Wet Tectonics: A New Global Synthesis

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Abstract
Introductory geology textbooks, many advanced texts and most common dialogue among geoscientists presumes that plate tectonics is a “solid-Earth” phenomenon, with fluids playing an important role in most geodynamic processes. Evidence summarized below suggests that Earth’s tectonic system itself is the dynamic result of water interacting with the silicate Earth. The synthesis/concept outlined herein redefines Earth’s plate tectonic system [the tectosphere; an open system extending from the base of the asthenosphere to the top of the crust, evolving as a dynamic pattern of organization that creates, orders and perpetuates itself], and elucidates its specific and fundamental genetic linkages with liquid water oceans. Fully interdependent and mutually-causational dynamics for the coupled hydrosphere and tectosphere constitute a collectively autocatalytic system, a concept of authentic circular causality that is distinct from other concepts based upon cause-to-effect explanatory chains. The “wet tectonics” model elucidated herein is simple, internally consistent, testable and constitutes a new planetary synthesis with fundamental implications for geological, geophysical, Earth system and planetary sciences, as well as geoscience education.

Introduction
Plate tectonic theory is the foundation of modern geological and geophysical sciences. In this model, radioactive decay throughout the mantle [supplemented by smaller but significant thermal contributions via relict heat of accretion] and heat transfer across the core /mantle boundary propels heat and matter transport via convection of Earth’s mantle, through whole-mantle convection or a stratigraphy of smaller convective systems. Some uncertain combination of processes are credited for the movement of Earth’s tectonic plates upon a low velocity – and presumably low viscosity – asthenosphere. In many convergent margin settings, subduction processes are accompanied by dehydration reactions in the downgoing slab; this process liberates water that facilitates partial melting, arc magmatism and the subsequent generation of new continental crust (Press and Siever, 2001).

The critical role of water is widely recognized in various geodynamic processes, including the following: magmatic systems, particularly partial melting in the mantle wedge (Ulmer, 2001) and asthenosphere (Karato, 2003; Hirth and Kohlstedt, 1996); metamorphism and metasomatic alteration (Hacker
et al., 2003a, b); crustal deformation processes [e.g. thrust faulting (Hubbert and Rubey, 1959), subduction zone seismicity (Peacock, 2001), the kinematics of accretionary wedges (Saffer and Bekins, 2002) and hydrothermal phenomena (Stein and Stein, 1994; Fisher et al., 2003a, b). The role of water in mantle dynamics has received particular attention in recent years and will be surveyed herein.

Some recent studies suggest linkages amongst climatic and tectonic phenomena, including problematic linkages between Late Cenozoic mountain building and climate change [(Molnar and England, 1990; Raymo et al., 1988); i.e. Did accelerated orogenic rates drive Pleistocene glaciations or did glacial climate create the false impression of accelerated uplift rates?]. Lamb and Davis (2003) suggest that Cenozoic uplift of the high-relief Andes orogen may be attributable to strong coupling across a thin veneer of subducting sedimentary “lubricant”, that is in turn a consequence of cool and arid coastal climates that produced low weathering rates and low rates of sediment delivery to the Andean forearc. These and other similar studies lend penetrating insight into the many interconnected aspects of plate tectonic phenomena with water, however they shed little light upon the fundamental origin and operation of the global plate tectonic phenomenon itself.

With respect to the overall operation of Earth’s tectonic system, most geoscientists apparently regard water role as a peripheral or even central modifier of global processes that are largely rooted in mantle convection and the dynamics of interacting mantle and lithosphere (Bercovici, 2003; c.f. Anderson, 2001; Hamilton, 2003). Some workers have noted very generally that water may be a prerequisite for plate tectonics, (Bercovici, 1998; Regenauer-Lieb and Kohl, 2003; Taylor, 1999) however, a comprehensive model has not been presented. I address this gap by outlining a synthesis suggesting that the dynamic and persistent hydroospheric and plate tectonic systems on planet Earth are fully interdependent and co-evolving phenomena. In short, we shall conclude that the plate tectonic phenomenon itself is the dynamic result of, participant in and perhaps driver of a circulating upper mantle interacting with a liquid water envelope on planet Earth.

The paper proceeds by introducing a new heuristic [clarifying characterization] for planet Earth and the plate tectonic system, introduces the concepts of circular causality and autocatalysis as characteristic of
many dynamic systems, and then focuses on the “wet tectonics” model. In particular, discussion of seafloor spreading, plate motion, subduction processes and asthenosphere dynamics focuses upon the genetic coupling between the plate tectonic phenomenon and liquid water oceans that permits and perpetuates them both as persistent and dynamic systems. The paper closes with a summary and discussion that includes a list of specific directives for testing this unconventional yet compelling hypothesis.

Introducing the Tectosphere

The Earth system encompasses two major realms distinguished by their primary energy sources (Figure 1). The ectosphere consists of the atmosphere, hydrosphere and biosphere, whose dynamics are largely dependent upon solar fusion and subsequent electromagnetic flux [“sunshine”] to Earth’s surface. The core, mantle and tectosphere collectively comprise the endosphere, energized largely by fission of radiogenic isotopes in Earth’s interior.

We define herein the tectosphere as the realm of global plate tectonics, a global-scale system of plate formation, plate motion, and recycling. The lower boundary of the tectosphere is defined at the base of the asthenosphere, the layer in the upper mantle distinct for its low seismic velocity, high seismic wave attenuation, and high electrical conductivity (Karato, 2003). The upper limit of the tectosphere is defined at the top of the crust. Seismically, tectosphere contains the Moho and G-discontinuities and is floored by a return to faster wave velocities that characterize the mesosphere. Designations of continental tectosphere and oceanic tectosphere are determined by the composition and origins of the crustal component. [Our usage of the term tectosphere differs entirely from the usage defined in Jordan (1975), who used it to highlight unique characteristics of the subcontinental lithosphere].

The tectosphere is defined as an interactive functional unit: its boundaries are distinct from compositional delineations of mantle and crust, and from mechanical classification of lithosphere and asthenosphere as rheological subunits of Earth’s mantle. Beyond enhancing clarity of the concepts outlined below, we find the tectosphere concept very helpful for educating students and the general public about Earth’s plate tectonic system.
Prominent phenomena of the tectosphere include formation of oceanic crust and lithosphere (= oceanic tectosphere) at divergent plate boundaries and the consumption of hydrated oceanic tectosphere in subduction zones, where mineral dehydration, partial melting, magmatism, and mountain building are concentrated. We assert that any comprehensive hypothesis for plate tectonics must account for the dynamics and mechanism of plate motion, a phenomenon we regard as an intrinsic aspect of the tectosphere phenomenon itself. In addition, we aim to demonstrate that the tectosphere is correctly conceived as an open system and dynamic pattern of organization whose dynamics result in self-organization and self-perpetuation.

Self-Organization and Autocatalysis

Articulating complexity is a prerequisite to comprehending this new planetary view. Consequently, we digress briefly to survey the linked concepts of self-organization and autocatalysis.

A Benard cell illustrates the complex flow organization that spontaneously emerges within convecting fluids systems. In this experimental system, a thermal gradient is applied to a thin fluid film sandwiched in glass; a complex and varied array of self-ordering flow patterns appear and evolve through time.

Miso soup — a common first course in Japanese restaurants and sushi bars — illustrates dynamic convection processes that illuminate the plate tectonic phenomenon. In it, suspended particles of miso constitute flow tracers; patient observation of fluid behavior in a soup bowl reveals self-organization, as described below. Diapir-like columns of hot liquid rise buoyantly to release heat at the soup/air interface that is visible as steam. Cooler, denser liquid sinks circumferentially along the outer perimeter of each rising plume, to form a toroidal (doughnut-shaped) convective pillar. The interaction of numerous convective pillars produce a quasi-hexagonal array of convective subsystems in plan view. In each case of this ubiquitous self-organization phenomenon, the hexagonal pattern is a lowest surface energy configuration, that results from vertical convective processes while itself governing the positioning of these dynamic subsystems through time. The dynamic association of vertical pillars and the quasi-hexagonal plan view pattern is one of mutual dynamic governance, that is, interdependent or circular causality (Kauffman, 1995). [Note to reader: If
your soup does not display the behavior sketched above, send it back! It is either lacking sufficient miso [viscosity too low] or it is insufficiently hot.

Articulating complexity is challenging and essential. The “chicken and egg paradox” familiar to every schoolboy appears insoluble because it is imbedded in a one-dimensional worldview of linear cause-and-effect chains. The science of cybernetics and the broader emerging science of complex systems embraces the ubiquity of circular causality for dynamic self-organizing systems (Lewin, 1992). For example, autocatalysis is a category of coupled circular interactions that occur in open chemical and biochemical systems that develop, maintain and perpetuate themselves (Figure 2; Kauffman, 1995).

Specifically, autocatalysis occurs when a reaction product is itself the catalyst for the reaction that created it; autocatalytic phenomena include stratospheric ozone destruction (Geiger et al., 2001), the citric acid (Krebs) cycle of aerobic catabolism that provides energy to each of the reader’s cells (Purves, 1992.) and perhaps the origin of Life itself (Kauffman, 1995; Kauffman, 2000). More widely, autocatalysis describes the linkage of two or more distinct subsystems that mutually permit and participate in one another’s spontaneous formation through an interconnected network of interactions.

In general, autocatalytic phenomena resemble positive (i.e. destabilizing or runaway) feedback systems, with the additional limitation that accelerating inter-reactions are limited by the availability of reactants and/or by limited production and/or transfer rates of reactants and/or catalysts. In complex adaptive systems, if sufficient reactants occur in sufficient density and with sufficient energy to propel their inter-reaction, the network of functional interrelationships that defines the system can move to a threshold, beyond which the system can spontaneously function as a collective autocatalytic whole persisting as a dynamically stable entity (Lewin, 1992). The dynamics of such systems at the “edge of chaos” occupy a phase transition of sorts, between the static order of crystalline solids and the disordered behavior alongside statistical uniformity that characterizes chaotic gas mixtures (Kauffman, 1996; Chaisson, 2001). In short, autocatalysis and more specifically collectively autocatalytic systems (Kauffman, 1996)— appear to be a distinct signature of self-ordering, self-governing and self-perpetuating systems.
A more detailed discussion of circular causality and autocatalytic phenomena is outside the scope of this short review. For our purposes these terms are effectively synonymous. Literature on these themes and broader complexity science contribute to the conceptual and perceptual underpinnings of the model described below.

The Wet Tectonics Hypothesis: How it Works

Seafloor spreading, plate motion, subduction zones and the asthenosphere are four major aspects of the tectosphere. The discussion below reviews each of these subsystems, with attention to the essential role of water, and advances to an integrated systems view.

Free water is distinct from bound water within different geological materials, where water occurs as H2O, as well as hydrogen, oxygen and hydroxyl ions and a diversity of polymorphic forms (Williams and Hemley, 2001). For simplicity of discussion, description of water associated with rocks and minerals refers to any of these species, unless otherwise specified.

Divergent plate boundaries (and their associated transform faults) on planet Earth are arranged along a near-continuous circumplanetary belt, much like the seams on a baseball. Sea floor spreading occurs along mid oceanic ridges. Hydrothermal circulation occurring along the divergent zone constitutes a convective cooling process, with profound impact upon the chemical composition of seawater and the oceanic tectosphere. For example, in the exhalative systems associated with fast-spreading sites, cold, oxic and alkaline oceanic bottom percolates vertically downward through fractures, where it quenches, cools, and chemically interacts with the oceanic crust, to produce a diverse assemblage of hydrated minerals (e.g. serpentine, phlogopite, amphibole) as well as the hot, anoxic, and acidic hydrothermal outputs that contribute substantially to bulk seawater chemistry (Elderfeld and Schultz, 1996).

Water is primarily responsible for the dramatic heat loss that accompanies quenching and cooling of oceanic crust and lithosphere. Convection at spreading centres extend to depths approaching 500-1000m and is the primary
mechanism of heat loss from the slab (Stein and Stein, 1994). Beyond ridge proximal processes, the presence of young (4300yBP) overpressured fluids in 3.5 Myr ocean crust suggests that rock/fluid interaction extends well beyond the ridge axis (Cowen, 2003). Furthermore, Fisher et al., (2003a) report rapid, large volume hydrothermal fluxes between seamount outcrops emergent above nearly impermeable sediment cover at distances exceeding 50 km; noting the commonality of seamounts and other basement outcrops on the global seafloor, they credited hydrogeological interconnectivity thru bedrock outcrops for striking heat flow anomalies via advective heat transfer (i.e. liquid water). These suggestions of deep and widespread advection of water in the oceanic tectosphere complement the conclusions of (Hacker et al., 2003a) that global ocean crust is partially hydrated (<1.3 wt. % H2O), and the uppermost mantle ranges between unhydrated to 20% serpentinized (~2.4 wt. % H2O).

Seafloor spreading occurs as buoyant upper mantle rises and undergoes adiabatic (decompression) melting, resulting in magma genesis at shallow subcrustal depths. As partial melting of rising mantle material proceeds, higher water solubility in the melt phase uptakes water from surrounding source rock, and through a process termed dehydration strengthening, melt is focused along narrow linear belts corresponding to the ridge axis (Hirth and Kohlstedt, 1996). Magma quenching occurs in the direct presence of water and/or is facilitated by steep thermal gradients resulting from convective and advective heat transfer. Hot, young and low-density oceanic tectosphere is isostatically buoyant; as the slab of oceanic tectosphere is quenched and cooled, hydration reactions accompany cooling and densification of the plate, causing vertical subsidence (Stein and Stein, 1992).

The age/depth relationship of the oceanic seafloor along traverses perpendicular to the spreading axis records an exponential subsidence path, to a near-equilibrium depth of about 4.5 km for crust at an age of about 90 Myr (Stein and Stein, 1992). Subsidence is attributable to heat loss from the oceanic crust and lithosphere to the overlying ocean, resulting in hydration, cooling and densification of oceanic tectosphere. Seen in cross-section, one may envision hot young tectosphere near the ridge crest in an elevated position with respect to Earth’s gravitational centre, and the top of older, colder and denser oceanic tectosphere some hundreds of kilometers distant about 2 km vertically downslope.
We suggest that formation and spreading of oceanic tectosphere proceeds by gravitational sliding along a topographic gradient resulting from the convective and advective cooling and subsidence of the tectosphere slab itself; we term this gravity-driven mechanism slab pull and envision its operation wherever divergent plate boundaries and sufficient liquid water are present. We suggest that gravitational potential energy via mantle-derived thermal buoyancy of young tectosphere may be the fundamental driving force of tectonic plate motion. In addition, slab pull requires mechanical decoupling of the rigid lithosphere from the low-viscosity asthenosphere, each a functional unit of the tectosphere (see below). In this sense, the asthenosphere may perhaps be regarded as the slippery layer upon which rigid plates glide.

In short, slab pull operates via thermal densification and subsidence of oceanic tectosphere, creating topography that results in extensional forces propelling plate motion. Gravitational sliding of the plate along a topographic gradient created by the thermal subsidence of the plate itself is credited for driving plate motion and perpetuating seafloor spreading. This process resembles a simple example of autocatalytic technology given in Kauffman (2000). Large pumps kept otherwise flooded mines clear for miners and permitted the British industrial revolution: iron and coal fueled the manufacture and operation of pumps that permitted the mining of iron and coal.

Subduction Zones: Trench Pull and Planetary Recycling

Subduction zones host underthrusting and dehydration of oceanic tectosphere; resultant free water in the mantle wedge and overlying crust facilitates partial melting, magmatism, plutonism, and volcanism (Ulmer, 2001). The distribution of water in subduction zones dramatically influences wave propagation and seismicity (Bostock et al., 2002; Peacock, 2001), as well as electrical resistivity (Booker, 2004). In fact, modeling results suggest that initiation of subduction itself may result from feedback processes associated with lubrication by water (Regenauer-Lieb et al., 2001). Furthermore, Peacock (2001) noted that hydration of tectosphere at spreading centres may be restricted to crustal levels, whereas deeper (25-50km) hydration may occur by thermal convection and/or seismic (dilatancy) pumping associated with fault/fracture zones.
associated with outer rise earthquakes directly outboard of subduction zones.

The magnitude of subduction and related magmatic and volcanic processes in the larger water cycle on planet Earth is uncertain. Peacock (1990) estimated that $8.7 \times 10^{11}$ kg of H$_2$O are subducted annually, with $1.4 \times 10^{11}$ kg per year being returned via arc magmatism. Williams and Hemley (2001) used these results to calculate that approximately $7.4 \times 10^{20}$ kg of water is subducted every billion years – a value approximately equal to half of the current hydrosphere – and credited subduction as the primary mechanism for regassing of the mantle. Carmichael (2002) asserted that rising plumes of water-rich magmas to the overlying crust and surface volcanoes constitute a volatile recycling mechanism he termed “the andesite aqueduct”, concluding that these return flows were approximately in balance with the mass of water globally subducted.

In simplest terms, hydrospheric water – captured via mineral hydration processes at spreading centers spreading and liberated via dehydration reactions during subduction – permits partial melting, magmatism and rock recycling that is a prerequisite to a dynamic and persistent tectosphere. Plate tectonics constitutes a recycling mechanism for water and other volatiles that is required for a dynamic and persistent hydrosphere.

Rates of plate motion on planet Earth follow a very simple pattern. Ocean basins that lack subduction zones record slow seafloor spreading ($\leq 3$ cm per year, e.g. Atlantic), whereas ocean basins rimmed by subduction zones record rates greater by a factor of 3-5x (e.g. Pacific). Conrad and Lithgow-Bertelloni (2002) compared observed plate motions associated with nine subduction zones with predicted motions computed for those same zones using different driving forces, concluding that the gravitational descent of attached slabs accounted for about half of the driving force on those plates. Further discussion subduction-related mechanical dynamics – here clustered under the term trench pull – are beyond the scope of this paper (c.f. Hamilton, 2003). We conjecture that motion of Atlantic and Pacific tectosphere may be fundamentally driven by slab pull processes as outlined in the previous section, with accelerated Pacific rates attributable to trench pull.
Asthenosphere: Earth’s "slippery layer"

Water bound into crystal structures plays a central role in mantle stratigraphy and rheology (Stevenson, 2004; Williams and Hemley, 2001), as well as the genesis of mantle-derived magmas and rocks (e.g. Bercovici and Karato, 2003). The asthenosphere is a distinctive layer in Earth’s mantle characterized by low seismic velocity, low viscosity, high seismic wave attenuation and low electrical conductivity (Karato and Jung, 1998), as well as the development of seismic anisotropies in some settings (Jung and Karato, 2001). Typically, the asthenosphere is not well-developed below continents, whereas it is a distinct and ubiquitous component of oceanic tectosphere, typically occurring between the depths of 75-150 km (Karato, 2003).

Early workers suggested that intergranular partial melts were responsible for the asthenosphere’s distinctive physical characteristics. Water was widely credited for initiating and maintaining intercrystalline partial melts — and thus low viscosity — in the asthenosphere. Most geological textbooks perpetuate this view, however this widespread belief is not supported by more recent seismological and mineral physics observations (Karato, 2003).

Many of the unique properties of the asthenosphere have been attributed to solid phase deformation processes facilitated by incorporation of water within the crystal lattice of mantle minerals, creating point and line defects. Hirth and Kohlstedt (1986) discovered that the viscosity of olivine aggregates was reduced by a factor of at least 140 in the presence of water. Karato & Jung (1998) reviewed mineral physics observations, determining that intracrystalline water significantly reduces seismic wave velocity and viscosity of mantle rocks; furthermore, they concluded that partial melting actually results in an increase in seismic wave velocity through the transfer of water from solid phase minerals into melts, suggesting that partial melting in the asthenosphere occurs only in the vicinity of mid-ocean ridges. Karato and Jung (2002) report that strain rates in olivine crystals increase a factor by 10-100 with increasing H2O content, in the absence of partial melting. The broad phenomenon
of reduced viscosity when water is incorporated into a solid
phase is termed water weakening (Karato, 2003).

In the bulk mantle, most water is generally presumed to be
primordial (Williams and Hemley, 2001; c.f. Hamilton, 2003)),
whereas sources of water in the asthenosphere remains uncertain.
Recent studies suggest that subduction processes may be capable
of delivering slab-bound hydrospheric water to asthenospheric
depths of 75 to 150 km and perhaps considerably deeper. For
example, Zhang et al. (2004) utilized high pressure mineralogical
experiments to demonstrate that subduction-zone earthquakes at
depths between 100-250 km may result from dehydration
embrittlement and associated precipitation of water at grain
boundaries. Similarly, Jung et al. (2004) utilized deformation
experiments to infer dehydration embrittlement of hydrous
minerals (principally serpentine) at depths of 50-300 km.

Bostock et al. (2002) attributed slow S-wave velocities for
mantle wedge rocks in the Cascadia subduction zone to 50-60%
serpentinization, via dehydration and upward migration of free
water from the subducting oceanic plate. We reason that if water
is liberated at a P/T threshold constituting what may effectively
be a point source, the landward horizontal gradient of decreased
water content they report may reflect lateral migration of slab-
derived water within the mantle wedge. Hacker et al. (2003a)
interpreted that mantle wedges locally reach 60-80% hydration,
while Hacker et al. (2003b) interpreted that some intermediate-
depth earthquakes are linked to slab mantle dehydration occurring
at depths perhaps as deep as 180km. Peacock (2001) credited
dehydration embrittlement of the serpentine mineral antigorite
for Pacific Rim earthquakes between 100-160 km depth.

These results converge on a working hypothesis that slab
dehydration in subduction-zones liberates mineral-bound
hydrospheric water to asthenospheric depths. As a cautionary
note, Booker (2004) used magnetotelluric data to infer
subduction-related deep (≥ 250 km) melting facilitated by water,
however, they favored a model by Bercovici and Karato (2003)
positing free water liberated via mineralogical phase change of slowly upwelling mantle from greater depths.

In sum, physical properties of the asthenosphere are largely attributable to bound water within crystalline solids. It is uncertain what proportion of that water is primordial [derived from below] or hydrospheric [derived from above]. The provenance of asthenospheric water is an intriguing topic for further interdisciplinary research.

Conclusions and Discussion:
Figure 1 presents a simple new representation of the Earth system. The tectosphere is defined herein as Earth’s plate tectonic system, which is an open system, a manifestation of self-organizing processes, and a dynamic pattern of organization that creates and perpetuates itself. The tectosphere is defined as a functional entity, that extends from the base of the asthenosphere to the top of the crust, and includes the processes of plate generation, plate motion, as well as plate consumption and recycling.

Many workers have clearly recognized that water is essential to many different aspects of Earth’s geodynamism. The wet tectonics model posits that the Earthly phenomenon of plate tectonics is the direct result of liquid water oceans at the interacting with a dynamic silicate planet.

The coupled processes of seafloor spreading (crust and lithosphere formation) and slab pull (gravity-driven plate motion) are mutually dependent upon liquid water: convective and advective quenching, cooling (and hydration) of oceanic crust and lithosphere (herein termed oceanic tectosphere) drives densification, subsidence and slab pull, further perpetuating seafloor spreading. Mass balance requires consumption of oceanic tectosphere at subduction zones, where slab dehydration permits partial melting, magmatism, plutonism, volatile recycling, crustal recycling and accelerated spreading rates via trench pull. Observations by seismologists and experimental
mineralogists are widely agreed that that low viscosity of the asthenosphere requires intracrystalline water to permit solid-state dislocation creep; we have presented results of numerous studies suggesting that asthenospheric water may be sourced from hydrosphere via slab dehydration in subduction zones (cf. Bercovici and Karato, 2003).

The maverick hypothesis presented herein posits that the origin, evolution and continuity of dynamic and persistent tectosphere and hydrosphere systems on planet Earth are linked in a circular loop of mutual causality. This view differs fundamentally from the view of most geoscientists — as explicitly described in basic textbooks and as described or implicit in many advanced texts and research articles — that plate tectonics is largely a “solid-Earth” phenomenon (e.g. Bercovici, 2003), and that fluids play an important modifying role in most geodynamic processes. Many geoscientists have accurately recognized the central role of water in many aspects of plate tectonics. This model is unique in its coupling of liquid water with the structure and operation of the plate tectonic phenomenon (tectosphere) itself.

Simply stated, we postulate herein that the tectosphere and hydrosphere are fully interdependent and mutually-causational (autocatalytic) systems. In autocatalytic chemical systems, the product molecules catalyze and perpetuate the reactions by which they themselves are formed. We envision similar genetic linkages for liquid water oceans and the global plate tectonic system (Figure 3). In short, plate tectonics is autocatalytic and all wet.

The autocatalytic aspect superficially resembles the water-free model in Bercovici (1998) who envisioned plate tectonics as an outcome of nonlinear rheological behavior resulting from the feedbacks between viscous heating and temperature-dependent viscosity in the mantle. We concur in many respects with Anderson (2001) who regarded plate tectonic plates as an open, far-from-equilibrium dissipative and self-organizing system, taking matter and energy from the mantle and converting it to mechanical forces.
that drive plate motion; this alternative to the mainstream
“bottom-up” conception of lithospheric dynamics as a surface
manifestation of self-organized mantle convection processes (e.g.
Davies, 1999; Press and Siever, 2001; Bercovici, 2003), suggests
that plate tectonics is a “top-down” process, a self-organizing
dissipative system acting to facilitate and organize mantle
convection. We concur with most aspects of his dynamic systems
view, yet we conclude that a coupled (i.e. top-down and bottom
up) systems perspective better represents the tectosphere’s
genetic relationship with itself and perhaps portions of the sub-
tectosphere upper mantle.

While peripheral to the autocatalytic model herein, we suggest
that the steady-state tectosphere may be effectively closed
materially, deriving heat energy from the mantle, but minimal
inputs of “primitive” matter from subasthenospheric depths (c.f.
Hamilton 2003). Larger subasthenospheric material fluxes such as
superplume episodes posited during Earth history (Anderson, 1994;
Coffin and Eldholm, 1994) and substantial changes in the
mechanical coupling between mantle and tectosphere (true polar
wander of Kirschvink et al., 1997) may be more accurately
understood as perturbations to steady-state tectosphere dynamics.

Hamilton (2003) posits that plate formation occurs at spreading
ridges when near-solidus asthenosphere melts adiabatically along
gaps between divergent plates (Note: more autocatalytic
coupling!). In his model, rifting of the oceanic plate permits
asthenospheric upwelling and melting that perpetuates the oceanic
plate; top-down cooling of asthenospheric material produces the
lithospheric plate. Hamilton argues that global plate circulation
results from subduction-related processes that are in turn
attributable to density contrasts attributable to top-down
cooling of oceanic mantle by seawater. The hinge rollback model
for global plate motion in Hamilton (2003) is compatible with
the autocatalytic model described herein.

Circular causality and emergent complexity is at the core of this
working hypothesis. In sum, we suggest that the tectosphere is a
self-organizing process and dynamic pattern of organization
producing and perpetuating itself at the interface of a liquid
water oceans and a dynamic silicate planet.

Testability and falsifiability is central to any new hypothesis.
Towards these ends, we list predictions of the Wet Tectonics
model to facilitate discussion and hypothesis testing:

1. Balanced global fluxes of water into and out of the
tectosphere (e.g. Carmichael, 2002)

2. The asthenosphere — like other components of the tectosphere
— is generated by and simultaneously permits global plate

3. Substantial or even predominant quantities of water in the
asthenosphere are derived from the hydrosphere, delivered
to the mantle wedge via subduction processes and laterally
distributed through an as-yet unidentified mechanism (c.f.
Bostock et al., 2002). The mechanisms and rates of
bidirectional exchange posited between the mantle wedge and
adjacent asthenosphere and hydrosphere are very poorly
constrained and certainly warrant simple modeling studies.
We anticipate that direct fluxes of water into and out of
subduction zones may not balance. In fact, if subduction
zones do recharge the asthenosphere via vertical and
horizontal migration of volatiles, balanced tectonic water
fluxes may require estimation of subducted hydrospheric
water bound into slabs, liberation of this water in
subduction zones and return fluxes to the hydrosphere
through and adjacent to oceanic tectosphere (e.g. Fisher
etal., 2003a, b).

4. The origin of the dynamic tectosphere can be successfully
modeled as the result of a superficial mobile layer on a
silicate planet interacting with a liquid-water envelope at
the planetary surface (c.f. Regenauer-Lieb and Kohl, 2003).

5. The lithosphere and asthenosphere are mechanically
decoupled; that is, the asthenosphere operates mechanically
as a slippery layer upon which the lithosphere glides. This
mechanical interaction may be reflected in seismic
anisotropies directly above and below the top of the asthenosphere (Jung and Karato, 2001).

6. Future kinematic analyses contrasting slow Atlantic versus fast Pacific seafloor spreading rates may be attributed to subduction-related, trench-pull processes that accelerate background rates attributable to gravity-driven slab pull. Alternatively, the tectonic mechanism of top-down cooling of oceanic tectosphere and plate drive via hinge rollback of subducting plates and associated mechanical coupling as described by Hamilton (2003) is compatible with the autocatalytic model outlined herein. Furthermore, since fast spreading ridges are associated with very high convective heat loss (Fisher et al., 2003b) and more rapid subsidence of young tectosphere (Stein and Stein, 1994), fast spreading may also perpetuate circular dynamics, with hydrothermal cooling driving faster subsidence rates and accelerated spreading.

7. Silicate planets possessing a convecting interior and a sufficiently voluminous liquid hydrosphere sufficient to participate in convective crustal cooling will develop a global recycling mechanism constituting plate generation, motion and consumption (Taylor, 1999; Regenauer-Lieb and Kohl, 2003) and record the association in their geologic history. For example, Sleep (1994) attributed global geomorphology on Mars to early plate tectonics, that may have been extinguished when a liquid hydrosphere was lost from the red planet (Grimm, in prep.).

8. The rapid self-organization and spontaneous complexification recorded by dynamic autocatalytic systems passing through a phase transition (Lewin, 1992; Kauffman, 1995 and 2000) suggest that the compositionally differentiated Earth possessing a circulating mantle and liquid water oceans may have developed plate tectonics very early in her history. This suggestion is partly corroborated by Wilde (2001) who discovered 4.4 Ga cores of zoned zircons reflecting origins within a granitic melt, that evolved via partial melting of a pre-existing supracrustal material that experienced low temperature
interaction with a liquid hydrosphere. Mojzsis et al. (2001) report similar findings for zircon cores dated 4.3 Ga. These studies do not confirm but are entirely consistent with an early tectosphere (=plate tectonic system) developing rapidly as the spontaneous consequence of liquid water oceans interacting with a dynamic silicate planet.

**Closure**

In sum, we regard this autocatalytic hypothesis as a testable and new fundamental theory of Earth and planetary sciences. This hypothesis of circular causality whereby open systems mutually interact to create and perpetuate a deeply coupled dynamic pattern of organization that perpetuates itself differs fundamentally from a linear worldview of “cause-to-effect” relationships or linear cause-to-effect chains.

The origins of complexity are probably simple (e.g. Lewin, 1992; Chaisson, 1998, 2001), yet they manifest in a seemingly puzzling diversity of pattern, creating a problematic intersection with deeply inculturated linear and deterministic worldviews. For example, exclusive contrasts of “top-down” versus “bottom-up” alternatives for comprehension of the plate tectonic phenomenon may be informed by decades of deliberation over irresolvable “nature or nurture” and “chicken or egg” paradoxes. In fact, these latter debates may lend little insight into the specific phenomena under consideration; rather, they reveal the fundamental ineffectiveness of linear cause-and-effect chains for interpreting an open systems world of spontaneous complexification and self-perpetuation.

Geosciences are unique amongst the natural sciences, for we possess a tangible static record of genuinely complex phenomena spanning a stupendous spatiotemporal range, alongside the opportunity to closely observe active phenomena in natural, experimental and model systems. Complexity is complex, however it is not likely complicated, and it is probably simple. We anticipate that the Earth sciences shall soon transcend linear
simplification, to embrace the uncertainty, certainty and spontaneous novelty of an authentically complex world.

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Figure Captions

Figure 1: The Earth System. The exosphere is energized by solar fluxes, the endosphere by radioactive decay and relict heat of accretion. Arrows constitute exchanges of matter and energy between different subsystems. (Although peripheral to this study, solid arrows constitute exchanges that are substantial fluxes for biogeochemical cycling at the rate scales at which self-regulation occurs; dashed arrows constitute weak or nil linkages during steady state conditions (c.f. Grimm, 2003; Hamilton, 2003).

Figure 2: The autocatalysis concept (after Fig. 3.1 in Kauffman, 1995). In autocatalytic chemical systems, the product molecules catalyze the very reactions by which they themselves are formed. In this cartoon, the product AB is a requisite catalyst for the formation of BA and the product BA is a requisite catalyst for the formation of AB. For example, the citric acid (“Krebs) cycle operates autocatalytically and is the prominent mechanism of energy liberation (catabolism) in your body (Purves, 1992).

Figure 3: Circular causality on planet Earth. Plate generation and plate motion resulting from a mobile upper layer on the silicate Earth interacting with liquid water perpetuates the self-organizing tectonic processes that propel and result in plate motion, plate generation and crustal recycling; plate tectonics permits a persistent and dynamic hydrosphere through volatile recycling. We postulate that liquid water oceans at the surface of the hot circulating mantle permitted and perpetuates spontaneous organization of the tectosphere (i.e. Earth’s plate tectonic system, extending from the base of the asthenosphere to the top of the crust). In other words, the Tectosphere is a self-making, self-maintaining and self-perpetuating pattern of organization, arising from the autocatalytic interaction of Earth’s endosphere and liquid-dominant hydrosphere. The dynamic and persistent hydrosphere is autocatalytically linked to a dynamic and persistent tectosphere and vice versa.
Exosphere "Fusion"

Atmo-

Hydro-

Bio-

Mantle

Core

Tecto-

Endosphere "Fission"
Autocatalysis (Kauffman, 1995)

○ = Reactants  ○○ = Products
■ = Interaction  ------ = Catalysis