LARGE EFFECT OF SMALL PLANET ON PLATE TECTONICS AND THERMAL EVOLUTION: APPLICATION TO MARS. T. Matsuyama, Tokyo Institute of Technology (I2-12, Meguro, Tokyo, 152-8550, Japan, matsuyama@geo.titech.ac.jp).

Introduction: The likelihood of plate tectonics on other planets has been investigated especially in the last two decades [1, 2]. In terms of a larger planet than the Earth, a super-Earth is an instance [3]. Geodynamicists have analyzed the probability that plate tectonics operates on its surface, and some results claim that the plate tectonics is conceivable [4].

As regards a smaller planet than the Earth, Mars is a representative example. Although several observations of the Martian surface [5, 6] indicate the existence of plate tectonics for the first ~500 Myr, calculated thermal history with plate tectonics [7] seems inconsistent with the thermal evolution estimated from other observations [8] and, as a result, the early Martian plate tectonics was concluded to be unlikely[9].

To those planets, this study applies the thermal evolution model of the Earth, which has been investigated much more than the other planets, and especially follows a recently proceeded theory about thermal evolution with plate tectonics on Earth [10]. In addition to the application, focusing on the effect of gravity, in particular small gravity of Mars, this study provides its thermal history, which supports the early Martian plate tectonics.

Basic Theory of Thermal Evolution: In this study, calculation of thermal history mainly follows the theory developed by [10]: in the generation of plate beneath mid-ocean ridges, the dehydration of the mantle is assumed to take place when the upwelling mantle crosses the solidus. The initial depth of decompression melting is assumed to be the thickness of lithosphere. With the solidus for dry pyrolitic mantle [11], the plate thickness, h_p, is expressed as

$$h_p=(T_m - 1423)/100\rho g, \quad (1)$$

where T_m is the mantle potential temperature (in K), ρ is mantle density, and g is gravitational acceleration. Accordingly, the hotter the mantle, the thicker and the stiffer the plate (blue line in Fig. 1), leading to more sluggish plate tectonics due to the difficulty in subduction and less surface heat flux. This seemingly counter-intuitive theory, i.e., the hotter mantle releases less surface heat flux, explains a long-standing problem regarding Urey ratio of the Earth and is consistent with the thermal history obtained by petrological data [12].

Effect of Planet Size: The theory of [10] is applied to different-size planets on the assumption that plate tectonics is operating on their surface and I focus on the variation of plate thickness induced by the different gravity. Equation (1) shows that a smaller planet is likely to have thicker plate (Fig. 1), which results in the less heat flux on the surface. Fig. 1 confirms that, although the initial high temperature of large planet makes the plate thicker because the initial depth of melting increases, the effect of gravity is more dominant and, as a result, a small planet can keep the temperature longer than a large one owing to the thicker plate. This influence of thickening plate on a small planet, like Mars in its early stage, cannot be ignored.

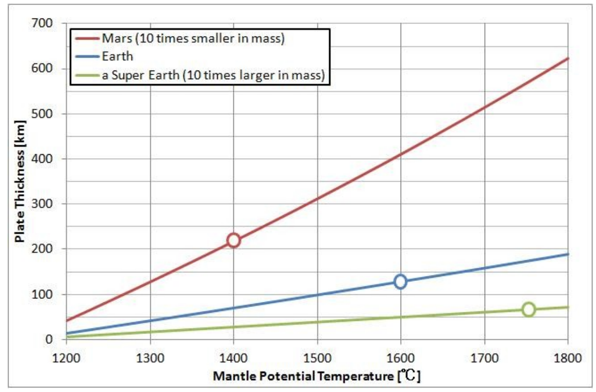

Fig. 1. Plate thickness and mantle potential temperature. Red, blue, and green lines represent the result of Mars, Earth, and a super-Earth, respectively. The small circles are arbitrarily chosen mantle potential temperature in the initial state to show the thermal effect on plate thickness.

Early Thermal Evolution of Mars: In order to clarify the effect of plate thickness variation on the early thermal history, I calculate the initial time rate of change of temperature, $dT(t=4.6Ga)/dt$, with variation of planet size, from the equation in [10]:

$$dT(t=4.6Ga)/dt = (H - Q)/C,$$

where H is the internal heat production in the mantle, Q is surface heat flux by mantle convection, and C is the heat capacity of the whole planet (Earth: ~7×10^{27} J K^{-1} [13]) (Fig. 2). C and H are assumed to be proportional to the planetary volume and Q depends on T_m, h_p, and the geometry of subducting plate, such as the radius of curvature for bending plate [10]. Fig. 2 suggests that there is a critical planet size, ~ $1.1\times R_E$. A planet smaller than the critical size, such as the Earth and Mars, first increases the temperature, though a larger planet decreases the temperature as we conventionally expected.

Based on the result of Fig. 1 and 2, using the Martian properties [14, 15, 16], I calculate the early thermal evolution of Mars with plate tectonics to 4.0 Ga and then employ the stagnant-lid convection [14, 15] from 4.0 Ga to the present (Fig. 3). Fig. 3 shows two important points. First, the application of the thermal history with plate tectonics on Earth [10] to Mars is able to reproduce the Martian thermal history. Second, if the plate tectonics ceased at 4.0 Ga, the cessation occurred in a hotter condition than the initial one, though the mantle must have convected more vigorously than ever.

Discussion: Whereas the result of Fig. 3 depends on some uncertain parameters, such as the initial temperature and the geometry of subducting slab, those uncertainties do not change the essence, that is, Mars with plate tectonics tends to keep the heat in, as shown in Fig. 2. It means that, if there was plate tectonics in the early stage of Mars, the drastic temperature drop shown in a conventional theory (Fig. 3) is unlikely, which results in a realistic temperature evolution after the cessation of plate tectonics. Moreover, the effect of increasing temperature due to plate tectonics is suitable to the estimate of high temperature of Martian mantle [8] despite the intuition that the smaller a planet, the faster it becomes cool.

Plate tectonics cessation with the hot mantle in Fig. 3 means that other factors than temperature are indispensable to retain plate tectonics. One of the candidates is liquid water on the surface. In fact, [17] demonstrates that, whereas the interaction between mantle and the ocean stabilizes plate tectonics, no such an interaction and high temperature mantle cause the stagnant-lid convection regime. Applying the model of [17] to this Martian model yields that plate tectonics halts around 4.0 Ga if there is no water interaction. Consequently, disappearance of liquid water on the surface at that time might have hampered the operation of plate tectonics. Further investigation into the cause why plate tectonics on Mars stopped is surely essential to comprehend the reason why plate tectonics on Earth initiated and has continued to the present.

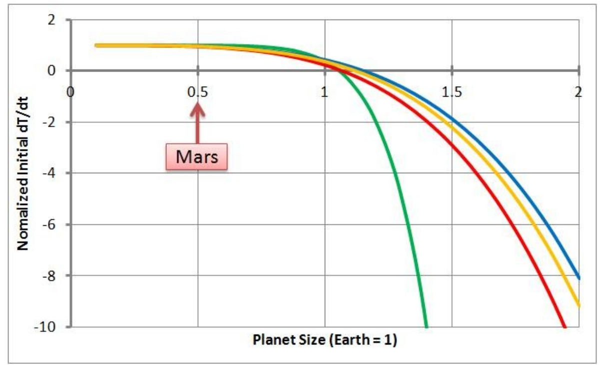

Fig. 2. Initial *dT/dt* and planet size. *dT/dt* is normalized so that *dT/dt=1* as planet size approaches *0*. Planet size is expressed in Earth size, R_E. Red, orange, and blue lines show the result with constant radius of curvature for bending plate, R_c, and the initial temperature, T_i (^{o}C) of 2000, 1600, and 1400, respectively. The green line represents the result in which $T_i=1600$ and R_c is proportional to the plate thickness. I adjust parameters so as to reproduce the initial state of the Earth in [10].

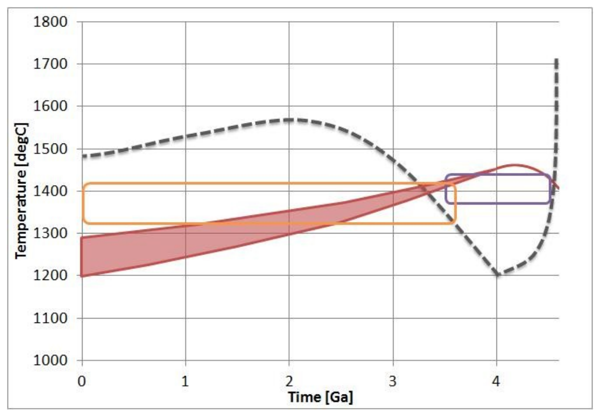

Fig. 3. Thermal evolution of Mars. Red line and shaded area express one possible case of Martian thermal history. R_c and T_i are set 600 *km* and 1400 ^{o}C, respectively. Dashed line shows the result by conventional thermal evolution theory with plate tectonics [7]. Purple and orange squares show the potential temperature of Martian mantle estimated by [8].

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