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The generation of plate tectonics from mantle convection

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Abstract

In the last decade, significant progress has been made toward understanding how plate tectonics is generated from mantle dynamics. A primary goal of plate-generation studies has been the development of models that allow the top cold thermal boundary layer of mantle convection, i.e. the lithosphere, to develop broad and strong plate-like segments separated by narrow, weak and rapidly deforming boundaries; ideally, such models also permit significant strike-slip (toroidal) motion, passive ridges (i.e. pulled rather than pried apart), and self-consistent initiation of subduction. A major outcome of work so far is that nearly all aspects of plate generation require lithospheric rheologies and shear-localizing feedback mechanisms that are considerably more exotic than rheologies typically used in simple fluid-dynamical models of mantle flow. The search for plate-generating behavior has taken us through investigations of the effects of shear weakening ('stick-slip') and viscoplastic rheologies, of melting at ridges and low-viscosity asthenospheres, and of grain-size dependent rheologies and damage mechanics. Many such mechanisms, either by themselves or in combination, have led to self-consistent fluid-mechanical models of mantle flow that are remarkably plate-like, which is in itself a major accomplishment. However, many other important problems remain unsolved, such as subduction intiation and asymmetry, temporal evolution of plate geometry, rapid changes in plate motion, and the Archaean initiation of the plate-tectonic mode of convection. This paper presents a brief review of progress made in the plate-generation problem over the last decade, and discusses unresolved issues and future directions of research in this important area.

Keywords: mantle convection; plate tectonics

1. Introduction

All celestial bodies, be they stars or planets, slowly approach thermal death as they come to equilibrium with nearly empty space. While nuclear fusion in stars or radiogenic heating in planets might postpone this fate, it is the very act of equilibration toward final stasis that makes these bodies dynamic now. In particular, because planets cool at their surface, and because most known materials become denser as they get colder (water near freezing being a rare exception), planetary interiors are gravitationally unstable: they are colder and thus denser near their surface than in their interior and thus tend to convect. The oc-

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currence of such convection in the Earth's mantle has been postulated since at least the 1930s [1–3], and one of the primary motivations for its study was to explain Continental Drift, which, after decades of oblivion, was revived and revised as the theory of Plate Tectonics. Plate Tectonics has been hailed as the grand unifying principle of geology, although its success at explaining a multitude of geological and geophysical phenomena has overshadowed the effort to explain the existence of the plates themselves.

Many students of geology are taught how mantle convection drives plate tectonics in much the same way that Arthur Holmes envisioned it 70 years ago, i.e. convective 'wheels' driving the tectonic 'conveyor belt'. Although this picture is appealing in its simplicity, there are several fundamental aspects of it that are misleading at best; in particular, it portrays the plates and convection as separate entities, with convection currents prying open mid-ocean ridges and dragging down subducting slabs. The other limit of plate models disregard convection, referring instead to pre-existing plates moved by forces such as slab pull and ridge push [4,5] that are somehow unrelated to the convective energy source that fuels these forces (although in fact the seminal papers on quantifying plate forces [6] and on models of plate-driven mantle flow [7–9] explicitly identified these forces as convective). In either case, the implicit acceptance of the plates' existence precludes any attempt to explain how the plates are generated and evolve in the first place. The answer to this fundamental question of how plates arise from mantle convection has been the focus of an active yet technically difficult field of research, but which has neverthless made significant progress in the last decade. The purpose of this review is to first briefly explain why generating plates is such a problem, and then to survey some of the various directions and progress made in trying to generate them from mantle dynamics theory.

2. The plates are convection

A fair question to ask is, if plate tectonics is so difficult to generate from convection, then might it in fact have nothing to do with convection [5]? We certainly know that plates cool as they move since they have measurable amounts of heat flowing from them, and they thicken and grow heavier in the direction of motion, causing subsidence of sea floor away from spreading centers [10,11]. Plates generally subduct when they are heavy enough to completely founder, although initiation of subduction of a cold strong plate (even if heavy) is a serious problem that we will discuss later. Nevertheless, the entire process of a plate cooling and sinking as a subducting slab rather exactly describes convective motion, in particular the evolution and fate of the convective top thermal boundary layer, which is the layer over which occurs most of the temperature change between the cold surface and the convectively well mixed hotter interior of a fluid. This process of thermal boundary layers sinking as cold slab- or sheet-like currents is commonly (although certainly not universally) observed in laboratory experiments and numerical simulations of three-dimensional convection (Fig. 1). My description of the plate leading to a slab is, however, somewhat backward since it is the sinking slab that pulls the plate. Perhaps no better evidence of this exists than the correlation between plate velocity and the fraction of plate boundary that is subduction zone [6], as shown in Fig. 2. In particular, all the relatively fast-moving, or 'active' plates (with velocities of order 10 cm/yr, e.g. the Pacific plate) are connected in a very significant way to subducting slabs, while the slower or 'passive' plates (with velocities of order 1 cm/yr, e.g. the African plate) have effectively no connected slab. That a cold sinking slab has the necessary force to pull a plate at the typically observed plate velocities is easily demonstrated [12–14]. Indeed, the mantle convective velocities predicted nearly 70 years ago by Pekeris [2] and Hales [3] were quite close to typical plate velocities measured 30 years later. Global heat flow can also be used to predict slab and plate velocities, thus demonstrating that slabs are an integral part of convective heat transport. At a few hundred kilometers depth beneath the lithosphere, mantle heat loss is primarily due to the downward injection of cold material by subducting slabs (analagous to dropping ice-cubes in

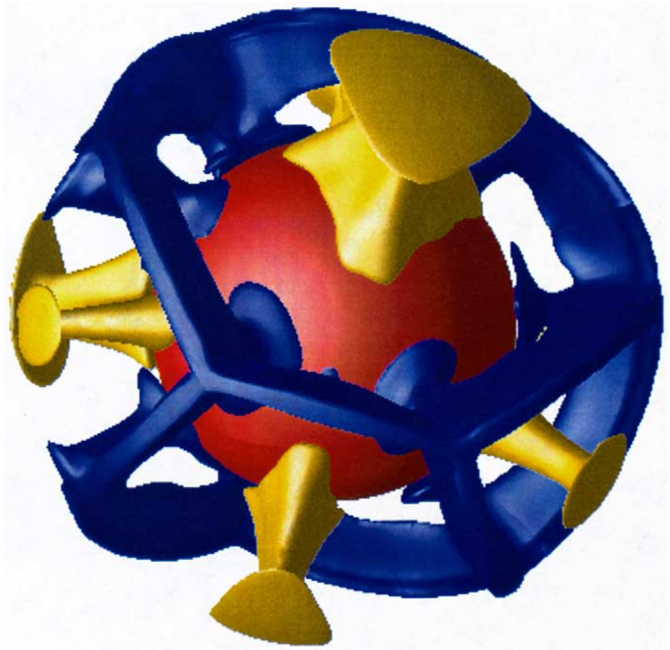

Fig. 1. A simple example of a three-dimensional simulation of mantle convection accounting for the spherical-shell geometry of the mantle. The red sphere represents the core, and yellow mushroom-shaped structures are hot upwelling plumes. The blue structures represent cold downwellings which, near the surface, are linear and sheet-like, crudely similar to the planar structure of subducting slabs on Earth. Many dissimilarities with Earth remain, however. Since this simulation is driven by heating from the core and cooling from the surface, the upwellings and downwellings are of similar intensity. In the Earth, most heating is thought to come from radiogenic sources distributed in the mantle, which causes stronger downwelling sheets (which must cool the heated mantle) and relatively weaker upwelling plumes. Moreover, the downwelling sheets in the simulation are symmetric across their width; i.e. unlike on the Earth, material enters the downwelling from both sides, and the sinking currents point straight down instead of at an angle. After Zhong et al. [84].

hot water). The energy-flux balance would thus require that $fQ = wA\rho c_p \Delta T$, where $Q \approx 30$ TW is the net heat output through the top of the mantle [15], $f = 0.9$ is the fraction of Q accounted for by slab cooling (since the remaining heat transport by mantle plumes accounts for less than 10% of the net heat flux [16–18]), $\rho \approx 3000$ kg/m^3 is slab density, $c_p = 1000$ J/kg/K is heat capacity, $\Delta T \approx 700$ K is the average slab thermal anomaly [12], and w is a typical vertical velocity of a slab. Lastly, $A \approx 2\pi R\delta$ is the total horizontal cross-sectional area of all slabs crossing this particular depth, where $\delta \approx 100$ km is a typical slab thickness, and the horizontal length of all slabs is estimated by the circumference of the Earth, since most slabs occur in a nearly large circle around the Pacific basin and thus $R \approx 6000$ km. Using these numbers we can solve for slab velocity $w = fQ/(\rho c_p \Delta T \delta 2\pi R) \approx 10$ cm/yr, which is precisely the typical velocity for fast, active plates. In the end, that 'active' plates cool, thicken, subside and eventually sink as subducting slabs that cool the mantle is tantamount to saying they are convective currents, and that, in effect, plate tectonics is the surface expression of mantle convection.

3. The plate-generation problem

The simple picture of subducting slabs as convective currents works quite well at explaining the driving force for past and present plates [14]. However, beyond that the picture of plates as convection gets complicated. In many ways, plates are not well described by simple fluid-dynamical convection theory. Indeed, the mathematical

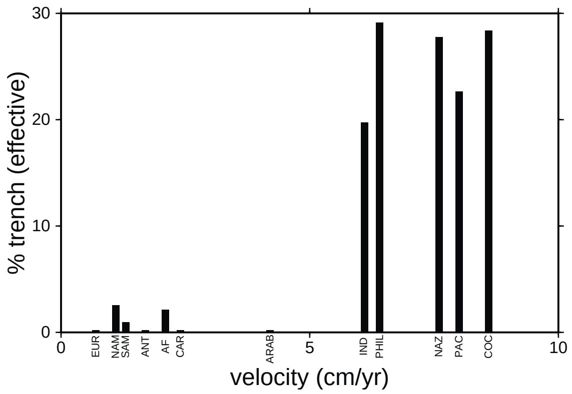

Fig. 2. Percent of plate boundary that is trench or subduction zone versus plate velocity for each plate. (Acronyms are as follows: EUR is the Eurasian plate, NAM is the North American plate, SAM is the South American plate, ANT is the Antarctic plate, AF is the African plate, CAR is the Carribean plate, ARAB is the Arabian plate, IND is the Indo-Australian plate, PHIL is the Philippine plate, NAZ is the Nazca plate, PAC is the Pacific plate, and COC is the Cocos plate.) The effective trench length corrects for subduction zones whose associated slab-pull forces presumably cancel. After Forsyth and Uyeda [6].

theory of plate tectonics [19] works as well as it does because the plates appear to be fairly solid bodies and their motion can be treated with simple rigid-body dynamics. This assumes that all the deformation in the lithosphere primarily occurs between the plates at narrow boundaries. In recent years this model has been found to fail in certain instances [20], requiring either the subdivision of plates into yet smaller plates, or the introduction of diffuse plate boundaries. Nevertheless, the plates are to a large extent rigid, which from a fluid-dynamical perspective is enigmatic since simple viscous fluids have continuous deformation and, by definition, do not act like rigid bodies. Thus, if convective flow, with obviously more complex fluid behavior, were to appear plate-like in the top thermal boundary layer, then it would need much of the horizontal surface motion to occur in nearly rigid blocks, while all the deformation would take place in narrow zones (Fig. 3); this feature is generally referred to as 'plateness' [21]. However, contrary to what the term suggests, 'plateness' is not a unique measure of how plate-like a flow really is since it says little about the unique nature of each type of plate boundary, which we discuss forthwith.

3.1. Strike-slip zones

The type of plate boundary that is perhaps most enigmatic from the perspective of convection theory is the strike-slip or transform boundary. The motion at this boundary is referred to by the convection community as 'toroidal' flow, and it involves *vertical vorticity*, i.e. any type of rotation about a vertical axis including strike-slip shear and plate spin (Fig. 4). The strength of toroidal flow is measured relative to the 'poloidal' flow field, which involves convective-type vertical circulation leading to divergent and convergent zones at the surface (Fig. 4). In the Earth, toroidal motion is a significant part of the surface velocity field [22,23], although whether it is on par with the poloidal field depends on how much significance one places in the hotspot frame of reference, given that much of the toroidal energy is contained in the net rotation of the lithosphere [24]. The toroidal field has no direct energy source, i.e. since its motion is purely horizontal, it neither directly draws from nor facilitates the release of gravitational potential energy (which only directly fuels and is released by vertical motion – or poloidal flow) and thus heat. For this reason, toroidal motion is often referred to as the non-convective component of flow. What role toroidal motion serves is therefore not immediately obvious and thus warrants (and has received) considerable attention.

3.2. Subduction zones

As discussed above, convergent plate boundaries, or subduction zones, are, if anything, the quintessential mark of mantle convection since these are where cold, heavy plates sink into the mantle. However, subduction zones are really only crudely predicted by simple convection theory, and there is much to them that is highly atypical of convection. First, if one were to only consider the strength of cold super-viscous lithosphere, one would not expect to see subduction zones at all. Convection with purely temperature-

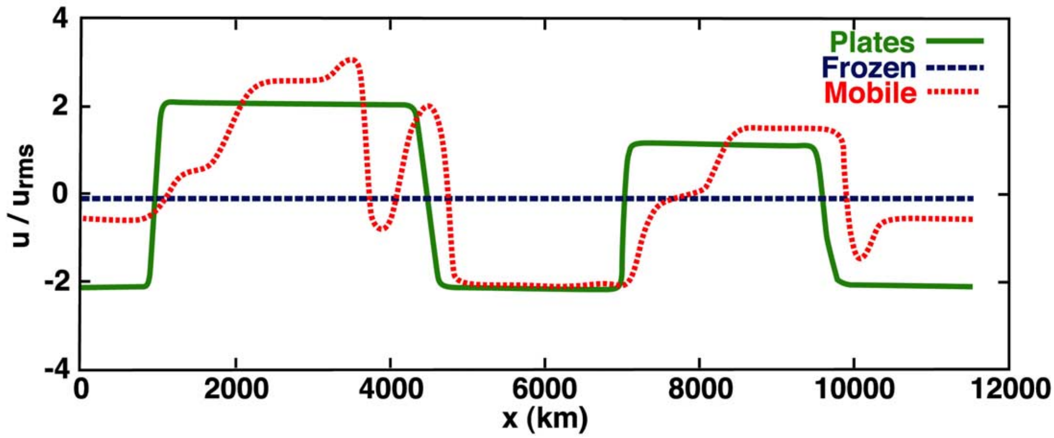

Fig. 3. Surface velocity above two-dimensional simulations of convection with a variable-viscosity top boundary. A mobile top boundary occurs when the fluid is entirely or nearly isoviscous such that the top thermal boundary layer acts viscously and deforms continuously and smoothly. The 'frozen' top boundary occurs when the fluid viscosity is strongly temperature-dependent and the cold top boundary layer becomes stiff and immobile. The plate-like top boundary occurs when the fluid has a strongly non-Newtonian or plastic rheology; here, the surface velocity is composed of nearly block-like structures of almost constant velocity, separated by narrow zones of intense deformation. The mobile boundary is defined to have 'plateness' near zero, while the plate-like one has 'plateness' near unity [21]. Figure after Richards et al. [43].

dependent viscosity typical of the Earth's tends to form a cold, hard, and immobile layer on the top, and all convective motion occurs beneath it, as if it were a rigid lid [25,26]. Indeed, Earth seems particularly anomalous since it appears to be the only terrestrial planet with prominent subduction zones. Thus, subduction initiation presents a formidable problem to convection models. Second, in most forms of thermal convection, both surface boundary layers converging on a sheet-like downwelling will descend (see Fig. 1), while this occurs nowhere at any terrestrial subduction zone; i.e. all subduction is one-sided, with only one plate descending into the mantle. This asymmetric downwelling is yet another major enigma not yet well explained in convection theory.

3.3. Spreading centers

Finally, spreading boundaries or mid-ocean ridges and continental rift zones are in some ways not atypical of convection since they represent divergent flow above convective upwellings. However, it is very unlikely that deep mantle upwellings are driving this motion; it is far more probable that plate divergence is drawing up the mantle such that the upwelling is shallow and 'passive' (i.e. not moving under its own buoyancy). The clearest evidence for this is the weak gravity anomalies associated with ridges, which strongly indicates that ridge topography is isostatically supported by a shallow buoyant root, not a deep, hot upwelling root. Recent extensive seismic and marine-geophysical surveys of the East Pacific Rise confirm the idea that ridges involve only shallow passive upwellings [27]. Ridges are therefore drawing up mantle rather than being pried apart by convective upwellings, and thus the Earth's regions of focused spreading activity are in fact atypical of convection.

4. The physics of plate generation

To a large extent, the plateness of the lithosphere and the various plate-boundary enigmas mean that the lithosphere is not obeying simple fluid dynamics, which is indeed rather self-evident. However, the nature of the complicated physics that leads to plates and plate boundaries is both the key and the mystery of how plates are generated.

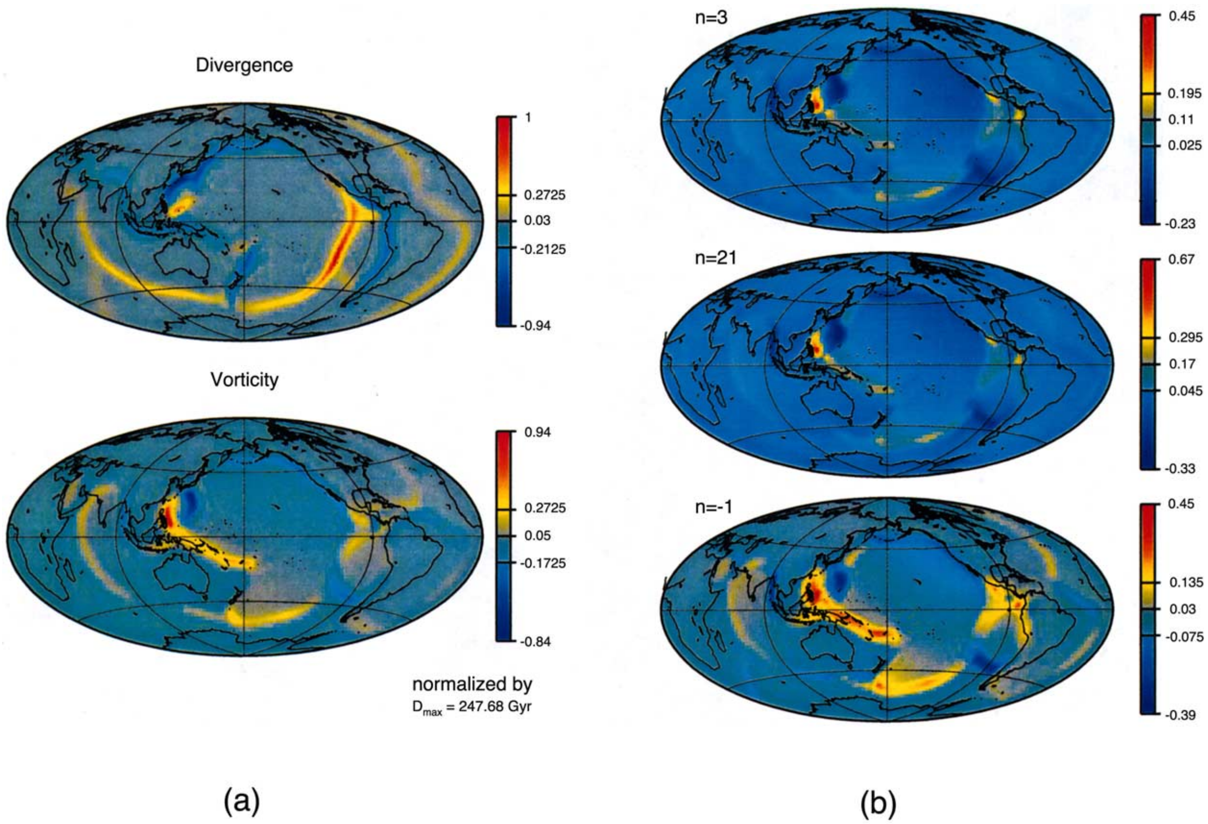

Fig. 4. Divergence rate and vertical vorticity (rate of spin and strike-slipe shear) of present-day plate motions (a), representing poloidal and toroidal motion, respectively. Red and yellow divergence is positive over spreading centers and blue is negative, or convergent, over subduction zones. Red and yellow vorticity represents left-lateral strike-slip motion and counter-clockwise spin, while blue is right-lateral motion and clockwise spin. Fluid-dynamic calculations use the Earth's divergence as a source–sink field to drive flow in various non-Newtonian shallow-layer model lithospheres, thereby generating toroidal motion which is shown in terms of vorticity (b). Power-law rheologies with indices $n=3$ and even as high as $n=21$ (where stress goes as strain rate to the $1/n$ power) generate vorticity fields that do not compare well with the Earth's vorticity field. A self-lubricating or pseudo-stick-slip rheology, represented by $n=-1$, however, generates vorticity that compares well with the Earth's present-day case. After Bercovici [37].

4.1. Does the lithosphere just shatter?

If the Earth's lithosphere behaves like so many discrete blocks, then it is fair to ask whether it does not simply break brittly under the various convective stresses, leaving plates as the remaining shattered pieces. Unfortunately, such simple brittle behavior only applies across the top few kilometers or so (up to about 10 km) of lithosphere, which is itself on average about 100 km thick. Towards the base of the lithosphere, deformation is dominated by ductile (i.e. viscous) flow. However, experimental work shows that the transition from brittle to ductile behavior is very broad, involving several tens of kilometers of combined brittle and ductile behavior (Fig. 5; see review by Kohlstedt et al. [28]). The deformation mechanism in the brittle–ductile regime is highly complicated and not well understood (hence, it is represented by a dashed line in Fig. 5) and is therefore a vital area of future research (as discussed below with regard to 'damage' theories). Nevertheless, the rheology in this large portion of the lithosphere is certainly markedly different from simple brittle (as well as viscous/ductile) behavior and thus the assumption that the litho-

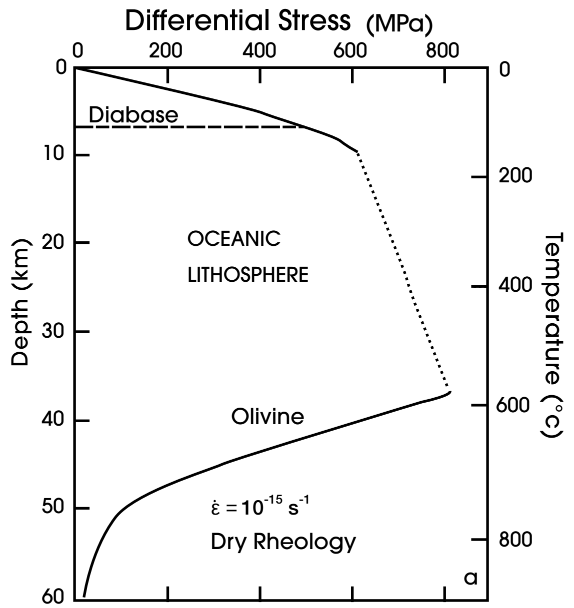

Fig. 5. Strength of oceanic lithosphere (in terms of differential stress necessary to cause failure) versus depth and temperature for a model lithosphere of approximately 60 Myr age. The top straight segment represents brittle failure; the central dashed segment is combined brittle–ductile behavior (the strength values of which are not well constrained, hence the dashed line should not be interpreted literally), and the lower curved segment represents the transition to fully ductile behavior (with no strength). After Kohlstedt et al. [28].

sphere merely shatters across its entire depth is essentially incorrect.

Although simple brittle behavior across the entire lithosphere is unlikely, pervasive cracking and ductile-cracking may leave faults and weak zones that are later reactivated to make 'new' plate boundaries [29]. This assumption is at the heart of models of mantle flow with prescribed lithospheric faults [30–33] which have been used to study deformation inside a plate (between the imposed faults), how faults guide fluid motion, and how plate-like motion influences observables such as geoid and topography over, say, subduction zones. One drawback of this approach is that it must prescribe a fault instead of letting it arise and evolve from the physics of the system; thus, for example, it cannot account for how a fault or weak zone is formed in lithosphere that is newly created at ridges. Nevertheless, these studies have clearly demonstrated that without low-friction, fault-like concentrations of deformation, called 'shear localizations', simple fluid behavior cannot generate plate-like motion [33].

4.2. Simple non-Newtonian behavior

What, therefore, is the simplest rheology one might use to allow plate-like behavior to self-generate? As discussed above, the quality of 'plateness' is defined by a lithosphere that moves horizontally in the form of nearly rigid blocks separated by narrow zones of concentrated deformation ('shear localizations') which are necessarily much weaker than the more block-like areas of fluid (otherwise they could not accommodate their relatively rapid deformation). Variations in strength, or viscosity, with deformation (strong where block-like, weak where deforming) indicate that the first ingredient of a plate-like flow is that the convecting fluid have a non-Newtonian rheology, which means that viscosity reduces with increased deformation rate, or strain-rate (Fig. 6). Non-Newtonian rheology is also required for strike-slip or toroidal motion; however, proof of this condition is somewhat technical and beyond the scope of this paper (see Bercovici et al. [13] for discussion).

In fact, much of the mantle naturally deforms by dislocation creep [34], which entails a non-Newtonian power-law rheology wherein strain rate is proportional to stress to the power $n>1$ (Fig. 6), and hence the effective viscosity (stress divided by strain rate) decreases with increased strain rate. However, numerical studies of mantle flow with such a rheology consistently show that it generates rather poor plate-like properties even for $n \gg 1$ [35,11,36–39] (see Fig. 4).

4.3. Exotic non-Newtonian behavior

Throughout the 1990s, a school of thought arose which argued that since the simple power-law non-Newtonian rheology proved inadequate at generating plate-like motion, and since it was likely that mechanisms other than simple dislocation creep contributed to lithospheric deformation (e.g. frictional heating, hydration, etc.), then a more exotic rheological behavior with more ex-

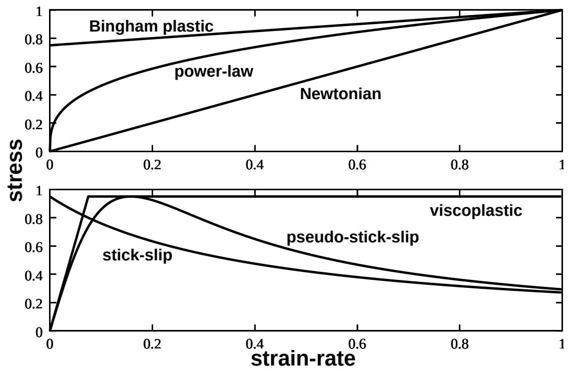

Fig. 6. The stress versus strain-rate curves for various rheologies. A Newtonian rheology is represented by a linear constitutive relation between stress and strain rate. A non-Newtonian power-law rheology has a non-linear constitutive relation in which strain rate goes as stress to some power $n>1$ (the curve shows the case for $n=3$ which is typical of deep mantle silicates). Both Bingham plastic and viscoplastic rheologies describe discontinuous stress – strain-rate relations whereby, at a particular yield stress, an abrupt transition in flow behavior occurs from strong (immobile or highly viscous) to weak (viscous or with only a maximum strength or allowable stress). Stick-slip and pseudo-stick-slip behavior make transitions at a peak stress from strong (immobile or highly viscous) to one where strength (i.e. the allowable stress or resistance to deformation) is lost with faster deformation.

treme softening behavior was both required and expected to generate plate-like behavior [36–39]. One such rheological mechanism is called pseudo-stick-slip (also referred to as self-lubrication or self-weakening) [36] wherein, unlike a power-law rheology, both viscosity and stress, and thus the very resistance to motion, decrease with increased strain rate (Fig. 6). When this pseudo-stick-slip rheology was used in simple models of lithospheric deformation, it generated highly plate-like behavior, in particular strong plate-like strength distributions as well as significant and focused strike-slip (toroidal) motion [36–38], at least relative to similar cases with a simple power-law rheology (Fig. 4).

The pseudo-stick-slip rheology, however, has proven difficult to implement in mantle convection simulations. Convection studies have been, in general, more successful using a simple visco-plastic lithosphere overlying a viscous convecting mantle [40–43]. The viscoplastic rheology dictates that at low strain rates material deforms like a very stiff, viscous fluid, but at a given stress (a 'yield stress'), the resistance to motion stops increasing with strain rate and remains constant (Fig. 6). However, these models produce only moderate plate-like behavior [41,42], unless used in conjunction with an imposed low-viscosity asthenospheric channel [44,43] or viscosity reduction due to melting in near-surface mantle upwellings [44] (Fig. 7). Although these viscoplastic models still have difficulty generating isolated strike-slip (toroidal) zones, as occurs along the San Andreas system, the inclusion of melting leads to very localized spreading centers with shallow passive upwelling (Fig. 7).

One fundamental question that the continuum approach to plate generation has been able to address concerns the role of strike-slip or toroidal motion. Given that toroidal motion does not facilitate heat flow (or gravitational potential energy release), and is purely dissipative, it is unclear what its purpose is in the overall convective system. However, continuum models show that the low-viscosity strike-slip regions associated with toroidal motion act as lubricated tracks and thus enhance the efficiency of convection by reducing the overall dissipation in the system [33,45].

In total, the first forays into generating plates with fluid dynamics and exotic non-Newtonian rheologies showed that one can generate plates and plate boundaries from continuum physics, and therefore it is possible to allow the plates to arise or self-organize naturally from the convecting system, instead of having the plates imposed a priori on the convecting model. However, to some extent, the search for rheological mechanisms that yield plate-like behavior has been driven more by what works than by what is the actual physics leading to such behavior. Plastic and pseudo-stick-slip/self-weakening rheologies are not entirely relevant to lithospheric deformation (e.g. the lithosphere is not truly plastic, but such a law is a simplified parameterization of failure and weakening), or they are largely ad hoc. Moreover, the non-Newtonian-rheology approach has assumed plate boundaries form as the instantaneous response to deformation of the material; ergo, if the deformation ceases, the weak plate

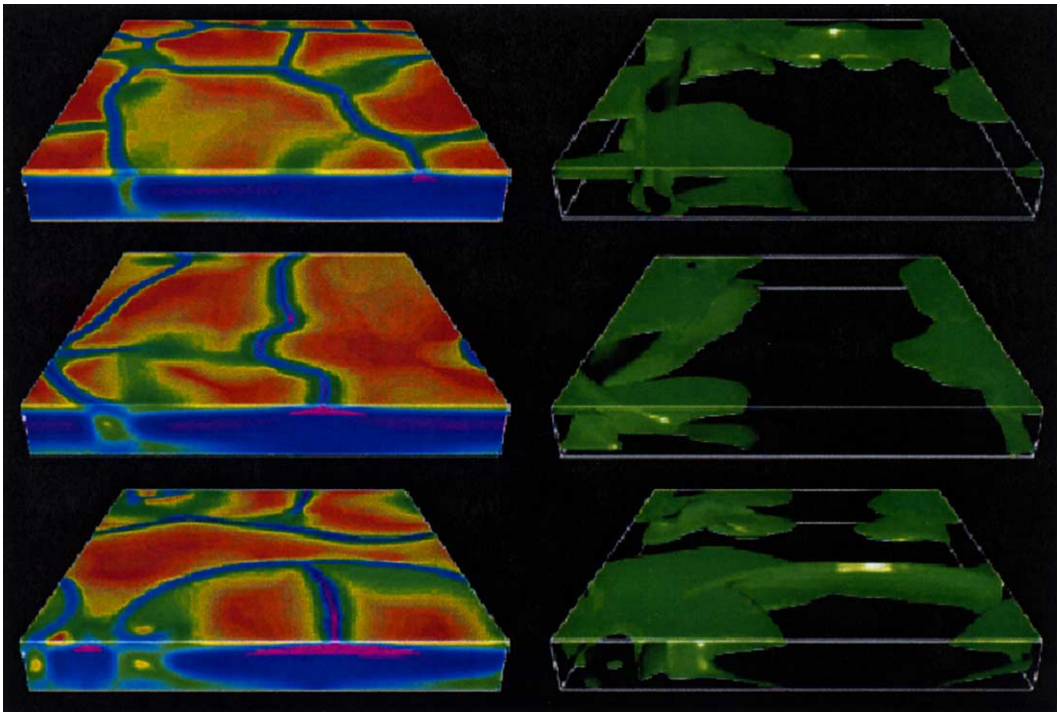

Fig. 7. Three-dimensional simulations of convection with a viscoplastic rheology in the top layer, and including viscosity reduction by melting. Convection is driven primarily by internal heating and thus cold downwellings are the dominant current. The left panels show the viscosity fields, where purple and blue are low viscosity and red and yellow are high viscosity. The right panels show the associated cold isothermal surfaces which outline the downwelling convecting currents that drive motion in the system; therefore any low-viscosity surface region coinciding with a cold isotherm is a convergent zone. The plate-like geometry is apparent in the surface viscosity fields (left panels); in particular the focused spreading centers overlying melt lenses (purple zones) are diverging passively, i.e. they are not associated with any active upwelling rising from deep in the layer. However, strike-slip motion is relatively weak and not isolated, being associated primarily with obliquity and offsets in the spreading centers. After Tackley [44].

boundaries would instantaneously vanish [29]. Given the quantity of inactive plate boundaries on the Earth that are also available for re-activation, this is an obvious failing of the time-independent non-Newtonian-rheology approach. These studies have therefore led to more rigorous investigations of the physics that would permit not only a shear localization leading to formation of plate boundaries, but also rheological weakening that has a long decay time, thereby providing plate longevity as well.

4.4. Shear-localizing feedback mechanisms

The instantaneous stick-slip rheology discussed above arises from the steady-state (time-independent) limit of various shear-localizing or self-weakening mechanisms. These mechanisms, however, are actually time-dependent and thus generate weak zones that have a finite decay time after being made inactive. The most well understood of such mechanisms entails the feedback between the temperature dependence of viscosity and viscous heating. In this case, deformation causes frictional heating, which softens the material; deformation subsequently focuses on the weak zone, which heats further, causing further softening, and so on. However, models of convection and lithospheric motion have never shown this mechanism to be sufficient to generate strong shear-localization or plate-like motion (Fig. 8), except over small length scales [46,47].

The oft-observed reduction in mineral grain size in mylonitic continental shear zones [48,49] also suggests a correlation between shear-localization and grain evolution. One possibly causative mechanism involves the feedback between the dependence of viscosity on grain size and changes in grain size due to deformation [50]. In particular, grain size reduction induces weakening if the medium deforms by diffusion creep (i.e. diffusion of atoms from compressive to tensile regions), although the reduction in grain size by deformation only occurs if the system is in the regime of dislocation creep (deformation through the propagation of dislocations) and undergoes 'dynamic recrystallization' wherein growing dislocations form new grain boundaries. Given the complexity of this feedback mechanism (requiring the effective coexistence of disparate creep regimes), it has been implemented into relatively few geodynamical calculations [51–54] which have yielded only moderate success in obtaining plate-like shear localizations. However, these implementations are possibly too idealized and thus more research on incorporating the grain-size mechanism into geodynamical models is warranted.

As discussed earlier, the large region of the lithosphere that is thought to undergo combined brittle–ductile behavior (Fig. 5) is suggestive of a damage-induced shear localization whereby microcracks forming in zones of ductile deformation focus into weak zones that thereby concentrate deformation and accelerate their own nucleation and growth, in the end creating shear bands that appear like faults. Damage-induced shear localization is also appealing given the various roles it offers for water, which is thought to be a facilitator of plate tectonics, and the cause for plate tectonics on Earth but not the other terrestrial planets [55]. For example, volatiles such as water can either facilitate damage through hydro-fracturing, pore-pressure reduction of friction and simple lubrication of slip zones. The physics of damage, however, is both rich and complicated [56–60]. An idealized but easily implemented damage theory appropriate to mantle-convective time scales produces highly plate-like motion in simple flow models [47] (Fig. 8) and in two-dimensional convection [61,62]. This damage approach has also been combined with visco-plastic behavior in three-dimensional convection calculations, but this promotes too much damage, causing plate-like regions to go unstable and disintegrate into smaller regions [44]. However, since the idealized model loses much of the physics controlling damage and shear localization, a first-principles approach called the 'two-phase damage' theory [63–66] has recently been proposed. In this theory, the energy necessary to create a void or a microcrack [67] is treated as the surface energy on the interface between a host phase (rock) and the void-filling phase (e.g. water). Deformational work is stored as this interfacial energy by generating more voids, thus inducing weak zones on which deformation localizes. Preliminary calculations show that this mechanism can lead to a spectrum of shear-localizing behavior, from more diffuse to very sharp or intense shear zones (Fig. 9), in addition to broadly distributed damage when the entire system essentially shatters [65,66].

5. How far have we come?

Twenty years ago the relation between plate tectonics and mantle convection was called the 'plate–mantle coupling' problem, referring to the influence of plate geometry on mantle flow, and the subsequent influence of mantle flow on rigid plate motion. In the last decade, the problem has largely changed to the 'plate-generation problem'; it has become more of a holistic one, i.e. not how the plates and mantle, treated as two separate systems, interact, but how the plates arise self-consistently as an integral part of mantle convection. While philosophically this question has existed since at least the early 1980s [68], it has only been approached with some success in the last decade, in particular with the demonstration of rather plate-like motion with fluid-mechanical theories and models. With these models we have seen not only plate-like strength distributions (strong plates separated by weak boundaries) but also the generation of focused, plate-like strike-slip margins as well as the formation of passive rifts, both of which were considered some of the greatest enigmas from the standpoint of convection theory. This demonstration came

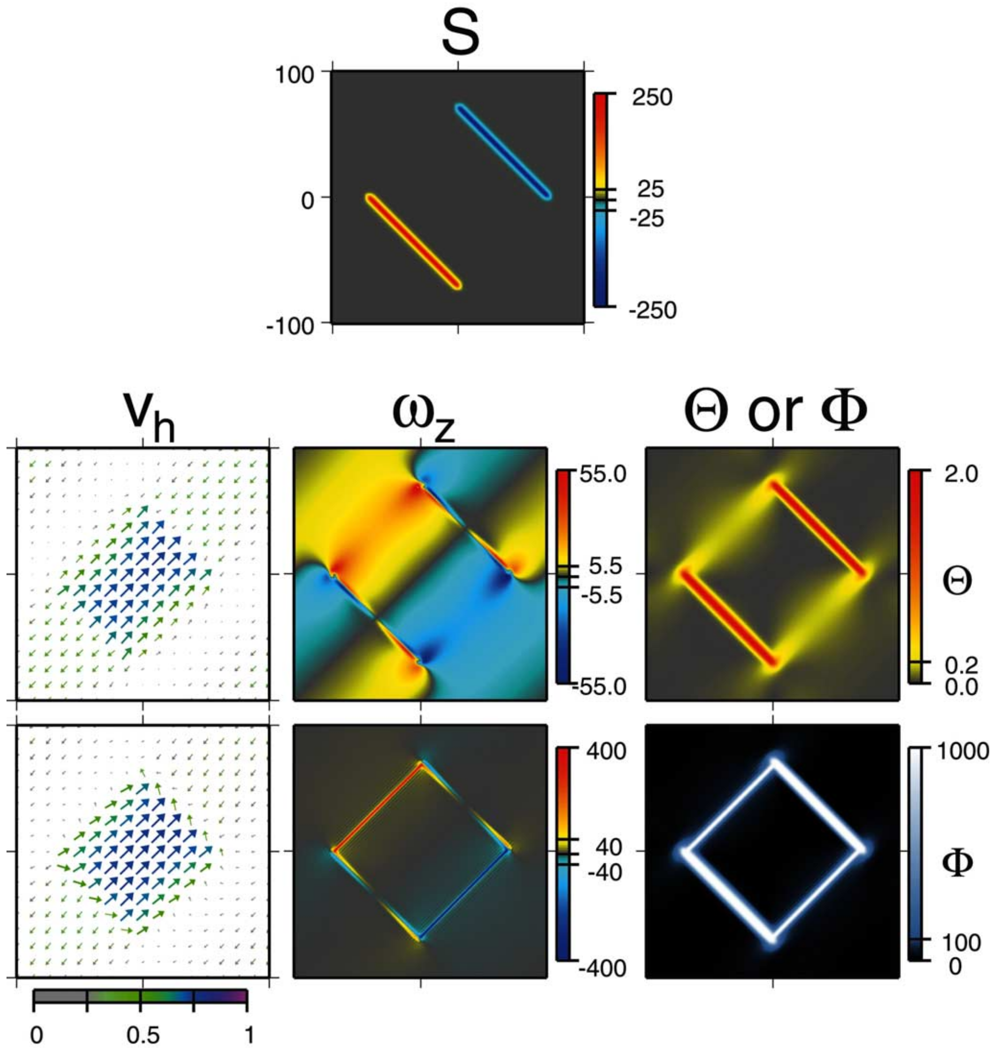

Fig. 8. A simple source–sink flow model illustrating two different shear-localization mechanisms, i.e. (1) temperature-dependent viscosity and shear heating, and (2) void-volatile weakening (simple damage). The top frame, labeled S, shows the source–sink field used to drive horizontal flow in a two-dimensional shallow layer; yellow and red represent the source and blue the sink. The three underlying columns are horizontal velocity v_h, vertical vorticity or rate of strike-slip shear ω_z, and the scalar field that determines weakening, either temperature Θ or void/volatile volume fraction Φ. Without any variable viscosity, the velocity field v_h would look more or less like a dipole field, and there would be no vertical vorticity ω_z. With variable viscosity, the velocity field looks more plate-like and there is significant vorticity, or toroidal motion, generated. The first row of the six lower frames corresponds to the case with temperature-dependent viscosity and shear heating. Softening due to shear heating generates weak zones of strike-slip shear that connect the ends of the source and sink. Although the velocity superficially appears plate-like, in fact significant deformation of the plate-like region is occurring, as depicted in the diffuse zones of vorticity. The temperature field Θ also shows only a weak hot anomaly over the strike-slip zones, and thus a viscosity distribution that is not very plate-like either. With weakening due to creation of voids by damage (bottom row), the velocity field is very plate-like and the vorticity field is similar to what one expects for discontinuous strike-slip faults, i.e. very narrow, intense zones of deformation. The void/volume fraction Φ is also very high over the strike-slip zones, yielding a contiguous weak boundary surrounding a uniformly strong plate-like area. After Bercovici [47].

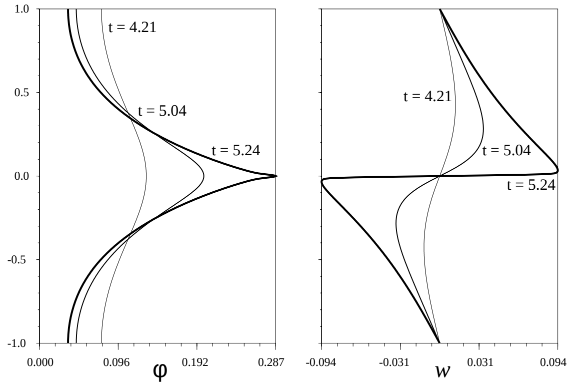

Fig. 9. Simple one-dimensional shear-flow calculation demonstrating the two-phase damage theory. Damage occurs as a result of deformational work creating surface energy on void walls (here treated as the interface between two phases, e.g. rock and water); shear localization occurs because the voids cause weak zones on which deformation and further damage concentrates, leading to more voids, etc. The result here is for an infinitely long layer subjected to simple shear by an imposed shear stress (say, by a top boundary at $y = 1$ moving right and the bottom boundary at $y = -1$ moving left). The left panel shows the distribution of void volume density or porosity ϕ across the layer (in the y direction) which indicates the location of the generated weak zone at $y = 0$. The right panel shows the velocity w in the y direction of the matrix (rock) phase; upward motion ($w > 0$) above and downward motion ($w < 0$) below the centerline $y = 0$ indicates the matrix is dilating. The different curves show different times (as indicated) in the calculation. The porosity ϕ evolves to a sharp cusp-like distribution, indicating development of a nearly singular (fault-like) weak zone, and the cross-layer velocity w becomes nearly discontinuous at $y = 0$, indicating fault-like dilation. After Bercovici and Ricard [66].

about by both a complete reconsideration of the physics necessary to generate plate-like motion, along with great increases in computational power and skill. Although we have far to go in fully understanding the mechanisms for generating plate tectonics, progress has been profound; perhaps no better testament to this is the recent development of three-dimensional convection models – most notably those of Paul Tackley from UCLA – that yield highly plate-like motion [41,39,42,44,69,43] as depicted in Fig. 7.

6. And where might we go next?

Aside from progress made on understanding strike-slip margins and passive divergent zones, much remains for understanding what is arguably the most important of boundaries, i.e. subduction zones. Both the initiation of subduction and the asymmetry or one-sidedness of subduction remain open first-order questions. Initiation might require some sort of mechanism to weaken thick cold lithosphere, such as a rifting event [70,71] or sediment loading combined with both hydrolitic and thermal softening [72]. Alternatively, subduction zones perhaps never initiated out of pristine lithosphere but always took advantage of existing weak zones that were more readily formed and accumulated through time [29,73]; the possibility of their initiating at pre-existing transform faults [29] lends extra significance to the problem of understanding how strike-slip boundaries are generated. Although one-sided subduction has been hinted at in convection calculations with self-weakening rheologies [44], a robust cause for this asymmetry has yet to be identified [74]. The presence of buoyant continents and/or thick continental lithosphere might be required, although it is doubtful that the asymmetry is merely due to continental mass plugging up one side of the downwelling region, since it should in theory plug up the entire downwelling (e.g. as possibly occurred in the Himalayan collision zone), and this hypothesis does little to explain oceanic subduction zones. It may very well be that melting (and/or hydration) and subsequent viscosity reduction in the mantle wedge (the acute corner of mantle above the slab) plays an important role in causing the downwelling asymmetry, as well as subduction dynamics in general [75,76].

For the last decade, the 'plate-generation' community has focussed largely on explaining how and why convection looks plate-like at present. Yet little has been done to address another important feature of plate tectonics, i.e. plate evolution and rapid plate-motion changes. The plate-tectonic record is filled with apparent plate-reorganization events, and the ultimate plate itself, the Pacific plate (which dominates the present-day plate configuration in terms of its speed, size and quantity of subduction zones), barely existed 200 Myr ago, equivalent to only one convective overturn. Plate motion changes are typically assumed too rapid to be caused by convection [77] and are often assumed to result from relatively rapid evolution of plate boundaries (e.g. due to release of elastic energy [78]) or sudden changes in boundary forces (e.g. when a buoyant continental mass reaches a subduction zone); recent work, however, has suggested that hot mantle accumulating beneath plates can be swept toward and annihilate downwellings, leading to a relatively rapid adjustment in plate driving forces [79,80]. Lastly, the ultimate temporal plate-generation problem concerns the origin of the first protoplates. At what stage in the evolution of the Earth did plate-like motion begin to occur [81]? In particular, did the likely higher temperatures, and extra melting and production of buoyant crust inhibit motion of the surface [82,83]? Did an ancient subducton zone form in hot, soft lithosphere and induce a weak region around which other weak zones nucleated? Or did the first accumulation of crust into proto-continents give rise to lithospheric thickening and thus the first kernel of a plate interior around which boundaries formed through strain localization? While it will probably take understanding the physics of plate-generation and plate-boundary evolution to approach many of these temporal issues, it should not be forgotten that they remain immensely important first-order questions for understanding the origin of plate tectonics.

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