

# **Occam's Razor; Simplicity, Complexity and Global Geodynamics**

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## **Simplicity**

While complexity is moving into every corner of the physical, chemical and biological sciences, simplicity, elegance and economy provide the bedrock criteria for choosing among competing hypotheses. Complexity can be viewed as a branch of mathematics. Simplicity can be viewed as a branch of philosophy or aesthetics.

Richard Feynman 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.”

Theories of planetary accretion, mantle dynamics and chemistry, plate tectonics and crustal growth evolved independently in the last century, and have been patched together to give our current view on how Earth operates. The standard view involves *rigid* plates, *fixed* plumes, *primordial* mantle, and concepts of *permanence*, *uniformitarianism* and *steady-state*. Paradoxes, inconsistencies and special pleading in standard views often can be traced back to unnecessary or non-fruitful assumptions. This is where William of Occam comes in.

## Occam's Razor

*Entia non sunt multiplicanda praeter necessitatem.*

William of Occam  
Doctor Singularis et Invincibilis  
(c. 1285-c. 1349)

William of Occam, the most influential philosopher of the 14<sup>th</sup> century, is given credit for the principle which bears his name. It is also called the Law of Economy or Parsimony.

*Entities are not to be multiplied beyond necessity.*

In science, it is best known as

*What can be done with fewer [assumptions] is done in vain with more.*

Assumptions are an important part of science but unnecessary or unfruitful ones must be pruned.

Dante Alighieri, a contemporary of William of Occam, elevated the principle to a virtue.

He wrote, in about 1300,

*All that is superfluous displeases God and nature. All that displeases God and nature is evil.*

A number of medieval writers defended the principle that nature always chooses the simplest path. William of Occam opposed this tendency to read into nature human ideas about simplicity. He felt that God may well choose to take the most complicated route. Occam shifted emphasis from the course of nature to theories which are formulated about it. He used simplicity as a criterion of concept formation and theory construction. He held that superfluous concepts are to be eliminated and that the simpler of the theories that account for a type of phenomena is to be preferred.

*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 an

hypothesis. There are many criteria for judging theories. These include elegance, power, falsifiability, predictability, contradictions and coincidences. Simplicity is one of the most useful.

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 *deus ex machina*, or a retreat to a previous stage and reconsideration of the choices that were made. The uncovering of paradox, fallacy or error is often the motivation to retreat or reconsider but the temptation is strong to plunge ahead. This is where Occam's Razor is most powerful. The retreat often allows one to develop an even more general and simple view that not only solves the immediate problem but solves what were thought to be unrelated problems. Newton's theory of gravitation is the best known example. Newton's theory explains the motions of planets and apples, glaciers and rivers, tectonic plates and erosion of mountains, and the accretion of planets.

### **Plate Tectonics**

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. Separate hypotheses 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. The concept of *absolute fixity* has been applied to oceanic island volcanoes and has 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. Rivers and glaciers stay together because parcels of water and ice experience common forces and are guided by their neighbors. 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. 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 plates have failed in tension.

There are about 150 regions of Earth's surface that have been designated as *hotspots* because of their locations, volumes of volcanics, elevation or characteristics of their magmas. These regions – many are oceanic islands - are thought to be fueled by deep narrow jets from a different part of the mantle – a deep motionless part - than is sampled by plate boundary volcanoes. This deep part of Earth is viewed as *stationary, primordial, undegassed, permanent, and accessible*. *Primordial mantle* is *assumed* to be the repository of Earth's primordial gases such as  $^3\text{He}$ . The upper mantle is viewed as *homogeneous, isothermal* and *degassed*. Volcanoes are *assumed* to have access to the deep mantle. These assumptions control thinking on how our planet operates. The *fixed hotspot* hypothesis has replaced the *fixed continents* hypothesis, which was heatedly defended between the world wars. It was war-time ocean-going technology that permitted scientists to break out of the *continental fixity* mode of thinking.

The *hotspot, plume* and *primordial* mantle hypotheses constitute the **Standard Model** of deep Earth science. This model is based on the above assumptions and is separate and

independent of the **Plate Tectonic** hypothesis which accounts for most of the architecture, volcanism and dynamics of Earth and the chemistry of most rocks and volcanoes. The magmas and “primordial” gases (e.g.  $^3\text{He}$ ,  $^{20}\text{Ne}$ ) associated with plate boundary volcanoes account for more than 99% of the magma-gas budget of Earth. Plate tectonics accounts for most of the terrestrial heat-flow. Can plate tectonics – if pushed hard enough – explain the rest of surface geology and geochemistry?

### **Radical Conservatism**

John Wheeler fortified Occam’s Razor by introducing *Radical Conservatism*. It is *conservative* in its reluctance to introduce new assumptions. Power is added by taking a *radical* approach to the few assumptions that are adopted. The assumptions must be formulated precisely and pushed hard and applied to as many situations as possible. If nature resists the pushing, a theory may self-destruct. One must know when to retreat. But the tendency is to add more assumptions, and parameters, to the existing theory. Occam’s razor can be used to improve, simplify and discard theories, but is most useful when it is used to compare theories.

Occam’s Razor is illustrated by two examples taken from the prevailing paradigm of mantle dynamics and chemistry. These are the *Primordial Mantle* hypothesis and the *Deep Mantle Plume* or *Fixed Hotspot hypothesis*. In one, the unneeded assumptions create a series of paradoxes which have been given official names such as the Lead Paradox, the Helium Paradoxes, the Heat Flow Paradox and so on. There are also unofficial paradoxes in the standard model; observations that are labeled as surprising, unexpected and counter-intuitive. These are all bell-ringer signals of a paradigm in distress.

In the other example, the observations which run counter to the predictions of the model are incorporated into it as auxiliary hypotheses or extra assumptions. In the *Fixed Hotspot*

*Hypothesis* these amendments include True Polar Wander, Mantle Roll, Lithospheric Drift, Magma Tunnels, Superplumes, and so-on. In both cases the plate tectonic hypothesis may not have been pushed hard enough.

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. Alternative and simpler ideas which relate them to stress or cracks must be re-evaluated.

On one hand the "facts to be explained" are highly selected and filtered. Discrepant observations are set aside. There are numerous assumptions and adjectives. On the other hand there is a separate auxiliary hypothesis to explain each new observation.

It is in such cases that Occam's Razor demonstrates its usefulness.

## Plate Tectonics – the standard model

Plate tectonics is a descriptive and kinematic hypothesis. It has enormous predictive power. However, there is no dynamic theory of plate tectonics beyond the understanding that cooling plates and gravitational forces are important. There is a general feeling that mantle convection is involved and plates are the top part of the convecting system. The branch of geophysics called *mantle geodynamics* focuses on the fluid dynamics of the mantle, treated as a fluid. The fluid dynamic approach has not been successful in answering the first order questions of plate tectonics, such as; why does Earth have plate tectonics in the first place, why are there twelve plates (instead of two, or fifty), what is the minimizing principle, what controls the size and shape of the plates, why are plates coherent, is there an equilibrium or ground state, and so on. It may be time to step back and reconsider.

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

*Earth's surface is composed of about twelve rigid plates which move with respect to each other. Volcanoes and earthquakes delineate the plate boundaries.*

*Midplate volcanoes are not related to plate tectonics. They are related to core heat.*

The adjectives *rigid* and *midplate* (which are actually unnecessary and inaccurate) have spawned a series of paradoxes and auxiliary hypotheses which are external to the original hypothesis. The plates are usually considered to be driven by some sort of mantle convection and this *convecting mantle* is assumed to homogenize the temperature and chemistry; *high-temperatures* and *anomalous* chemistry of volcanic products require additional assumptions. A

convecting mantle is assumed to be *well-mixed*. Midplate volcanic chains are assumed to be due to motions of the plates over *fixed* hotspots in the mantle, maintained by core heat. Note the numerous *assumptions*.

In our alternative hypothesis, plates drive and organize themselves, the mantle is hot and inhomogeneous, and the outer shell is cracked, and permeable to melt, rather than absolutely rigid. An *isothermal* and *homogeneous* mantle and *absolute rigidity* are impossible to attain and are extraneous constraints.

Many of the concepts and assumptions of the standard model are ill-defined. The terms *plate*, *midplate*, *rigid*, *high-temperature*, *anomalous*, *well-mixed*, and *fixed* are ambiguous but 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  $\pm 200$  °C<sup>1</sup>. These are the rms temperature fluctuations expected in a convecting material with the physical properties and dimensions of the Earth's mantle. 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. Actually, other factors such as mantle composition, volatile content, prior history of the area and lithospheric architecture and stress are more important factors. The word *hotspot* itself is a misnomer, and is based on assumptions, not on observations of temperature.

*Anomalous* chemistry is based on assumptions about the normal range of expected chemistry. For example, ocean island (“hotspot”) basalts usually differ in trace element or isotopic chemistry from *normal* midocean ridge basalts, although there is a large overlap and the

normal range is truncated to exclude *anomalous* values. When the distribution of helium isotopes was analyzed statistically, anomalous values were found to generally fall within two standard deviations of the mean of midocean ridge basalts<sup>2</sup>. The “anomalous,” values found along the midocean ridge system are generally attributed to hotspots or plumes, and a reservoir that is remote from the upper mantle, the presumed reservoir for the oceanic ridge system.

*Midplate* volcanoes are generally on or near plate boundaries. Regions of higher than average rates of magmatism are expected in some places since linear tabular upwellings are unstable and the mantle is not homogeneous or isothermal. The word *midplate* implies a mechanism different than the passive upwellings associated with plate divergence and convergence.

A plate can be *rigid* in the sense that relative plate motions can be described by rotations about Euler poles on a sphere but can still have meter wide cracks which is all that is needed to create volcanic chains from the hot underlying mantle. What is meant by *rigidity* is relative coherence in motions, not absolute strength.

The term *plate* itself has no agreed upon formal definition. If plate is defined operationally as that part of the outer shell that moves coherently then several interpretations are possible:

1. Plates are *strong* and *rigid* (the conventional interpretation).
2. Plates are those regions defined by lateral compression since plate boundaries are formed by lateral extension.
3. Plates move coherently because the parts experience similar forces or constraints.

With the first definition the local strength must be overcome by local heating or stretching and this reasoning has 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 from the underlying mantle which is already at the melting point.

The term *fixed* is also relative. 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 have moved relative to each by three to six centimeters per year, which is about the average relative plate velocity<sup>3</sup>. Some continents move with respect to each other, or to some oceanic plates, with much smaller velocities, yet they are not regarded as fixed.

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 shell broken into 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.*

*Corollaries:*

1. Extension is localized at plate boundaries
2. Plates are primarily under horizontal compression
3. Stresses in the outer shell are superpositions of all the gravitational and thermal stresses and are not uniform.

4. Plate boundaries and volcanic chains are the locus of maximum strain.

In many geodynamic calculations the boundaries and shapes of the plates, and their motions, are controlled “by the hand of God.” In the geodynamic equivalent of **The Theory of Everything** a computer program would provide, as output, a map of the stress field of the lithosphere, the locations of plate boundaries and volcanic chains, the forces on all the plates, and their motions relative to each other and to the interior.

If such a program calculated areas of tensile stress that correlated with plate boundaries and active volcanoes, and if these regions were relatively stationary, with respect to each other, then there would be no need for extra hypotheses, or styles of convection, to explain midplate volcanoes and their relative motion. One hesitates to use Occam’s Razor to cut off the hand of God, particularly because of Occam’s piety, but the fixed hotspot hypothesis is an extraneous assumption. As Pierre Simon de Laplace said in response to Napoleon’s complaint that there was no room for God in his theory of the universe “Sire, I have no need of that hypothesis.” The hand of God is frequently employed in current theories of mantle dynamics and geochemistry. These are sometimes called *boundary* or *initial* conditions or, by the skeptics, *tooth fairies* or *singularities* or *extraneous assumptions*.

Plate tectonics is just one manifestation of mantle dynamics. An even more general statement of the problem is as follows:

*Considering the size of Earth and its physical properties it must convect. Convection is driven by thermal and density variations. These inhomogeneities and motions act on the surface plates, both by direct contact and by Newton’s force-at-a-distance. Gravitational attraction of mass anomalies throughout the body deform and move the surface layer and determine the location of plate boundaries, i.e. regions of high strain and incipient*

*boundaries, i.e. volcanic chains. Convection is organized or modulated by plates and slabs. Lithospheric architecture and stress controls the locations of volcanoes and the cooling of the Earth.*

In a planet cooled from above the cold surface boundary layer is the *active* element. 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. Convection does not homogenize a planet; it stratifies it. Cooling plates *cause* mantle convection.

The above statement of mantle dynamics illustrates several of the attributes of a good theory. It should have broad scope, extending far beyond the observations it was designed to explain; it should be simple, bringing order to phenomena that otherwise are isolated and confused; it should be fruitful. A good theory can be tested and falsified. A good scientific theory can even be wrong.

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 insulates the mantle and isolates it from subduction cooling. The temperature increases by about 200°C under a large supercontinent, this being added to the  $\pm 200^\circ\text{C}$  range normally available in an Earth-size convecting planet<sup>4</sup>. Lateral temperature gradients and plate boundary forces break up the supercontinent 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. 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 a more general and powerful theory than generally acknowledged.

In the models that emphasize *rigid* plates, *homogeneous* and *isothermal* mantle, and *steady-state*, the break-up of continents and creation of island chains are attributed to deep thermal anomalies, independent of plate tectonics, which 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. Smoke escaping through an igloo's roof from an Eskimo's fireplace identifies the cracks, not the location of the fireplace.

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 – then a *nearly* fixed reference frame is predicted without anchoring volcanoes to a deep immobile layer. The assumptions of absolutely *rigid* plates and a *rigid* interior are unnecessary and, in Occam's terms, are unfruitful. Most volcanic chains are along breaks in the plate and are not part of any

rigid reference frame. Separate theories are needed for these unless one prunes the assumptions. The *isothermal* and *homogeneous* assumptions are not supported by models of mantle convection. A homogeneous isothermal Earth does not convect.

Plate boundaries are *ephemeral*. Ridges – regions of plate divergence – migrate around, thereby enlarging or shrinking the plates they bound. Ridges run into trenches, annihilating both and suturing two plates together. Oceanic ridges are successful tensile cracks. At one time they were incipient plate boundaries – volcanic chains that did not connect with others. An aspiring new plate boundary could be called *midplate volcanism* and viewed as an essential element in plate tectonics, when the temporal element is taken into account, or as an *extraneous* feature in a *steady-state* and *rigid-plate* context, requiring *auxiliary hypotheses*.

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.

### **Primordial**

*It is my opinion that Earth is very noble and admirable . . . and if it had contained an immense globe of crystal, wherein nothing had ever changed, I should have esteemed it a wretched lump of no benefit to the Universe.*

Galileo

The idea of a primordial unchanging Earth, eschewed by Galileo, is the simplest view of our planet. Einstein, Newton and Jeffreys, at various times proposed static universes, unchanging planets and permanent mountains. But complex scenarios must be invented in order

to achieve stasis. Simple observations contradict the idea of a primordial unchanging Earth. Recycling, a necessary consequence of plate tectonics, is essential for geology and life. Subduction recycles sediments, water and volatile elements into the mantle.

### Permanence

*I cannot without great wonder, nay more, disbelief, hear it being attributed to natural bodies as a great honor and perfect that they are immutable, inalterable, etc. . . . Those men who so extol incorruptibility, inalterability, and so on, speak thus, I believe, out of the great desire they have to live long and for fear of death . . . These people deserve to meet with a Medusa's head that would transform them into statues of diamond and jade, that so they might become more perfect than they are.*

Galileo  
Dialogue on the Great World Systems (1632)

Most of the  $^3\text{He}$  in the universe was made by the Big Bang and is therefore called a *primordial* isotope. Materials from Earth's mantle contain a small amount of  $^3\text{He}$  and this has led to a resurrection of the Primordial Mantle hypothesis, the *assumption* being that volatile or primordial components such as  $^3\text{He}$  must be contained in parts of the mantle that have never melted or degassed over the 4.5 billion years of Earth's existence or during the Earth accretion process. Some oceanic island volcanoes have higher  $^3\text{He}/^4\text{He}$  ratios than some oceanic ridges and these are *assumed* to tap the deep primordial reservoir. The *assumption* here is that *high*  $^3\text{He}/^4\text{He}$  ratios imply *excess*  $^3\text{He}$ . There is very little  $^3\text{He}$  in these basalts compared to ocean ridge basalts or lithospheric fragments so it is further *assumed* that  $^3\text{He}$  is transferred from the primordial reservoir to those other parts of the mantle which should, by *assumption*, be devoid of  $^3\text{He}$ . In

other words, new assumptions are introduced to undo the damage caused by the original (unnecessary) assumptions.

The Primordial Mantle hypothesis has little support from observations and it takes too much special pleading to be viable. Even without an alternative hypothesis Occam would not view this hypothesis with favor.

### **Philosophy**

If every new observation requires a new hypothesis then a theory becomes suspect. If every prediction fails, the hypothesis is probably wrong. It is permissible to rescue a falsified theory by means of a change in the auxiliary assumptions if such a change increases the empiric content of the theory. If the adjustments do not increase the predictability, but only explain the observed deviation, then Karl Popper dismisses the adjustments as *ad hoc*. If a research program is characterized by the endless addition of *ad hoc* adjustments that merely accommodate whatever new facts become available, it is labeled *degenerating*.

However, a theory plagued by many anomalies and auxiliary hypotheses is not discarded if there are too many adherents with too much to lose. Theories are steadfast in the face of recalcitrant data, to be jettisoned only when the time is right or when another theory is available to take its place, *and* the time is ripe.

Popper stated that a good theory must explain how it can be proved wrong. The plume theory has made various predictions about the fixity of hotspots, the parallelism of island chains, mantle heatflow, the style of mantle convection, uplift prior to magmatism and the locations of high-temperature magmas, among many others. These predictions have all been shown to be false and the hypothesis is continually being modified to include all new observations, even those

that are contrary to expectations. This means that it is no longer a scientific theory in Popper's sense. The hypothesis cannot be falsified by the rules which are currently in place.

Deep mantle *plumes* in a cold isothermal and homogeneous Earth or *cracks* and *stress* in the plates of a hot convecting Earth are alternate explanations of volcanoes. A convecting planet has lateral temperature variations and a planet with plate tectonics develops large transient temperature excesses under large episodically stationary plates. Recycling and magma removal introduce chemical heterogeneities into the mantle.

A cold non-convecting static planet can retain a primordial undegassed nucleus. A cooling convecting recycling planet creates and removes heterogeneities and the apparent heterogeneity depends on how it is sampled. Mid-ocean ridges are enormous blending and averaging machines and yield homogeneous melts from an inhomogeneous mantle. Other kinds of volcanoes and individual rocks are small grab-samples by comparison and yield a larger, more representative, variability. The *assumption* that a *homogeneous* product implies a *homogeneous* source is to a large extent responsible for both the plume and the deep primordial reservoir hypotheses. Convection and recycling maintain variations in temperature and chemistry and makes it difficult to support these assumptions. *Homogeneous, isothermal, isolated, permanence* and *steady-state* are simple philosophical concepts but natural scientists have shown that such states, if achievable at all, involve chains of complex hypotheses. These states *may* be the result of a general Earth evolution program but if they are put in as assumptions at the start it can be guaranteed that the program will be complex and extra assumptions will be needed as paradoxes accumulate. Earth dynamics is probably much simpler than we think. It is the assumptions that are complex. The science of complexity has shown us that simple rules can give complex

results. The hypothesis of plates tectonics is based on a few simple rules and has enormous predictive power.

The *hotspot*, *plume* and *primordial* mantle hypothesis, by contrast, are constantly adding and changing rules and therefore have little predictive power.

The history of science is full of hypotheses that were held onto long beyond their time. These include the ideas of phlogiston, ptolemy, polywater, ether, caloric, spontaneous generation and so on. Philosophers of science delight in these vignettes in the history of science. But it is hard to recognize these situations except by hindsight. This is true in spite of the fact that good science involves the constant questioning of assumptions, testing of hypotheses, and comparing various explanations. When the bedrock assumptions are withdrawn, confusion reigns. It is difficult, and dangerous, for a practitioner in a paradigm to question the beliefs and conclusions of his mentors and colleagues. Philosophers of science depend on historians, not scientists, and it is doubly difficult for them to recognize an on-going paradigm shift. How does one know when to retreat?

### **The Retreat; Topside Convection**

In 1900 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 instability of a fluid heated from below<sup>5</sup>. Since that time Rayleigh-Bénard convection has been taken as the classic example of thermal convection and the hexagonal “honeycomb” plan form has been considered to be typical of convective patterns at the onset of thermal convection. Ilya Prigogine 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<sup>6</sup>. Ironically, we now know that the Bénard experiments and the hexagonal patterns were controlled

by surface tension at the top of the fluid<sup>5,7</sup>. 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 have little to do with either. There is a lesson here for mantle geodynamics and plate tectonics.

The strong outer shell of Earth – the lithosphere – is often regarded as the top layer of mantle convection and plate tectonics as a manifestation of this convection. But 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.

Ilya Prigogine has shown that open systems, far-from-equilibrium have tendency to self-organize. The structures 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 stationary states.

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, the presence of continents and tectonics plates changes the surface boundary condition and serve as a template for mantle convection. It 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 plates, the locations of plate boundaries and the directions and

velocities of individual plates is controlled by interaction between the plates and the distribution of buoyancy in the plates. Plate tectonics 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, will do what it wants. Just as fluctuations of temperature can drive a convecting fluid to a new state so a fluctuation of stress 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.

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 provide the system with enough degrees of freedom so it can self-organize.

Ironically, the science which has evolved from these far-from-equilibrium considerations is called, by some, the science of *complexity*.

## **Platonics**

In Plato's philosophy the Earth is either *being* or *becoming*. The *ideal* world must be distinguished from the *real* world. 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*. One might ask if plate tectonics has a *ground state* or if constant evolution (*becoming*) is a requirement of the system. If one counts only the major long-lived ones there are about a dozen plates on the surface of the Earth. Most of these are bounded by five other plates and most have five next-nearest neighbors. This simple observation suggests that there may be a simple underlying pattern.

About 200 million years ago all of the continents were nestled in one hemisphere. This *supercontinent* is 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 one of Prigogine's *stationary*, but non-equilibrium, states of *being* rather than *becoming*.

Fragments of plates have been recognized on the seafloor and old plate boundaries are recognized on land. Just after *Pangea* broke up, about 120 million years ago, there were about twelve plates; most of the Phoenix plate has since disappeared under Antarctica, the Izanagi plate under Japan, and the Farallon plate under the Americas. The Pacific and Eurasian plates grew by accretion and the American, Antarctica and African plates added enormous amounts of oceanic lithosphere by seafloor spreading. Other plates included the Indian and Australian plates, which may have been one. Although plates grow, shrink, amalgamate, separate and disappear, there seem to have been about a dozen plates over the time that we can actually estimate the number.

Sleep<sup>8</sup> argues that plates were about the same size in the Archean, the earliest part of the geologic record.

The simplest way to subdivide the surface of a sphere with identical faces that meet three at a time is with twelve pentagons (one cannot tile a sphere with just hexagons). This is the basic structure of buckminsterfullerenes, or buckyballs. C-20 has this structure. All other fullerenes have 12 pentagons and two or more hexagons. These are the stable structures. The minimum energy shapes of bubbles in a froth are pentagonal dodecahedrons and 14-gons (twelve pentagons and two hexagons)<sup>9</sup>.

### **Platonic solids**

The pentagonal dodecahedron consists of twelve pentagonal faces, thirty edges between faces, and twenty vertices, or triple junctions, where three faces meet. Each face has five nearest neighbors and five next nearest neighbors. The pentagonal dodecahedron was considered by Plato to be the *fifth essence* or *quintessence*, and was taken by him to represent the Universe (the other bodies represented Earth, Air, Water and Fire).

The problem of the optimal size and shapes of plates on a sphere falls under the realms of topology, differential geometry and geometric measure theory. Methods of these sciences have been applied to the physical universe, soap bubble clusters, black holes, defects in materials, turbulence and crustal growth. The governing principle is often some kind of minimization or economy. The isoperimetric problem of the optimal way to subdivide space (the beehive conjecture) and the packing problems of discs, spheres and soap bubbles are examples.

The hexagonal patterns of our local flatland world are well-known (mudcracks, columnar jointing, salt flats, patterned ground, tiling, beehives, Marangoni convection). The physics of these various phenomena are quite different but the resulting patterns are strikingly similar. This

indicates that there are simple overriding topological constraints and that one can proceed far with a physics – free analysis. The physics of C-60 and soccer balls is quite different but the structures are identical. The smallest buckyball is a pentagonal dodecahedron, as is a pyrite crystal. One has hope, therefore, that the *ground* state of plate tectonics, and the elementary rules, may be discerned by applying simple geometric considerations and some minimization principle.

*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 plate tectonics. 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* view from the point of view that plate tectonics is a self-organized system and that mantle geodynamics is controlled from above. This emphasis on the *superficial* and the *geometric* rather than the *profound*, I propose to call this *Platonics*, short-hand for *plate tectonic self-organization*.

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 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.

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.

### **The Geometry of Plate Tectonics; Simple?**

In Marangoni convection and soap bubble problems the quantity to be minimized is the surface energy which is equivalent to the surface area. It is not clear what is to be minimized in the plate tectonic problem. Candidates include surface area plate, perimeter, tensional stresses and dissipation. It seems evident that the *ideal* plate tectonic planet will have plate boundaries that are arcs of great circles and that for a homogeneous planet, plates will be equant. The simplest assumption is that all plates are equal. The spherical pentagonal dodecahedron is the simplest configuration for this spherical polyhedron.

The planforms of a bubble raft and of Marangoni convection are identical close-packed hexagons. However, perturbations of the structure result in clusters of pentagons and heptagons which then form chains or dislocations of non-hexagons. Coarsening of foam involves mixed populations of large and small bubbles with various shapes ( squares, pentagons, hexagons, heptagons). The present plate-tectonic state of the Earth involves various size and shape plates. Some are shrinking, some are *coarsening* (in analogy to soap bubble foams). Just as in the soap bubble case, four – plate vertices are unstable and plates meet at triple junctions at angles of  $120^\circ$ . During plate reorganizations, one expects a variety of plate shapes and sizes. Nevertheless, the basic pentagonal dodecahedron form can be perceived for the plate topology.

The western hemisphere plates, at least, were similar in size prior to the addition of the large oceanic portions onto the continental plates bordering the new Atlantic and Indian oceans. The lost Izanagi, Phoenix and Farallon plates and the proto-Pacific plate may have been similar in size. *Supercontinent* implies a coherent welded body but supercontinents themselves may be composed of subplates which are moving slowly relative to one another, causing rifts, mountains and shear zones.

The plate tectonic situation during the precambrian is controversial. The situation may have been much the same as now, or the plates may have been much smaller or they may have been permanently buoyant. Sears<sup>10</sup> has recently suggested that the plates on the precambrian Earth had the symmetry of a truncated icosahedron, a semi-regular polyhedron with twelve pentagonal faces.

In a dynamic Earth (active plate tectonics) the plates cannot all be identical. Each boundary is a ridge, trench or transform fault. This breaks the symmetry and the faces of the plate tectonic polygon are more akin to crystal faces than to Bénard cells or soap bubbles, with isotropic tension. One must consider clusters of two or three plates in order to tile a sphere to satisfy the dynamic geometric constraints (on the present Earth about 40% of the boundaries are ridges, 40% are trenches and 20% are transform faults and most triple junctions are unstable).

On a pentagonal dodecahedron there are twenty triple junctions, or vertices. On the present Earth there are also about twenty triple junctions where ridges (R), trenches (T) and transform faults (F) meet. These are designed RRR, TTT, RTT etc... Considering the polarity of trenches and transform faults, there are, in all, 16 different kinds of triple junctions. They are not all stable. In fact, most of them evolve or change with time. In order to design a dynamic plate tectonic planet that is stationary in time, one must have all stable triple junctions.

Otherwise, the sizes of plates and the locations of boundaries will be constantly changing. This problem appears to be much more difficult than the isoperimeter, bubble, foam, packing, covering, honeycomb, fullerene structure and related problems that have occupied topologists for millennia.

### **Marangoni Convection**

Marangoni convection is a flat pan in probably the closest analog to plate tectonics. A pan of viscous fluid heated from above or below, even in the absence of gravity, will organize itself into a close-packed structure of hexagonal cells with upwellings in the center and downwellings along the linear boundaries which meet at triple junctions. The driving force is surface tension which pulls material along the surface from the hot to the cold regions. Fluid retreats in all directions from the center of the cell. The surface film of a fluid is strong in tension and fluids can be pulled along the surface.

This differs from plate tectonics in the following ways. *Plates* move coherently in one direction, a property called *rigidity*. Plates are strong under lateral compression but weak when extended. In this sense, plate tectonics is the opposite of surface tension driven convection.

The driving forces in Marangoni convection are molecular in nature and short-range. The driving forces in plate tectonics include the cooling and thickening of the plates, and their interactions. That is, they are thermal and gravitational in nature and they cannot change rapidly. It is an open question whether the hexagonal planform of surface tension driven convection can be maintained if surface tension is anisotropic, or the surface film is, rigid, or if the experiment is done in a small spherical container.

In Marangoni convection all cell boundaries are regions of convergence and downwelling, and the upwellings are in the centers of cells. In plate tectonics upwellings are also induced by divergence of the surface film, but they are linear and form plate boundaries. The equivalent of a Marangoni cell is two plates separated by a ridge, In both Marangoni convection and plate tectonics, converging regions are linear.

In Marangoni convection the surface expression of upwellings are depressed, downwellings are high and the cells are concave upward. In plate tectonics, ridges are high, trenches are low and the plate is convex up as viewed from above the ridges.

The plates on the surface of the Earth have approximately the same scale as the depth of the mantle. This has been taken as evidence that they reflect mantle wide thermal convection currents. However, Marangoni cells are also about as wide as the container is deep. I speculate that Marangoni convection on the surface of a small sphere (millimeters) or in a spherical container would organize itself into a series of pentagonal cells. The hexagonal symmetry commonly observed is due to the planar geometry, not the physics.

Likewise, I speculate that the style of convection in a spherical homogeneous planet, cooled from above will be controlled by the locations of cold downwellings, and that the planform is dominated by plates with mostly five nearest neighbors, similar in size and shape.

### **Planform of Plate Tectonics on a Ideal Sphere**

There are ten possible configurations of great-circle arcs that meet three at a time on the surface of a sphere with angles of  $120^\circ$  at their vertices<sup>9</sup>. In five of these, all faces are identical in shape. These figures are the simplest candidates for the ground state of plate tectonics on a sphere.

In the soap bubble problem the appropriate minimizations show that eight of these figures are possible soap bubble shapes. However, only one is a stable configuration. In the absence of a minimization principle it is difficult to do a similar analysis for the plate tectonic problem. As a challenge to geometric measure theoreticians I conclude by proposing the following conjectures:

**Static Conjecture (SC)**

- a. The optimal shapes of plates on a sphere are primarily spherical pentagons.
- b. The most *efficient* way to cover a sphere involves 12 plates<sup>12</sup>.

**Dynamic Conjectures (DC)**

- a. Every edge of a plate can be R,T or F. Two types of plates are required to pave a sphere that permits self-consistent instantaneous relative motions across all plate boundaries.
- b. No combinations of plate boundaries and triple junctions can be found that are stable for any spherical polyhedron having 12 or more plates (e.g. all triple junctions cannot be stable)<sup>11</sup>.

If DCb is true then plate tectonics is likely to be a constantly evolving process. If it is false, then the surface of the Earth may evolve to this state and circumstances such as the entry of a continent into a subduction zone may be required to trigger a reorganization.

The *drifting continents* – *fixed hotspot* hypotheses replaced the *fixed continents* – *shrinking Earth* hypotheses. Early geologists thought they saw global patterns of mountain and deformation belts and interpreted these in terms of an expanding or contracting Earth. These attempts are now regarded as little more than numerology and wishful thinking. Léonce Elie de Beaumont (1798-1874) connected all the world's mountains by a series of great circles that

defined a pentagonal network, or *réseau pentagonal*, along which global contraction occurred. Naomi Oreskes<sup>13</sup> criticized Elie de Beaumont's attempts to explain the entire world in terms of geometry as a case study in the mathematization of nature common in the nineteenth century. “His spectacular failure is a significant point: not all mathematization in science has been successful or productive.”

The success of mathematicians in predicting or matching structures of carbon cages, viruses, clathrates, pores, boron hydrides, foams and so on, using only economy, geometry, symmetry and simplicity as guides, should give us pause.

## Footnotes

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