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Plate tectonics and planetary habitability: current status and future challenges

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Plate tectonics is one of the major factors affecting the potential habitability of a terrestrial planet. The physics of plate tectonics is, however, still far from being complete, leading to considerable uncertainty when discussing planetary habitability. Here, I summarize recent developments on the evolution of plate tectonics on Earth, which suggest a radically new view on Earth dynamics: convection in the mantle has been speeding up despite its secular cooling, and the operation of plate tectonics has been facilitated throughout Earth's history by the gradual subduction of water into an initially dry mantle. The role of plate tectonics in planetary habitability through its influence on atmospheric evolution is still difficult to quantify, and, to this end, it will be vital to better understand a coupled core–mantle–atmosphere system in the context of solar system evolution.

Keywords: terrestrial planets; mantle dynamics; planetary magnetism; atmospheric evolution

Introduction

Under what conditions can a planet like Earth—that is, a planet that can host life—be formed? This question of planetary habitability has been addressed countless times in the past,[1–3] as it is deeply connected to the origin of life, perhaps the most fascinating problem in science. In the last decade or so, research activities in this field have been invigorated, fueled by a rapidly expanding catalog of extrasolar planets.[4–6] The habitability of a planet depends on a number of factors including, for example, the mass of the central star and the distance from it, the atmospheric composition, orbital stability, the operation of plate tectonics, and the acquisition of water during planetary formation. The mass of the star determines the evolution of its luminosity, and the heliocentric distance of a planet as well as the volume of the atmosphere and its composition then control the surface temperature of the planet. The surface temperature has to be in a certain range so that we can expect the presence of liquid water provided that water exists, and orbital dynamics affect the stability of the planetary climate. Plate tectonics controls the evolution of the atmosphere through volcanic degassing and subduction, and it is also essential for the existence of a planetary magnetic field, which protects the atmosphere from the interaction with the solar wind. These factors affecting planetary habitability are thus interrelated to various degrees. Whether or not plate tectonics is operating on a planet, for example, would give rise to vastly different scenarios for its atmospheric evolution, affecting the definition of the habitable heliocentric distance, that is, the habitable zone.

The focus of this contribution is on plate tectonics. Plate tectonics refers to a particular mode of convection in a planetary mantle, which is made of silicate rocks, and so far it is observed only on Earth. Earth's surface is divided into a dozen plates or so, and these plates are moving at different velocities. Most geological activities, such as earthquakes, volcanic eruption, and mountain building, occur when different plates interact at plate boundaries. The realization that Earth's surface is actively deforming via plate tectonics was achieved through the 1960s and 1970s, revolutionizing almost all branches of earth sciences. Plate tectonics is a fundamental process, yet we still do not understand it in a satisfactory manner. For example, whereas the present-day

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plate motion is known in considerable detail,[7] reconstructing past plate motion becomes quite difficult once we enter the Precambrian (before 540 million years ago), and even the gross characteristics of ancient plate tectonics is uncertain.[8] Naturally, when plate tectonics started to operate on Earth is still controversial.[9] Part of the difficulty originates in the paucity of observations; we have fewer geological samples from greater ages. The situation is even more compounded by the lack of theoretical understanding. Geophysicists have yet to form a consensus on why plate tectonics takes place on Earth and not on other terrestrial (e.g., Earth-like) planets such as Venus and Mars.[10] The physics of plate tectonics is still incomplete, and this creates a serious impediment to the discussion of planetary habitability. Under what conditions could plate tectonics emerge on a planet, and how would it evolve through time? Without being able to answer these questions, it would be nearly impossible to predict the atmospheric evolution of a given planet and thus its habitability.

Fundamental issues regarding the physics of plate tectonics may be paraphrased by the following questions: how did plate tectonics evolve in the past?, why does plate tectonics take place on Earth?, and when did plate tectonics first appear on Earth? Considerable progress has been made on the first question in the last decade, and this progress turns out to help better address the second and third questions as well. In the following sections, I will review each question one by one and conclude with a synthesis of current status as well as major theoretical challenges to be tackled in the coming years.

How did plate tectonics evolve?

As plate tectonics is just one type of thermal convection, it is reasonable to speculate on the evolution of plate tectonics on the basis of fluid mechanics. Earth's mantle in the past was generally hotter and thus probably had lower viscosity than present. Elementary fluid mechanics tells us that this reduction in viscosity should have resulted in more vigorous convection, that is, higher heat flux and faster plate tectonics.[11] Geological support for such faster plate tectonics has long been lacking,[12] but this lack of observational support is usually not taken seriously because geological data become very scarce and more difficult to interpret in the Precambrian. The notion of faster plate tectonics in the past, however, has been known to predict an unrealistic thermal history called "thermal catastrophe,"[13] unless one assumes that Earth contains considerably more heat-producing elements than the composition models of Earth indicate (Fig. 1). This can be understood by considering the following global heat balance:

$$C\frac{dT}{dt} = H(t) - Q(t), \quad (1)$$

where C is the heat capacity of the entire Earth, T is average internal temperature, t is time, H is internal heat production owing to the decay of radioactive isotopes, and Q is heat loss from the surface by mantle convection. By the nature of radioactive decay, the internal heat production monotonically

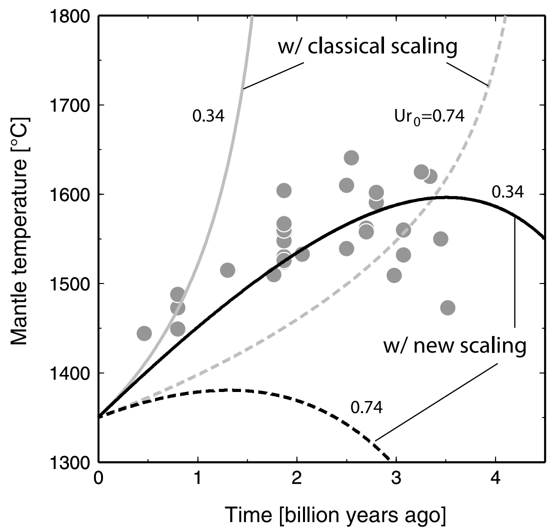

Figure 1. Thermal history prediction for four combinations of heat flow scaling and internal heat production (see Ref. 17 for modeling detail). The new scaling of plate tectonics predicts relatively constant heat flux independent of mantle temperature, whereas classical scaling predicts higher heat flux for hotter mantle. The Urey ratio is a measure of the amount of heat-producing elements in the mantle, and the chemical composition models of Earth suggest that its present-day value ($Ur_0 = H(0)/Q(0)$) is relatively low, ∼0.3.[14] Constant heat flux with a low present-day Urey ratio (*solid*) is the only one that can reproduce the observed concave-downward thermal history with an average cooling rate of ∼100 K Ga^{-1} (*circles*).[27] In this prediction, Earth was warming up during the first one billion years; such a situation is possible with the efficient cooling of the magma ocean.[50] Classical scaling with a low Urey ratio results in thermal catastrophe (*gray line*). Classical scaling with a high Urey ratio (*gray dashed line*) can reproduce a reasonable cooling rate, but a thermal history is concave upward. Constant heat flux with a high Urey ratio (*dashed line*) results in too cold a thermal history.

decreases with time, with an effective half-life of about three billion years. The convective heat loss can be parameterized as a function of average temperature as

$$Q \propto T^m, \quad (2)$$

where the exponent m is predicted to be $\sim$10 by the classical theory of thermal convection;[11] heat loss is extremely sensitive to a change in internal temperature. The present-day internal heat production $H(0)$ is only about 30% of the convective heat loss $Q(0)$,[14] so about 70% of heat loss must be balanced by the rapid cooling of Earth; that is, Earth must have been much hotter than at present to explain the present-day thermal budget. Because convective heat loss rises sharply with increasing temperature (Eq. 2), however, heat loss must have been extremely high in the past, resulting in a more severe imbalance between heat production and heat loss, as we consider further back in time. This positive feedback is what causes thermal catastrophe in the middle of the Earth history. The only way to prevent it, while keeping the classical scaling ($m \sim 10$), is to assume that internal heat production is close to convective heat loss at present, that is, $H(0) \sim Q(0)$, but this violates our understanding of the chemical budget of Earth. This conflict between the geophysical theory of mantle convection and the geochemical model of Earth has inspired a variety of proposals (see Ref. 14 for review), many of which hide an excessive amount of heat-producing elements in the deep, inaccessible mantle—a possible but rather *ad hoc* solution.

A novel solution was suggested in 2003 based on the effect of mantle melting on mantle convection.[15] Faster plate tectonics in the past is based on simple fluid mechanics that do not capture realistic complications associated with silicate rocks. An important difference from classical thermal convection is chemical differentiation; when the mantle is rising toward the surface, it usually melts, and this melting can affect mantle dynamics. Upon melting, impurities in the mantle, most notably water, are largely partitioned into the melt phase, leaving the residual mantle very stiff.[16] A hotter mantle in the past means more extensive melting, making thicker stiff plates and slowing down plate tectonics. Considering both the physics and chemistry of Earth's mantle thus points to an entirely opposite prediction: slower plate tectonics in the past, which is equivalent to using $m \leq 0$ in Eq. (2). With this nonclassical scaling of plate tectonics, it has become possible to reconstruct a reasonable thermal history without violating the geochemical constraints (Fig. 1). This solution, which was further elaborated in 2006,[17] met considerable skepticism because of its counterintuitive nature. Some doubted the robustness of the geochemical constraints on the amount of heat-producing elements, but the uncertainty of the mantle composition has been shown to be tight enough to discount such leeway.[18] Others suspected that the relative contribution of heat-producing elements may be increased by lowering the estimate on present-day heat flux instead,[19,20] but this possibility has been shown to be inconsistent with available geological records.[21,22] Additionally, the counterintuitive prediction was based on an approximate theory (known as the boundary layer theory) with several simplifying assumptions, and some questioned the validity of this approach.[23] Recently, however, the original prediction has been given full theoretical support from extensive numerical simulation and scaling analysis.[24,25]

Equally important is the appearance of new decisive observations. In 2008, the compilation of the geological records of ancient passive margins was published, which indicates that the tempo of plate tectonics in the past was indeed slower than present.[26] In 2010, the thermal history of Earth's upper mantle was reconstructed by applying the latest petrological technique to an extensive compilation of Precambrian volcanic rocks (Fig. 1).[27] The concave-downward nature of this thermal history is particularly important, as it provides strong support for the notion of slower plate tectonics and the relatively low abundance of heat-producing elements at the same time; it is impossible to reproduce this curvature by assuming faster plate tectonics for a hotter mantle. Most recently, a new constraint on the abundance of heat-producing elements in the mantle was reported based on geoneutrino observations, which favors the relatively low abundance as indicated by the geochemical estimate.[28]

The radically new view on the evolution of plate tectonics, therefore, has been corroborated both theoretically and observationally in recent years, and it has become difficult to refute the notion of slower plate tectonics in the past, however counterintuitive it might be. Actually, what is counterintuitive is a subjective matter, and in this case, it is largely educational. Faster plate tectonics for a hotter Earth is predicted by the fluid mechanics of a nearly isoviscous fluid. No theoretical justification exists for its applicability to Earth's mantle. The classical theory is still widely used in planetary sciences, but it simply fails to reproduce the thermal history of the best-understood planet (Fig. 1). There would be little merit in extrapolating a theory that cannot explain Earth to other terrestrial planets, for which we have considerably fewer observational constraints. This is especially true when discussing the dynamics of Earth-like, potentially habitable planets.

Why does plate tectonics happen?

There are two fundamentally different modes of mantle convection: (1) plate tectonics and (2) stagnant lid.[29] In stagnant-lid convection, the entire surface of a planet forms a rigid spherical shell, and convection can take place only under the shell. In plate tectonics, the surface is broken into pieces, most of which can return to the deep mantle, enabling geochemical cycles between the surface and the interior. Among the four terrestrial planets in our solar system, Earth is the only planet that exhibits plate tectonics, and the other three (Mercury, Venus, and Mars) are believed to be in the mode of stagnant lid.[30] It is easy to explain why plate tectonics does not take place on other planets, because stagnant-lid convection is the most natural mode of convection in a medium with strongly temperature-dependent viscosity, such as silicate rocks that constitute a planetary mantle.[29] Mantle viscosity is extremely high at a typical surface condition, so virtually no deformation is expected there. The mode of plate tectonics is possible, therefore, only when some additional mechanism exists to compensate the effect of temperature-dependent viscosity. Ongoing debates are mostly regarding this additional weakening mechanism.

In addition to ductile deformation characterized by viscosity, silicate rocks can also deform by brittle deformation such as cracking and faulting. Weakening by brittle mechanisms is limited by frictional strength,[31] however, and with a typical frictional coefficient of order 1, brittle weakening is insufficient to cause plate tectonics.[32] In order to simulate plate tectonics in numerical models, therefore, it has been a common practice to assume a much lower friction coefficient, but a physical mechanism that could lead to such a low coefficient has been poorly understood.[33] One plausible mechanism is a reduction in an effective friction coefficient by high pore fluid pressure, with water being the fluid medium. For plate tectonics to occur with this mechanism (i.e., to break a thick stagnant lid), however, water has to be transported to substantial depths and then isolated from the surface to achieve high pore fluid pressure. The mere existence of surface water does not guarantee either of these requirements. If deep water is connected to the surface, for example, it would be at hydrostatic pressure, meaning that pore fluid pressure is too low to achieve a sufficiently low friction coefficient. In this regard, the thermal cracking hypothesis,[33] in which a rigid lid is extensively fractured by strong thermal stress and then later sealed by hydration reactions, has so far been the only tangible mechanism that could generate plate tectonics in the presence of surface water (Fig. 2).

When discussing the mode of mantle convection, it is important to avoid being trapped in a chicken-and-egg situation. The bending of a subducting plate, for example, may fracture and weaken the plate by hydration,[34] but one cannot invoke this mechanism for the onset of plate tectonics; a weakening mechanism must be operational even without plate tectonics. The same caution applies to various dynamic weakening mechanisms associated with earthquake dynamics.[35]

Finding a physical mechanism for weakening is just one side of the coin. The other side is to understand the critical strength of a surface lid that can be overcome by convective stress exerted by the mantle below. Both sides are necessary to understand under what conditions plate tectonics can happen. This issue has been studied by various authors using numerical simulation (e.g., Refs. 36 and 37), but in most previous attempts, the temperature dependency of mantle viscosity was not strong enough to be Earth-like. A quantitative criterion for the onset of plate tectonics was found in 2010, for the first time with realistic mantle viscosity, while conducting a number of numerical simulations to establish the scaling of plate tectonics for thermal evolution modeling.[24] Revisiting the notion of slower ancient plate tectonics with this new criterion turns out to yield an intriguing insight for the initiation of plate tectonics on Earth, as discussed in the next section.

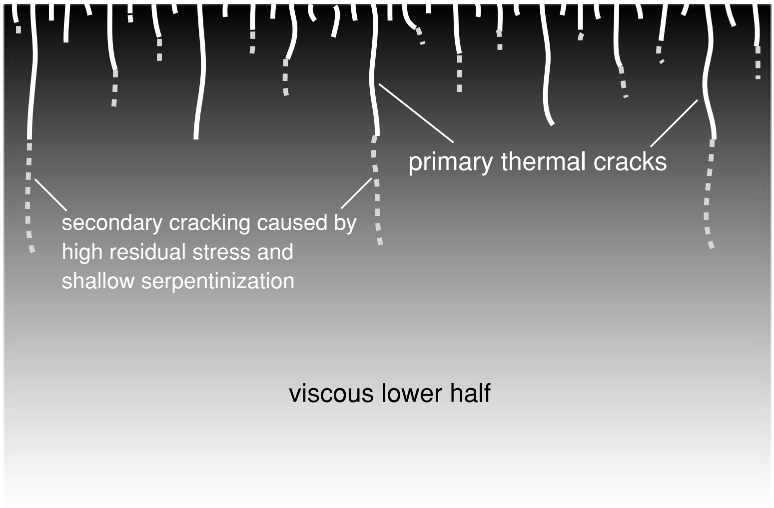

Figure 2. Schematic illustration for rheological evolution within a plate under oceans.[33] Optimal release of thermal stress developed in a cooling plate is achieved by a cascade crack system (primary cracks). Any residual stress will eventually be released by secondary crack propagation if partial crack healing by shallow serpentinization raises the pressure of trapped seawater to lithostatic pressure. The stiffest part of plate due to strong temperature-dependent viscosity can thus be pervasively weakened by thermal cracking and subsequent hydration.

When did plate tectonics start?

Based on field evidence, many geologists would concur with the operation of plate tectonics back to about 3 billion years ago,[38,39] but anything beyond that is controversial. Earth's history is divided into four eons: the Hadean (4.6–4.0 billion years ago), the Archean (4.0–2.5 billion years ago), the Proterozoic (2.5–0.54 billion years ago), and the Phanerozoic (0.54 billion years ago to present). The Hadean–Archean boundary is defined by the age of the oldest rock found on Earth. The Archean–Proterozoic boundary is defined by the relative abundance of rocks—that is, rocks of Archean ages are much rarer than those of younger ages. These definitions of the geological time scale indicate that finding unambiguous geological data for the first appearance of plate tectonics on Earth's history, which might be in the Hadean era,[40] would be quite challenging. Building a theoretical foundation for this problem is thus of critical importance.

As mentioned earlier, slower plate tectonics in the past results from the formation of thicker stiff plates by more extensive melting. Thicker plates slow down plate tectonics, but if too thick, they could potentially jeopardize the operation of plate tectonics itself. The likelihood of shutting down plate tectonics in the past can be high because much lower convective stress is expected for a hotter, less viscous mantle beneath plates; thicker plates and weaker convective stress both act to impede plate tectonics. Indeed, a quantitative assessment of this possibility using the new criterion indicates that plate tectonics is viable only for the last one billion years,[41] which grossly contradicts with geological evidence.

One possible resolution to this conundrum came from an apparently unrelated thread of thought, though in hindsight it is a natural extension of the existing theory. By incorporating geological constraints on the past sea level into thermal evolution modeling, one can reconstruct the history of ocean volume, and slower plate tectonics corresponds to greater ocean volume in the past.[42] The Archean oceans are estimated to have been about twice as voluminous as the present oceans, and this difference in ocean volume is roughly equivalent to the amount of water stored in the present mantle. Earth's mantle could have been drier and thus more viscous in the past, and if this exchange of water between the mantle and the oceans is taken into account, the operation of plate tectonics becomes viable throughout Earth's history.[24,41] It has long been suggested that plate tectonics could result in net water influx to the mantle,[43,44] and modeling the mantle as an open system now appears to be a necessity, rather than an option.

Plate tectonics, therefore, could have started on Earth shortly after the solidification of a global magma ocean, which probably existed only for the first few tens of millions of years of Earth's history.[45] One interesting finding from Earth's evolution with a hydrating mantle is that the subduction of water is essential to maintain a dry land mass, which in turn plays an indispensable role in stabilizing the climate. Without a dry land mass, no silicate weathering could take place so that the atmospheric composition could not be regulated efficiently by carbon cycle.[1]

Summary and outlook

An emerging view on the evolution of plate tectonics on Earth can be summarized by the following. Plate tectonics started probably in the very early Earth, shortly after the solidification of the putative magma ocean. The onset of plate tectonics was facilitated by an initially dry mantle, which has since been slowly hydrated by plate tectonics. While Earth has been cooling down, plate tectonics has been speeding up, instead of slowing down. This is because a colder mantle leads to thinner, easily deformable plates and because the effect of hydration on viscosity tends to cancel the effect of temperature. This scenario has been shown to be internally consistent and dynamically plausible by the scaling laws of plate tectonics. Though being unconventional in nearly all aspects, it is the only hypothesis that is consistent with all of major observations relevant to Earth's evolution, including petrological constraints on the thermal history, geochemical constraints on the thermal budget, and geological constraints on the tempo of plate tectonics, the mode of mantle convection, and the global sea level change.

Water is thus expected to play fundamental roles in the initiation of plate tectonics and its evolution over Earth's history. The physics of elementary processes involving water in the above scenario, however, still requires considerable future development. The plausibility of the thermal cracking hypothesis, for example, needs to be tested further by modeling the physicochemical evolution of a multiple crack system. The hypothesis has indirect observational support through its impact on effective thermal expansivity,[46,47] but more direct evidence may be obtained by large-scale field experiments. Additionally, the rate of water transport to the deep mantle by subduction should be quantified from first principles. Though it is a highly complex problem involving petrology, mineral physics, and fluid mechanics, its solution is essential for a theory with predicting power.

If a terrestrial planet starts out with a dry mantle and surface water, which appears to be a likely initial condition for subsolidus mantle convection,[3] the onset of plate tectonics is probably justifiable. Predicting its subsequent evolution is, however, still a formidable task. One of the major uncertainties is the amount of surface water. On the basis of the planetary formation theory, the origin of Earth's water is often considered to be in the outer solar system,[48] and the delivery of water is a highly stochastic process. The quantity of water to be delivered does not have to be large; one ocean worth of water corresponds to only 0.02% of Earth's mass. A difficult part is how to maintain it over the geological time. The existence of a planetary magnetic field, which could provide a shield against solar wind erosion,[49] depends on the rate of core cooling. Earth's thermal history indicates that the mantle was warming up in the early Earth (Fig. 1). The core could still have been cooling during that time if the core was initially superheated by its formation process, but to answer whether the cooling rate was sufficient to drive a planetary dynamo, modeling the thermal evolution of a coupled core–mantle system would be critical. Understanding the atmospheric evolution of a given terrestrial planet, or its habitability at large, therefore, requires us to create a unified theoretical framework that spans from the solar system evolution to the dynamics of planetary interior.

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Conflicts of interest

The author declares no conflicts of interest.

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