it remains inconclusive if the measured water content concentrations are representative of the entire lunar mantle or a water-enriched reservoir [3], the existence of water in the lunar interior could well have had a significant effect on the early lunar thermochemical evolution [1,4] and may have aided the cooling of the early Moon [9,10]. From experimental studies of the Earth's upper mantle (300 MPa), small amounts of water (~20 ppm) can result in a viscosity reduction in excess of 10^2 Pa-s [4]. Water in the deep lunar interior must have been accreted prior to and perhaps during lunar magma ocean solidification. Under the lunar magma ocean model, water would be progressively enriched with the incompatible elements during solidification and a fraction may have been retained by the lunar mantle [8].

In this study, we address the influence of water on the early lunar evolution by incorporating an attenuating strain rate (i.e. decreased viscosity) [1,4] for potential wet regions in the lunar interior.

Model: The standard convection equations are solved by a modified version of CITCOM2D, a spherical axisymmetric, finite-element convection model [5, 6]. We employ initial density and temperature profiles representative of the post-magma ocean solidification and overturn [7]. The water content is represented as a region of reduced viscosity [1], and radioactive heat generation [10] is included via a thin 20-km KREEP layer that remains under the base of the crust during magma ocean overturn. We employ a temperature- and depth-dependent rheology and a reference viscosity of 10^{20} Pa-s with a maximum viscosity variation of 10^3 Pa-s.

Results & Discussion: As our baseline, we use a dry mantle with uniform material properties (Fig. 1). Within the first few million years, the crust conductively cools the excess heat from the overturn (Fig. 2) and approaches a steady-state thermal profile. We examine two model scenarios relative to the dry mantle case, to gauge the effect of water content in the deep interior, Case A, and water mixed throughout the entire mantle, Case B. To account for water that may have been concentrated within the KREEP layer at the base of the crust, we apply a 10^2 Pa-s reduction in the viscosity within the KREEP layer in both cases.

Case A: Water content in the deep interior. Below 750 km, we account for water by decreasing the viscosity by a factor of 10 Pa-s, which represents a very conservative estimate for the minimum reduction of the viscosity in the presence of water [1,4]. Relative to the azimuthally-averaged temperature profile from our dry mantle baseline, the deep interior temperature is decreased by approximately 20% within the first 50 Ma and efficiently transports the heat upwards (Fig 3A).

Case B: Mixed mantle water. Similar to the previous case, we apply a factor of 10 reduction to the viscosity, but for the whole mantle below the KREEP layer. As in the previous case, there is a substantive reduction in the temperature below 750 km coupled with a 10% increase in temperature immediately above.

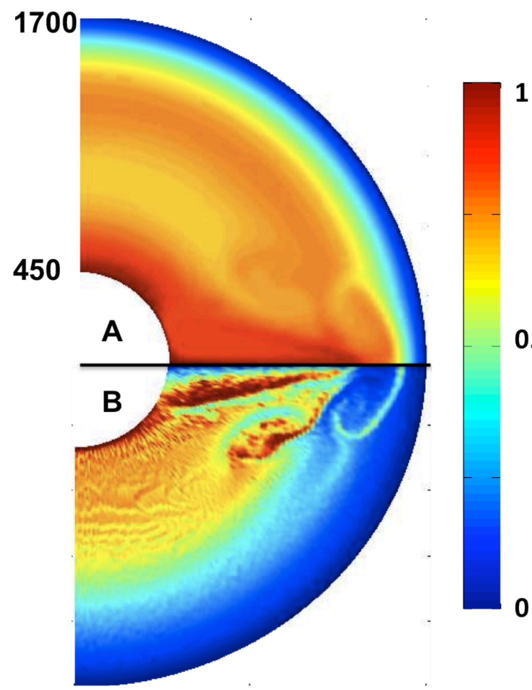

Figure 1. Dry mantle hemisphere at ~3.9 Ga. **A)** Normalized model temperature scaled, between the surface temperature (0°C) and the temperature difference across the mantle, 1600 °C. **B)** Variable density scaled between the reference density (3000 kg m-$^{-3}$) and the maximum mantle density 3700 kg m-$^{-3}$)

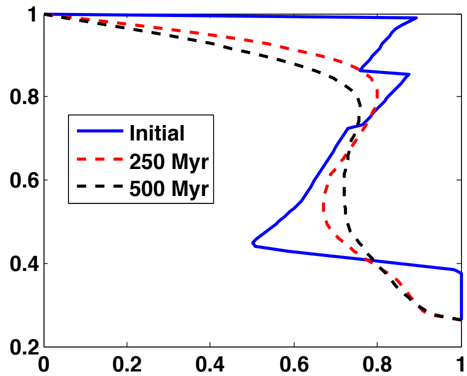

Figure 2. Dry Mantle Thermal Profile. The figure above represents the thermal (super-adiabatic) evolution of a standard dry mantle normalized by the reference temperature on the horizontal axis and the radius on the vertical axis. The initial temperature profile (blue line) represents the end state of magma ocean solidification and beginning of the convection model. After convection begins, the mantle begins to cool as shown at 250 Ma (red-dashed line) and 500 Ma (black-dashed line) after magma ocean solidification.

Water in KREEP Layer. While we incorporated a larger viscosity reduction for the water content in the KREEP layer, in the cases above the water was not transported away from the base of the crust. However, on the Moon, water transported to the deep interior via cumulate sinking may have played a delayed role in reducing the lower mantle viscosity over time.

Conclusion: In the early Moon, if water was transported to the deep interior, even in small amounts [4], it would have played a significant role in transporting heat out of the deep interior and reducing the lower mantle temperature. Given the potent effect of water on mantle viscosity, throughout the first 300 Ma, the presence of water may have consequences regarding the final compositional layering and perhaps in sustaining a core dynamo [11].

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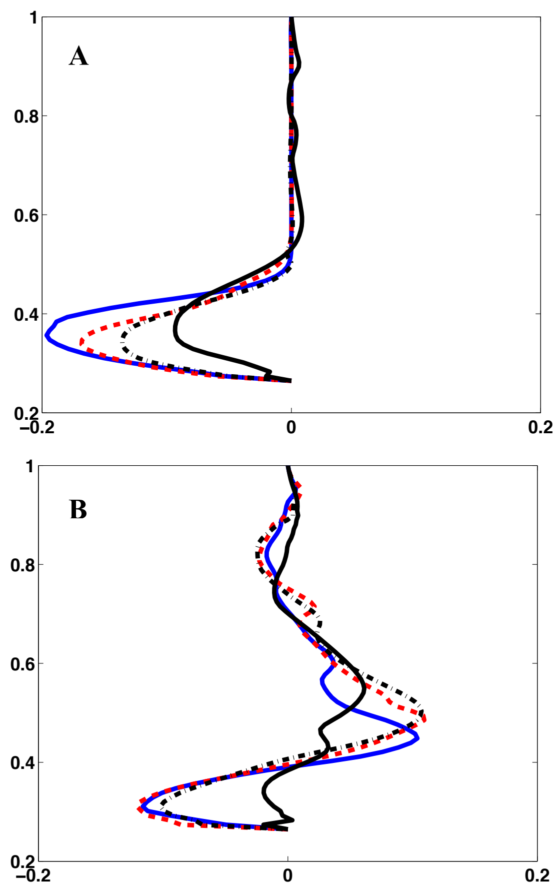

Figure 3. Case Thermal Profiles. Shows the evolution of the mantle temperature relative to the dry mantle profile at 50 Ma (blue solid), 100 Ma (red dashed), 150 Ma (black dash-dot), and 300 Ma (black solid). A) Thermal evolution representing water in the deep interior modeled by a factor 10 reduction in the regional viscosity. B) Thermal evolution of mantle with water (viscosity reduced by factor 10).