Warm and wet conditions on early Mars achieved by a return of hydrogen from the core

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Introduction and Summary: Many lines of geological and geochemical evidence, such as valley networks and Al-rich clays, indicate the existence of surface liquid water for geological time periods (e.g., ~1 Myrs) on early Mars [e.g., 1, 2]. The surface temperature during the wet periods may have reached 30–40 °C in maximum in order to form crystallized Al-rich clay minerals [2]. The occurrence of the surface water seems to be concentrated at 3.8 billion years ago (3.8 Ga), around the boundary of the Noachian and Hesperian periods [e.g., 1]. Previous studies attempted to explain the occurrence of transient (~1 Myr-long) wet conditions by stochastic geological events, such as large asteroidal impacts and volcanic eruptions [3]; however, no studies have explained the concentration of warm and wet periods at around 3.8 Ga. Furthermore, high surface temperatures, such as 30–40 °C, may be also hard to be achieved on early Mars in the stochastic geological events.

Here, we propose a new scenario to make Mars warm both intensively and episodically in a certain period (0.1–1 Gyrs) of time after the formation. Mars metallic core, with the high abundances of H and S [4], would have segregated upon cooling of the interior, accompanying with the disappearance of magnetic field (~4.2–4.1 Ga). The core segregation would have resulted in the occurrence of a H-rich Fe melt (Fe-H) layer in the outer region of the core (Fig. 1) [5]. Through the exchanges of H between the Fe-H layer and basal magma in the mantle [4], the density of the basal magma would have gradually become lighter over time, finally leading to upwelling of the basal magma due to the buoyancy.

A part of the upwelled magma may have erupted on the surface, degassing a large amount of H_2 (0.1–0.5 bar) and, consequently, warming the surface intensely for a geological time (~30 °C and ~1 Myrs: see below). The upwelled basal magma, if occurred, should be highly enriched in Fe compared with Mg [6] and may have formed a flat plain, e.g., flood basalt, owing to its high temperatures. The findings of Fe-rich igneous rocks in the northern basalt plain of current Mars by the Perseverance Rover [7] are consistent with our scenario. The high levels of H_2 in the atmosphere, in turn, would have reduced atmospheric CO_2 into CO during the warm period, possibly preventing extensive deposition of carbonate minerals on the surface.

Density decrease of basal magma due to H addition from the core: To examine the above scenario, we first estimate the required H content in the Fe-H layer in the core to acquire a sufficient buoyancy for upwelling in the mantle. Since the composition of the basal magma is largely unclear, we assume that the parental (source) magma composition derived from the igneous rock of the northern plain by the Perseverance Rover [7] as an example of basal magma composition. For simplicity, we considered only the major elements, Mg, Fe, Si, and O, together with H for the magma. The estimated parental magma is characterized by a very high Fe and, thus, low Mg# (~27) [7]. This high Fe content in the basal magma is consistent with the interior composition and its evolution of early Mars after solidification of magma ocean [6].

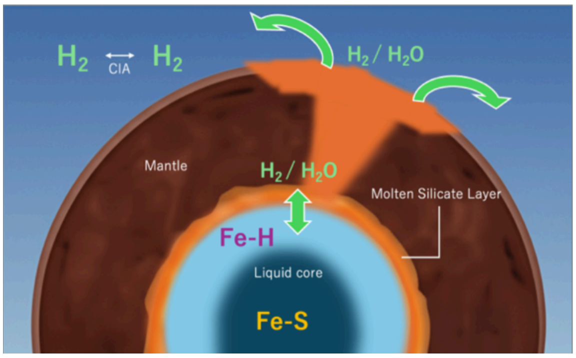

Figure 1: A schematic illustration of our scenario (see the main text for the detail).

The present study estimates the density decrease of the basal magma by the addition of H using a 4th-order Birch-Murnaghan equation of state for a simplified system of three components: SiO_2-MgO-FeO. There are two mechanisms capable of lowering the density of magma by the addition of H. One is a density decrease owing to the addition of H_2O, which is produced by the combination of H from the core and O in the magma. The other is a reduction of FeO in magma into metallic Fe, which would be readily incorporated into the Fe-H core. The former is caused by breaking the network structure of the magma by H_2O. We used the previous results (an empirical equation of the density of silicate magma as a function of added H_2O) based on the first-principles molecular dynamics simulations [8]. As for the latter effect, we calculated the density decrease as a loss of Fe element from the magma based on the following stoichiometry:

$$2H + FeO = Fe\downarrow_{core} + H_2O.$$

With various H contents in the Fe-H layer and the temperature of the core-mantle boundary, the hydrogen partitioning into the basal magma layer was calculated using the partitioning coefficient based on the high-pressure experiments [9]. Then, the composition (i.e., Fe and Mg contents) of the basal magma was re-calculated considering a loss of Fe via the above reaction, while keeping the Mg:Si ratio of the magma. Finally, the density of the basal magma was calculated by considering an addition of H_2O into the magma.

Figure 2 shows our results of the density decrease of the basal magma normalized by the initial density of the parental magma for the temperature of the core-mantle boundary and H content in the Fe-H layer in the core. The horizontal axis of Fig. 2 is normalized by a suggested H content in the Martian core before the segregation, ~0.9 wt.% H, based on building materials (a combination of different chondrites) of Mars [10]. The density of the solidified mantle is suggested to be ~4.0 g/cm^3 [e.g., 4]. Figure 2 shows that when the Fe-H layer is enriched in H about 4–5 times that of the initial core owing to the core segregation at 2000 K of the core-mantle temperature, the basal magma can be upwelled in the mantle due to the buoyancy. This upwelled basal magma contains ~0.7 wt.% of total H due to a supply from the core.

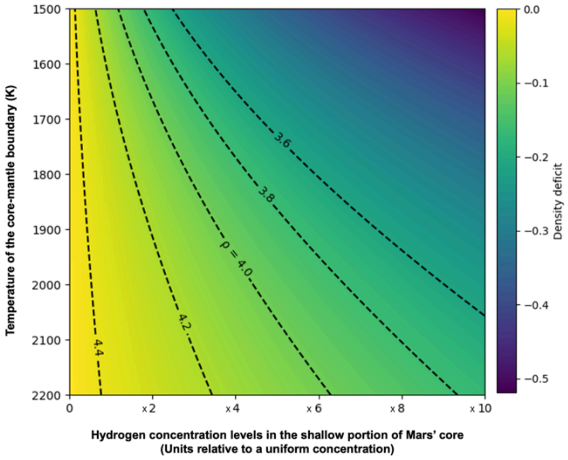

Figure 2: The density decrease in the basal magma as a function of temperature of the core–mantle boundary and H content in the Fe-H layer in the core. The dotted lines show the density contours of the magma.

Greenhouse effects owing to H_2 released from the magma eruption: Although the volume of the erupted basal magma onto the surface in the past cannot be constrained, the thickness of the current basal magma on Mars is about 100–150 km [4], corresponding to a global magma thickness of 20–50 km if all were erupted onto the surface. In reality, only a part of upwelled basal magma would have erupted onto the surface. The InSight Lander finds a discontinuity in several km depth within the crust of the northern hemisphere [11]. Assuming this discontinuity as a flood basalt layer of the basal magma eruption with total H (a sum of H_2 and H_2O) for upwelling, we can estimate a released H_2 partial pressure in the atmosphere after the eruption as 0.5–1.0 bar.

We estimate the surface temperature and partial H_2 pressure evolutions after the eruption. The surface temperature of greenhouse effect of H_2-H_2 collision induced absorption was calculated for various albedo due to scattering by H_2 molecules, based on the empirical equation of pure H_2 atmosphere using the results of a radiative transfer model [12]. A loss of H_2 over time was simply considered as a H_2 loss rate of ~10^{11} molecules/cm^2/s [13].

Figure 3 shows our results of surface temperature and partial H_2 pressure evolution after the eruption with the initial H_2 pressure of 0.5 and 1.0 bar. Without any other greenhouse effect gases, the surface temperature can reach as high as 50–150 °C depending on the H_2 abundance. Warm climates, with temperatures higher than the freezing point of water, can be sustained for 1–4 Myrs after the eruption. The temperature higher than 100 °C may not be consistent with the presence of extensive smectite on Mars given the conversion of smectite to talc at the high temperatures. However, Al-rich clay may need a relatively high temperature, such as 30–50 °C, sustaining for ~1 Myrs [2], which is achieved in our calculation when 0.5 bar of H_2 erupted onto the surface.

Many previous climate models of early Mars assumed a thick CO_2 atmosphere (e.g., 1–2 bar) with relatively small amounts of H_2 (CO_2/H_2 > ~5–10). However, these models may suffer from carbonate mineral formation during warm periods. In addition, CO_2 levels in the atmosphere on early Mars may have been as high as ~0.3 bar [14]. In our model, a transient H_2-rich atmosphere with $CO_2/H_2 < 1$ may have achieved warm conditions if assuming a return of H from the core to the surface.

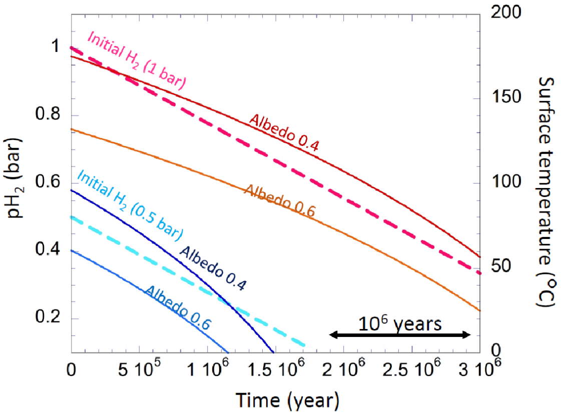

Figure 3: Evolution of surface temperature (solid curves) and partial H_2 pressure (dotted curves) after basal magma eruption. Different colors represent different initial H_2 and albedo.

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