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Plate Tectonics ;
The General Theory

The Complex Earth is Simpler Than You Think

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"....In science, conventional wisdom is difficult to overturn. After more than 20 years some implications of plate tectonics have yet to be fully appreciated by isotope geochemists... and by geologists and geophysicists who have followed their lead."
" A myth is an invented tale, often to explain some natural phenomenon... which sometimes acquires the status of dogma... without a sound logical foundation. It is a dogma that has distorted thinking about the Earth for decades, In science this is an old story, likely to be repeated again, as the defenders of conventional wisdom are seldom treated with the same scepticism as the challengers of the status quo... the dogma has been defended with false assertions, defective data, misconceptions and misunderstandings, and with straw-man arguments... The justification ... boils down to a statement of belief, an opinion, rather than a deduction from observations."
"... geochemists are reluctant to abandom cherished concepts they grew up with and have vigorously defended during their education and research careers."

Richard L. Armstrong, The Persistent Myth of Continental Growth, Austr. J. Earth Sci. (1991) 38, 613-630

ABSTRACT

The standard model of mantle dynamics and chemistry involves complex interactions between rigid plates and hot plumes, and exchanges of material between a homogeneous upper mantle and a 'primitive' lower mantle. This model requires many assumptions and produces many paradoxes. The problems and complexities can be traced to a series of unnecessary and unfruitful assumptions. Dropping these assumptions, or assuming the opposite, removes many of the paradoxes. A theory of plate tectonics can be developed that is free from assumptions about absolute plate rigidity, hotspot fixity, mantle homogeneity and steady-state conditions. A simpler and more general hypothesis is described that is based on convective systems that are cooled and organized from the top. Plate tectonics causes thermal and fertility variations in the mantle and stress variations in the plates, thus obviating the need for extraneous assumptions about the deep mantle. The general theory of plate tectonics is more powerful than the current restricted forms that exclude incipient plate boundary (also known as volcanic chains and hotspot tracks) and athermal (e.g. melting point, fertility, and focusing) explanations of melting anomalies. Plate tectonics, geology, mantle dynamics, magmatism, and recycling are upper mantle processes, largely independent of the deep mantle. These ideas came about by examining the paradoxes and assumptions in current models of mantle structure, evolution and chemistry. By identifying the assumptions that generate the anomalies, one can have a zero-paradox hypothesis. Eventually, new paradoxes will be identified, and a new paradigm will be introduced. This is the way science progresses.

INTRODUCTION

The recognition that earthquakes and volcanoes delineate the boundaries of constantly moving plates at Earth's surface led to a new paradigm for understanding the Earth—plate tectonics. Viewing the surface of the planet as a set of moving plates required an intellectual about-face of the first order from previous theories that viewed the surface as immobile. This is sometimes called *the plate tectonic revolution* but Alfred Wegener is the true father of continental mobility. Plate tectonics has been one of the most successful theories in the history of the natural sciences and has revolutionized thinking in all of Earth sciences. It is a testimony to its usefulness and predictive quality that it was accepted over the course of less than a decade in spite of its descriptive nature. All geology textbooks were rewritten, with plate tectonics as the reigning paradigm. The idea of continental fixity, however, has been replaced by the idea of oceanic island fixity–the so-called *hotspot* or *plume* hypothesis. Volcanic islands are now generally viewed as the tops of narrow hot upwellings from fixed points deep in the mantle that are independent of plate tectonics at the surface. This plume hypothesis was invented to explain some features that were apparently outside the realm of plate tectonic theory. It is generally thought–and taught–that both plates and plumes are required to explain various surface features.

Ordinarily, science progresses slowly by incremental improvements in data and theory. Science can advance, or change direction, through the testing, and discarding of theories and *conventional wisdom*, or can stagnate by sticking too long to a dogma. Plate tectonic and plume theory are currently undergoing such an examination.

Students learn about plate tectonics and plumes from textbooks and lectures. Active researchers learn about the Earth by observation and experiment. Learning about a hypothesis is different from learning how to frame or test a hypothesis. Going from an idea to a theory involves *assumptions, auxiliary hypotheses* and *amendments.* Philosophers teach about logic, paradox and ways of thinking; philosophers of science talk about the logic of scientific discovery, paradigms, falsification and research programs and what it takes to evolve or overthrow established ideas. This is seldom taught to students of science. The history of science is replete with examples of scientific revolutions and paradigm shifts. The Earth sciences have their share. Plate tectonics was one, and we are currently living through another.

WHAT'S THE PROBLEM ?

In spite of its usefulness, there remain a number of observations that are difficult to reconcile with the standard conception of plate tectonics and mantle geochemistry, e.g. Albarede and Boyet [2003], Ballentine et al., [2002], and van Keken et al., [2002]. These are known as paradoxes or even crises. Philosophers of science have identified ways that active scientists deal with crises, conflicts and contradictions in their science [Kuhn, 1962, Popper, 1962, Armstrong, 1991, Dickinson, 2003]. Currently, there are three approaches for reconciling geological, geophysical and geochemical observations with plate tectonic theory:

1. Introduce additional features to the basic theory. This approach is taken by those who propose something outside the framework of plate tectonics; for example, plumes to break up continents and to create volcanic chains, and deep core-heat driven thermal instabilities in deep reservoirs to explain variations in magma chemistry, bathymetry and crustal thickness.
2. Drop various assumptions, such as; the plates are uniform, permanent, and rigid, and the underlying mantle is homogeneous. This is the approach advocated in this paper.
3. Ignore conflicting evidence and live with the paradoxes.

Note that in the first approach assumptions and auxiliary hypotheses are added to the basic framework, while in the second approach, some or all of the assumptions are pruned. I will examine the origin of these assumptions and make a case that not only are they unnecessary but that by eliminating them the predictive and explanatory power of plate tectonic theory is enhanced. First, however, I examine the criteria used by scientists to evaluate theories as a foundation for comparing competing approaches.

SIMPLICITY

Simplicity is a useful concept when judging the merit of alternate philosophies or deciding between cause and effect. Simplicity can be judged by looking at the assumptions, adjectives, anomalies and auxiliary hypotheses that accompany the hypothesis. There are many criteria for judging theories. These include elegance, power, falsifiability, predictability, contradictions and coincidences. Simplicity is one of the most useful.

Richard Feyman said "You can recognize truth by its beauty and simplicity . . . When you get it right, it is obvious that it is right . . . because usually what happens is that more comes out then goes in . . . truth always turns out to be simpler than you thought."

OCCAM'S RAZOR

Occam's razor is a method extensively used by geologists; on the surface is a relatively straightforward point that does not need to be belabored. However, is it the theory–the process– or the result, that should be simple? A homogeneous mantle is certainly a simple assumption. But simple straightforward geological processes often to lead to complex structures. It turns out that incredibly complex and contrived processes are needed in order to create a homogeneous planet from the debris of space, or even a homogeneous upper mantle, which is the hallmark of modern mantle geochemistry [Hofmann, 1997, Schubert et al., 2001]. But a set of simple physical rules can be used to predict that the Earth should be a gravitationally stratified body, with a dense core, a buoyant crust, and a heterogeneous mantle. Continental fixity is a simpler idea than continental drift, but a large number of *ad hoc* amendments and assumptions are required to explain the observations.

Occam's razor can be used to improve, trim, simplify and discard theories, but is most useful when it is used to test and compare theories. Quite often in the development of an hypothesis there arises an impasse. Techniques used to overcome the difficulty include new assumptions, auxiliary hypotheses, procrustean stretching, tooth fairies, and *deux ex machina*, or a retreat to a previous stage and reconsideration of the choices that were made. The uncovering of paradox, fallacy or error may be suggesting that a theory is wrong. However, theories create their own inertia, and we are often tempted to add embellishments to the theory that allow it to continue to meet the requirements of the data. Advocates of a theory argue " surely we are allowed to 'complexify' models as we learn more - the current version of the model is not necessarily wrong, just because the original wasn't perfect". Occam's razor, however, encourages us, at the same time, to reconsider , with an open mind, the original theory and its assumptions. On hindsight, some of the original assumptions of a hypothesis are no longer viable. In so doing, it is often possible to develop an even more general and simpler view that not only solves the immediate problem but solves what were thought to be unrelated problems. This is the opposite from *ad hoc* modifications to the original hypothesis, modifications that do not make the hypothesis more powerful or predictive. Recognizing and discarding un-useful assumptions can be more powerful than amending an endangered idea.

The theory of plate tectonics replaced the ideas of continental fixity, permanence of the ocean basins and Earth expansion because it provided a simpler and more general explanation of geological and geophysical observations. Although the theory has great explanatory and predictive power it seems to fail in regions of continental deformation and breakup, large igneous provinces and island chains; there are *anomalies*. Separate hypotheses have been advanced to address these phenomena, most notably, the popular plume hypothesis. The adjective *rigid* has been attached to plate tectonics, and *fixed* has been applied to oceanic volcanic islands and the underlying mantle. Volcanoes are called *hotspots*, volcanic chains are called *plume tracks*; oceanic plateaus and LIPs are called *plume heads*. Another term for hotspot is *midplate volcanism*, even though most such features are on plate boundaries, or started on plate boundaries. Even the term *melting anomaly* implies that the results of plate tectonic processes should be uniform. These assumptions and definitions have diverted attention away from the true source of the phenomena.

PLATE TECTONICS – CRACKS IN THE EDIFICE

Plate tectonics is sometimes defined as a kinematic or descriptive theory that describes motions on a sphere, However, plate tectonics is much more powerful than that. The conventional statement of rigid plate tectonics with the hotspot amendment is as follows;

Earth's surface is composed of about twelve–some say about 20– rigid plates that move with respect to each other. Volcanoes and earthquakes delineate the plate boundaries. Midplate volcanoes and volcanic islands are called hotspots; they are not related to plate tectonics; they are related to core heat and deep mantle materials. Plates and plate boundaries are mobile; hotspots are not.

This statement, short as it is, makes several unnecessary assumptions that introduce a series of paradoxes and unneeded auxiliary hypotheses. Before accepting the amendments to the central theory, we must return to an examination of the underlying assumptions, as recommended by Occam's razor. In particular:

Are the plates really rigid; can they not crack and allow magma to escape?
Are the plates riding on a convecting mantle driven by heating from below, or do they drive themselves?
Is the system in a steady state; can the present plate system dissolve, to be replaced by a completely different configuration?
Can there be new (incipient) plate boundaries and volcanic chains that do not have their origin outside of the framework of plate tectonics? Can former and new plate boundaries look like "hotspot tracks"?

In the standard model, the homogeneous upper mantle is assumed to be the source of the homogeneous magmas that emerge at midocean ridges and form the new oceanic crust. So-called hotspot magmas are assumed to be derived from a deeper part of the mantle. The upper mantle is sometimes called *the convecting mantle*. The convecting mantle is assumed to be well-mixed and homogeneous because midocean ridge basalts are homogeneous [e.g. Hofmann, 1997]. Midplate volcanic chains are assumed to be due to motions of the plates over fixed hotspots (assumed to be hot) in the mantle. These hotspots are assumed to be maintained by core heat.

Note the numerous assumptions, many more than necessary. Note also the unnecessary adjectives–homogeneous, hotspot, convecting. Sometimes one can make progress by dropping, rather than adding, adjectives and assumptions. When a theory runs into trouble with new measurements and observations, one should examine the *assumptions*; they may be wrong, or unnecessary. In an alternative cooled-from-above hypothesis, plates drive and organize themselves, the mantle is hot and inhomogeneous, and the outer shell is cracked, and permeable to magma, rather than absolutely rigid. Volcanic chains can reflect zones of weakness rather than zones of hotness. An isothermal, motionless and homogeneous mantle, everywhere subsolidus, and absolute plate rigidity are impossible to attain and are extraneous constraints.

After one examines the assumptions, and possible alternate assumptions, one should make sure that the definitions and words used in the theory are precise. Many of the concepts and assumptions of the standard model, which includes both plates and plumes, are ill-defined. The terms *plate, midplate, rigid, high-temperature, anomalous, well-mixed, and fixed* are ambiguous or relative terms; precise definitions, or agreed upon usages, are necessary in order to proceed. Unfortunately, some of these concepts are statistical in nature and statistics is seldom applied in tests of the standard model. For example, the normal temperature variations of the mantle are several hundred kelvins. These are the temperature fluctuations expected in a convecting material with the physical properties and dimensions of the Earth's mantle, and the temperature variations expected from slab cooling and continental insulation. All phenomena attributed to hotspots and plumes have inferred temperatures in this range but they are usually interpreted as manifestations of *excess* temperature, under the assumption that *excess* volumes of basalt or crust, or *high elevations*, require temperatures well outside the normal range (and require explanations other than plate tectonics). Thus, the plume hypothesis makes assumptions about what is normal, and what is anomalous–what is in the plate tectonic domain, and what is in the plume domain. A misapplication of Occam's razor is that plate tectonics should lead to uniform and homogeneous results; e.g. midocean ridges should all be at the same elevation, the same amount of basalt should come out of ridges everywhere, the mantle should not vary in temperature, and if basalts are uniform the source must be uniform. However, according to Occam's Razor, it is the theory that should be simple, not the result.

Factors such as mantle composition, fertility, focusing of upwelling magmas, volatile content, prior history of the area and lithospheric architecture and stress are important in determining the volume of magma produced at the surface. These are all familiar concepts in geology and volcanology. The word *hotspot* itself is based on assumptions, not on observations of temperature. "Melting anomaly " is a better term but even this implies that–without plumes–there should not be regions that provide more magma than average. Bathymetric *anomalies*, or swells, are usually attributed to *hotspots*; this assumes that *normal* mantle is homogeneous in temperature, density and composition, that all oceanic ridges should rise to exactly the same depth and that ocean floor of a given age should always be at the same depth.

"Midplate" volcanoes are generally on or near plate boundaries, or were when they first formed. Regions of higher than average elevation or rates of magmatism are expected in some places since the mantle is not homogeneous or isothermal; even if it were we expect updrafts and downdrafts. The word *midplate* implies a mechanism different than the passive upwellings or dikes associated with plate divergence, convergence, bending or shrinking; normal plate tectonic processes.

A CONVECTING MANTLE?

The outer shell of the Earth – the lithosphere – is often regarded as the top layer of mantle convection and plate tectonics is regarded as a manifestation of this convection. Unfortunately, while this approach has yielded some important insights, it has failed to answer many first order questions: how is plate tectonics initiated? why are there twelve or twenty plates (instead of two or fifty)? what controls the size and shape of the plates [Anderson, 2002a]? why are subduction zones one-sided, instead of symmetric? These problems suggests that the mantle departs from an ideal fluid in significant ways and that a different approach may be needed.

An alternative conception is that mantle convection is mainly driven by cooling from above and the negative buoyancy of the cold outer shell. The plates drive themselves, by their cooling, and they in turn organize the flow in the mantle [Appendix]. Computer simulations of mantle convection have been unable to reproduce plate tectonics and this may be because cause and effect have been reversed.

A fluid heated from below or within will undergo a series of transitions from static equilibrium to organized cells to chaotic convection as the temperature is raised. In the absence of surface tension–or plates and continents–the fluid self-organizes itself; it is not responding to an external template although it needs an external source of energy. However, continents and tectonic plates change the surface boundary condition; they serve as a template for mantle convection. The 'fluid' mantle is no longer free to self-organize but, given the appropriate conditions, the plates themselves may become the self-organizing system. The sizes and shapes of the coherent entities called plates, the locations of plate boundaries and the directions and velocities of individual plates are controlled by interaction between the plates and the distribution of buoyancy (density variations) in the plates.

Just as fluctuations of temperature can drive a convecting fluid to a new state so a fluctuation of stress (in the lithosphere, for example) can cause the plate tectonic system to completely reorganize. Such global plate reorganizations are recognized in the geological record. They are often attributed to convective overturns in the mantle, as in Rayleigh-Bénard convection. They may, however, be controlled from the top, by the interacting plate system itself, as in Bénard-Marangoni surface-tension driven convection, or as when two continents collide. The difference between plate tectonic and surface-tension controlled convection is that tension holds surface films together while lateral compression or common forces is what holds plates together. Plates are weak in tension and fluctuations in stress can cause new plate boundaries to form. These are usually along old plate boundaries, and they are usually called *hotspot tracks*.

The interesting thing about convection and plate tectonics is that a few simple rules control the evolution of the system. Self-organization does not require templates or fine-tuning; it takes care of itself. It just requires that the investigator, or modeler, provide the system with enough degrees of freedom so it can self-organize. Geological examples of self-organization include mudcracks, basalt columns , salt domes, and sand dunes. Plate tectonics may be a case of self-organization. Ironically, the science that has evolved from these far-from-equilibrium considerations is called the science of complexity. It is actually an example of Occam's razor; the assumptions, and parameters are minimized and the rules are simple. Beautiful complex forms are often the result.

TWO MODES OF CONVECTION?

In systems cooled from above, the instability of the surface layer drives the motions of both the surface and the interior; this is the kind of convection involved in plate tectonics and the thermal evolution of the Earth. Think of a glass of ice tea; the ice cubes and the shape of the glass control the style of convection. The ice cubes move about, constantly changing the top boundary condition. Yet it is motions of the mantle, and temperature variations in the deep mantle, independent of the surface conditions, that are often assumed to drive the plates and create volcanic chains. In one theory the plates control their own fate and the mantle passively follows. In the other theory, many surface features are controlled by deep convective motions and core heat; the surface passively responds or at most is just the surface boundary layer of a system where the bottom boundary layer is as important as the top boundary layer, in spite of the effects of pressure and sphericity.

Temperature variations in the upper mantle are caused by plate tectonic processes such as continental insulation and absence of subduction cooling. Swells, superswells and large-scale magmatism (so-called ‘anomalies’) are consequences of plate tectonics rather than independent phenomena. The idea that the surface of the Earth is slaved to the mantle is based on the rather obvious point that the mantle is much more massive than the plates. However, the concept of far-from-equilibrium self-organization turns this viewpoint around. This kind of organization requires a large outside source of energy and material, and a place to discard waste products. The plate system, viewed as an open thermodynamic system, requires the mantle’s resources but does not need the mantle to organize it. The biosphere is one of the best known examples of this process. The biosphere is small; it depends on the Sun and the Earth for energy and matter, but it organizes itself.

It was more than fifty years after Bénard experiments that it was realized that the hexagonal pattern did not require thermal convection in the underlying fluid. It is the other way around. The hexagonal cells in the fluid are imposed from the surface. A similar transition in thinking may be required to understand plate tectonics.

If the top and bottom faces of a tank of fluid are kept at constant temperature, and if density depends only on temperature, then thermal instabilities (plumes) form at both interfaces and serve to drive convection in the tank. This symmetry is broken if pressure is taken into account, or if other properties are functions of temperature and pressure, or if the container is a spherical shell, or if there are phase changes, or if only one surface is stress-free or isothermal. Geodynamicists speak of the plate-mode and the plume-mode of mantle convection, these being the independent responses of the top and bottom thermal boundary layers (TBL), respectively. Geochemists speak of the upper and lower boundary layers as being distinct reservoirs, and mantle in between as *the convecting mantle* (the presumed–or assumed–homogeneous source of midocean ridge basalts, or MORB *)*.

The plate-mode must be, by far, the most important mode for the following reasons; because of secular cooling of the mantle and the distribution of radioactivity, at least an order of magnitude more heat crosses the upper TBL than crosses the lower. That is, the mantle is more cooled from above than it is heated from below. Furthermore, because of the temperature and pressure dependence of the thermal expansion, there is much more (negative) buoyancy created at the top than positive buoyancy at the bottom. In these respects, mantle convection differs from laboratory or kitchen experiments. The other factors controlling the vigor of convection (thermal conductivity, viscosity) also favor more vigorous convection at the top. Instabilities at the base of the mantle, because of pressure, will be sluggish, immense and long-lived, in contrast to the plate tectonic mode. Finally, the processes of gravitational differentiation during the high-temperature accretion of the Earth will isolate the upper and lower mantles, even if there is only a small density contrast between them. The effects of pressure and chemical layering are almost always ignored in mantle dynamics simulations, and, often, the plates are ignored as well, or put into the calculation in an approximate way. Convection of the mantle cannot be treated as a homogeneous fluid with simple (and unchanging) boundary conditions.

Small-scale convection, and stress variations and cracks in the plates are consequences of plate tectonics, and offer alternative explanations of volcanic chains and midplate volcanism. Lateral variations in temperature and density (which drive mantle convection) and fertility of the upper mantle are also consequences of plate tectonics, recycling, continental insulation and slab cooling and can explain variations in volcanic output from place to place. These options are not available if the plates are really rigid and the mantle is really isothermal and homogenous, as often assumed. By dropping unnecessary assumptions, the plate theory becomes more powerful, plume theory becomes less plausible, and upwelling plumes become unnecessary.

FIXED RIGID PLATES

The term *plate* itself has no agreed upon formal definition but is defined operationally as a part of the outer shell that moves coherently. Plates are rigid in the sense that relative plate motions can be described by rotations about Euler poles on a sphere. We often assume therefore that plates are strong, brittle, permanent, rigid and elastic. The word *plate*, in fact, implies strength, brittleness and permanence. However, there are several possible scenarios in which plates move coherently:

Plates are strong and rigid (the conventional interpretation).

Plates are those regions defined by lateral compression since plate boundaries are formed by lateral extension. Plates may be collages, held together by stress and adjacent portions rather than by intrinsic strength.

Plates move coherently because the parts experience similar forces or constraints.

With the first definition, deformation and volcanism within the plate are only possible if the local tensile strength is overcome by local heating or stretching. This reasoning spawned the plume hypothesis.

With the second definition the global stress field, dictated by plate boundary and subplate conditions, controls the locations of stress conditions appropriate for the formation of dikes and volcanic chains, and incipient plate boundaries, from the underlying mantle,which is already at the melting point. Plates break at suture zones (former plate boundaries), fracture zones and subplate boundaries, usually generating volcanic chains in the process.

With the third definition the concept of *plate* almost disappears and the concept of 'plate rigidity' is replaced by ' coherency of motion' as in a flock of birds or a billowing cloud.

The metaphor of a plate implies a fixed shape, and strength, but scaling relations, dating back to Galileo, show that large objects have essentially no strength. Plates are actually segments of spherical deformable shells or domes, aggregates of rock pushed together. Gravitational forces and lateral compression keep plates and domes and igloos together. This metaphor fails because plates do not have fixed shapes like the stones in a cathedral. Plates have higher viscosity than the underlying mantle but they are easily pulled apart, like shoals of fish. They are more akin to crystals in deforming ice–or the bubbles in a foam–constantly recrystallizing as conditions change. Volcanic island chains and transient bursts of magmatism appear at the seams between new plates and at the sutures and cracks of old ones. These eruptions only occur because the surface has failed in tension. The lithosphere does not necessarily fail because it is pushed up, or heated, from below.

The notion that mid-plate volcanoes are 'fixed' is a remnant from the early development of plate tectonic theory. Island chains at one time were regarded as a fixed reference frame, anchored by deep motionless parts of the mantle. Originally, hotspots were thought to be rooted in the interiors of convection cells, but later they were moved down to the 'non-convecting lower mantle' and ultimately to the core-mantle boundary. It is now known that these "fixed" points move relative to each by three to six centimeters per year, which is about the average relative plate velocity. Some continents move with respect to each other, or to some oceanic plates, with much smaller velocities, yet they are not regarded as fixed, or anchored to the deep mantle.

This illustrates that both definitions and assumptions should be analyzed when applying Occam's razor. It also is a reminder that sometimes our favorite ideas are based on interpretations of data that are no longer valid.

AN ALTERNATE FORMALIZATION

An alternate way of expressing plate dynamics is the following;

Earth's surface is covered by a cold scum temporarily divided into ephemeral domains, called plates, which are defined by the condition that horizontal extensional stresses are minimized. Motions of the plates over the planet's interior are caused by the integral of gravitational attraction of all points in the interior, and on the surface, acting on the outer skin.

This theory has several corollaries:

Extension is localized at plate boundaries
Plates are primarily under horizontal compression
Stresses in the outer shell are superpositions of all the gravitational and thermal stresses and are not uniform.
Plate boundaries and volcanic chains are the locus of maximum strain.

In a planet cooled from above the cold surface boundary later is the active element (it drives plate motions and mantle convection). The mantle below responds passively. Upwellings are a consequence of mass balance, not thermal instability. The unnecessary and non-fruitful adjectives – *rigid, fixed, well-mixed* - require auxiliary hypotheses and are candidates for trimming by Occam's razor. In fact, plates are deformable, breakable and ephemeral and in a convecting planet there are no fixed or absolute reference frames, and the convecting part cannot be isothermal. Convection does not homogenize a planet; it stratifies it. Cooling plates *cause* mantle convection.

Plate tectonics on a sphere *must* be episodic; steady-state and uniformitarianism reign for only short periods of time. Earth history can be divided into Supercontinent Cycles. A supercontinent (or any large, slowly moving plate) insulates the mantle and isolates it from subduction cooling. The temperature increases by about 100°C under a supercontinent and other large plates , this being added to the ±100°C, or more, range normally available in an Earth-size convecting planet. Lateral temperature gradients and plate boundary forces break up the supercontinent–or superplate–and cause the fragments to move away from the thermal anomaly, forcing a global reorganization of plates, stress and motions. New plate boundaries are accompanied by transient bursts of magmatism, including large igneous provinces from previously insulated regions of the mantle. There follows a period of relatively steady motion but each time a continent overrides a ridge or a trench, or collides with or slides past another continent, the global stress pattern changes.When this happens the existing plates and plate boundaries are no longer appropriate for the new stress sate. New plates must form. An analogous situation occurs when a bubble-raft, or foam, or a bed of particles, is sheared. There are islands of little deformation, but they are transient.

Continents slow down and come to rest over cold mantle. This signals the end of a cycle. Chains of volcanic islands signal the formation of a new ridge or crack or the death of an old one. Subduction cools the mantle and introduces chemical anomalies into it. This episodic non-steady aspect and the creation of thermal and chemical anomalies are essential aspects of plate tectonics. Plate tectonics is thus a more general theory than generally acknowledged. The plate tectonic hypothesis is a powerful one and if pushed hard enough can explain phenomena that are now treated outside of the paradigm. It is the adjectives – rigid, fixed, isothermal, homogeneous – that are the suspects in suspected failures of an otherwise successful hypothesis. As usual, one can make progress by deleting adjectives, and dropping assumptions. This is the essence of Occam's razor.

THE SOURCE OF MANTLE HETEROGENEITY-RECYCLING

Most of the chemical heterogeneity of the upper mantle is due to subduction of sediments, fluids, crust and plates of various ages, including young plates; the mantle is polluted by the processes of plate tectonics. Only thick old oceanic plates achieve enough negative buoyancy to sink rapidly through the upper mantle but even these may contribute their fluids , and even parts of their crusts, to shallow mantle heterogeneity. Other sources of recycled material which cannot sink out of the shallow mantle include refractory products of melt extraction, back-arc basins , erosion at the top, edge and bottom of the lithosphere, delaminated crust etc. In the standard model of mantle geochemistry material in the asthenosphere that provides magma to oceanic islands, is brought into the upper mantle by deep plumes from the core-mantle boundary, rather than by direct transfer from slabs.

The distribution of ages of subducting plates is highly variable (Rowley, 2001). There is a large amount of material of age 0- 20 Myr and 40-60 Myr at subduction zones. The former is relatively hot and buoyant and will underplate continents, become flat slabs or will thermally equilibrate in the shallow upper mantle. The rate at which this young crust enters the mantle is about 2 to 4 km^3 /yr. The global rate of 'hotspot' volcanism is ~2 km^3 /yr (Phipps Morgan, 1997) . This rough equality encourages us to think that 'melting anomalies ' may be due to fertile patches, occupied by subducted oceanic crust which was young at the time of subduction. Isotopic shifts in elements with long-lived radioactive parents document chemical variations in the Earth's mantle that have been preserved for periods of at least 10^8 to 10^9 years. This has been equated with the timescale of whole mantle convective overturn but it is also the isolation time of the upper mantle, given typical ridge migration rates. Ancient material also gets recycled into the mantle and this, in part, is responsible for some of the apparently long isolation times.

RIDGES AND TRENCHES MOVE ABOUT

Some textbook views of mantle convection give the impression that material rises at midocean ridges and is carried away on a conveyor belt that transports the plate to a trench where it subducts. This is often equated to the top of a convection cell. The real mantle is much more complex. Ridges and trenches, as well as plates, migrate about the surface of the Earth. At typical ridge and trench migration rates of 1 cm/yr, relative to the underlying mantle, a section of the shallow mantle will be visited by a ridge about once every 2 Gyr and about 1 Gyr after being visited by a subduction zone. Depending on the geometry and depth of the return flow, the horizontal component of mantle convection will be of the order of 5 to 30 times less than the plate speeds or about 1 to 0.16 cm/yr. Hotspots do not need to be fixed to stationary plumes. The time available for isotopic anomalies to grow is controlled by ridge migration rates, more so than by the overturn time of the mantle, assuming whole mantle convection. The typical times of 1 to 2 Gyr usually quoted for the isolation times of mantle reservoirs and interpreted as whole mantle overturn times can also be understood even if plate tectonic processes such as subduction, recycling and melting are confined to the shallow mantle.

Oxburgh and Parmentier (1977) calculated that normal oceanic lithosphere older than 8 or 10 my should have negative buoyancy and hence be subductible. Slightly thicker crust , or the presence of sediments and altered crust and lithospheric mantle, further reduce the density of the young plate. In order for a plate to be denser than the underlying mantle, and hence, subductable , there has to be enough cold deep lithosphere to counteract the bouyant crust (12 % less dense than “normal” mantle) and the refractory garnet-free residue (3-6 % less dense). The “elastic” or rheological thickness of the plate is about 40 km after 80 my of cooling and the thermal boundary layer (TBL) is about twice this. The bottom part of TBL is hot so it is the mid-TBL that contributes most to the offset of the bouyant upper parts.

We can infer that there is likely much oceanic crust jammed into the shallow mantle. Mixing, stretching, and stirring of this recycled debris require turbulent or chaotic convection and even in these cases the simulations give long lasting blobs (Bunge et al., 1996). The presence of plates, continents, pressure effects on physical properties and stratification all serve to help organize mantle flow (which is mainly a passive response to plate tectonics) and keep inhomogeneities from mixing . The conventional model has a homogeneous upper mantle (convection has been confused with “ stirring”, “mixing” and homogenization). The real Earth likely has recycled crust/lithosphere, metasomatic bits, trapped melts , migrating fluids, subduction processed residual, and ridge processed residue in the upper mantle , and trapped young crust at collision zones . The mantle at mature ridges only appears to be homogeneous because of sampling processes . Application of the central limit theorem to volcano and ridge sampling processes eliminates the need for the large scale isolated reservoir and box models , and narrow plumes, which form the basis of modern mantle geochemistry, and what has become known as *chemical geodynamics.*

THE PLUME ASSUMPTION

Plate tectonics apparently is the style of convection adopted by a hot, but cooling, planet with water, a cold atmosphere and with an interior that is buffered by the melting point of rocks containing volatile elements. In a planet as large as the Earth the effect of pressure makes the gravitational separation of different density materials during the hot accretion process irreversible. After accretion the planet is stratified according to volatility, melting point, chemistry and density. The top of the mantle–since it is cooled from above–is characterized by narrow dense downwellings and broad warm passive upwellings . The warmer and more fertile regions are at or above the (variable) melting point. Most of the radioactive elements were placed in the crust and upper mantle during accretion and upward transport of melt.

A small fraction of the total surface heat flow comes from the core. The high pressure at the base of the mantle, and the low heating rate means that buoyant upwellings must be huge, long-lived and slow to develop. Even a small intrinsic density contrast between the deep layers in the mantle will trap the upwellings, since pressure lowers the thermal expansivity of silicate rocks, and increase the viscosity and thermal conductivity.

Text books show narrow plumes of material rising from the core-mantle boundary directly to Yellowstone and Iceland and about 40 other volcanoes designated as *hotspots*. These cartoons are based on simple laboratory experiments involving the injection of hot fluid into a tank of stationary fluid, or the pot-on-the-stove analogy. Pressure is unimportant in these simulations. For simplicity, all the thermal properties are more-or-less constant.

Among the more critical assumptions that have been made in developing the plume hypothesis are;

. *the mantle is below the melting point*

. *melting anomalies are due to localized high temperature (not low melting point)*

. *the mantle is almost isothermal*

. *cracks in the plates will not be volcanic unless the local temperature is anomalously high*

. *high temperatures require importation of heat from the core mantle boundary in the form of narrow jets.*

Other assumptions that motivated the plume hypothesis such as the fixity of hotspots, and the parallelism of island chains, need not concern us here. Problems with these assumptions are behind many of the paradoxes and problems associated with the standard model of mantle dynamics and chemical geodynamics. They motivated the search for alternate models, which now turns out to be plate tectonics itself, operated on by Occam's Razor.

Ptolemy's scheme of planetary motion on geocentric spheres eventually collapsed because of the large number of epicycles, eccentrics and equants introduced to patch up observational inconsistencies. William Derham (1657 – 1735) appealed to the principle of economy in opposing the Ptolemaic system;

"The Copernican System is far more agreeable to nature, which never goes in a roundabout way but acts in the most compendious, easy, and simple method." The Ptolemaic system is "forced to invent diverse strange, unnatural, interfering eccentrics and epicycles – a hypothesis so bungling and monstrous" that a king noted that he would have advised God to mend his ways.

In the Fixed Plume hypothesis it is required, that the outer shell of Earth drift westwardly relative to the deep mantle, that the mantle rolls underneath the plate, that plumes feed distant islands and that hotspots are actually large areas inside of which the volcano can move and still be regarded as fixed. Most island chains, called hotspot tracks, are not concentric circles and do not have simple age progressions as predicted and as required by Euler's equations and many are set aside since they do not satisfy the hypothesis. Volcanoes do not define a fixed reference system. Many plumes are assumed to initiate at long-standing tectonic boundaries of the plates. Alternative and simpler ideas which relate volcanoes to stress or cracks must be re-evaluated.

SUMMARY

Science can often advance by the application of the principle of simplicity. The ultimate goal of science is *unification*. By removing assumptions, amendments and auxiliary hypotheses it is possible to make plate tectonics a simpler and at the same time a more general theory. *The General Theory of Plate Tectonics* unifies plate tectonics and so-called *midplate phenomena*, and explains the diversity of magmas and other phenomena labeled as *anomalies* in the standard model.

This chapter has emphasized how philosophy and semantics can be applied in science. But logic and physics must also be involved. Plate tectonics is usually regarded as a kinematic theory, a theory of motions of rigid blocks or plates on a sphere. However, the creation and cooling of plates, and their ultimate subduction at trenches create forces that drive and break up the plates. This process also introduces chemical and thermal inhomogeneities into the mantle. The mantle, in a plate tectonic world, cannot be isothermal and chemically homogeneous, and plates cannot be under uniform stress. The melting points of mantle materials cannot all be the same. These assumptions have created the many amendments and paradoxes associated with current models. The forces that drive and reorganize plate tectonics, and create cracks and volcanic chains, cannot usefully be treated outside the context of plate tectonics itself. Plate forces such as ridge push, slab pull, and trench suction are basically gravitational forces generated by cooling plates. They are resisted by transform faults, bending and tearing resistance, collisional resistance and bottom drag. The thermal and density variations introduced into the mantle by subduction also generate forces on the plates.

Plate tectonics introduces physical heterogeneities into the mantle having dimensions typical of slabs (tens of kilometers). The density anomalies generate a force known as *slab pull*. Trench migration and the time delays associated with thermal equilibration mean that this effect is not limited to current subduction areas. Density anomalies in the mantle contribute to the deformation, elevation and motion of the lithosphere. Uplift, extensional stresses and volcanism are most likely to occur above low-density regions of the mantle, even if these are confined to the shallow mantle. Lower mantle density anomalies give broader uplift features, even if they are trapped in the deep mantle. Mantle flow is passive, is organized by the plates and is not vigorous or turbulent. Slabs sink to various depths depending on their ages and other factors. These other factors serve to limit the depth of penetration, rather than allowing young slabs to sink deeper than their buoyancy limit. Young slabs and delaminated crust also warm up quickly. A large fraction of material presently at the solid surface under oceans and a substantial amount of material currently entering subduction zones, will never sink far into the mantle, and is available as ridges and incipient ridge migrate about. In principle, ridges and trenches should be much more mobile than plates or embedded mantle heterogeneities. Particularly fertile patches of mantle, due in part to ancient subducted crust, may appear to be relatively “fixed” when compared to the mobility of surface features. It was the assumption that they were absolutely fixed that led to the plume hypothesis.

The materials introduced into the mantle at subduction zones and through cracks provide part of the material subsequently reprocessed at ridges and island chains. Thus, plate tectonics is far from being just a kinematic theory that requires extraneous theories to explain its existence and so-called ' midplate' phenomena. It is a self-contained and complete theory of geodynamics, mantle geochemistry, and mantle thermal and chemical structure and evolution. It implies the creation and migration of plate boundaries, the growth and shrinkage of plates, and global reorganizations. Magma diversity is a result of plate tectonic recycling. Mantle convection is a result of topside cooling, plate tectonics and of lithospheric architecture and motions. Lateral variations in mantle temperature, melting temperatures, melt volumes, chemistry and "age" (i.e. *anomalies*) are an inevitable result of plate tectonics.

Often, new assumptions are needed to undo the damage done by the initial unnecessary assumptions, such as fixity, rigidity, elasticity and uniformity. The *general theory of plate tectonics,* discussed here, drops most of the assumptions, adjectives and limitations of the special theory and makes it evident that plate tectonics is a much more powerful concept than generally believed. The general theory is a topdown, stress and plate controlled, largely tectonic and athermal alternative to the bottoms-up deep thermal plume hypothesis. Lithospheric architecture and stress, not concentrated hot jets, localize volcanism. Melting anomalies are due, in part, to fertility variations (Anderson, 1999, 2002a,b, Foulger, 2002, Foulger et al., 2001). The perceived limitations of the plate tectonic theory, which are thought to require special mechanisms to drive and break-up the plates and create volcanic chains, are semantic, not real, limitations.

Pluto is the god of the underworld. His name has been applied to plutonic rocks, plutons and plutonic processes. Hotspots, plumes and mantle convection can be viewed as the use of Plutonics in the rationalization of "hotspots", plumes and the organization of plates. In this view the world is organized from below. Creatures of the deep include superplumes, megaplumes, hotlines, massive mantle overturns, and mantle avalanches. I distinguish this plutonic (plume) view from the point of view that plate tectonics is a self-consistent self-organized system and that mantle geodynamics is controlled from above. Platonics places emphasis on the superficial and the geometric rather than the profound, or deep [see Appendix].

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APPENDIX

DICTIONARY

Plate tectonics

Geol., a theory of the Earth's surface based on the concepts of moving plates (PLATE n.) and sea-floor spreading, used to explain the distribution of earthquakes, mid-ocean ridges, deep-sea trenches, and orogenic belts; hence plate-tectonic a., plate tectonicist..

platonic

A. adj.

1. a. Of or pertaining to Plato, a famous philosopher of ancient Greece (B.C. c429-c347), or his doctrines; conceived or composed after the manner of Plato.
1.b. The Platonic philosophy says that the imagined world is more real than the actual world .

2. a. Applied to love or affection for one of the opposite sex, of a purely spiritual character, and free from sensual desire.
Also of affection for one of the same sex. Hence in various allusive applications. (Now usu. with lower-case initial.) …
8 A. HUXLEY in Point Counter Point xiii. 232 He had such a pure, childlike and platonic way of going to bed with women, that neither they nor he ever considered that the process really counted as going to bed. 1957 J. BRAINE Room at Top vii. 64 'Teddy wouldn't understand. Our relationship is strictly platonic.' 'Yes, I understand,' Teddy said, putting his arm round June's waist. 'I'm trying to take June on a platonic weekend. Of course, it'll be too bad if she has a platonic baby.' b. Feeling or professing platonic love.

Platonics

1. Geol., a theory of the Earth's surface based on the concept that gravitational forces in the superficial parts of the Earth, such as plates , sometimes called ridge-push and slab-pull, move and break the plates and organize mantle flow. This is a top-down theory in contrast to the bottoms-up plume hypothesis that attributes surface phenomena to deep mantle processes.In platonics volcanic chains are the result of stress and fabric in the plates. Plate tectonics as a far-from-equilibrium self-organized system is a branch of plate tectonics. Platonics is to plutonics as Marangoni convection is to Rayleigh-Benard convection. Cf. Plutonics, plumes
Also includes small-scale convection, Edge Driven Gyres and Eddies (EDGE) convection, Richter rolls,diffuse plate boundaries, continental tectonics, dikes, volcanic chains, leaky transform faults, extensional transfer

Pluto

The god of the underworld, King of Hades. Closely linked to Satan, who resides in the solid inner core of the Earth (Dante's Inferno). Also, the fallen angel, who splashed up molten rock at the antipode (pr.Easter Isl.) as he fell to his permanent abode. Thus, the god of the plume and the profound (cf. Platonics, the shallow, superficial)

Plutonic

1. Geol. a. Pertaining to or involving the action of intense heat at great depths upon the rocks forming the earth's crust; igneous. Applied spec. to the theory that attributes most geological phenomena to the action of deep internal heat: cf.
PLUTONIST.