Terrestrial planets, depending on their first-order geophysical parameters, should evolve through various modes of mantle convection, including magma ocean, plate tectonic, and stagnant lid convective processes [1]. For example, the surface environment of Earth has been largely controlled by plate tectonics and superplume activity over the 3.9 Gy of its history that is recorded in preserved rocks and structures [2,3]. We report here on a theory that shows how these processes explain the geophysical character and geological history of Mars [4,5].

A successful theory of terrestrial planetary evolution needs to account for many seemingly anomalous observations in regard to the geological history of Mars. The Martian crust shows major variations from thin beneath the northern plains (~30 km) to thick (~60 km) beneath the southern highlands and Tharsis [6]. Unlike Earth, however, the surface materials overlying the thin crust have andesitic compositions, while the thick highland crust is overlain by surface materials with basaltic compositions [7]. Even more striking are linear crustal magnetization anomalies of remarkable intensity that occur in the southern highlands [8]. The responsible remnant magnetization of crustal rocks implies that the Martian dynamo shut off in the Noachian, at about 4.0 Ga [9]. Though this indicates greatly reduced heat flow, episodic volcanism and related tectonism persisted through subsequent Martian history concentrated at Tharsis [10]. While much activity occurred during the heavy bombardment, Mars lacks the thick lunar-type megaregolith that had been postulated by numerous investigators [e.g.,11]. Instead, the upper crust of Mars is extensively layered, probably with both sedimentary and volcanic rocks [12,13]. During post-Noachian Mars history, immense volumes of water were released from the Mars subsurface through outflow channels [14]. The water was delivered to the northern plains, where phenomenal topographic smoothness is consistent with sedimentation in a temporary “ocean” [15]. Water-related activity on Mars persisted up to nearly present day [16]. However, the lack of carbonate exposures on the planetary surface [17] seems to be inconsistent with an ocean of past surface water on Mars. Nevertheless, areas of hematite mineral deposits indicate aqueous processes, either ponding or hydrothermal, early in Martian history [18]. Associated with the aqueous activity may be a relict or extant biosphere [e.g.,19].

Our theory [3,4,5] brings together these and other facts in a mutually consistent manner that also shows interesting parallels to the probable early history of Earth [20]. As a working hypothesis, this does not provide a final picture, but it may point in a productive way to the qualities of a “true” representation. After initial accretion from water-rich planetessimals, Mars rapidly differentiated to a liquid metallic core and solid mantle, degassing a steam atmosphere rich in CO2 and H2O. The magma ocean that formed between the intense greenhouse and the hot planetary interior then developed a solid crust. As the planet and its atmosphere cooled, the latter condensed to form an ocean over a crust with fully developed plate tectonics, the latter being a natural consequence of the progressive decline in heat flow [21]. Subduction of oceanic lithosphere would move water, carbonates, and sulfates in the Martian mantle, while also initiating arc volcanism. Continued evolution of the core then produced a remarkably strong dynamo and consequent magnetosphere.

Extremely rapid plate motion and subduction resulted in (a) very fast accretion of thickened “continental” crust [22] and (b) removal of the ocean water to the mantle boundary layer over the cooling and solidifying core. Magnetized oceanic plateaus were accreted to the “continents”, resulting in the prominent magnetic anomalies. Immense hematite deposits could have been emplaced in association with large igneous provinces, as hypothesized for the early Earth [23]. Continued planetary cooling and core solidification terminated the dynamo while plate tectonics continued. The last remnant of oceanic crust beneath the northern plains shows no magnetic lineations [8] but is marked by the large impact signatures of the heavy bombardment [24]. At this time (early Noachian into middle Noachian) the linear subducting plate boundary between the oceanic northern plains and the “continental” southern highlands was deformed into a loop or bight at Tharsis, perhaps by the antipodal effect of the Hellas impact basin formation. The result was a plate boundary analogous to that now occurring in southeast Asia [25]. A high concentration of water-rich oceanic crust and hydrated slab peridotite was conveyed to the mantle boundary layer beneath Tharsis by this process.
As plate tectonics terminated in a cooled Mars, about 3.9 Ga, it was replaced by stagnant lid convection and episodic plume activity on a one-plate planet. Water, carbonates, and sulfates had been largely conveyed to the mantle boundary layer, immediately above the more slowly cooling solid core. The surface was now cold and dry, but the seeds of its episodic transformation had been sown into the deep mantle. The water-rich lower mantle decreased melting temperatures and viscosities in the mantle above preferential zones of the cooling core (Tharsis, Elysium). The Tharsis superplume was born, leading to immense outpourings of lavas in the late Noachian [26]. These lavas continued to emerge through Martian history, and samples indicate that they were water-rich [27]. Moreover, magmatic-driven structural landform complexes of the Tharsis superplume were associated with immense outflows of water beginning in the Noachian [28]. A huge sedimentary basin developed at Tharsis during its early history [29], in analogous fashion to the history of terrestrial superplumes. The floods eroded into the deep andesitic crust of the highlands, delivering the resulting sediments to cover the oceanic crust of the northern lowlands with a thin andesitic blanket, while the highlands were mantled by the products of younger, plume-related basaltic lavas. Although considerable CO₂, H₂O and SO₂ were temporarily delivered to the atmosphere in episodic outbursts [30], these were subsequently trapped in the near-surface permafrost zone as ground ice and gas hydrates. Any remaining atmosphere was progressively altered by the long-term action of the solar wind, unconstrained by effects of a magnetosphere. Extant Martian life, which enjoyed earlier phases of near-surface activity, is probably now confined to a subsurface zone beneath the permafrost and to possible “windows” at local zones of near-surface hydrothermal activity.