The Thermal Evolution of Mars and Mars-type Planets: Geodynamic and Geochemical Potential for Early Mobility.

M. B. Weller[1], [1]Department of Earth Science, Rice University, Houston, TX 77005, USA (matt.b.weller@rice.edu).

Introduction: The early geological history of Mars suggests an active, and perhaps hospitable world, with evidence of ~1 bar atmospheric pressures, flowing water, and significant volcanism [e.g. 1]. Evidence further suggests that ancient Mars exhibited a core dynamo that shut off by ~4.1 Ga [2], and soon after, a transition to an ice dominated surface [e.g., 3]. Magmatism, however, persisted from Noachian through Amazonian time, as evidenced by the emplacement of Tharsis ~3-4 Ga and by volcanic eruptions with very young ages inferred =from low crater densities, including a ~100 Ma eruption of Olympus Mons [e.g. 4]. In contrast to the intermittent volcanism, the large scale tectonic evolution of Mars appears to have arrested early in planetary development, coincident with the emplacement of Tharsis at ~ 3.6 Ga, and likely well after the formation of the hemispheric dichotomy between the northern lowlands and southern highlands. While there exists an intermittently volcanically active Mars, it is unclear if Mars has always operated in a stagnant-lid regime, or if it ever possessed active (or mobile) tectonics.

Planetary Tectonic Evolution: While the tectonic evolution of the Earth, and consequently Venus (due to its similar size and bulk composition) are hotly debated [e.g., 5-10], the tectonic evolution, and lid-state, of smaller terrestrial planets (e.g. Mars) is often assumed *a priori*. These assumptions are the result of the lack of clear indicators of mobility in the martian geologic record and canonical thermal models which assume smaller planets contain insufficient energy to drive plate-tectonics, whereas larger (and hotter) planets have ample energy to do so. However, recent work has shown that lower internal temperatures (T_i) tend to favor a greater potential for mobility, and higher temperatures a lower potential [11,12]. All things being held equal, this implies that Mars type planets should have an increased potential of an early stage of mobility. Indeed, recent models have shown that parameter ranges thought to be relevant to Mars can allow for early phases of surface mobility [13], in line with proposed models of early martian plate-tectonics [e.g., 14,15]. While the model space allows for regions of mobile behavior, the question remains has Mars undergone an early mobile phase of evolution, or has it remained stagnant through its lifetime?

Mantle Temperature and Tectonic States : Key to understanding the internal evolution of Mars, is the internal temperature of the mantle. Mantle Potential Temperatures (T_P) can be obtained from erupted basalts through well established geochemical relationships using mineralogy from direct and orbital measurements [e.g., 16, 17]. It has been shown that the T_i of numerical simulations follow well prescribed scaling laws, given as a function of system Rayleigh number (Ra) and internal heating rate (Q) [e.g. 18-20]. Further, each specific lid state has specific predictions T_i, given the assumption of pure solid-state convection (melting processes are not considered), and fixed boundary temperature conditions [20]. It has been shown that T_i of long-lived stagnant-lids should be measurably higher than a respective mobile-lid system [20], with episodic-lids falling in between. Therefore in this simplified solid-state system, T_i (approximated by the mantle potential temperature) may be used to infer lid-states and help to constrain the thermal-tectonic evolution of the system.

Results and Discussion: The mantle T_p for Mars [e.g., 16,17,21] are non-dimensionalized for comparison with numerical models [20] using $T_p = T_s + T_{nd} \cdot \Delta T$, where T_s is the surface temperature, T_{nd} is the non-dimensional temperature, and ΔT is the temperature contrast from the core to the surface. Mars' Ra is taken to be of order 1e6 (with 2.14e6 given as the median value), Q_{inital} = 132 (non-dimensional form of [22]), ΔT = 1600 K, and T_s = 210 K. Results are shown in Figure 1, where Q is also a proxy for time. Core cooling is not explicitly accounted for in the non-dimensionalization, and Ra variation is considered to be small compared to Q depletion (e.g. [24]).

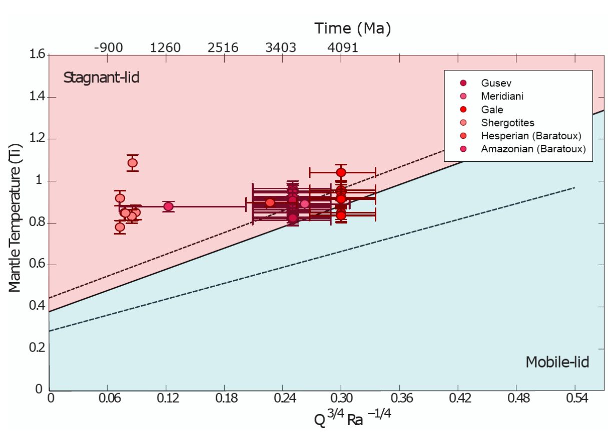

Figure 1: Non-dimensional Mantle Potential temperature obtained from direct and orbital measurements [16, 17, 21] plotted in internal temperature regime diagram space as a function of Ra and Q [18 - 20], and time. The red region denotes stagnant-lid temperatures, where the blue region denotes mobile-lid temperatures. The solid line corresponds to the critical temperature separating mobile- and stagnant-lid values. Dashed lines denote best fit trends from simulations each lid-state. Error bars in T_i are related to uncertainties in the thermo-barometric equations (see [17] and references therein). Error

bars in $Q^{3/4}$ $Ra^{-1/4}$ result from uncertainty in surface ages. The outlier Shergottite value (T_i = 1.1) corresponds to Y98. Parameter values used in plot follow: Ra = 2.14e6; Q_{inital} = 132; ΔT = 1600 K; T_s = 210 K; R_{mantle} = 1.56e3 km; R_{core} = 1.83e3 km.

The majority of Martian evolution indicates internal temperatures that are consistent with that of a stagnant-lid style of convection (Amazonian into the Hesperian). However, as regions become older (> 3.8 Ga) temperatures begin to show greater affinity for mobile-lid fields, with Hesperian aged Meridiani allowing for mobility within error, and the older Noachian units plotting within both mobile-lid and stagnant-lid fields, a strong indicator of an episodic-lid regime. These results, however, are sensitive to choice of Ra and ΔT. Increasing the Ra to 6e6 (likely at the upper most range of accepted values for Mars [e.g. 23,24]) shifts the data points to the left, towards stagnant-lid solutions, but still allows for mobile-lid temperatures within the uncertainty. However, the Ra for Mars may similarly be lower. Decreasing the Ra to 1e6 shifts the Noachian data points almost entirely within mobile-lid temperatures. Hesperian points plot on the critical temperature line separating mobile and stagnant-lid solutions. ΔT realistically may vary between 1600 K and ~2200 K (limited by solidus temperatures) [e.g., 24]). Increasing ΔT from 1600 K shifts the values down the T_i axis into mobile-lid temperature fields.

In aggregate, for reasonable martian parameter values, the data suggests a strong potential for an early phase of martian mobility. This potential mobile phase ceases near the Hesperian transition. Overtime, as the planet evolves, the Amazonian temperatures are higher than those expected by simple secular cooling, this suggests that Mars may have cooled much more slowly than canonical models would assume over its lifetime, in agreement with recent 3D [23] and 1D parameterized studies [24].

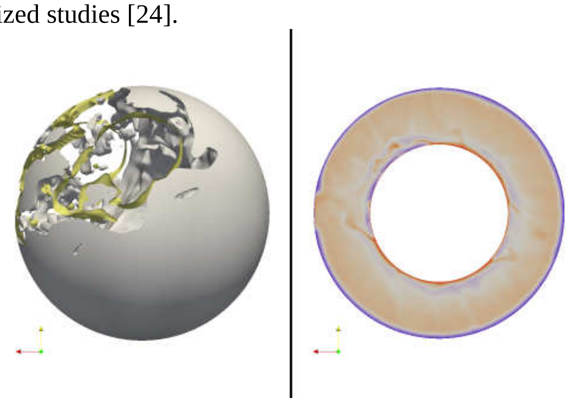

Figure 2: Simulation of an episodic early Mars using martian parameter ranges: Ra = 3e6; Q = 93.4; Yield = 6.48e4. left: viscosity plot (grey shells = high viscosity “plates”, yellow bands = yielding); right: profile from the core mantle boundary to the surface, warm colors = high temperatures, cool colors = low temperatures.

The implications for the coupled thermal-tectonic evolution of Mars sized bodies is significant. An early mobile to episodic-lid may have favored a warmer surface, and allowed for transient dynamo to be generated. Additionally, an early phase of mobility would predict lower T_i, but greater melt being generated than a pure stagnant-lid would indicate (heat-pipe modes of operation are not directly considered, however early hot stagnant-lids have the potential to operate in this regime). The northern lowlands and southern highlands dichotomy has the potential to be described by such an early episodic overturn, as Figure 2 tantalizingly suggests. Contrary to the results of [25], these results indicate episodic-lids can be found to be hemispherically restricted if thermal evolution is accounted for [e.g., 12]. The maximum extent of the episodic overturn is ~ 30% of the planetary surface and results in a thin lithosphere in the overturning region, and a thicker lithosphere in the 'intact' hemisphere. Average internal temperatures (~0.58) match scaling and potential temperature results for T_i > 1800 K. As the system transitions out of mobility, there should be a relative increase in internal temperature, indicating that post-transition Mars would have a warmer mantle than pre-transition Mars, compounding existing thermal models which assume only one lid-state and secular cooling. There are strong indications that Mars may have been mobile while the early Earth may not have been, further suggesting that mobility (and plate-tectonics) may be a phase of terrestrial evolution that many planets have the ability to migrate through in their lifetimes [12].

References: [1] Baker et al. (1991) Nature 352, 589–594.; [2]Lillis et al. (2013) JGR, 118, 1488–1511. [3] Bibring et al., (2006) Science, 312, 400-404. [4] Werner (2009) Icarus, 201, 44-68. [5] Schubert et al. (1997) *Venus II*, Univ. Arizona Press. [6] Turcotte, (1993) *JGR*, *98*, 17,061-17,068. [7] Fowler & O’Brien, (1996) *JGR*, *101*, 4755-4763. [8] Kiefer (2013) LPSC 44, #2554. [9] O'Neill et al. (2013) Geo. Soc. London, 389. [10] Debaille et al. (2013) EPSL, 373, 83-92. [11] Stein et al. (2013) EPSL, 361, 448–459. [12] Weller, et al. (2015) EPSL, 420, 85-94. [13] Zhang and O'Neill (2016) Icarus, 265, 187–208. [14] Sleep (1994), JGR, 99, 5639–5655. [15] Lenardic, et al. (2004), JGR, 109, E02003. [16] Filiberto, J. & Dasgupta, R. (2011) *EPSL*, *304*, 527-537. [17] Weller and Duncan (2015) 46th LPSC, abstract #2749. [18] Sotin & Labrosse (1999) *PEPI*, *112*, 171-190. [19] Moore, W. (2008) *JGR*, *113*, B11407. [20] Weller et al. (2014) AGU fall meeting. [21] Baratoux, et al. (2011) Nature, 7343. [22] Dreibus and Wänke (1985) Meteor., 20, 367-381. [23] Plesa et al. (2015), JGR. [24] Duncan et al., 46th LPSC, abstract #2900. [25] Han et al. (2012), Icarus, 218, 320 - 330.