4/18/04

First Draft 1 April 2003

Plate Tectonics ;
The General Theory

The Complex Earth is Simpler Than You Think

Don L. Anderson
dla@gps.caltech.edu

"....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."
" The only part of ' chemical geodynamics' invented in the 80s was the name. The ideas were developed in the 60s and earlier... geochemists are reluctant to abandon 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 between the upper and lower mantles. This model requires many assumptions and produces many paradoxes. The problems and complexities can be traced to a series of unnecessary and unfruitful assumptions. A simpler and more general hypothesis is described that is based on cooled from above convective systems. It relies on a theory of plate tectonics unconstrained by assumptions about absolute plate rigidity, hotspot fixity, mantle homogeneity and steady-state conditions. 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 and core. The general theory of plate tectonics,

described here, is more powerful than the current restricted forms that, by assumption, exclude incipient plate boundaries (volcanic chains) and athermal explanations (e.g. fertility variations, focusing) of melting anomalies. The tool used to simplify scientific hypotheses is known as Occam's razor.

INTRODUCTION

Ordinarily, science progresses by incremental improvements in data and theory. This paper is about how science advances through the testing, and discarding of theories, or *conventional wisdom*. Plate tectonic theory is currently undergoing such a revolution. This paper explains why plate tectonic theory, as generally understood, is in need of revision and the difficulties the geoscience community faces in making such a major change. The recognition that earthquakes and volcanoes delineate the boundaries of constantly moving plates at Earth's surface led to a new paradigm for understanding 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*. Plate tectonics has been one of the most successful theories in the history of the natural sciences and it 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. All geology textbooks were rewritten, with plate tectonics as the reigning paradigm. The idea of continental fixity has been replaced by the idea of continental mobility, and oceanic island fixity. Volcanic islands are now generally viewed as the tops of narrow hot upwellings from deep in the mantle. This plume hypothesis was invented to explain some features that were apparently outside the realm of plate tectonic theory. Students learn about plate tectonics and plumes from textbooks and their professor's lectures. Active researchers learn about Earth by observation and experiment. The two methods often are out of phase and give disparate results. 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* (the AAHA! stage). When there are too many *rationalizations, adjustments, ad hoc additions, unexplained coincidences, or failed predictions*, the community of researchers starts to lose interest and searches for more productive ideas. Meanwhile, the community of students and teachers, and researchers on the periphery of new developments, continues along the comfortable path of conventional wisdom. They are unaware of the ferment at the frontier. Scientists are involved in making discoveries, transmitting facts to students, and teaching students how to think for themselves. 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 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 had their share. Plate tectonics is 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: a set of rigid plates with narrow boundaries overlying a chemically homogeneous shallow mantle that is homogeneous and that has a simple lateral and radial temperature structure. In particular, this conception of plate tectonics does not account for broad deformed zones of the crust, some aspects of continental geology, melting anomalies (called 'hotspots') along ridges, volcanoes away from plate boundaries, and numerous geochemical paradoxes (Anderson 1999, Anderson 2002). Plate tectonic theory is further limited by the lack of agreement regarding its driving mechanisms.

There are two 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 to explain variations in bathymetry and crustal thickness.

2. Drop the assumptions that plates are fixed, rigid, and elastic, and that the underlying mantle is homogeneous. This is the approach advocated in this paper.

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, and the basic framework may even be overthrown. Later in this paper I 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 (Anderson 2002). 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." Albert Einstein is erroneously) reputed to have said that theories should be as simple as possible… but no simpler.

OCCAM'S RAZOR

Occam's razor can be used to improve, trim, simplify and discard theories, but is most useful when it is used to 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 to, at the same time, reconsider, with an open mind, the original theory and its assumptions. 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.

Radical conservatism is an approach to science that is conservative in its reluctance to introduce new assumptions; a radical approach is taken to the few assumptions that are adopted. The assumptions, as few as possible, are formulated precisely and pushed hard and applied to as many situations as possible. When Nature resists the pushing it may be time to explore an alternate lean theory rather than adding more assumptions. One must know when to retreat. But the tendency is to add more *ad hoc* assumptions, embellishments and parameters, to the existing theory. If these additions make the theory more powerful, that is, more predictive, then they are more than *ad hoc* changes to satisfy a single new datum. A theory that needs amendments for each new observation is termed *degenerating*.

I suggest that plate tectonic theory has reached such an impasse. 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 distributed continental deformation, continental breakup, large igneous provinces and island chains. Geochemical models of so-called midplate volcanoes and large igneous provinces have evolved independently of plate tectonics. Separate hypotheses, most notably, the popular plume hypothesis, have been advanced to address these phenomena. The adjective *rigid* has been attached to plate tectonics, and *fixed* has been applied to oceanic volcanic islands and the underlying mantle. These particular assumptions have diverted attention away from the true source of the phenomena, just as concepts of *ether, geocentric, phlogiston, caloric, impetus, permanence* and *immutability* held back the natural and physical sciences for millennia.

PLATE TECTONICS – CRACKS IN THE EDIFICE

The conventional statement of rigid plate tectonics with the hotspot amendment is as follows;

Earth's surface is composed of about twelve rigid plates that move with respect to each other. Volcanoes and earthquakes delineate the plate boundaries. Midplate volcanoes and volcanic islands are not related to plate tectonics. They are related to core heat and deep mantle materials.

I contend that 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 plates really rigid ?
Are they riding on a convecting mantle driven by heating from below or from within ?
Is the system in a steady state?
Can there be new (incipient) plate boundaries?

In the standard model, the upper mantle is assumed to be the source of the magmas that emerge at midocean ridges to 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. 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. There are more assumptions than necessary. Sometimes one can make progress by dropping, rather than adding, 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 sometimes cracked, and permeable to melt, rather than absolutely rigid (Anderson 2001, Anderson 2002a, Anderson 2002c, Anderson 2000, Favela and Anderson 2000). An isothermal and homogeneous mantle, everywhere subsolidus, and absolute rigidity are impossible to attain and are extraneous constraints.

As 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 standard models. For example, the normal, or expected, temperature variations in the mantle are ±200 °C (Anderson 2000). These are the temperature fluctuations expected in a convecting fluid 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 regions of high elevation, require temperatures well outside the normal range (and explanations other than plate tectonics).

Actually, other 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 a misnomer, and is based on assumptions, not on observations of temperature or heat-flow."Melting anomaly " is a better term but even this implies that there should not be regions that provide more, or less, magma than average. Bathymetric *anomalies*, or swells, are usually attributed to *hotspots*; this assumes that *normal* mantle is homogeneous in temperature, density and composition, and that all oceanic ridges should rise to exactly the same depth and have exactly the same crustal thickness.

"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. The word *midplate* implies a mechanism different than the passive upwellings or dikes associated with plate divergence, convergence, bending or shrinking.

A CONVECTING MANTLE?

Plate tectonics is a descriptive, kinematic hypothesis—it describes how plates move on the surface of the Earth. There is no consensus about what causes the plates to move beyond the understanding that cooling plates and gravitational forces are important. The plates are usually considered to be driven by some sort of mantle convection. The other extreme is similar to a flowing glacier. The glacier slides downhill and is not dragged by the underlying bedrock. Plates can also shrink, move, crack and drag themselves around, simply by cooling.

One way that geoscientists try to understand the forces driving plate tectonics is by modeling the behavior of the mantle based on principles of thermodynamics and fluid mechanics (this branch of geophysics is called mantle geodynamics). In most cases, this problem is made tractable by approximating the mantle as an ideal fluid and ignoring the effects of changes in physical properties, pressure and boundary conditions.

In 1900 a French scientist, Henri Bénard, heated whale oil in a shallow pan and noted a system of hexagonal convection cells. Lord Rayleigh analyzed this in terms of the gravitational instability of a fluid heated from below. Since that time Rayleigh-Bénard convection has been taken as the classic example of thermal convection and the hexagonal "honeycomb" planform has been considered to be typical of convective patterns at the onset of thermal convection.

The strong outer shell of 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 plates (instead of two or fifty)? What controls the size and shape of the plates? 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 (Anderson 2001, Anderson 2002c).

Ilya Prigogine (Prigogine 1980) considered the onset of thermal convection to be a spectacular example of far-from-equilibrium self-organization and the pictures of Bénard's honeycomb pattern appear as such in his books on dissipative structures. Ironically, we now know that the Bénard experiments and the hexagonal patterns were controlled by surface tension at the top of the fluid. This is now known as Marangoni or Bénard-Marangoni convection. Convection in the fluid is organized by the surface tension on top,which serves as a template. Bénard's original experiments which prompted the theories of thermal convection and self-organization of the fluid have little to do with either. There is a lesson here for mantle geodynamics and plate tectonics.

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. Computer simulations of mantle convection have been unable to reproduce plate tectonics and this may be because cause and effect have been reversed.

Prigogine has shown than open systems which are far-from-equilibrium, have a tendency to self-organize. The structures that form are relatively stable as long as the external source of energy, or matter, is maintained. Such systems, however, are sensitive to small fluctuations in temperature or stress and can change rapidly to new non-equilibrium, relatively stationary, states (Anderson 2002, Frigogine 1980).

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 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. Plate tectonics (rather than the bulk of the mantle) may be an example of Prigogine's dissipation controlled far-from-equilibrium non-linear self-organization. This may be why it has been so hard, with computer simulation, to make the surface of the Earth do what one wants. A self-organized system, if given the necessary degrees of freedom (i.e. make as few assumptions about how it *should* behave as possible), will do what it wants. In the absence of plates and continents and strong pressure effects the mantle would likely be convecting turbulently or chaotically. In the standard model of mantle geochemistry, it is assumed to do so, thereby homogenizing the 'convecting' upper mantle.

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 convection. 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. Rocks, and structures made out of rocks, are weak in tension and strong in compression. This is the basic physics behind cathedral architecture and plate tectonics (*architecture* and *tectonics* derive from the same root).

The interesting thing about this view of 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; in other words, leave it alone and it will do what it wants. 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, by some, the science of complexity. It is actually an example of Occam's Razor; the assumptions, constraints and parameters are minimized.

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 and this is the kind of convection involved in plate tectonics and the thermal evolution of the Earth (Anderson 2001). Think of a glass of ice tea; the ice cubes and the shape of the glass control the style of convection. And 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 is often assumed to drive the plates and create volcanic chains. In one theory the plates control their own fate. 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.

Hot regions of 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 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. This is also in contrast to current views of plume dynamics, which ignore the all-important role of pressure on physical properties. Finally, the processes of gravitational differentiation during the high-temperature accretion of the Earth will isolate the various regions of the mantle , even if there is only a small density contrast between them (Anderson 2002). 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; the goal of geodynamic modeling, in fact, is to determine the surface boundary condition (i.e. plate tectonics).

Small-scale convection, such as Richter rolls and sprouts and edge-driven convection, and stress variations and cracks in the plates are consequences of plate tectonics, and offer alternative explanations of volcanic chains and midplate volcanism (Anderson 2002, Jackson and Shaw 1975, Janney et al. 2000, Lynch 1999). Lateral variations in the temperature, and density (which drive mantle convection) and fertility (Cousens 1996) 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, as often assumed.

FIXED RIGID PLATES

The term *plate* itself has no agreed upon formal definition but is defined operationally as the 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 extend this observation to assume that plates are strong, brittle, permanent, rigid and elastic. The word *plate* 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 (Anderson 2001, Anderson 2002a)

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 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. Plates have higher viscosity than the underlying mantle but they are easily pulled apart, like shoals of fish or a bar of taffy. 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 buoyant magma below helps this failure by a process known as *magma-fracture*. 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, controlled by deep motionless parts of the mantle. It is now known that these "fixed" points move relative to each by three to six centimeters per year (Koppers et al. 2001), which is about the average relative plate velocity. Some continents move with respect to each other, or relative 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.

A STEADY STATE SYSTEM?

In Plato's philosophy the Earth is either *being* or *becoming*. Plate tectonics on Earth is a constantly evolving system. Plates are growing, shrinking, amalgamating and splitting, and plate boundaries are migrating and changing, The parallel between Plato's philosophy and far-from-equilibrium self-organization is so close that Prigogine entitled one of his books ***From Being to Becoming*** (Prigogine 1980). 'Uniformitarianism' and 'the present is the key to the past' are bedrock principles of classical geology. It took a very long time before catastrophes such as giant floods and impacts were considered to be respectable geological agents.

Typically we assume that plate tectonics, as it is currently manifested, is in a steady or equilibrium state. Similar amounts of crust are produced at ridges as are consumed at subduction zones. New plate boundaries look like mature plate boundaries. However, one might ask if plate tectonics has a ground state or if constant evolution (*becoming*) is a requirement of the system. One of the paradoxes that suggest that plate tectonics is not an equilibrium process is the existence of long lived supercontitnents. About 200 million years ago all of the continents were nestled in one hemisphere in a supercontinent called *Pangea*. What was happening in the rest of the world is unknown since most of the evidence has subducted (roughly 50% of the Earth's surface can recycle into the Earth's interior while the rest is unsubductable). The assembly and breakup of continents is called the *supercontinental cycle*. Although Pangea was stable for a long period of time it is unlikely that plate tectonics came to a halt. It may have been in a stationary state (which does not imply stationary plates), but in a non-equilibrium state of *being* rather than *becoming*. Heat builds up under large slowly moving plates, and is released when the plate breaks. A transient condition may be mistaken as a new phenomenon (plume) if the steady-state or uniformitarianism concept is pushed too far.

Many geoscientists agree that uniform spreading ridges and deep subduction of old dense lithosphere are aspects of steady-state plate tectonics that may not be appropriate for the opening and closure stages of oceans. The opening stage is often associated with bursts of magmatism (Large Igneous Provinces, Seaward Dipping Reflectors, Continental Flood Basalts) and acronyms (LIPs, SDRs, CFBs) that are generally attributed to plume heads. But lateral temperature gradients, tensile stress, EDGE (Edge Driven Gyres and Eddies) convection, and focusing can be important at this stage. In addition, break-up at sutures may involve particularly fertile and low melting point mantle, the remnants of young trapped oceanic plates.

Young lithosphere near ridges or in back-arc basins (BAB) are buoyant. Obduction, underplating, and flat subduction are expected to be more common than deep subduction of thick negatively buoyant slab. Most of the younger (<20 million years old) material in a closing ocean basin that is caught between converging continents is expected to stay in the shallow mantle. This includes mantle wedge material, dehydration fluids, oceanic crust and thin warm lithosphere. Continental margin basalts and thick oceanic plateaus such as Iceland, Bermuda, Rio Grande Rise and Kerguelen are possible products of this fertile shallow mantle. The mantle is unlikely to be laterally isothermal and chemically homogeneous, as in the plume models, since plate tectonics itself introduces heterogeneity, cooling and warming.

Given our acceptance of these non-steady state phenonmenon, the question becomes how much material might be involved in this end game? Since the oceanic crust and young lithosphere near ridge are buoyant compared to normal mantle the final 500 km or so of ocean closure may involve unsubductable material, or at least, material that cannot subduct below about 200 km. Near-ridge crust and lithosphere, island arcs and BAB are trapped in the shallow mantle but are deformed, obducted, shortened, and thickened. 'Subduction' and 'slab' may be foreign concepts in the terminal stages of suturing. Steady-state plate tectonics (uniformitarianism), the kind illustrated in text-books, is only appropriate for the Middle Game.

AN ALTERNATE FORMALIZATION

An alternate way of expressing plate dynamics is the following;

Earth's surface is covered by a cold shell broken into 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 shell.

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.

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 often overlooked 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 END GAMES

The endgames of plate tectonics are particularly interesting. When continents collide, and oceans close, young buoyant lithosphere and crust is inserted into the shallow mantle and some is caught in the suture. When continents break up, usually along old plate boundaries, the accessible material is different than is available in the middle game of plate tectonics, the more steady phase of the supercontinent cycle.

In the models that emphasize rigid plates, homogeneous and isothermal mantle, and steady motions, the break-up of continents and creation of island chains are attributed to deep thermal anomalies, independent of plate tectonics. These thermal upwellings also advect chemical heterogeneities into the upper mantle. Hotspots and large igneous provinces are attributed to unique and active upwelling locations in the deep mantle rather than to a stress state of the plate, which allows magma ascent from the shallow mantle.

Plate boundaries change their configurations very slowly except at times of global plate reorganizations. Plates themselves are even more constrained to change their motions – velocities and directions – slowly. The surface stress reference system therefore changes slowly. Since regions of extensile stress control the locations of magma ascent – volcanoes and dikes – a nearly fixed reference frame is predicted without anchoring volcanoes to a deep immobile layer.

THE SOURCE OF MANTLE HETEROGENEITY-RECYCLING

Although much current attention is focused on how deeply into the mantle the oldest lithospheric slabs can sink, there is abundant evidence that some recycled materials, including young slabs, never leave the shallow mantle. Some slabs are obducted (thrust over the crust), some slide at low angles under continents (flat-slab subduction), and some are trapped at various upper mantle depths, depending on their age and buoyancy. Even in deeply subducting slabs much of the material near the surface of the slab, including continental debris and altered oceanic crust, is removed or dehydrated and stays in the shallow mantle. Any such material in the outer 200 km or so of the mantle is in a mechanical, buoyant or thermal boundary layer, or in the buoyant residue of plate tectonic magmatism, and is isolated from any homogenization effects of the deeper so-called 'convecting mantle'. In spite of the wealth of recycled material available in the shallow mantle (Cousens 1996, Janney et al. 2000, Chauvel and Hemond 2000 , Meibom and Anderson, 2003) current geochemical models focus only on ultra-deep cycling of surface material, even buoyant continental lithosphere, to the CMB (Core-Mantle Boundary), before it is incorporated into OIB.

What has been overlooked is that a large amount of material created by plate tectonics, and at midocean ridges, is unsubductable or at best becomes only marginally and temporarily denser than the ambient mantle. Oceanic crust and lithosphere generated in closing ocean basins (Iapetus), small plates (Juan de Fuca), sutures (Caledonian), aseismic ridges (Cocos, Broken Ridge, Chile Rise), continental fragments (Madagascar, Seychelles, Kerguelen, 90^{o} E.Ridge), backarc basins (Lau, Manus)… contribute to upper mantle chemical (and seismic) heterogeneity as does dehydration, metasomatism, over-ridden and thickened continental crust (Tethyan belt) and delaminated continental lithosphere.

Fragments and isotopic signatures of crust, lithosphere and sediments have been identified in oceanic samples and there is no requirement or evidence that these were embedded in dense oceanic plates, or deeply recycled and returned to the shallow mantle from the core-mantle boundary). It is the *assumption* that the upper mantle is uniform and homogeneous that has led to these kinds of models. The homogenization of magma from diverse lithologies in magma chambers beneath the axis of the midoceanic ridges provides an alternate explanation for the apparent homogeneity of midocean ridge basalts. This is a consequence of sampling theory, in particular, the central limit theorem, a well known result in statistics (Meibom and Anderson 2003, Meibom et al. 2003).

I suggest that 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 which either get overridden by continents, experience flat-subduction or are quickly warmed up to a condition of neutral buoyancy. 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 continental lithosphere, 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, which 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 the mantle wedge or slabs.

RIDGES AND TRENCHES MOVE ABOUT

The textbook view of mantle convection gives 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 a convection cell. Actually, ridges and trenches migrate about the surface of the Earth. At typical ridge and trench migration rates of 1 cm/ yr 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 of the return flow (asthenosphere or upper mantle or whole mantle) 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. The time available for isotopic anomalies to grow is controlled by ridge migration rates (usually ignored), 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, or components, 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.

Ridges and trenches are not static and in fact they must move (Hamilton 2002). Large-scale regional heterogeneity, for example, near Iceland and the Azores, has been ascribed to plumes or blobs of relatively enriched material rising from great depths in the mantle (Shilling 1973). Individual OIB (Ocean Island Basalts) and some MORB (MidOcean Ridge Basalts) analyzes, however, occasionally show isotopic compositions as extreme as these, in spite of their origin from areas lacking tomographic or other manifectations of plume activity. Hotspots themselves show little evidence of elevated temperatures (Favela and Anderson 2000, Presnall et al. 2002, Green et al. 1999), either in magma temperature, heat flow, uplift, lithosphere rejuvenation, or extent of melting. Intrinsic heterogeneity is implied by geochemical sampling and deep recycling as a source of this heterogeneity is becoming an accepted dogma. I suggest, however, that much of this recycling is shallow and involves oceanic crust that was young upon subduction. This buoyant material can be isolated for long periods of time in the shallow mantle. Shallow chemical heterogeneities comprised of oceanic crust or lithosphere can also cause topographic anomalies (of both signs) and fertility and melting point variations, without thermal anomalies.

The rapid spatial and temporal changes in magma chemistry at oceanic islands are consistent with shallow heterogeneity. The abrupt chemical changes at fracture zones (often just an increase in scatter of composition) and from volcano to volcano or island to island are examples. The spatial scales of these heterogeneities are often the same scale as plate thicknesses. Seismic scattering of high frequency seismic waves is one way to test the hypothesis that crustal scale heterogeneities exist in the shallow mantle (Whitcomb and Anderson 1970, Nielsen et al. 2001).

Oxburgh and Parmentier (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 negative buoyancy of the plate.

We can therefore infer that there is likely much oceanic crust (crust that was young at the time of subduction) jammed into the shallow mantle. Mixing, stretching, and stirring of this young plate require turbulent or chaotic convection and, even in these cases, simulations give long lasting blobs (Bunge and Richards 1996). The mantle is closer to a laminar flow low Ra regime (little mixing) than to a turbulent regime. 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 assumes 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. Convection specialists are reinforcing the isotope specialists by concentrating on convective stirring, and large reservoirs instead of sampling processes, components and statistics. 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.*

COMPLETING THE LOOP

Old plates that subducted more than 30 Ma (million years ago) reside mainly in the bottom part of the transition region, near and just below 650 km (Wen and Anderson 1995, Wen and Anderson 1997). Plates which were young (< 30 Myr) at the time of subduction (e.g. Farallon slab under western N.America) and slabs subducted in the past 30 Myr are still in the upper mantle.

The distribution of ages of subducting plates is highly variable (Rowley 2002). There is a large amount of material of age 0- 20 Myr and 40-60 Myr at subduction zones. The former will underplate continents, become flat slabs or will thermally equilibrate in the shallow upper mantle. About 15 % of the surface area of oceans is composed of young or buoyant lithosphere approaching trenches (Rowley 2002) and young back-arc basins. This material will not subduct or will subduct only to 300 km or so before it is neutrally buoyant in a relatively short time. This is some of the material available for aging and ultimate use for OIB, as well as by ridges. The rate at which this young crust enters the mantle is about 2 to 4 km^3 /yr (Meibom and Anderson 2003). 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

There is no need to enter into the debate about whether some slabs can or do sink to 650, 1000 km depth or CMB (Wen and Anderson 1995). Buoyant or almost buoyant slab will certainly not get far and is likely sitting at the top of the mantle (perisphere). The pieces old enough for the eclogite phase change to make a difference may sink to greater depths but only the very oldest slabs can sink deeply and for long periods. There seems to be plenty of potentially buoyant material going down into the mantle. Since ridge re-visitation times are of the order of billions of years , there should be a range of isotopic ages and isotopic ratios in the shallow mantle . These various age slabs may well contribute to the chemical, isotopic and seismic heterogeneity of the shallow mantle. The possible presence of SOME deep-going slabs in no way affects these conclusions.

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.

This completes the loop ; we have a source of heterogeneous material of various ages and lithologies, we have arguments against effective stirring and mixing, we know how to isolate the material so isotopic anomalies can grow, we know how to sample it so it appears homogeneous, and we have arguments for variable productivty of recycled materials, and hence 'hotspots' (melting anomalies) without high temperatures, IN THE SHALLOW MANTLE! On the other hand we have petrological and isotope evidence in ocean island basalts for the various components in slabs, sometimes side-by-side (e.g. Loa, Kea trends in Hawaii).

THE PLUME ASSUMPTION

Plate tectonics is the style of convection adopted by a hot wet planet with 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 material, 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 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 are in the crust and upper mantle because of fractionation 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 heat flow, 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, however, show narrow plumes of primitive 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. And 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 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.*

. *the deep mantle is primitive (undegassed and similar to the original undifferentiated planet-forming material)*

Other assumptions that motivated the plume hypothesis such as the fixity of hotspots, and the parallelism of island chains, are also false but 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.

A historical example may help put this discussion into a broader context. Ptolemy's scheme of planetary motion 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' (volcanoes) appear 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.

SEMANTICS

The first thing to realize about hotspots is that they are not hot. It is important to realize that they are not, strictly speaking, spots either, but it is easiest if you try and realize that a little later, after you've realized that everything you've realized up to that moment is not true.

Scientific descriptions should consist of small groups of linked words that convey concepts without fixing theories. *Melting anomaly* and *midplate volcanism* are more-or-less neutral words but these have morphed to *hotspot*, and then to *plume* so we now have the Iceland and Hawaiian plumes, instead of volcanoes, and *plume* or *lower mantle* components in oceanic basalts, for materials indistinquishable from those found in sediments and crust. Alternative hypotheses for age progressive volcanic chains, such as propagating cracks and lithospheric extension, were dropped because of the perceived fixity and high temperatures of hotspots. *Anomaly* is also not a completely neutral word. It implies that something unusual, rather than expected, is going on. However, in the general theory of plate tectonics *anomalies* are expected. Likewise *midplate* neglects the fact that most such volcanism started at a plate or sub-plate boundary.

One secret about *hotspots* is that they are not particularly hot [see www.mantleplumes.org] and words like *coldspots* and *crackspots* are starting to invade the literature. They are also not 'spots'. Neither are they 'fixed' nor always unambiguously age progressive (Koppers at al. 2001). Although the belief in mantle plumes is unlikely to be soon shaken (more scientists believe in plumes than ever believed in the outdated theories of phlogiston, aether or continental fixity; belief in astrology and angels is still widespread) it seems an appropriate time to find a suitable name for alternative theories. One name is simply 'plate tectonics' itself, with the adjectives removed and the secondary features elevated to prominence. Plate collision, separation and reorganization, are natural parts of plate tectonics (the endgames). Cracks and incipient plate boundaries are part of the fabric of the plates. Only in an idealized or Platonic world can one expect plates to be rigid or elastic and their boundaries to forever fixed, and volcanoes to be restricted to the edges. The words 'imperfect' or 'non-ideal' plate tectonics do not have the appropriate ring.

'The General Theory of Plate Tectonics' , or 'Plate Theory', can include all the imperfections (such as physics and geology) of the real world and the dynamics as well as the kinematics. 'The Special Theory of Plate Tectonics' can then refer to the instantaneous or steady-state kinematics of idealized (permanent) plates, which for many non-geological purposes is accurate enough and all we need. In both cases, all motions are relative and the concepts of fixity or absolute motions do not arise.

SUMMARY

This essay shows one method by which science can advance, 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.

Plate tectonics is usually regarded as a kinematic theory, a theory of motions of rigid blocks or plates on a sphere. However, the creation of new plates at ridges, the subsequent cooling of these plates, and their ultimate subduction at trenches introduces forces that drive and break up the plates and introduce 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. 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, thermal and chemical heterogeneity 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 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 perhaps to ancient subducted crust, may appear to be relatively "fixed" when compared to the mobility of surface features.

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. Mantle convection is a result of topside cooling, plate tectonics and of lithospheric architecture and motions. Lateral variations in mantle temperature, 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 put forward as 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 (Cousens 1996, Meibom and Anderson 2003, Presnall et al. 2002). 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-organized system and that mantle geodynamics is controlled form above. Platonics places emphasis on the superficial and the geometric rather than the profound, or deep [see Appendix].

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.

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

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.

REFERENCES

Anderson, D. L., 1999, A Theory of the Earth: Hutton and Humpty-Dumpty and Holmes, *in* James Hutton - Present and Future, Craig, G.Y. and Hull, J.H. eds, Geological Society, London, Special Publications, v. 150, p. 13-35.

Anderson, D.L., 2000, Thermal State of the Upper Mantle; No Role for Mantle Plumes: Geophysical Research Letters, v. 27, no. 22, p. 3623-3626.

Anderson, D. L., 2001, Topside Tectonics: Science, v. 293, p. 2016-2018.

Anderson, D. L., 2002a, How many plates?: Geology, v. 30, p. 411-414.

Anderson, D. L., 2002b, Occam's Razor: Simplicity, Complexity, and Global Geodynamics, *in* Proceedings of the American Philosophical Society, v. 146, no. 1, p. 56-76.

Anderson, D.L., 2002c, Plate tectonics as a far- from- equilibrium self-organized system: AGU Monograph, Plate Boundary Zones: Geodynamics Series, v. 30, p. 411-425.

Anderson, D.L., 2002d, The case for irreversible stratification of the mantle: International Geology Review, v. 44, p. 97-116.

Bunge, H.-P. and Richards, M.A., 1996, The origin of large scale structure in mantle convection: effects of plate motions and viscosity stratification: Geophysical Research Letters, v. 23, p. 2987-2990.

Chauvel, C., and Hemond, C., 2000, Melting of a complete section of recycled oceanic crust: Trace element and Pb isotopic evidence from Iceland: Geochemistry, Geophysics, and Geosystems, v. 1, p. 1999, GC000002.

Cousens, B.L., 1996, Depleted and enriched upper mantle sources for basaltic rocks from diverse tectonic environments in the northeast Pacific Ocean: The generation of oceanic alkaline vs. tholeiitic basalts, *in* Hart, S.R., and Basu, A., (eds.), Earth Processes: Reading the Isotopic Code. Geophysical Monograph 95: Washington, American Geophysical Union, p. 207-232.

Favela, J. and Anderson, D. L., 2000, Extensional Tectonics and Global Volcanism, *in* Problems in Geophysics for the New Millennium, p. 463-498.

Green, D. H., Falloon, T. J., Eggins S.M., and Yaxley. G.M., 1999, Primary magmas and mantle temperatures: European Journal of Mineralogy, v. 13, p. 437-451.

Hamilton, W., 2002, The Closed Upper-Mantle Circulation of Plate Tectonics, *in* Stein, S. and Freymueller, J.T., eds., Plate Boundary Zones, Washington, D.C, American Geophysical Union, pp. DOI: 10/1029/030GD21.

Jackson, E.D., and Shaw, H.R., 1975, Stress fields in central portions of the Pacific plate: delineated in time by linear volcanic chains: Journal of Geophysical Research, v. 80, p. 1861-1874.

Janney, P. E., Macdougall, J. D., Natland, J. H. and Lynch, M. A., 2000, Geochemical evidence from Pukapuka volcanic ridge system for a shallow enriched mantle domain beneath the South Pacific Superswell: Earth and Planetary Science Letters, v. 181, p. 47-60.

Koppers, A.A.P., Morgan, J.P., Morgan, J.W., and Staudigel, H., 2001, Testing the fixed hotspot hypothesis using Ar-40/Ar-39 age progressions along seamount trails: Earth and Planetary Science Letters, v. 185, p. 237-252.

Lynch, M. A., 1999, Linear ridge groups: Evidence for tensional cracking in the Pacific Plate: Journal of Geophysical Research, v. 104, p. 29, 321-29, 333.

Meibom, A., and Anderson, D.L., 2003, The Statistical Upper Mantle Assemblage: Earth and Planetary Science Letters, v. 217, p. 123-139.

Meibom, A., Anderson, D. L., Sleep, N. H., Frei, R., Chamberlain, C. P., Hren, M. T., and Wooden, J. L., 2003, Are high $^3He/^4He$ ratios in oceanic basalts an indicator of deep-mantle plume components?: Earth and Planetary Science Letters, v. 208, p. 197-204.

Nielsen, L., Thybo, H., and Egorkin, A. V., 2001, Constraints on reflective bodies below the 8 degrees discontinuity from reflectivity modeling: Geophysical Journal International, v. 145, p. 759-770.

Oxburgh, E. R. and Parmentier, E. M., 1977, Compositional and density stratification in oceanic lithosphere- causes and consequences: Journal of Geological Society of London, v. 133, p. 343-355.

Phipps Morgan, J., 1997, The generation of a compositional lithosphere: Earth and Planetary Science Letters, v. 146, p. 213-232.

Presnall, D. C., Gudfinnsson, G. H., and Walter, M. J., 2002, Generation of min-ocean ridge basalts at pressures from 1 to 7 GPa: Geochimica et Cosmochimica Acta, v. 66, p. 2073-2090.

Prigogine, Ilya, 1980, From Being to Becoming: San Francisco, W. H. Freeman and Company.

Rowley, D. B., 2002, Rate of plate creation and destruction: 180 Ma to present: Bulletin of the Geological Society of America, v. 114, p. 927-933.

Schilling, J.-G., 1973, Iceland mantle plume: Geochemical study of Reykjanes ridge: Nature, v. 242, p. 565-571.

Wen, Lianxing and Anderson, D. L., 1995, The Fate of Slabs Inferred from Seismic Tomography and 130 Million Years of Subduction, Earth and Planetary Science Letters, v. 133, p. 185-198.

Wen, Lianxing and Anderson, D.L., 1997, Slabs, hotspots, cratons and mantle convection revealed from residual seismic tomography in the upper mantle: Physics of the Earth and Planetary Interiors, v. 99, p. 131-143.

Whitcomb, H. H. and Anderson, D. L., 1970, Reflection of P'P' seismic waves from discontinuities in the mantle. Journal of Geophysical Research, v. 75, p. 5713-5728.