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The diversity of tectonic modes and thoughts about transitions between them

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Plate tectonics is a particular mode of tectonic activity that characterizes the present-day Earth. It is directly linked to not only tectonic deformation but also magmatic/volcanic activity and all aspects of the rock cycle. Other terrestrial planets in our Solar System do not operate in a plate tectonic mode but do have volcanic constructs and signs of tectonic deformation. This indicates the existence of tectonic modes different from plate tectonics. This article discusses the defining features of plate tectonics and reviews the range of tectonic modes that have been proposed for terrestrial planets to date. A categorization of tectonic modes relates to the issue of when plate tectonics initiated on Earth as it provides insights into possible pre-plate tectonic behaviour. The final focus of this contribution relates to transitions between tectonic modes. Different transition scenarios are discussed. One follows classic ideas of regime transitions in which boundaries between tectonic modes are determined by the physical and chemical properties of a planet. The other considers the potential that variations in temporal evolution can introduce contingencies that have a significant effect on tectonic transitions. The latter scenario allows for the existence of multiple stable tectonic modes under the same physical/chemical conditions. The different transition potentials imply different interpretations regarding the type of variable that the tectonic mode of a planet represents. Under the classic regime transition view, the tectonic mode of a planet is a state variable (akin to temperature). Under the multiple stable modes view, the tectonic mode of a planet is a process variable. That is, something that flows through the system (akin to heat). The different implications that follow are discussed as they relate to the questions of when did plate tectonics initiate on Earth and why does Earth have plate tectonics.

This article is part of a discussion meeting issue 'Earth dynamics and the development of plate tectonics'.

1. Introduction

One of the themes of the Royal Society meeting in London, UK, which served as the foundation of this discussion meeting issue, was addressing the question of 'When did plate tectonics begin on Earth?' This is not a new question (e.g. [1–5]). It is simply phrased but it comes with layers of depth that require unpacking. To have any hope of answering it, in a community sense, requires an agreed upon definition of what plate tectonics is. By association, we would also need to have some criteria to identify geological activity that can occur on a planet lacking plate tectonics. Stated another way, we would be well served to categorize the range of tectonic modes that can operate on a terrestrial planet (the term 'tectonic mode' serves as a short-hand for the global mode of geological activity that characterizes a planet—this includes tectonic deformation, volcanic/magmatic activity, metamorphic activity and, to the degree that a planet has an atmosphere and hydrosphere that allows for weathering, sedimentary activity). The last unpacking is the most philosophical as it relates to the meaning we attach to the word 'begin'. At face value, the question suggests an answer in the form of an age range (e.g. plate tectonics began 3.5–3.0 billion years ago). Uncertainties in geological dating will always lead to age range uncertainty but the issue to be unpacked is not one of dating uncertainty but one of the transitions between tectonic modes: are they relatively sharp, as per classic regime transitions, or can the transition to plate tectonics occur over a protracted period of geological time during which essential elements, for the operation of plate tectonics, appear progressively and contingently? The other issue to be unpacked, regarding transitions, is directionality: do transitions between specific modes occur only once along a planet's thermal and geological evolution with a specific directionality between modes or can they occur multiple times with transitions between two specific modes being able to proceed in either direction between modes?

The goal of this contribution is to address the three unpacking factors noted above. (i) What defines plate tectonics? (ii) What other tectonic modes are viable? (iii) How might a planet transition between different modes?

2. Plate tectonics

Within the history of science, plate tectonics stands as one the foundational theories of the twentieth century (others being quantum mechanics and relativity). Plate tectonics theory is held in this high regard, in no small part, because of its precision—a precision that allows it to make predictions that can be quantitatively compared with observations to validate the theory for the geologically modern Earth [6–10] and to refute it as a tectonic mode on other terrestrial planets [11].

The success of plate tectonics in explaining a range of Earth observations is not a matter of semantics. Defining the essential factors required to say that a planet is operating in a plate tectonics mode, on the other hand, can and does vary among working scientists. A question that sprang from the Royal Society meeting, if for no one other than this author, was the degree to which debates about the origin/development of plate tectonics are a failure of language as opposed to a true clash of ideas. To paraphrase George Orwell: 'The slovenliness of our language makes it easier for us to have foolish debates.' So what is the best path to avoid debates about terminology and to stay grounded in debates about ideas and evidence? I am hoping this will not be an overly personal view but the best path is to stick with the original definition of plate tectonics that was laid out by the scientists who developed and tested the theory to begin with (e.g. [12] and multiple references therein). If new observations and/or expanded theory indicate that the definition is incomplete and/or in need of modification then that is a different matter.

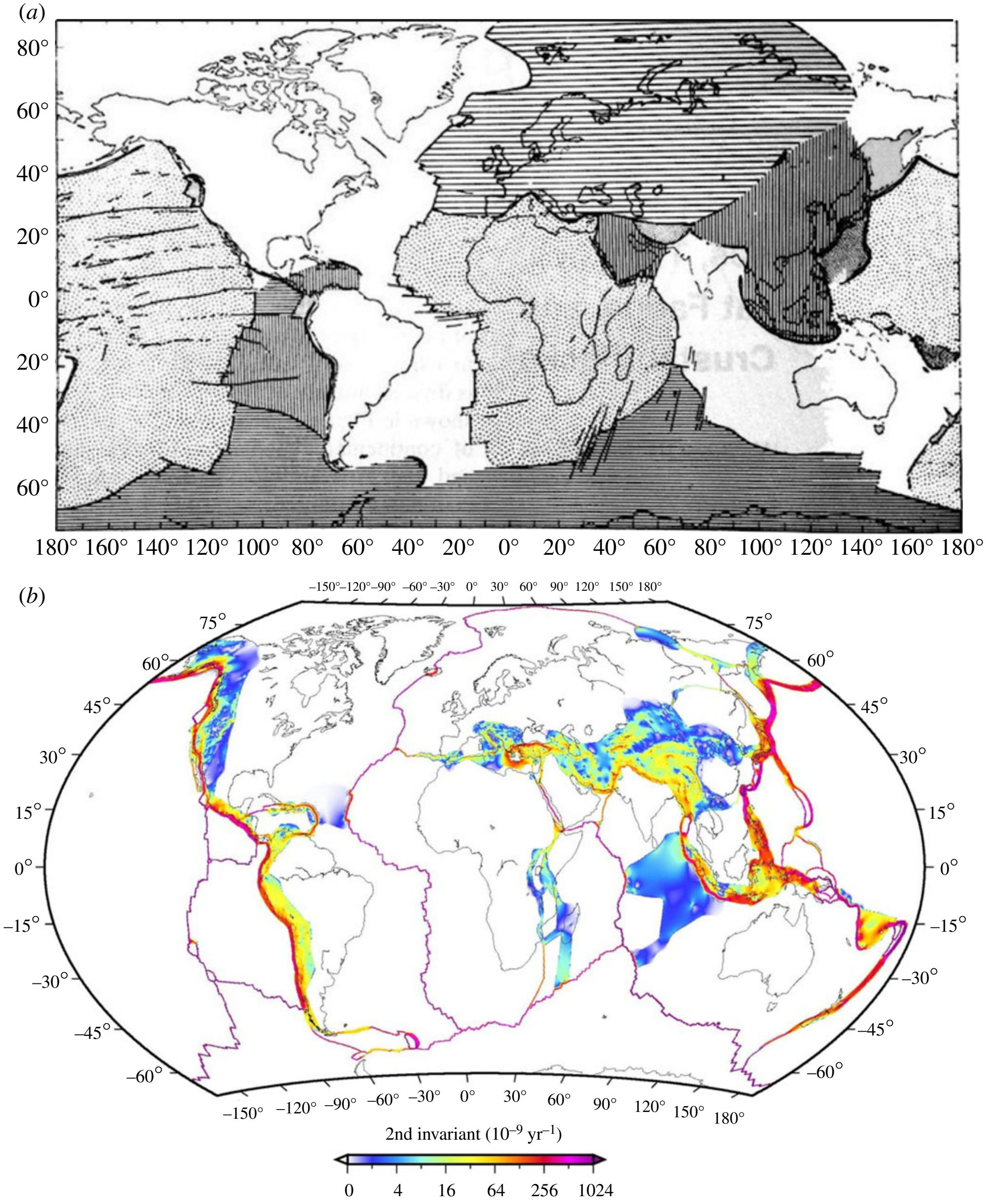


Figure 1. (*a*) Map of tectonic plates and plate boundaries from Morgan [8]. (*b*) Map of deformation zones from Kreemer *et al.* [14]. It is worth noting in (*b*) that although continental regions constitute a significant portion of the distributed deformation zones such zones also occur in the oceanic lithosphere. (Online version in colour.)

Short of that, loosening or cherry picking an established definition makes communication more difficult.

Plate tectonics is defined by rigid plate interiors and narrow zones of active deformation, i.e. plate boundaries [6–8,12]. Even allowing for diffuse plate boundaries [13,14], plate tectonics is associated with deformation zones that cover a relatively small portion of the Earth's surface area (figure 1). Across their full lateral dimensions, plate interiors do not experience significant levels of deformation. The lack of deformation is what defines 'rigid' plate interiors and allows Euler's theorem for rigid body rotations on a sphere to be applied to the relative motion of plates [7,8].

The fact that a mathematical theorem sits at its core highlights the precision associated with plate tectonics theory (it is no accident that plate tectonics was also referred to as tectonics on a sphere during its development). It is that precision that makes the theory testable. It also distinguishes plate tectonics from other potential tectonic modes.

The creation and maintenance of a global network of narrow plate boundaries is a critical condition for plate tectonics. This is what allows Euler's theorem to be applied to plate motions. It is also why continental reconstructions can be used to determine continental configurations in the Earth's past—continents are not being deformed to the degree that the 'pieces of the jigsaw puzzle' get too mangled to put them back together. This applies to the shallow structure of continents and, for the time range that temporal constraints are available, also to the deep structure of continental lithosphere [15,16]. Plate tectonics, under that definition, requires plates with an emphasis on the plural. A plate boundary separates two distinct plates. Localized regions of subduction, not connected to a mosaic of plate boundaries that delineate plates, are not evidence of plate tectonics on a planet. The same holds for a rift within a single plate and/or mountainous regions that are not part of an interconnected chain of deformation.

One can loosen definitions, if one chooses to, and introduce terms such as 'plate tectonic like' to describe modes that share some attributes of plate tectonics or use quotes to distinguish a 'plate' boundary from a plate tectonic plate boundary [17]. The question is what value does that bring? I would argue that communication is better served if we stay precise when precise definitions already exist. Tectonic modes that do not fit the characteristics of plate tectonics, as defined by the theory of plate tectonics, are best called what they are: distinct tectonic modes. By association, deformation zones that do not form a planetary network (mosaic) are not plate boundaries, as they do not delineate distinct plates that move relative to each other.

An example from planetary exploration can make it clear that focusing on precision, and the quantitative defining features of plate tectonics, is not a pedantic exercise [11]. When radar mapping images of Venus' surface first became available, there was a debate on whether the surface morphology was consistent with plate tectonics (certain deformation features looked visually similar to plate boundaries on Earth). It was the defining characteristics of plate tectonics that allowed the debate to be quantitatively addressed [11]. It was not only Euler's theorem that came into play but also the predicted topography moving away from a relatively narrow, divergent plate boundary [10]. The conclusion was that Venus, which shows evidence of volcanism and tectonics (e.g. [18]), lacks plate tectonics [11]. Had the quantitative aspects of plate tectonics not been brought to bear the debate could not have been resolved to the degree it was.

The Venus example also underlines a previously touched on issue: the existence of a local zone of tectonic divergence, lateral shear and/or convergence is not the same as the existence of plate tectonics. Convergence is of particular interest as several studies have argued for subduction on Venus [19,20]. If we are not clear about definitions, this can lead to a false conflict between evidence for subduction on Venus and evidence that Venus lacks plate tectonics. The conflict is false in the sense that subduction is a component of plate tectonics but subduction does not constitute a plate tectonic planet. The degree to which subduction initiation can lead to the development of plate tectonics is an issue returned to in §7. It can be noted at this stage that observations related to the early Earth cannot rule out that potential for our home planet. On the flip side, the evidence from Venus warns us not to assume that that needs to be the case in general.

An additional interesting aspect of the Venus example is one of scale. It was the near-global coverage of radar mapping that allowed for a quantitative assessment of whether Venus does or does not have plate tectonics. Global coverage for the early Earth will be impossible to obtain and there will always be preservation biases. This brings an added challenge for field geologists (it may be easier to determine if a planet other than Earth has plate tectonics than to determine if the early Earth had plate tectonics). This issue will be touched on in §7 when potential transitions between tectonic modes are discussed.

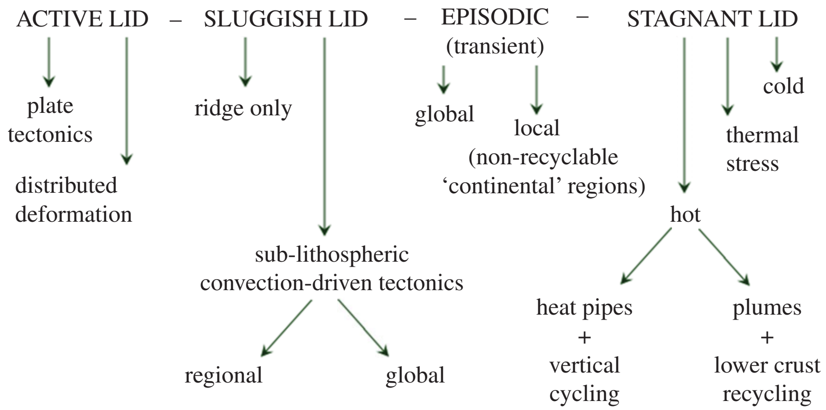


Figure 2. Potential tectonic modes for terrestrial planets.

3. A range of tectonic modes

In discussions of tectonics, particularly as related to interdisciplinary topics, one can often hear a view expressed, implicitly or explicitly, that considers tectonics to be binary: a planet has plate tectonics or it is tectonically dead like the moon. It is hard to track the source of this view but it does persist (e.g. [21]). The purpose of this section is to review the range of potential tectonic modes that have been proposed to date. The review, and in particular the referencing, will not be complete given the range of work to date. The hope is it will, at least, make it clear that tectonic potential is far from binary.

Figure 2 is a categorization of potential tectonic modes [22]. It is adapted from a paper written in the context of exo-planet exploration (i.e. future exploration of terrestrial planets orbiting stars other than our own). Within the exo-planet community, the issue of tectonic modes has gained interest, driven by considerations of how volcanic and tectonic activity can affect the ability of a planet to maintain conditions suitable for life (e.g. [23–28]). Reviewing, and expanding on, the discussion of Lenardic [22] is pertinent to the issue of when plate tectonics initiated/developed on Earth as all the modes listed, except the cold stagnant lid, are potential pre-plate tectonic modes. It also provides an opportunity to clarify how the terms active, stagnant, episodic and sluggish lid relate to tectonic modes.

Plate tectonics shapes and reshapes the Earth's surface and cools its interior. A critical aspect of plate tectonics is that the lithosphere, despite having high bulk strength due to the temperature dependence of mantle viscosity [29], is an active part of mantle convection. The lithosphere participates in convective overturn due to the formation of weak zones that define plate boundaries [30]. This allows the cold upper boundary layer of mantle convection to sink back into the interior. This has led to the terminology 'active lid convection' to describe any terrestrial planet where the lithosphere participates in mantle convection and also drives convective overturn—the negative buoyancy of the lithosphere is the principal driver of its subduction back into the mantle [31]. If the cold upper boundary layer does not partake in convective overturn, then the cooling of a planet will differ. The term 'stagnant lid' originally referred to that situation, as it related to the cooling of a planet [32–35]. It was not meant to imply that tectonic deformation could not occur in a stagnant lid regime.

Figure 3 shows results from numerical experiments that highlight the active and stagnant lid end-members [36,37]. The efficiency of heat transfer from a planet's interior to its surface is different between end-member modes, as reflected in the heat flux plots. Plate tectonics is an example of an active lid regime of mantle convection but not all active lid regimes need be plate tectonics, as discussed below. As with the active lid regime, a stagnant lid regime of mantle convection is associated with multiple modes of volcanic and tectonic activity (see §5).

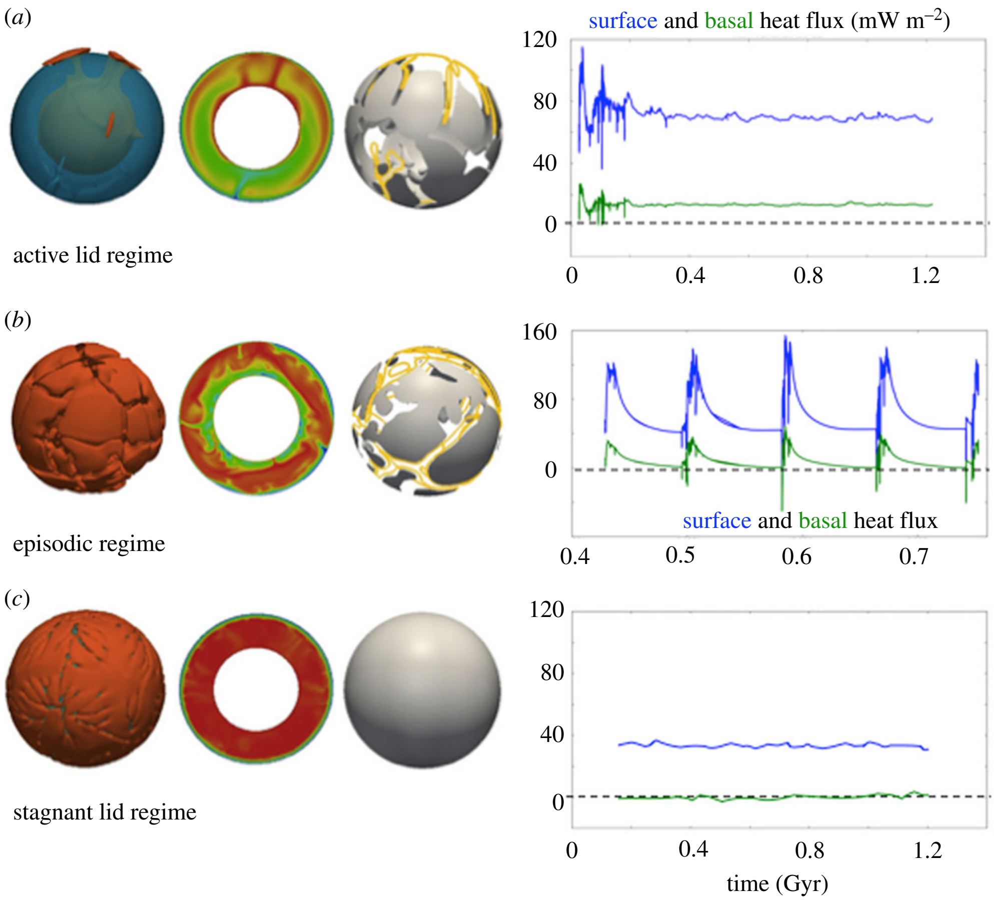
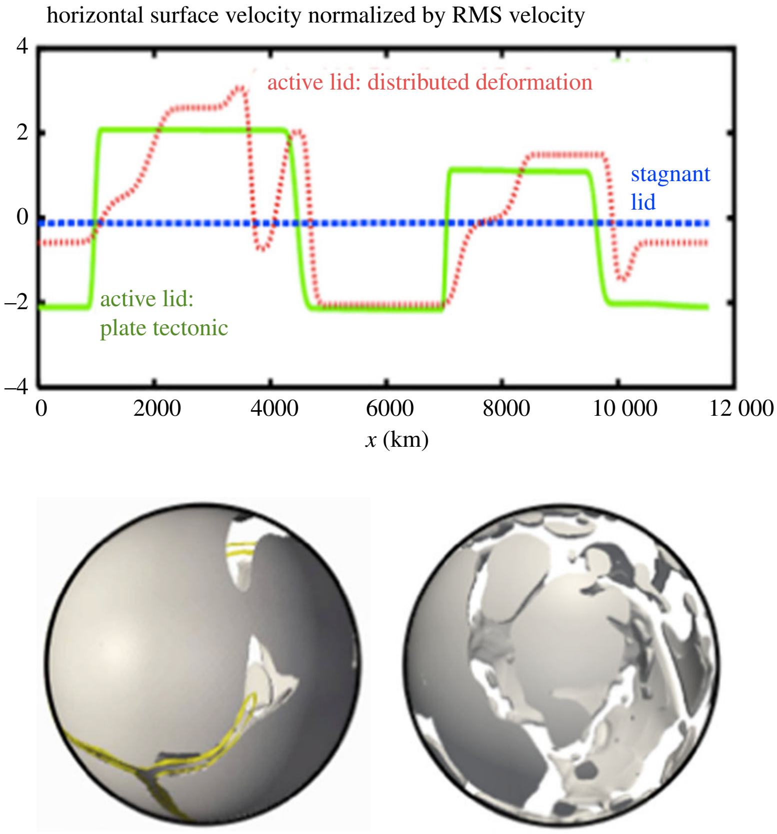


Figure 3. Results from numerical mantle convection experiments (shown as iso-temperature images, temperature cross sections and surface projection of low strain rate regions, shown in grey, together with regions of concentrated deformation shown in yellow). Three modes are shown: active lid (*a*); episodic lid (*b*); stagnant lid (*c*). Surface (blue) and basal (green) heat flux time series are plotted to the right of the images for each respective numerical experiment.

Episodic and sluggish lid regimes sit between active and stagnant lid end-members. The episodic regime characterizes a planetary state with alternating periods of active and stagnant lid behaviour (figure 3*b*). In a sluggish lid regime of convection, lithosphere velocities are finite (not stagnant) but lower than those of the mantle below. This differs from an active lid regime in that lithosphere motion and associated surface deformation are not self-driven. Instead, convective tractions on the base of the lithosphere drive surface deformation. For this reason, one will also hear the term convection-driven tectonics applied to this mode [38]. Modes that sit between active and stagnant end-members are discussed in §6.

4. Active lid tectonic modes

Plate tectonics is defined by rigid plate interiors and narrow zones of active deformation. Even allowing for diffuse plate boundaries, plate tectonics is associated with deformation zones that cover a relatively small portion of the Earth's surface (figure 1). One can imagine active lid planets that are dominated by broad zones of deformation, as opposed to narrow boundaries that define tectonic plates. Beyond imagining, this mode has been explored through a number of geodynamic models. Figure 4 shows the results from two representative studies [36,39]. The



active lid: plate tectonic

active lid: distributed deformation

Figure 4. (*a*) Results from two-dimensional numerical experiments of coupled mantle convection and tectonics [39]. Shown are plots of surface velocity from three experiments. One is in a stagnant lid mode of convection with zero surface velocity. The other two are in active lid modes. The surface velocity plots show how an active lid mode need not be one that represents plate tectonics as it operates on Earth at present. (*b*) Results from three-dimensional numerical experiments of coupled mantle convection and tectonics [36]. The grey regions, in the surface projection plots, show low strain rate regions (regions that behave as effectively rigid). The left case has narrow regions of deformation separating large surface regions that are not deforming. The right case is dominated by distributed deformation. (Online version in colour.)

surface velocity plots show the distinction between concentrated and distributed deformation—regions with lateral velocity gradients (i.e. deformation zones) cover large portions of the surface in the distributed mode but are confined to small, narrow areas in a plate tectonic mode.

Geodynamic models that are dominated by distributed surface deformation are considered unsuccessful when it comes to addressing the dynamics of plate tectonics because they do not account for key aspects of the process they seek to model, i.e. they do not produce plate boundaries nor do they predict surface velocities consistent with observations [30,39]. Although not plate tectonics, an active lid regime of convection dominated by distributed deformation is a possible tectonic mode for other terrestrial planets. A distributed deformation mode has also been argued to be a precursor to plate tectonics on Earth [40].

The distinction between a plate mode and a distributed deformation mode has been quantified in geodynamic models using a ‘plateness’ metric [39]. The metric tracks the percentage of a model’s surface that can be characterized as behaving like a rigid plate (i.e. a non-deforming region). There are no universally agreed upon criteria as to what value this metric must take in order for a model to be defined as operating in a plate tectonic mode but, in general, values near 0.8 are adopted (based principally on the observed percentage of the Earth at present that has very low levels of surface deformation as shown in figure 1*b*). At what stage surface deformation becomes widespread enough such that the kinematic laws of plate tectonics break down is, to the best of my knowledge, an unanswered question at present. It is not clear that a transition of that type will be a sharp one in parameter space. It could be a smooth transition (the potential of smooth versus relatively sharp transitions will be touched on again when sluggish lid modes are discussed and will be returned to in more detail in §7).

5. Stagnant lid tectonic modes

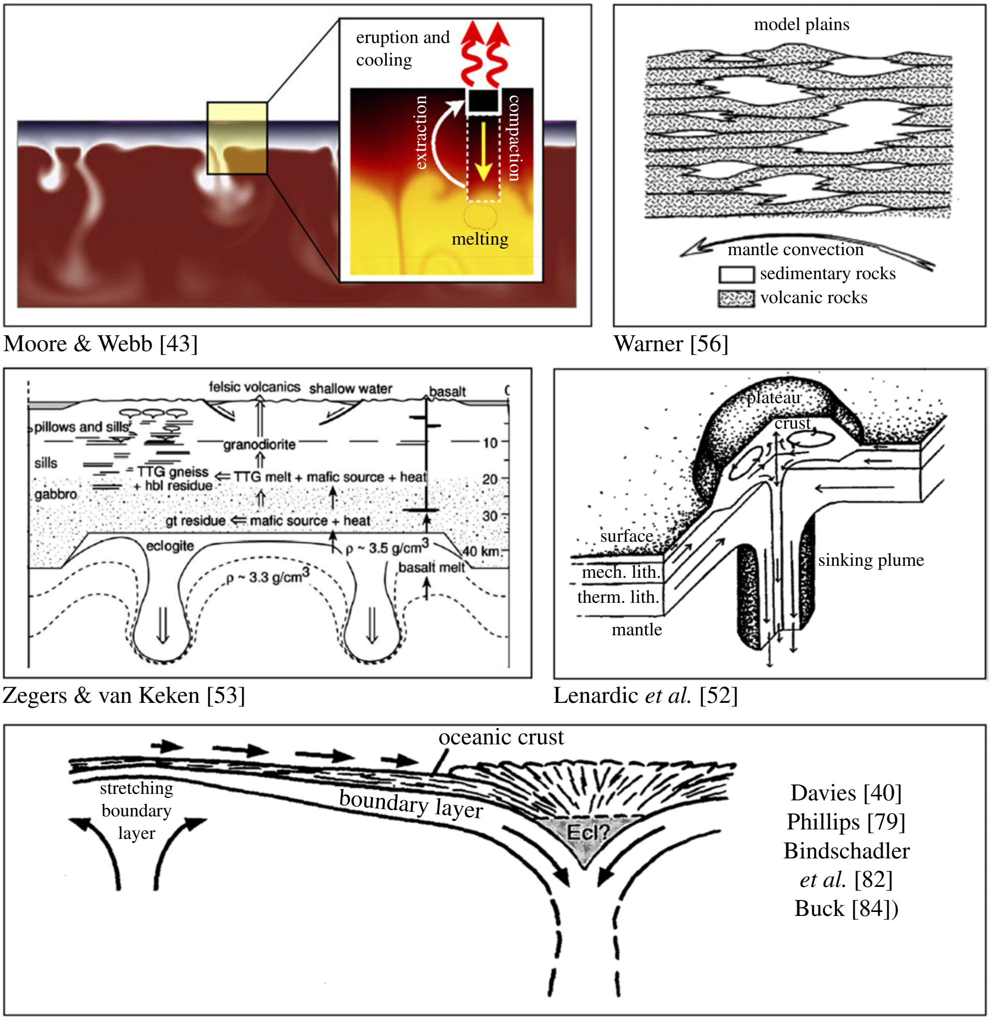
Stagnant lid (single plate) planets can be associated with subsets depending on internal temperatures. If the interior is so cold that no melting can occur then a planet will be volcanically inactive (a 'cold stagnant lid' [41]). Hot stagnant lid planets allow for volcanic and tectonic activity. For increasing interior temperatures, volcanism becomes more important as a heat transport process. A planet or moon enters a heat pipe mode when volcanism and/or plutonism dominates total heat transport from its interior to its surface. The heat pipe mode characterizes the tectonic state of Jupiter's moon Io [42] and has been argued to provide an explanation for many features of Earth's ancient geological record [43,44].

A heat pipe mode allows for degassing of volatiles and the creation of new topography. In addition, volcanism is a mass transport process that can cause the surface temperature to be advected downward as old, cool flows are buried by newer flows. This allows for a vertical cycling of crust from the surface toward the interior of a planet [43]. The vertical cycling can stress the planet's/moon's lithosphere and drive tectonic deformation [44]. The discovery of a significant number of exo-planets with orbital characteristics that favour a strong component of tidal heating [45] has rejuvenated interest in the heat pipe mode (e.g. [46]).

As volcanism/plutonism becomes less dominant as a heat transport process, a planet can transition from a heat pipe mode to a single-plate mode that remains geologically active. As an example, Mars is a single-plate planet that shows signs of volcanic activity not consistent with a heat pipe mode. Martian volcanic constructs are more consistent with a mantle plume origin in morphology, gravity and topography [47]. In order for volcanism to remain locally active in this mode, the residuum of crustal extraction, which is buoyant relative to bulk mantle, must be able to flow away from the volcanic centre [48]. A tectonic mode with upwelling plumes interacting with small-scale instabilities from the base of a single plate has also been invoked for the early Earth [49]. It is worth noting that the morphology of mantle plumes on a single-plate planet can differ from that of plumes on a plate tectonic planet [50,51]. As such, one should not expect surface signatures of plumes on a single-plate planet to correlate in a one-to-one manner with plume signatures from the geologically modern Earth. This goes beyond the fact that on a single-plate planet hot spot tracks will not be generated—the dimensions and temperature anomalies of plumes themselves can differ on single-plate planets relative to plate tectonic planets.

Recycling of mantle lithosphere and crust remains possible in a single-plate mode with several recycling mechanisms having been put forward [52–55]. Figure 5 shows several non-plate tectonic modes of recycling. The mechanisms can recycle igneous rocks and, if a single-plate planet has an atmosphere/hydrosphere that allows for weathering, sedimentary rocks can also be recycled without plate tectonics operating [56].

The issue of recycling relates to an observation noted in the introduction: opinions as to what constitutes plate tectonics can vary. Variations are based on particular views as to the most important aspect(s) of plate tectonics. More often than not, this is tied to a specific research topic that an author is addressing. Within the planetary science community, the most critical aspect of plate tectonics is often considered to be the cycling of volatiles between a planet's interior and its atmosphere. Volatile cycling can affect the ability of a planet to maintain climatic conditions that allow for liquid water and, by association, life (e.g. [23]). For this reason, within a particular community, the defining feature of plate tectonics is taken to be the recycling of material from the



Moore & Webb [43]

Warner [56]

Zegers & van Keken [53]

Lenardic *et al.* [52]

Davies [40]
Phillips [79]
Bindschadler
et al. [82]
Buck [84])

Figure 5. Recycling mechanisms that have been proposed for the early Earth and other terrestrial planets. (Online version in colour.)

atmosphere to the solid planet with the thought that plate tectonics is the only mode that allows for recycling that can stabilize climatic conditions conducive to life (e.g. [57]). The references for figure 5 bring this assumption into question. Moreover, several studies have argued that tectonic modes different from plate tectonics can allow for surface conditions conducive to life (e.g. [27,28,46,58–61]). The above provides an example of how cherry picking a scientific definition can muddy the waters. Picking one aspect of what defines plate tectonics, at the expense of other defining features, is, at best, driven by different goals between different research groups. This can be particularly problematic for multi-disciplinary topics (e.g. [62]).

Between the hot and cold stagnant lids lies the potential of tectonic deformation driven by transient cooling of the lithosphere. Lithosphere cooling, from a hot start, leads to thermal contraction and thermal stresses that can potentially generate tectonic deformation [63]. This mode of tectonics has been suggested for the Earth's moon [64] and for Mercury [65]. Tectonic deformation, under this scenario, would occur principally during the earliest geological phases of a planet. A variant of thermal stress tectonics has also been proposed for Venus. That variant is based on the idea that large (of the order of 100°C) surface temperature variations, driven by climatic shifts, can generate thermal stresses significant enough to cause surface deformation [66].

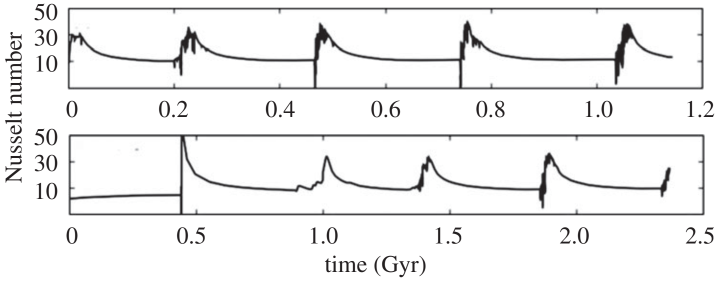


Figure 6. Time-series plots from two numerical experiments that are in an episodic mode of mantle convection [36,37].

This variant allows for the potential of tectonic deformation at later evolution times of a planet's geological history.

6. Episodic and sluggish lid tectonic modes

Figure 3*b* shows results from a model that is in an episodic regime [34]. Periods of lithosphere overturn are interspersed with stagnant lid behaviour. An episodic mode has been advocated for Venus [67] and early Earth [68–70]. Lithosphere can be recycled globally during overturn episodes. Alternatively, regions of thick and chemically buoyant lithosphere can resist recycling during overturn events [71]. Lithosphere recycling would not be global in such a case and zones of thickened crust could remain persistent over time. They could also 'drift' during periods of active lid behaviour [68] even though the planet may not possess a mosaic of plate boundaries that separate distinct plates.

The timing between overturn events in an episodic mode varies for different levels of internal energy, mantle viscosity structure and lithosphere strength. Figure 6 shows two examples from numerical models with different degrees of depth variable mantle viscosity (details can be found in [36,37]). It has been argued that different initial conditions, related to planetary formation and variable post-magma ocean conditions, can lead to episodic regimes that differ in terms of total time duration, within a planet's full geological evolution, and in terms of timing between active lid bursts [72]. The potential exists that a planet could have a small number of active lid bursts along its cooling trajectory. This may not appear in the geological record as a periodic process. Instead, it could appear as a transient episode of localized lithosphere overturn (i.e. a subduction pulse that does not transition into a sustained period of active lid behaviour).

The term active lid means that lithosphere subduction is self-driven by the negative buoyancy of the lithosphere. Stated another way, lithosphere motion drives motion in the mantle below. This is the classic view of plate tectonics connected to mantle convection with the plates being dominantly self-driven [73,74]. If the lithosphere is self-driven, then the mantle below plates resists plate motion. If the velocity of the mantle below the lithosphere exceeds surface velocities, then mantle flow would provide a driving force for lithosphere motion and deformation (figure 7). A mode of that type, in which lithosphere velocities are finite (not stagnant) but lower than that of the mantle below, has been termed a sluggish lid mode [32]. Theoretical and numerical work has shown that a sluggish lid mode can exist over a broad range of planetary parameter space [75–78]. Those studies also show that surface velocities in a sluggish lid mode can be variable as a function of system parameters. Surface velocities in a sluggish lid mode can be low relative to present-day plate velocities but they need not be, especially under hotter mantle conditions that may have prevailed in the Earth's past.

The velocity profiles of figure 7*b* indicate that the boundary between active and sluggish lid behaviour can be a fuzzy one. The models used for that figure have the same parameter values

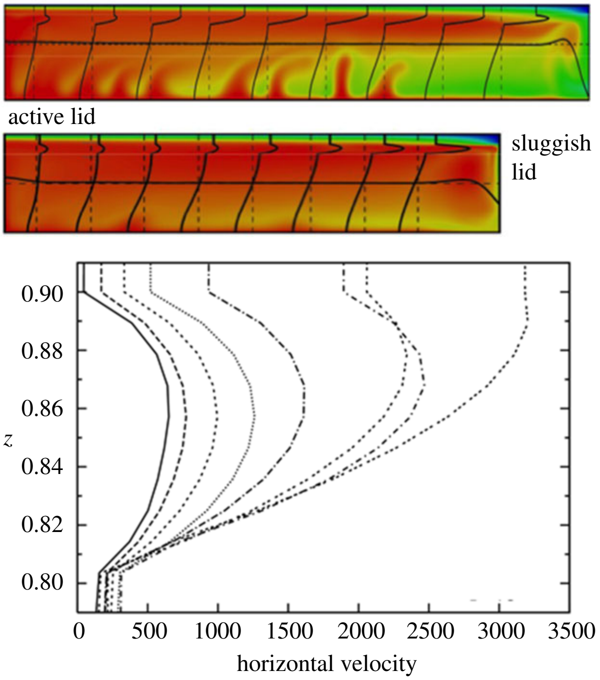


Figure 7. (*a*) Numerical experiments of coupled mantle convection and surface tectonics illustrating the distinction between active lid and sluggish lid modes [75]. Vertical profiles of horizontal velocity (black lines) are plotted over thermal fields (blue is cold upper boundary layer material—model analogue for a tectonic plate or a deforming lithosphere; red is warm upwelling mantle). (*b*) Vertical velocity profiles form models that transition between lid states as convective wavelength increases.

except for different convective wavelengths (details can be found in [75,76]). This brings up the potential that if a transition from a sluggish to an active lid mode on a planet was driven by changes in convective wavelength, then the transition could be a smooth (continuous) one as opposed to a relatively sharp (discrete) one. This potential will be returned to in §7.

Surface velocities in a sluggish lid mode can, on global average, be low with regions of large velocity gradients (i.e. deformation zones) confined to zones near convective upflows and downflows in the mantle. This is the classic idea of convection-driven tectonics as developed by Phillips [79]. It is also possible that a more global mode could exist with crustal thickening and creation of high topography near mantle downflows [80–83]. Convective stresses could form crustal faults that, in turn, could be set into motion or reactivated by ongoing mantle convection. An end-member is to imagine the Earth covered in continental crust. The crust is not subductable en masse but ongoing mantle convection can deform it and, potentially, recycle its lower portions [84]. Surface deformation might resemble that in active zones of continental deformation on Earth [85] but the planetary-scale tectonic mode would not be characterized as plate tectonics.

A sluggish lid regime has been proposed for the pre-plate tectonic Earth in its classic form [24,86] and a modified form that incorporates plate weakening due to plutonism [87]. It has been proposed for Venus in submodes where the lithosphere deforms globally [80] or in localized regions [79]. A sub-mode has also been identified in which lithosphere deformation, associated with sluggish lid convection, is a mix of concentrated and distributed deformation. In zones of divergence, within the convecting mantle, localized features, akin to mid-ocean ridges, can form while deformation above convergent zones remains distributed. This has been termed a ridge-only mode [88].

7. Transitions between tectonic modes

The goal of this section is not to answer the question: How and when did Earth transition to plate tectonics? What will be discussed are potentialities that are viable from a physical and an observational standpoint (observations and inferences from the rock record cannot, at present, exclude them). Having a range of what can happen in mind can help in interpreting the uncertain and incomplete record the Earth has left us about what did happen on one particular planet. Keeping the range of viable potentialities in mind can save one from falling too quickly into a singular interpretation of an incomplete record—multiple working hypotheses being a cornerstone of historical geology. The degree to which insights into the Earth's tectonic evolution can and cannot inform us about the tectonic evolutions of other planets will also be touched on.

Transitions between dynamic modes are connected to the nature of mode boundaries in parameter space. Parameters, in this context, are physical/chemical quantities that are key to the existence of a particular mode. For tectonic modes, lithosphere strength and the internal energy of a planet are considered key parameters and diagrams delineating tectonic modes are often drawn as two-dimensional (2D) projections spanned by these parameters (e.g. [34,89]). This is a visual simplification and studies of mode transitions generally consider a parameter space beyond two (e.g. the effects or depth variable mantle viscosity, variable mantle thermal properties, variable cell wavelengths, continents, mantle phase changes, magmatism). That said, 2D plots are still useful to highlight end-members (keeping in mind that the pertinent parameter space is of higher dimension).

Figure 8*a*,*b* shows what is, arguably, the most prominent thinking about tectonic mode transitions. Figure 8*b* resembles a phase diagram (e.g. the solid–liquid-gas phase plot of water). The boundaries delineating modes are drawn as lines to denote that transitions are relatively sharp, i.e. a mode change occurs over a narrow parameter variation (figure 8*a*). Figure 8 uses schematics to highlight generic behaviour. Specific transition plots and regime diagrams are not hard to find for the interested reader (e.g. [34,89–92]). Across a number of studies focused on mapping tectonic modes of behaviour, the regime diagram plot provides a commonality. Numerical calculations are used in an experimental mode by varying single parameters to map transitions (outputs looking akin to figure 8*a*). Following that procedure for multiple parameters allows a regime diagram to be mapped that delineates different modes (outputs looking akin to figure 8*b*).

The internal energy of a planet changes as the planet cools (e.g. [93,94]). Lithosphere strength can also change (e.g. [95–97]). This allows for the potential that a planet can evolve toward a regime boundary. The planet becomes primed for a transition. A prominent hypothesis is that a transition to plate tectonics is preceded by subduction initiation (e.g. [98,99]). The time scale to develop a network of plate boundaries, from that critical transition point, would be limited by the characteristic advective time scale of mantle convection. That time scale is commensurate with a mantle overturn time, which is of the order of 100 Myr [31]. The time scale can increase if several mantle overturns are required to develop weak plate margins [100]. Under a regime diagram view, transitions can be sharp in parameter space and still be protracted in time. Once a critical parameter threshold is crossed the planet will transition from one mode to another but the transition need not be sharp in time.

A modification to the regime diagram view is the possibility that tectonic transitions are not sharp, or even relatively sharp, in parameter space. Figure 7*b* provides a signpost of how this could occur. The models indicate that, all other conditions remaining equal, long aspect ratio cells (long convective wavelength) can be in an active lid mode while shorter aspect ratio cells operate in a sluggish lid mode (with the shortest cells having a surface velocity approaching a stagnant lid). This dynamic behaviour has been explored using numerical and analytic approaches with consistent results [76,77]. Plate dimensions on Earth are variable today, indicating that different wavelength cells coexist. Arguments have been put forward that not all plates on Earth are self-driven, as per active lid dynamics, but that some are driven by convective tractions from below [101,102]. This would indicate that even for the present-day Earth there is a component

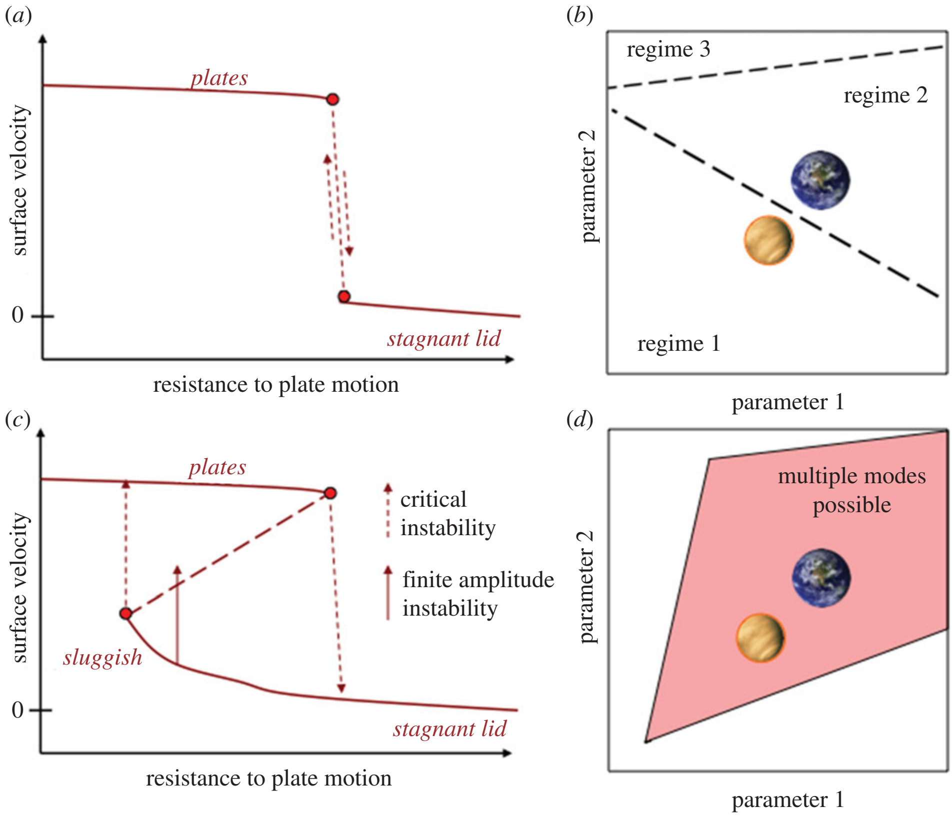


Figure 8. (*a–d*) End-member views of tectonic mode transitions. (Online version in colour.)

of sluggish lid convection. Slab pull and ridge push can remain spatially dominant such that the active lid component dominates planetary cooling. There are theoretical arguments that sluggish lid convection can come to dominate for a hotter, lower viscosity, mantle, i.e. in the Earth's past [25,76,77]. The sluggish lid component, in a mixed mode of behaviour, could thus progressively increase in the Earth's past [24,103]. Figure 7*b* shows that the final end-member would, for all intents and purposes, appear as a stagnant lid mode. The spatial percentage of a planet operating in a sluggish lid mode required to show that the planet is dominated by sluggish lid behaviour, in terms of tectonics and/or mantle cooling, will be fuzzy (fuzzy boundaries are not unusual, e.g. the distinction between short and tall, but, to the best of my knowledge, the potential that tectonic/convective mode transitions are fuzzy has not received much attention). This would still fall under the umbrella of a regime transition view but, to use an analogy, a tectonic transition could occur beyond the triple point—it would involve a progressive blending of different modes that would smoothly span end-members as a control parameter, mantle temperature, changed (similar considerations may hold for transitions between a distributed deformation mode and a plate tectonic mode).

An alternative to a regime diagram view, be it associated with sharp or fuzzy boundaries, is the possibility that multiple tectonic modes can exist for planets with the same physical and chemical characteristics (e.g. bulk composition, size, material parameters, volatile content, solar distance). That is, the possibility that coupled planetary evolution and tectonics is an example of a dynamic system that allows for bi-stable behaviour [104–106]. Figure 8*c*,*d* shows this schematically. The potential of bi-stable behaviour has a long history in global climate studies [107]. For global tectonics, the history is shorter, as discussed below. For now, it is simply presented as an alternative so that the main difference between the end-member views can be laid out. This will provide a foundation to discuss the implications for plate tectonics.

The first point to make relates to initial conditions. Initial conditions are taken to be distinct from physical/chemical conditions, e.g. planetary formation can set the initial chemical composition of a planet but that is better viewed as a physical/chemical characteristic. An initial condition, for the geological evolution of a planet, would be, for example, bulk planetary temperature coming out of a magma ocean phase. The regime diagram view does not preclude initial condition dependences. Different initial conditions can cause planets to evolve toward regime boundaries at different temporal points or to not cross boundaries at all. For a time, it was thought that initial condition variations would be rapidly damped as planets evolved thermally and, as such, would not play a major role in long-term evolution [108]. That has been questioned without invoking the potential of bi-stable states [109]. The point here is that both views allow initial conditions to play a role. Phrased another way, the major difference between the two views of figure 8 is not one of the initial condition issues.

The major difference between the two views of figure 8, as related to mode transitions, is one of strict determinism versus contingency. Under a regime diagram view, once a particular tectonic mode becomes unstable it transitions into a unique new mode, as determined by the physical and chemical characteristics of the planet at that time. Bearing in mind not to take the analogy too directly, this is akin to a first-order phase change with the phase of a material being uniquely determined by system control parameters. Under a regime diagram view, once a planet evolution causes it to cross a regime boundary, there will necessarily be a change from one uniquely defined mode to another uniquely defined mode. A regime diagram view brings a level of predictability with it that has significant implications for planetary exploration (e.g. [91]). Under a bi-stability view, the tectonic mode of a planet is not uniquely determined by planetary age and the physical/chemical characteristics of the planet—contingencies along planetary evolution paths can play a major role in determining mode transitions.

A contingent event is not the same as a random event [110]. A contingent event depends on several factors occurring simultaneously or in a certain order. Each individual factor can be deterministic but the intermingling of them in space and time makes the event unpredictable (or not necessary in the sense that crossing a boundary, in the regime diagram view, necessarily leads to a unique new state). Crucially, if one of the factors were to change then the event may not have happened. Consider the example of a planet starting its geological lifetime in a heat pipe mode. Under conditions that allow for that, multiple stable states would be unlikely as all the other modes of figure 2 are associated with sub-solidus convection (i.e. volcanism/plutonism cannot be the dominant cooling mode). Tectonic bi-stability allows for the potential of the planet moving out of a heat pipe mode, as it cools, and into an evolution window that allows for single plate behaviour and plate tectonics. Neither state will necessarily be the one that does occur. Different temporal paths and spatial variations coming out of the heat pipe mode will be associated with the system moving into a single plate or into a plate tectonic mode (both possibilities occurring under equivalent bulk physical/chemical conditions and at the same evolution time of the planet).

Characterizing the volcanic and tectonic activity of a planet provides a planetary-scale variable that can be used to compare different planets. The two differing views of figure 8 have implications for a meta-question: What type of variable is it? The phrase 'the tectonic state of a planet' appears often in the literature. State variables (e.g. temperature) and state descriptors (e.g. the state of matter) are connected to regime diagrams akin to figure 8*a*,*b*: the state of the system at any given time is uniquely characterized by the values of state parameters/variables. Figure 8*c*,*d* is associated with multiple equilibrium states and strong temporal path dependence. If the view of figure 8*c*,*d* is correct, then tectonics should be viewed as a process variable [111]. That is, something that flows through the system (e.g. heat). Although, to the best of my knowledge, the distinction has not been phrased that way before this does not mean that the idea of tectonic bi-stability is new.

The hypothesis that terrestrial planets allow for multiple stable tectonic modes, under equivalent physical/chemical conditions and evolution ages, was first explicitly stated by

Sleep [112]. It was noted, shortly after, that numerical models of coupled mantle convection and tectonics allow for a hysteresis effect that is a signal of bi-stability [113]. The idea sat dormant until debates about the tectonics of exo-planets (e.g. [114,115]) motivated more extensive suites of numerical models designed to map regions of parameter space that allow for multiple tectonic modes [116]. At the same time, a theoretical analysis elucidated the underlying physics that allowed for bi-stable tectonic behaviour [77]. The predictions of the theoretical approach were subsequently tested against numerical calculations with consistent results [117]. If we relax the need for tectonic bi-stability to be called out explicitly, I would argue that the history of the idea goes back further.

Bi-stable systems allow for regime transitions even if the system never becomes primed for a transition along its evolution path (figure 8*c*). The system can still transition as a result of a finite amplitude perturbation that causes it to cross a seperatrix between distinct modes [104–106]. All system parameters (e.g. internal energy, lithosphere strength) can remain constant in the process. Finite amplitude instabilities can occur in a range of physical systems (e.g. [118]). The fact that subduction initiation was argued to be a finite amplitude instability [119] suggests that the idea of multiple stable tectonic modes has been lurking in the background for some time. If subduction initiation is a finite amplitude instability, then the existence and non-existence of subduction are both viable under equivalent conditions. Although subduction need not lead to plate tectonics (it is not sufficient), plate tectonics does require subduction (it is necessary). For this reason, I would argue that the history of the idea that a regime diagram view of tectonic transitions can be misleading goes back to [119].

With some historical credit in place, we return to the implications of differing end-member views (figure 8). A regime diagram end-member implies that plate tectonics could emerge along some point in a planet's cooling history (from a sluggish, episodic or hot stagnant lid state) and then transition to a cold stagnant lid as internal energy is tapped (i.e. the thermal death of plate tectonics). This would lead to a single answer to the question of when did plate tectonics begin (the age range might be narrow or protracted but it would be a unique period along a planet's geological lifetime). This is a best-case scenario for using the geological record to answer the 'when' question (which is not to imply that it will be easy or even possible, to some level of collective agreement, given the incompleteness/uncertainty of the record and restrictions of spatial coverage). What follows are potential complications that cannot be ruled out at present.

Multi-stable behaviour allows for the possibility that plate tectonics could emerge, transition to another mode and re-emerge along a planet's cooling path [112]. The question of 'when' would then need to be clarified. One could ask 'When was the most recent emergence?' but the fact would remain that interpretation of the geological record, which could contain signals of prior emergence, would need to be treated differently. Evidence for single plate behaviour over the Earth's midlife [5] would, under that possibility, not be inconsistent with subduction and/or plate tectonic signatures earlier in the geological record.

Finite amplitude instabilities can fail. A perturbation can cause a system to move toward a different tectonic mode but if internal feedbacks are not activated the mode might not be stabilized and, for a bi-stable system, the prior mode can be re-established (figure 9*a*). Potential stabilizing feedbacks include: (i) a history dependence of fault zone strength that allows weak boundaries to progressively develop to the point that they can remain stable [100]; (ii) the development of an asthenosphere which can stabilize a plate tectonic mode of behaviour [39]; (iii) a history-dependent change in mean plate thickness which can alter system energetics in a way that favours prolonged active versus sluggish lid behaviour [77]; (iv) surface hydration effects that allow for plate margin lubrication [120,121]; (v) the growth of continents that can alter mantle/lithosphere stress in a manner that favours maintenance of plate tectonics [122].

All of the feedbacks above require time and specific sequences of events in order to become operational to the point of stabilizing plate tectonics. Turning a system on is not the same thing as having the system move into an operational phase of behaviour. For planetary evolution, the background thermal state is always changing due to planetary cooling and the interactions between that changing background, the nature of subduction initiation events and the dynamics

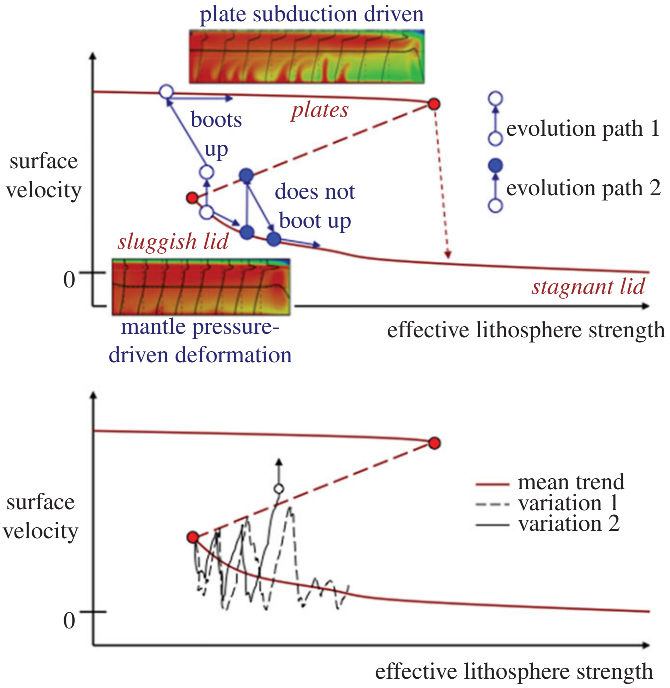


Figure 9. Schematics of different tectonic transition scenarios allowed for under the hypothesis of tectonic bi-stability. (Online version in colour.)

of stabilizing feedbacks allow for the potential that a transition towards plate tectonics can be started on a planet but the planet may not settle into a stabilized plate tectonic mode (the plate tectonics system may not boot up). In the geological record, this could show up as a sequence of events that look indicative of plate tectonic emergence but are associated with a failed mode transition.

The discussion above relates to another question that was at the heart of the Royal Society meeting: Why does Earth have plate tectonics? I take it to mean what factors allow for plate tectonics on Earth. This leads to the associated question of why other terrestrial planets lack plate tectonics; most notably Venus, which shares similarities to Earth in terms of bulk physical and chemical properties. No one will argue that certain conditions must be met to allow for the potential of plate tectonics on a terrestrial planet (e.g. the planet must have sufficient internal energy to allow for surface deformation, the strength of rock cannot be such that lithosphere failure and associated generation of plate margins could not occur under any level of internal energy). The divergence between the two views of figure 8 can be given added clarity by posing the question: Assuming that all the physical/chemical conditions we can think of that are critical to allow for plate tectonics are met, is it possible a planet could still not operate in a plate tectonic mode?

It was noted that several researchers have argued for subduction on Venus in the face of evidence that Venus lacks plate tectonics. How one squares that circle is telling. One answer is to say that both Venus and Earth have (or had) the internal energy and the lithosphere rheological properties necessary to allow for subduction initiation but that there is a third state parameter that differs between the two planets. The state parameter invoked to date is surface temperature [20,91,100]. The present-day surface temperature of Venus is ~450°C greater than Earth's—large enough to affect the deformational properties of rock. An alternative is shown schematically in figure 9*b*. Studies of planetary evolution often plot the time evolution of mean system outputs (e.g. average internal temperature, average lithosphere thickness). Care should be taken not to over-interpret such plots as being fully representative of planetary evolution. The chaotic nature of mantle convection will lead to fluctuations around mean trends (e.g. [27,41,123,124]). As with other chaotic systems, statistical properties, from multiple evolution paths, will be predictable but output values of any particular evolution relative to another evolution, at equivalent times, will be unpredictable. The histories of Venus and Earth do not allow for any reasonable statistical inferences to be made. It has been argued that along its evolution path a planet can enter and exit a 'temporal window' that allows for plate tectonics [72]. Collectively, this allows for the potential that two similar planets can diverge in evolution due to the stochastic nature of mantle convection operating against a continually changing background thermal state associated with secular cooling. Early in their lifetimes, the planets would have another stochastic process superimposed on top of chaotic convection: impacts (e.g. [125–128]). Stochastic fluctuations are not state parameters in the way the surface temperature of a planet is (the latter is measurable, which provides strong deterministic predictive potential; the former can only be determined in a statistical sense, which provides weak predictive power for an individual evolution or a handful of evolutions). For the question 'Why does Earth have plate tectonics?' this would imply that the answer could include a significant element of chance.

Data accessibility. This article does not contain any additional data.

Competing interests. I declare I have no competing interests.

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