MANTLE CONVECTION ON MARS WITH ENHANCED CRUSTAL RADIOACTIVITY: IMPLICATIONS FOR GEOPHYSICAL AND GEOLOGICAL OBSERVABLES

Walter S. Kiefer, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX, 77058
(281) 486-2110, kiefer@lpi.usra.edu, http://www.lpi.usra.edu/science/kiefer/home.html

The shergottites are basaltic meteorites from Mars, many of which have igneous crystallization ages of about 180 million years [1]. The existence of young volcanism implies that adiabatic decompression melting and hence mantle convection has remained an important process on Mars up to the present day. In previous work, I examined the magma production expected due to adiabatic decompression melting on Mars [2]. The convection simulations in that work considered as variables the Rayleigh number, the amount of radioactive heating in the mantle, and the thickness of the high-viscosity surface layer. In those models, radioactive heating was assumed to occur at a uniform rate from the surface of Mars to the base of the mantle. The radioactive elements uranium, thorium, and potassium all behave geochemically as incompatible elements and thus strongly partition into the melt phase. As a result, these elements will be preferentially concentrated in the crust rather than in the mantle. In this study, I investigate how this enhancement in crustal radioactivity affects magma production, the thickness of the mechanical lithosphere, and the heat flux out of the core on Mars.

Convection Simulations

The mantle convection simulations are performed using finite element methods in spherical axisymmetric geometry [3,4]. The best observational constraint on the distribution of mantle heterogeneity on Mars comes from the geoid. *Mars Global Surveyor* observations [5] show that the geoid has a high degree of axisymmetry about the center of Tharsis once the hydrostatic contribution to the geoid [6] is removed. This indicates that the spherical axisymmetric model is a very good approximation for modeling present-day convection on Mars.

Models for the mantle composition of Mars are constrained by the chemistry of the SNC meteorites and imply present-day radioactive heating rates of $4.2\text{–}6.8 \cdot 10^{-12}\,\mathrm{W\,kg^{-1}}$ [7-9]. Initial modeling focuses on these heating rates for the mantle. Later modeling will extend this to higher heating rates as appropriate for earlier geologic epochs. Because of the geochemically incompatible nature of the radioactive elements, the concentration of radioactive elements in the crust relative to the original mantle source should be approximately the inverse of the typical melt fraction. Trace element studies of the shergottites indicate melt fractions of 2-8% [10]. In this work, I consider crustal radioactive abundances that are from 1 to 100 times the mantle radioactive abundances. This parameter is called the crustal enrichment factor in the following discussion. Crustal radioactivity is assumed to be uniform throughout the crust, which has an assumed thickness of 50 km [11]. There is a high viscosity lid at the top of the model, with a viscosity contrast of 10^5 between the surface and the base of the lid. This viscosity contrast is sufficient to put the models into the sluggish or stagnant lid convection regime [12]. The characteristic flow velocity at the top of the high viscosity layer is only 0.01 mm per year, confirming that the models are in the stagnant lid regime. The finite element grid has a vertical resolution of 13 km. The assumed core radius is 1700 km.

Results

The mantle flow in these simulations is strongly time-dependent due to the development of boundary layer instabilities [4]. In order to understand the characteristic behavior of these models, each simulation was integrated for the equivalent of several billion years of real time. What follows is a preliminary interpretation of the model results.

Mantle Temperature Increasing the abundance of radioactive elements in the crust requires a higher conductive thermal gradient to accommodate the enhanced heat production. The implication is that temperatures at all levels below the crust will also be increased if the planet is in thermal equilibrium. The increase in the mantle temperature is small (< 50 K) for crustal enrichment factors of 10 or less. Larger crustal enrichment factors produce significant increases in the mantle temperature.

Mechanical Lithosphere Thickness The thickness of the mechanical lithosphere is controlled by the thermal structure of the lithosphere [e.g., 13]. Thus, the mechanical lithosphere will decrease in thickness as the crustal enrichment factor increases. The mechanical thickness is being calculated using a strength envelope approach.

Magma Production Several aspects of magma production on Mars are potentially testable by geophysical, geological, and geochemical measurements. (i) What is the rate of magma production? Testing model predictions as a function of time is not likely to be feasible because of the uncertainties in the cratering time scale. However, an integrated value over time can be tested by comparison to the total crustal volume (unless subduction or delamination has been important in recycling crust). (ii) What is the spatial distribution of magma production? Model predictions for this can be tested by comparison with geologic mapping. (iii) What is the characteristic melt fraction? This can be tested using geochemical methods [e.g., 10]. The effects of the crustal enrichment factor on these issues is currently being assessed using the methodology of [14] and melting relationships appropriate for the SNC meteorites [15].

Core Heat Flux If the heat flux out of the core exceeds the critical value required for core convection, a magnetic dynamo is expected to occur on Mars [16]. Thus, observations of the presence or absence of magnetic anomalies in terrains of different ages on Mars [17,18] can provide some clues about the time history of the core heat flux on Mars. The heat flux from the core decreases as the mantle temperature rises. In these simulations, increasing the crustal enrichment factor from 1 to 100 causes roughly a 50% decrease in the average heat flux out of the core. In all of these models, the time-dependent mantle flow causes the core heat flux to fluctuate by 30 to 40% relative to the time-averaged value. This degree of variability means that Mars might have spent a considerable period of time in the intermittent dynamo regime [19], in which the dynamo alternately turns off and on as the core heat flux (and hence the ability of the core to convect and sustain a dynamo) varies. This might be an important factor in understanding the complex pattern of magnetic anomalies observed on Mars.

[1] Nyquist et al., J. Geophys. Res. 103, 31,445-31,455, 1998. [2] Kiefer, LPSC 31, CD-ROM abstract 1527, 2000. [3] Kellogg and King, Earth Planet. Sci. Lett. 148, 13-26, 1997. [4] Kiefer and Kellogg, Phys. Earth. Planet. Int. 106, 237-256, 1998. [5] Smith et al., Science 286, 94-97, 1999. [6] Sleep and Phillips, J. Geophys. Res. 90, 4469-4489, 1985. [7] Treiman et al., Geochim. Cosmochim. Acta 50, 1071-1091, 1986. [8] Wanke and Dreibus, Phil. Trans. R. Soc. London A349, 285-293, 1994. [9] Lodders and Fegley, Icarus 126, 373-394, 1997. [10] Norman, Meteoritics and Planet. Sci. 34, 439-449, 1999. [11] Zuber et al., Science 287, 1788-1793, 2000. [12] Reese et al., J. Geophys. Res. 103, 13,643-13,657, 1998. [13] McNutt, J. Geophys. Res. 89, 11,180-11,194, 1984. [14] Watson and McKenzie, J. Petrology 32, 501-537, 1991. [15] Bertka and Holloway, Con. Min. Pet. 115, 313-322, 1994. [16] Nimmo and Stevenson, J. Geophys. Res. 105, 11,969-11,979, 2000. [17] Acuna et al., Science 284, 790-793, 1999. [18] Purucker et al., Geophys. Res. Lett. 27, 2449-2452, 2000. [19] Stevenson, LPSC 24, 1353-1354, 1993.