

Plate Tectonics: The General Theory

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OVERVIEW

The standard model of mantle dynamics and chemistry involves a complex interaction between plates and plumes, and the upper and lower mantles. This model requires many assumptions and produces many paradoxes. The problems and complexities can be traced to a series of unnecessary and unfruitful assumptions. A simpler and more general hypothesis is described which is based on convective systems which are cooled from the top and relies on a theory of plate tectonics that is not constrained by assumptions about absolute plate rigidity, hotspot fixity, mantle homogeneity and steady-state conditions. Plate tectonics causes thermal and fertility variations in the mantle and stress variations in the plates, thus obviating the need for extraneous assumptions about the deep mantle and a central role for core heat. The general theory of plate tectonics is more powerful than the current geodynamic models which, by assumption, exclude incipient plate boundaries (volcanic chains) and athermal explanations (e.g. fertility variations, focusing) of melting anomalies. Important concepts in the general theory are plates, cooling from the top, the surface thermal boundary layer, self-organization, stress, pressure, the central limit theorem, ponding, the end games, recycling and fertility variations. In contrast, the plume hypothesis is a strictly thermal theory and core heat is the essential element. A brief overview of the general theory of plate tectonics is provided. The bottom line is that, if the average temperature of the upper mantle is close to the solidus, as seems probable, then normal variations in mantle temperature, fertility and volatile content (consequences of plate tectonics) will generate “melting anomalies” without the need for deep mantle plumes. The localization and rates of these melting anomalies are controlled by the lithosphere. The total volumes are controlled by the fertility of the mantle.

BACKGROUND

Plate tectonics has been one of the most successful theories in the history of the natural sciences and has revolutionized thinking in all of the Earth sciences. Yet it remains a largely descriptive and kinematic theory, albeit a remarkably predictive one. It is, however, much more powerful than generally acknowledged. Plate tectonics causes thermal and chemical inhomogeneity in the mantle, and the forces that drive the plates also cause them to deform and break. Overlooked aspects of plate tectonics are the necessity for ridges and trenches to migrate, for triple junctions and boundary conditions to evolve and for plates to interact and to reconfigure when the boundary conditions change. Second order features of plates and plate boundaries (fracture zones, accreted terranes, transform faults, broad diffuse zones, swells, sutures and microplates) and boundary reorganizations are actually intrinsic and provide the key to a more general view.

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

PLATES

The word 'plate' implies strength, brittleness and permanence and often the adjectives rigid and elastic are appended to it. But plates are collages, held together by stress and adjacent portions rather than by intrinsic strength. Plates break at suture zones (former plate boundaries), fracture zones and subplate boundaries, usually generating volcanic chains in the process. The plume hypothesis assumes that continents break up along lines that have been pre-weakened by underlying plumes. In the general theory of plate tectonics, plate architecture, fabric and stress replace high temperatures, and the igneous activity at new plate boundaries (or reactivated old ones) is a result of breakup, not the cause.

MANTLE TEMPERATURE

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

A series of recent petrology and geophysics papers is elaborating on the theme that hotspot mantle is not particularly hot (see www.mantleplumes.org for references). The idea that the shallow mantle may have variable contents of eclogite or piclogite, and volatiles is also undergoing a revival. Variable fertility of the mantle is an alternate to high temperatures in the explanation of melting anomalies. When viewed in concert with recent papers by the Morgans, the Steins, John Tarduno, Marcia McNutt and Paul Wessel, and their colleagues, on the non-fixity, non-age progression, no heat flow anomaly and non-parallelism of hotspot tracks (actually, volcanic chains) this means that the last evidence for the thermal plume hypothesis has now been removed.

Numerous ad hoc amendments have been made to the plume hypothesis (polar wander, lithospheric drift, tilted conduits, multiple plumes along a track, large radius of influence, long distance lateral flow, group motions, numerous changes in Euler poles etc.) and it may be time to consider alternatives such as propagating cracks, leaky transforms, self-propagating volcanic chains, dikes, small-scale convection etc. which may explain the data without constant ad hoc adjustments. It can be recalled that the original crack and stress hypotheses of Jackson, Shaw, Oxburgh, Walcott etc. were abandoned because they did not explain fixity, parallelism, high temperatures or excess magmatism (see the review in the USGS Professional Paper on Hawaii,

Vol. 1). Many plume hypotheses (e.g., McKenzie, Campbell) assume an isothermal and subsolidus mantle, and the more successful ones require a deep origin (CMB) and high temperatures (1600 - 1650 C). The mean temperature of the mantle and its variability are obviously key issues.

The assumptions that the upper mantle is cold, subsolidus, dry and homogeneous (unless invaded by a plume) can no longer be supported. Nor can the assumption that 'hotspots' are substantially hotter ($> 200^{\circ}\text{C}$) than other parts of the mantle, or that 'excess' magmatism uniquely requires excess temperature. Proposed plume temperatures generate too much melting. The corner flow calculations of Keen, Korenaga, King etc. generate large volumes (LIPs, Iceland...) and rates, even from normal temperature or isothermal mantle. Thus, fertility and geometry can both generate large volumes of melt with not thermal anomaly.

The volume of melting depends on source fertility, composition, focusing, history and EDGE effects (dynamic convection and fluxing of upper mantle through the melting zone by horizontal temperature gradients) as well as temperature. Lithospheric architecture and stress may be more important than localized high temperature areas. No hot thermal boundary layer is required for surface volcanism but may participate in lower mantle dynamics.

The ideas that OIB may be H_2O and FeO (K_2O , eclogite...)-rich compared to MORB are not new but it is still generally perceived that 'hotspots' are hot and have something to do with deep convective instabilities in thermal boundary layers (rather than due to dikes in extending lithosphere). Usually, crustal thickness has been used as a proxy for mantle temperatures but there are now more direct estimates. The plume hypothesis is an extraordinary one, using core heat as a geologic agent. Feynman said 'extraordinary hypotheses require extraordinary evidence'. Is there any remaining 'extraordinary evidence' that favor deep mantle plumes over more mundane plate tectonic explanations?

THE OPENING AND END GAMES OF PLATE TECTONICS

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

Fragments and isotopic signatures of crust, lithosphere and sediments have been identified in oceanic samples and there is no requirement or evidence that these were embedded in dense oceanic plates or deeply recycled and returned to the shallow mantle from the core-mantle boundary. It is the assumption that the upper mantle is uniform and homogeneous that has led to these kinds of models. The homogenization of magma from diverse lithologies in magma chambers beneath the axis of the midocean ridges provides an alternate explanation for the

apparent homogeneity of midocean ridge basalts. This is a consequence of sampling theory, in particular, the central limit theorem, a well known result in statistics.

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

STRESS

Plate boundaries change their configurations very slowly except at times of global plate reorganizations. Plates themselves are even more constrained to change their motions – velocities and directions – slowly. The surface stress reference system therefore changes slowly. Since regions of extensile stress control the locations of magma ascent – volcanoes and dikes – then a nearly fixed reference frame is predicted without anchoring volcanoes to a deep immobile layer. Plate boundaries form as the result of the stress system which involves boundary and body forces. When the boundary conditions change the stress system changes and the plates must reorganize. This involves creating new plate boundaries (volcanic chains, mountain belts) and closing down old ones.

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. The creation of new plate boundaries does not require thermal weakening (plume tracks).

THE DEEP SLAB DIVERSION

I suggest that most of the chemical heterogeneity of the upper mantle is due to subduction of sediments, fluids, crust and plates of various ages, including young plates which either get overridden by continents, experience flat-subduction or are quickly warmed up to a condition of neutral buoyancy. Only thick old oceanic plates achieve enough negative buoyancy to sink rapidly through the upper mantle but even these may contribute their fluids, and even parts of their crusts, to shallow mantle heterogeneity. I suggest, however, that much of this recycling is shallow and involves oceanic crust that was young upon subduction. This buoyant material can be isolated for long periods of time in the shallow mantle. Shallow chemical heterogeneities comprised of oceanic crust or lithosphere can also cause topographic anomalies (of both signs) and fertility and melting point variations, without thermal anomalies. The materials introduced into the mantle at subduction zones and through cracks provide part of the material subsequently reprocessed at ridges and island chains.

WRAP-UP

Plate tectonics is far from being just a kinematic theory that requires extraneous theories to explain its existence and so-called ‘midplate’ phenomena. It is a self-contained and complete theory of geodynamics, mantle geochemistry, and mantle thermal and chemical structure and evolution. It implies the creation and migration of plate boundaries, the growth and shrinkage of plates, and global reorganizations. Mantle convection is a result of topside cooling, plate tectonics and of lithospheric architecture and motions. Lateral variations in mantle temperature, melt volumes, chemistry and “age” are an inevitable result of plate tectonics.

REFERENCES

References and further background are to be found at www.mantleplumes.org