MANTLE CONVECTION AND MAGMA PRODUCTION ON PRESENT-DAY MARS: THE EFFECTS OF WATER. Qingsong Li and Walter S. Kiefer, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058 (li@lpi.usra.edu).

Introduction: Several lines of evidence, including lower density of small craters on some Martian volcanoes and young isotopic ages of shergottites, suggest geologically recent volcanism on Mars [1]. This helps constrain the thermal structure of the martian mantle and the nature of present-day mantle convection. Kiefer [1] explored the implications of these constraints using spherical axisymmetric finite element simulations with depth-dependent viscosity and radioactive heating that was partitioned between mantle and crust. Li and Kiefer [2] extended these models to the more realistic case of a temperature-dependent Arrhenius viscosity law. An important limitation of the earlier study [1] was that the inferred heat flux out of the core was relatively large and suggested the likelihood of a present-day geodynamo. The thick stagnant lithosphere in the new models results in higher mantle temperatures [2]. This significantly reduces the heat flux from the core into the mantle, in agreement with the absence of a present-day magnetic dynamo. Here, we add water effects into the latest models to explore how water content may affect the mantle convection and magma production on present-day Mars.

Water Effects on Melting and Rheology: Most estimates of the present-day water content in the Martian mantle are a few hundred ppm or less [3-7]. The recent water-saturated melting study of Médard and Grove [8] may be relevant to the early history of Mars but does not directly address melting at the low water contents that are thought to occur in the present-day mantle. We therefore apply the melting parameterizations of Katz et al. [9] and Aubaud et al. [10], which show, for example, that 1000 ppm of the water lowers the peridotite solidus by ~150 K at 5 GPa. We use the anhydrous melting results from Bertka and Holloway's [11] melting study of a Mars-analog composition. We assume that for a given amount of mantle water, the decrease in the solidus temperature is the same for the Mars mantle as it is for the terrestrial mantle composition and therefore construct a series of wet solidii for different water abundances. Using these new values for the wet solidus, we calculate melting using the same computational approach as in Kiefer [1]. In our on-going work, we expect to improve upon this basic model in two ways. First, we will consider the possibility that the Martian mantle has a higher magnesium number [12] than in the Bertka and Holloway model [11]. Second, our current models make the simplification that melt productivity is a uniform function of the temperature above the solidus, whereas the available petrology literature suggests that melt productivity is low between the wet and dry solidii and increase once the temperature exceeds the dry solidus (e.g., [9]). Both of these effects will act to lower the predicted magma production rate relative to the values shown here.

For self-consistency, we also consider how water affects the mantle's viscosity. Latest experiments show that viscosity of olivine aggregates decrease roughly linearly with increasing water fugacity above a threshold fugacity [13, 14]. The translation from water fugacity to water content is temperature and pressure dependent [15]. As a first-order approximation, we assume that viscosity of Martian mantle decreases linearly with increasing water content if water content is larger than 5 ppm.

As water is added to the system, the viscosity decreases. There are two competing effects. First, the increased convective vigor (higher thermal Rayleigh number, Ra) cools the mantle. The lower plume temperature decreases the melt production. However, the higher Ra also results in a thinner near-surface boundary layer. This permits greater adiabatic decompression in the plume and enhances melt production.

Mantle Convection Model: Mantle convection simulation is performed using a spherical axisymmetric finite element model [16]. The non-dimensional model domain ($\theta = 0\text{-}\pi/4$, R = 1-2) is meshed with a 128×128 grid. The model includes both internal radioactivity heating (4.1×10^{-12} W/kg, [17]) and basal heating due to the heat flux out of the core. In the simulations, 30-80% of radioactivity is partitioned into the crust (50km thick). We use the Arrhenius form of the temperature-dependent part of the viscosity law [13, 14]. The maximum viscosity in the upper thermal boundary layer (lithosphere) is set at 10^6 times the viscosity at the bottom of the mantle. The surface and bottom boundaries are set with fixed temperature conditions and the side boundaries are thermally insulated. All four boundaries are free-slip.

Results: We first set reference model cases with a range of activation energy, thermal Ra and radioactivity partitioning. Model results of water effects with different reference model cases are similar. Here we focus on one reference case (Figure 1). The thermal Rayleigh number, defined with basal viscosity, equals 5.7×10^6. Activation energy equals 160 kJ/mole. 50% of the total radioactivity is partitioned into the crust. The model results, including heat fluxes, magma production rate, and melting fraction, falls into constraints set by previous studies [1, 18, 19]. Especially, the heat flux out of the core is low (11.3 mW/m^2) due to the thick stagnant lithosphere. This is in agreement with the absence of a present-day magnetic dynamo and an important improvement of the previous model with depth-dependent rheology [1].

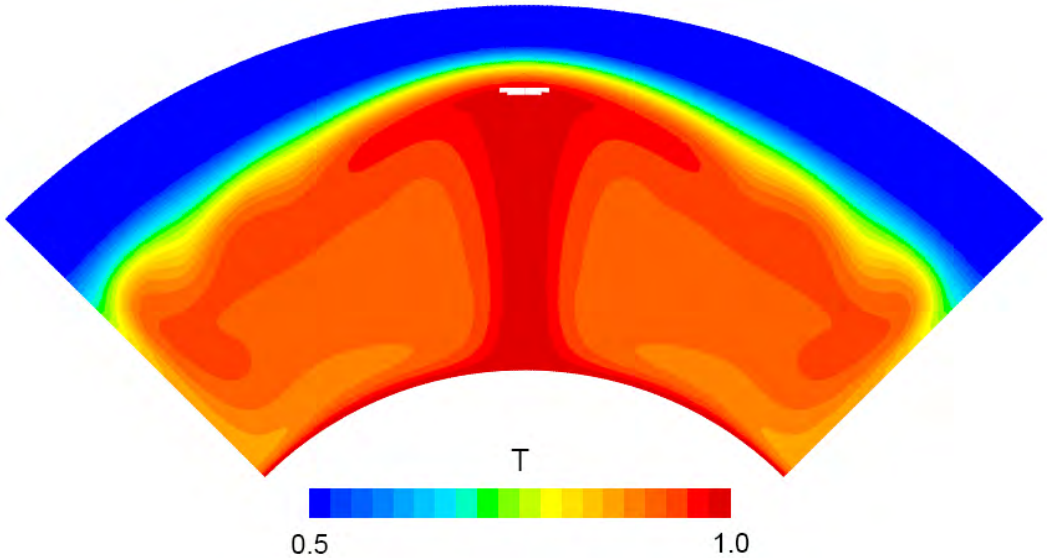

Figure 1. The super-adiabatic non-dimensional temperature is shown for a reference case (see the text). Because the mantle convection is time-dependent, the model case is run until a statistically steady state is reached. The white region shows the location of decompression melting.

As the water content increases from 50 ppm to 300 ppm, the mantle viscosity decreases by 6 fold and the solidus decreases by ~70 K. These cause the basal heat flux to increase by ~10 mW/m^2 and surface heat flux to increase by ~3 mW/m^2, indicating the thinning of upper thermal boundary layer. Moreover, both the magma production rate (Figure 2) and melting fraction increase significantly.

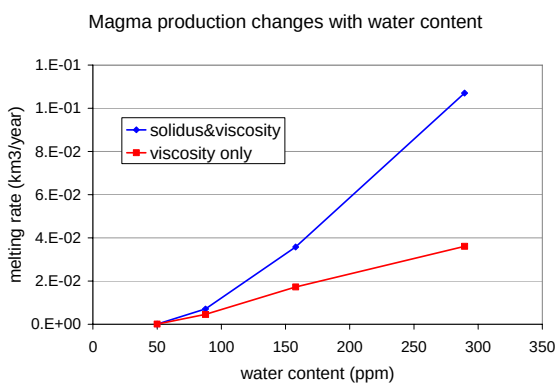

Figure 2. Magma production rates are plotted against water content. The water content in the reference case is assumed to be 50 ppm. The blue curve reflects water effects on both solidus and viscosity, and the red curve reflects water effects on viscosity only.

The red curve in Figure 2 shows the effects of water on melt production, assuming a fixed (dry) solidus and allowing water to change the viscosity. The fact that melt production increases with increasing water content shows that lithospheric thinning is more important than mantle cooling in controlling the melt production. The blue curve in Figure 2 includes the effects of water on both the solidus and the viscosity. Comparing the two curves shows that at low water content (<100 ppm), the effect of viscosity change dominates. For larger water abundances, the change in solidus temperature is the dominant control on melt production. If the mantle water content is as large as 300 ppm, either the Ra or core-mantle boundary temperature must be smaller than the reference values for the model to satisfy constraints on melt production rate and the absence of a magnetic dynamo.

References: [1] Kiefer, Meteoritics Planet. Sci. 38, 1815-1832, 2003. [2] Li and Kiefer, Eos. Trans. AGU 87, Fall Meet. Suppl., Abstract P31C-0150, 2006. [3] Carr and Wänke, Icarus 98, 61-71, 1992. [4] Leshin et al., Geochim. Cosmochim. Acta 60, 2635-2650, 1996. [5] Mysen et al., Am. Mineralogist 83, 942-946, 1998. [6] Dyar et al., Lunar Planet. Sci. Conf. 35, abstract 1348, 2004. [7] Jones, Lunar Planet. Sci. Conf. 35, abstract 1798, 2004. [8] Médard and Grove, J. Geophys. Res. 111, doi:10.1029/2006JE002742, 2006. [9] Katz et al., Geochem. Geophys. Geosyst. 4, 1073, doi:10.1029/2002GC000433, 2003. [10] Aubaud et al., Geophys. Res. Lett. 31, doi:10.1029/2004GL021341, 2004. [11] Bertka and Holloway, Contrib. Mineral. Petrol. 115, 313-322, 1994. [12] Agee and Draper, Earth Planet. Sci. Lett. 224, 415-429, 2004. [13] Mei and Kohlstedt, J. Geophys. Res. 105, 21,471-21,481, 2000. [14] Mei and Kohlstedt, J. Geophys. Res. 105, 21,457-21,469, 2000. [15] Kohlstedt et al., Contrib. Mineral. Petrol. 123, 345-357, 1996. [16] Kellogg and King, Earth Planet. Sci. Lett. 148, 13-26, 1997. [17] Wänke and Dreibus, Phil. Trans. R. Soc. London A349, 285-293, 1994. [18] McGovern et al., J. Geophys. Res. 107, doi:10.1029/2002JE001854, 2002. [19] McGovern et al., J. Geophys. Res. 109, doi:10.1029/2004JE002286, 2004.