EVALUATING FACTORS AFFECTING THE THERMAL EVOLUTION OF TERRESTRIAL PLANETS.
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Introduction: The cooling rate of a spherical body, such as a planet, depends on the ratio of heat loss (heat flux over the surface area of the body) to heat production (radiogenic heat production throughout the volume of the sphere). The surface area of a sphere scales with the square of its radius, while the volume of a sphere scales with the cube of its radius. This means that the cooling rate scales with the inverse of the radius. Conventional wisdom then dictates that a smaller radius leads to a faster cooling rate, leading to the general supposition that smaller planets cool faster than larger planets. Given several assumptions, namely that the density of heat-producing elements is roughly the same, the planets have plate tectonics, and that thermal effects on viscosity are the dominant effects, and therefore the only ones that need be considered, a general model for the thermal evolution of planets of different sizes demonstrates that smaller planets do indeed cool faster.

However, despite this conventional wisdom, calculated surface heat flows for Mars indicate that secular cooling may have had a limited contribution to the planet's heat flow for most of its history. In fact, the interior of Mars may have actually experienced heating rather than cooling during some portion of the planet's thermal history [1]. Evidence for a warming Mars defies conventional wisdom. If Mars is in fact warming, or was at some time, what factors might cause this?

Thermal Evolution: Extensive heating of the terrestrial planets is implied by their differentiated structures. Since differentiation most likely occurred shortly following formation, it is sensible to conclude that the terrestrial planets have been cooling from initially hot states for a majority of their histories. The primary control of this cooling is subsolidus convection in the mantle [2].

The vigor of mantle convection controls the effectiveness of interior cooling. Mantle viscosity, in turn, affects convective vigor – higher viscosity dampens the vigor of convection, while lower viscosity allows for more vigorous convection [3]. Mantle temperature and volatile content both strongly affect the mantle viscosity [3-5]. The combined feedback loops for both temperature and volatile content are complex, but, in general, viscosity decreases as temperature and volatile content increase, thereby increasing the vigor with which the mantle convects. More vigorous convection allows for both heat and volatiles to be released at greater rates, which increases viscosity and subsequently reduces convective vigor. This negative feedback loop between both temperature and volatile content and mantle viscosity can act as a thermostat, regulating the rate of mantle cooling [6, 3].

Thermal history models for Earth produce a declining Urey number (the ratio of internal heat production to heat loss) of less than unity from about 1 Ga forward. The Urey number exceeds unity when a water-dependent parameterization is employed, but only for an early period of rapid degassing. During this period the mantle dries out, increasing viscosity and reducing heat flow, thus producing a high Urey number. After this period, the temperature of the mantle increase, increasing heat flow, and a decling Urey number [4]. This trend fits with estimates for a present-day Urey number of around 0.23 [7].

In contrast, surface paleo-heat flow estimates for Mars, derived from estimates of the effective elastic thickness of the martian lithosphere [1], are generally lower than concurrent radioactive heat production values, suggesting that secular cooling has not been a significant contributor to the martian heat flow for a majority of the planet's history. Furthermore, these low surface heat flow values, compared with expected heat output, indicate a Urey number for Mars approaching or even exceeding unity. This contradicts most thermal history models for Mars, which obtained Urey numbers between 0.75 and 0.6 throughout the entire history of Mars [8-10].

However, parameterized mantle convection models that account for the effect on rheology of mantle volatile content suggest that high Urey ratios are obtained when there is inefficient volatile cycling between the surface and the mantle [3-5]. This situation would be expected for a planet such as Mars, for which geologic evidence indicates that the planet has operated within the stagnant-lid regime of tectonics for most of its history. Stagnant-lid tectonics, as opposed to mobile-lid (or plate) tectonics, which the Earth experiences, is characterized by very little or no horizontal surface motions. In effect, mantle convection is decoupled from surface deformation, which can lead to the loss of effective regassing of mantle volatiles [1].

Thus, thermal history models for Mars should account for not only the temperature dependence, but also the volatile dependence of viscosity, as well as the stagnant-lid tectonics that has likely operated on Mars for a majority of the last 4.5 billion years.

Results: This study investigates these effects on the thermal histories of planets, with Mars as a focus, in order to determine what might account for a warming Mars. A parameterized mantle convection model is modified by first adjusting planetary size, then accounting for the effects of a stagnant-lid regime (single-plate planet), as opposed to a plate-tectonic regime, and finally systematically varying the rate at which volatiles are degassed from the mantle.

These models indicate that size and tectonic regime, individually, have little effect on Urey ratio, while the combined difference in the Urey ratio from a planet that strictly degasses versus one that strictly regasses (end member cases for the volatile dependence of viscosity) is 0.65.

Conclusions: Our results indicate that differences in the nature of volatile cycling (degassing vs regassing over time) can outweigh the effects of size and tectonic mode for the determining the thermal state of a planet.

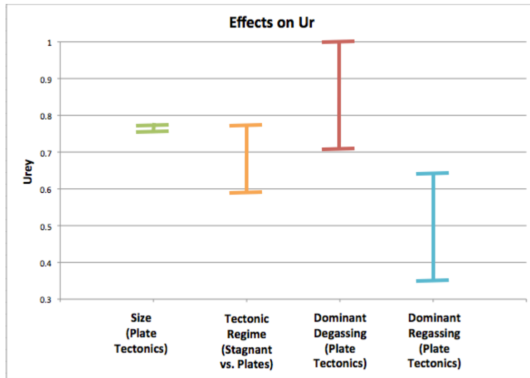

Figure 1: Range of Ur given different model scenarios. 1) For two planets with plate tectonics, where size is the only difference, the range in Ur is 0.02. 2) For two planets of the same size, where the only difference is the operation of plate tectonics, the range in Ur is almost 0.2. 3) For the same planet, with plate tectonics, end member cases for mantle volatile recycling (only degassing vs. only regassing) produce a combined difference in Ur of 0.65.

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