Plate Tectonics as a Far- From- Equilibrium Self-Organized System

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Word Count: 3,563

May 8, 2001

Abstract

Contained fluids heated from below spontaneously organize into convection cells when sufficiently far from conductive equilibrium. Fluids can also be organized by surface tension and other forces at the top. Plate tectonics was once regarded as passive motion of plates on top of mantle convection cells but it now appears that continents and plate tectonics organize the flow in the mantle. The flow is driven by instability of the cold surface layer and near-surface lateral temperature gradients. Plate tectonics may be a self-driven far-from-equilibrium system that organizes itself by dissipation in and between the plates. In this case the mantle is a passive provider of energy and material. The effect of pressure suppresses the role of the lower thermal boundary layer. I suggest that the state of stress in the lithosphere defines the plates, plate boundaries and locations of midplate volcanism, and that fluctuations in stress are responsible for global plate reorganizations and evolution of volcanic chains.

Introduction

The first order questions of mantle dynamics include;

1. Why does Earth have plate tectonics?
2. What controls the onset of plate tectonics, the number, shape and sizes of the plates, the locations of plate boundaries and the onset of plate reorganization?
3. What is the organizing principle for plate tectonics; is it driven or organized from the top or by the mantle? What, if anything, is *minimized*?

In 1900 Henri Bénard heated whale oil in a pan and noted a system of hexagonal convection cells (1). Lord Rayleigh analyzed this in terms of the instability of a fluid heated from below (2). Since that time Rayleigh-Bénard convection has been taken as the classic example of thermal convection, and the hexagonal planform has been considered to be typical of convective patterns at the onset of thermal convection. It was not until 1958 that Pearson (3) showed that Bénard's patterns were actually driven from above, by surface tension, not from below by an unstable thermal boundary layer. Later experiments showed the same style of convection when the fluid was heated from above, cooled from below or when performed in the absence of gravity (4,5). This confirmed the top-down surface driven nature of the convection which is now called Marangoni or Bénard-Marangoni convection (5). It is controlled by a dimensionless number, Ma;

$$Ma = \sigma\ \Delta TD/\rho\upsilon\kappa$$

where σ is the temperature derivative of the surface tension, S, ΔT is the temperature difference, D is the layer depth, and ρ, υ and κ are the density, kinematic viscosity and thermal diffusivity of the layer (4,5). Fluid is drawn up at warm regions of the surface and flows toward cell boundaries where it returns to the interior. Cell sizes in both Marangoni and Rayleigh convection are of the order of the fluid depth at the onset of convection.

Surface tension forces replaces thermal buoyancy, $g\alpha\Delta T$, which appears in the Rayleigh number;

$$\mathcal{R}a = g\ \alpha\ \Delta T\ D^3 / \upsilon\kappa$$

where g and α are acceleration due to gravity and thermal expansivity. Systems with large $\mathcal{M}a$ or $\mathcal{R}a$ are far from conductive equilibrium.

In a fluid cooled from above, even without surface tension, the cold surface layer becomes unstable and drives convection in the underlying fluid when the local Rayleigh number of the thermal boundary layer (TBL) exceeds a critical value, $\mathcal{R}a_{cr,}$

$$\mathcal{R}a_{cr} = g\ \alpha_\ell \Theta \delta^3 / \upsilon_\ell\ \kappa_\ell$$

where Θ is the temperature increase across the thermal boundary layer of thickness δ and the subscripts refer to properties of the boundary layer. Like Marangoni convection, this type of convection is driven from the top. Cold downwelling plumes are the only active elements; the upwellings are passive, reflecting mass balance rather than thermal instabilities(6-8).

Plate tectonics, to a large extent, is driven by the unstable surface thermal boundary layer and therefore resembles convection in fluids which are cooled from above. A similar analysis can be done for the lower TBL of a fluid heated from below. Pressure decreases α and increases υ and κ so it is hard to generate buoyancy or vigorous small-scale convection (high $\mathcal{R}a$) at the base of the mantle (9). In addition, heat flow across the CMB is about an order of magnitude less than at the surface so it takes a long time to build up buoyancy. In contrast to the upper TBL (frequent ejections of narrow dense plumes), the lower TBL is sluggish and does not play an active role in mantle convection (10). Core-mantle boundary (CMB) upwellings are thousands of kilometers in extent (9,11) and embedded in high-viscosity mantle.

There are additional surface effects. Lithospheric architecture and slabs set up lateral temperature gradients that drive small-scale convection (11,14). For example, a newly opening ocean basin juxtaposes cold cratonic temperatures of about 1000˚C at 100km depth with asthenospheric temperatures of about 1400˚C. This lateral temperature difference, Θ, sets up convection, the vigor of which is characterized by the Elder number,

$$\mathcal{E}\ell = g\, \alpha\, \Theta\, L^3 / \kappa\, \upsilon$$

where L is a characteristic horizontal dimension, e.g. the width of a rift or an ocean basin and υ is now the viscosity of the asthenosphere. Convective flows driven by this mechanism can reach 15 cm/yr. (15) and can explain volcanism at the margins of continents and cratons, at oceanic and continental rifts, and along fracture zones and transform faults (16-18). Shallow upwellings by this mechanism are intrinsically 3D or plume-like (15) and can create such features as Iceland and Bermuda (14,17).

Self-organization

A closed or isolated system at equilibrium returns to equilibrium if perturbed. A far-from-equilibrium dissipative system, provided with a steady source of energy or matter from the outside world, can organize itself via its own dissipation. It is sensitive to small internal fluctuations and prone to massive reorganization (19,20). The fluid in a pot heated on a stove evolves rapidly through a series of transitions with complex pattern formation even if the heating is spatially uniform and slowly varying in time. The stove is the outside source of energy and the fluid provides the buoyancy and the dissipation (viscosity). Far-from-equilibrium self-organization and reorganization require; an open system, a large steady outside source of matter or energy, non-linear interconnectedness of system components, dissipation and a mechanism for exporting entropy products (19). Under these conditions the system responds as a whole, and in such a way as to minimize entropy production (dissipation). Certain fluctuations are amplified and stabilized by exchange of energy with the outside world. Structures appear which have different time and spatial scales than the energy input (20).

Plate tectonics is driven by negative buoyancy of the outer shell and is resisted by dissipation forces in the lithosphere (e.g. bending, deformation, faulting, sliding resistance) and in the mantle (viscosity). If most of the buoyancy and dissipation is provided by the plates and the mantle simply provides heat, gravity, matter and an entropy dump then plate tectonics is a candidate for a self-organized system, in contrast to being organized by mantle convection or heat from the core (plumes). Plate tectonics is certainly a non-linear system and is far from stable mechanical or thermal equilibrium. Global plate reorganizations are recognized in the geological record. Multiple steady non-equilibrium states are possible (21-25).

Dissipative Structures

Patterns formed by instabilities in non-linear far-from-equilibrium open systems are called the *dissipative structures* of the system (19). Transitions can be caused by mechanical, thermal or chemical fluctuations. Thermal instabilities in fluid dynamics result in the onset of convection and transitions from one state to another (e.g. rolls, cells, chaos). However, mechanical forces can also initiate instabilities (e.g. in beams, membranes and thin shells, dike intrusion and the break-up of sea ice). The onset of convection, in an unstable system that is far from conductive equilibrium, at a critical Rayleigh number is the classic example of a self-organized buoyancy driven fluid dynamic system (19) although we now know that the original Bénard patterns were organized by surface tension. Dissipative structures maintain themselves in a *stationary* state but they may evolve, slowly or rapidly.

Mantle Dynamics

The history of ideas regarding mantle convection parallels the development of ideas in fluid dynamics. Although the role of the surface boundary layer and "slab-pull" is now well understood and generally accepted as the prime-mover in plate tectonics there is a widespread perception that active hot upwellings from deep in the interior of the planet are responsible for "extraordinary" events such as plate reorganization, continental break-up, extensive magmatism and events far away from plate boundaries (26-29). Plate tectonics is considered to be an incomplete theory of mantle dynamics. Active upwellings from deep in the mantle (25-27) are viewed as controlling some aspects of surface tectonics and volcanism, including reorganization, implying that the mantle is not passive. This is called the plume mode of mantle convection (29,30).

However, numerical experiments show that mantle convection is controlled from the top by continents, cooling lithosphere and plate motions and that plates not only drive and break themselves but can control and reverse convection in the mantle (31-35). Supercontinents and other large plates generate spatial and temporal temperature variations. The migration of continents, ridges and trenches cause a constantly changing surface boundary condition; the underlying mantle passively responds. Plates break up and move, and trenches roll back because of interactions of the surface with the slab created internal buoyancy of the mantle, not because of buoyancy that is independent of plate tectonics (7,31-35). Surface plates are constantly evolving and reorganizing although major reorganizations are infrequent. They are mainly under lateral compression although local regions having horizontal least-compressive axes may be the locus of dikes and volcanic chains (18,36-38).

The fact that most active plate boundaries on Earth are under water may be crucial in attempting to understand plate tectonics on Earth, and its absence on other planets (37). Water weakens rocks, lowers the melting point and lowers the viscosity of the mantle. A partially molten mantle lubricates the plate-mantle boundary; the buoyancy of magma (and water in the crust) fractures the lithosphere when it experiences even limited horizontal extension (18,36) The thickening of oceanic plates as they cool generates gravitational forces which drives the plates and, in general, puts them into lateral compression, holding out the surrounding fluids, and keeping the plates together. The lithosphere is cold, dry and stronger than the underlying mantle. Rocks, however, are weak and permeable to fluids when under extension (36-38). These are possible sources of positive feedback and amplification of stress fluctuations.

The forces on plates can be decomposed into components which have been called *ridge push*, *slab pull*, *trench suction*, *basal drag* and so on (39). The driving forces are thermal and gravitational in nature and change slowly. These are resisted by dissipative forces such as mantle viscosity, slab bending, transform fault friction and continental collision. These latter forces can change rapidly, causing changes in plate motions, internal stresses and the sizes and shapes of plates (40).

Plates attached to long slabs tend to move rapidly. Plates which have large continental areas, including thick cratonic roots, tend to be more fixed with respect to each other and the mantle. However, there is no correlation in each group with the plate area or the amount of slab, continent or transform boundary (39). This suggests that plate tectonics should be analyzed as a system rather than as a force balance on individual plates. The question then arises, are the plates, plate boundaries and motions a self-organizing system? And is it fluctuations in stress or temperature that trigger the reorganization?

Convection

For the last decade, three-dimensional spherical shell convection models have become progressively more sophisticated. However, in spite of progress in numerical accuracy and incorporation of pressure and temperature dependence of physical properties and of phase changes these models do not account for the first order tectonic features of the Earth, such as the number and sizes of plates (21-25,41). It has been possible to understand some of the features of plate tectonics by introducing mechanical heterogeneity and memory effects into the lithosphere (7,33). A remaining question, however, is what controls which weak zones are activated and what dictates their location and spacing and, hence, plate sizes and shapes. Active and inactive faults and old plate boundaries are numerous. They differ in strike, dip, orientation, age and age offset, mantle temperature, crustal thickness and strength. Such zones also concentrate stress so it may be stress rather than strength that dictates their availability for reactivation. Water pressure in the crust and lithosphere, and magma pressure below, may also control the locations of volcanic chains and new plate boundaries. The traditional way of trying to model plate motions is to start with a convecting mantle, driven by radioactive heating and heat from the core. Attempts are made to modify the rheology and failure criteria of the surface layer in order to initiate plate tectonic behavior (21-25,31-33). An important attribute of plate tectonics is the large amount of energy associated with toroidal (strike-slip) motions. This does not arise directly from buoyancy forces involved in normal convection. In a convecting system the buoyancy potential energy is balanced by viscous dissipation in the fluid. In plate tectonics, both buoyancy and dissipation are generated by the plates. The cooling plate and the slab provide the driving buoyancy and this may be balanced almost entirely by slab bending (42) and by transform fault resistance as suggested by the toroidal/poloidal energy partitioning of plate motions (43). Even the cooling of the Earth is not completely governed by the viscosity of the mantle (42,44). It is regulated by the plate tectonic system and, ultimately, by the distribution of stress in the lithosphere.

Plate Driven Flow

Marangoni convection is driven by surface tension (3-5). Since surface tension is isotropic the fluid flows radially from regions of low surface tension to the cell boundaries, which are hexagonal in planform, where linear downwellings form. The equivalent surface force in mantle convection is the ridge push-slab pull gravitational force which has the same units as surface tension. Since plates are not fluids the forces are not isotropic. Plates move from ridge to trench, pulling up material at diverging regions, which are the equivalent of the centers of Bénard-Marangoni hexagons, and inserting cold material at subduction zones. The other difference between Marangoni and plate-driven convection is that plates are held together by lateral compression and fail in lateral extension. Cell boundaries are convergent and elevated and are regions of compressive stress in Marangoni convection.

The plate tectonic equivalent of the Marangoni number can be derived by replacing surface tension by plate forces. I define the plate tectonic or Platonic number

$$P\ell = g \alpha \Delta T L^2 / u \mathcal{D}(\upsilon)$$

where L is a characteristic ridge-trench distance and u is plate velocity. $\mathcal{D}(\upsilon)$ is a dissipation function which accounts for plate deformation, intraplate resistance and mantle viscosity. When the only resisting forces are lithospheric bending we have the dimensionless lithosphere number

$$P\ell = \rho g \alpha \Delta T r^3 / \kappa \upsilon_\ell$$

where r is the radius of curvature of the bend and υ_ℓ is the lithospheric viscosity (42). When plate interactions are involved we also need coupling parameters across plates such as transform fault resistance and normal stress. In the plate-tectonic system the plates (and slabs) account for much of both the driving force and dissipation and in this respect they play the role of the convecting fluid in Rayleigh-Bénard convection (internal sources of both buoyancy and viscous dissipation). Both the buoyancy and dissipative stresses affect the whole system. The plate sizes, shapes and velocities are self-controlled and should be part of the solution rather than input parameters (21).

Multiple States

Far-from-equilibrium self-organized systems generally have multiple states available to them. They can stay in one state for a while ("stationary non-equilibrium") but fluctuations in the system (not necessarily imposed from outside) can cause dramatic reorganizations and the system ends up in a new state. There are *stationary nonequilibrium* states and *transitional* states, rather than *steady-state* or *equilibrium* states. Prigogine (19) uses the Platonic expression “from being to becoming” to distinguish these situations. In the case of the Earth the tectonic styles available include stagnant lid, mobile lid, large vs. small plates, slow vs. fast plates, steady motions and episodic overturn (22-25,28). Each state can be characterized by a variety of individual plate configurations. For example, Earth today is in a metastable slowly varying configuration with some plates growing and some shrinking. About 200 million years ago, when Panagea broke up, new plates and plate boundaries formed, even in the Pacific hemisphere. The lithosphere is midway through a *supercontinent cycle* (45).

Plate reorganizations have been attributed to temperature fluctuations in the convecting mantle (26-29) but in geodynamic models dominated by plate interactions it is fluctuations in stress that reorganize the system. These include changing the sign of the lateral stress in the plate or the magnitude of the normal stresses across plate boundaries. These changes affect permeability (38) and can initiate or turn off fractures, dikes and volcanic chains (18). The mantle itself need play no active role whatsoever in plate tectonic “catastrophes.”

Surface Rheology

Recently, attention has focused on the rheology of the lithosphere in order to try to reproduce plate-like behavior (23,31,37). These attempts have provided insight into the importance of the outer shell in controlling mantle dynamics and thermal evolution but they do not address the first order questions of mantle dynamics and they have not yielded anything resembling plate tectonics. The most successful attempts are those that account for lithospheric heterogeneity and fault reactivation (7,33). Brittle-like failure of the lithosphere is involved in plate tectonics but modeling shows that plate velocity is nearly independent of the yield stress.

This has been taken to mean that plate motion is resisted by viscous stresses in the mantle rather than by dissipation in the plate. However, bending stresses alone can be as important as mantle dissipation (42). The present system of plate motions serves to minimize the toroidal energy which implies a dominant role for the lithosphere in moderating plate driving forces (43). The minimum dissipation hypothesis (19,20,43) is useful in global geodynamic calculations (46). The fact that plate velocity on Earth does not depend on plate size and that the velocities of the fast plates do not depend on length of the subduction boundary suggests that it is the system, not the individual plate, that dictates plate motions. The system appears to minimize toroidal energy, the individual plates do not (43).

Transform faults and the transform component of obligue subduction zones may dominate over other sources of dissipation (bending, collisional resistance, mantle viscosity), at least for the present configuration of plates (47). It is conceivable that during the assembly of Panagea or the collision of Africa and India with Eurasia (49) that collisional and bending resistance may have dominated until the subcontinents were sutured together and a global plate reorganization repartitioned the dissipation forces according to the minimum dissipation principle. The formation of plate boundaries may also be a self-organized process, although on a completely different scale (38).

Various schemes of mantle dynamics have been investigated that involve a dominant or active role for mantle convection, heat from the core, or interactions between individual plates and mantle convection. Some schemes involve force balances on individual plates. Other models drive mantle convection entirely by imposed plate motions. The possibility that has been overlooked is that the plates define and organize themselves by mutual interactions of the whole plate system and that minimization of dissipation *in the lithosphere* may be the organizing rule.

Fluctuations of stress in such a system cause global reorganizations without a causative mantle convective event. The idea of minimum dissipation in global tectonics, but not of self-organization, was discussed briefly by Sleep *et al* (46).

Discussion

The difficulty in accounting for plate tectonics with computer simulations may be explained if plates are a self-organized system and *they* organize mantle convection rather than *vice versa*.

Far from equilibrium systems do strange things. They become inordinately sensitive to external or internal influences. Small changes can yield huge, startling effects up to and including reorganization of the entire system. We expect self-organization in slowly driven interaction-dominated systems. The resulting patterns do not involve templates or tuning. The dynamics is dominated by mutual interactions, not by individual degrees of freedom. Periods of gradual change or calm quiescence are interrupted by period of hectic activity. I suggest that such changes in the global geologic record are due to plate interactions and self-reorganizations, rather than events triggered by mantle convection. Apparent changes in orientation and activity of volcanic chains are likely to be due to changes and reorientations of stress (18, 50-54). The stress-crack hypothesis seems to apply to most volcanic chains (18,52,53).

Massive mantle overturns, and mantle avalanches have been proposed to explain certain aspects of plate tectonics and global magmatism (26-29). However, the proximity of the mantle to the melting point (55) and the recognition of stress controlled magmatism (17, 18, 52-53) obviate the need for a thermal trigger. Mantle geodynamics may be controlled from the top (33-35, 45,55,56) as is Bénard convection.

Plate tectonics is often described as “just the surface boundary layer of mantle convection.” However, if most of the buoyancy and dissipation is in the plate-slab system rather than in the mantle, then mantle convection patterns should be regarded as the result, not the cause, of plate tectonics. Whether the first-order features of plate tectonics emerge from this approach remains to be seen (57).

References and Notes

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10. The deep mantle (> 1000 km depth) has different spatial (11,12) and spectral (13) characteristics than the upper mantle and may be isolated from it in the sense that there is no exchange of material. However, density variations of the deep mantle certainly affect the surface elevation, lithospheric stress and the geoid even if the mantle is chemically stratified. Heat will also flow upwards and may influence the long wavelength thermal structure although plate tectonics and subduction may overwhelm this signature because of their shorter timescale. Because of the pressure dependence of α, 1% changes in intrinsic density can irreversibly stratify the mantle (9).
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20. At equilibrium the structure that minimizes the free energy is selected. The existence of an equivalent principle for dynamic non-equilibrium systems is an important unsolved problem. The organizing principle for plate tectonics is unknown. Since rocks are weak under tension the conditions for the existence of a plate probably involve the existence of lateral compressive forces. Plates have been described as *rigid* but this implies long term and long range strength. They are better described as *coherent entities*, organized by stress fields as well as by rheology. The corollary is that volcanic chains and plate boundaries are regions of extension. Plates probably also organize themselves to minimize dissipation.

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30. The idea that a deep thermal boundary layer may be responsible for narrow structures such as volcanic chains is based on heating below systems where effects of pressure on thermal properties are ignored (the Boussinesq approximation). In the Earth the effects of temperature and pressure on the convection parameters cannot be ignored and these must be determined as part of the solution in a self-consistent way. Such calculations suggest that it is highly probable that the mantle below 2000 km depth, and possibly below 1000 km depth is isolated from the surface, except by Newton's and Fourier's laws. Furthermore, it is cooling of the mantle that controls the rate of heat loss from the core. The core does not play an active role in mantle convection. The magnitude of the bottom TBL depends on the cooling rate of the mantle, the P- and T-dependence of the physical properties and the radioactivity of the deep mantle. The local $\mathcal{R}a$ of the deep mantle is very low (24).
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40. Changes in the activity and orientation of volcanic chains, such as the Emperor-Hawaiian bend, are often taken to represent changes in plate motions. These changes are extremely rapid. Forces on plates represent the integral of all driving and resisting forces and therefore change slowly. However, local stresses inside of a plate can change rapidly. I attribute the changes in volumes and orientations of volcanic chains to changes in the local stress field. Local tension is probably required for volcanism.
41. Presently there are about 12 plates. The smaller plates are arranged in a polar band that also includes the major geoid lows. The major plates (Pacific, African) are antipodal and lie over major equatorial geoid highs. There is a wide range in plate sizes and velocities. Some are growing and some are shrinking. The migrations of trenches and ridges, and the growth and shrinkage of plates may be as important in understanding plate tectonics as are driving and resisting

forces. A large majority of the tectonic plates are bounded by five other plates and, in addition, have five next – nearest neighbors. This is the symmetry of the pentagonal dodecahedron, a Platonic solid. Furthermore, any plate can be reached from any other plate by crossing one or two plates in between. Clearly, plates are a strongly interacting system and cannot be treated plate-by-plate. The plates organize each other and they probably do so in a manner as to minimize dissipation in the plate system (20).

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56. B. H. Hager, R. J. O'Connell, *J. Geophys. Res.*, **86**, 4843 (1981).
57. Plato introduced the cyclical theory of the world in his *Republic*. The world was created and then left to organize itself by a set of rules. The world oscillated between order, disorder and chaos. It alternated between control by "the finger of God" and self-organization. The deity would intervene as appropriate. In *Timaeus* Plato distinguishes between that which always is and never becomes (being, equilibrium) and that which is always becoming but never is. Plato believed that we need both *being* and *becoming*; *statis* and *change.* The plume hypothesis has been enormously popular partly because it is simple, seductive and has a catchy name. Alternative theories such as propagating cracks stress induced volcanism and extensional tectonics do not have memorable names. *Plutonics* can be described as the hypothesis that attributes surface processes to deep causes; plumes, super plumes, massive mantle overturns and mantle convection is considered to play the dominate and active role. The hypothesis that plates are a far-from-equilibrium self-driven self-organized system can be called *platonics*. In this hypothesis the upper mantle provides heat and material but is otherwise passive. The surface is constantly reorganizing itself, its

boundaries and orientations of volcanic chains. There is no “finger of God” or outside template.

58. This paper represents Contribution Number 8803, Division of Geological and Planetary Sciences, California Institute of Technology. I thank Michael Gurnis and Jeroen Ritsema for helpful comments. This work has been supported by NSF Grant EAR 9726252