Plates and Plumes: Dynamos of the Earth's Mantle

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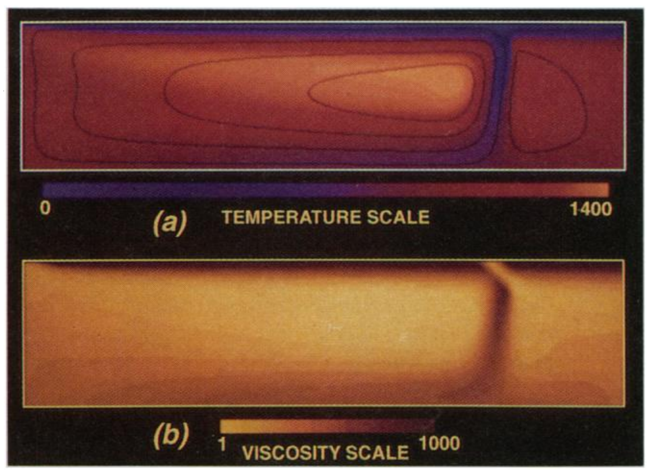
Although plate tectonics has revolutionized the geological sciences, it is an incomplete theory in two respects. It describes the motions of plates, but not the forces driving those motions, and it does not account for some events in the middle of plates, such as the Hawaiian "hot spot" volcanism or the vast Siberian "flood basalt" eruptions of 250 million years ago. Today, with the benefit of several decades of further study, we can begin to redress these deficiencies and to anticipate greater resulting insight into the earth's tectonic history.

Plate tectonics is widely believed to be an expression of convection in the mantle which, though solid, slowly deforms like a fluid on geological time scales, but there has been controversy over the details of the process. The relationship between plates and convection has been a great puzzle, in part because the plates have a variety of sizes and odd, angular shapes that shift, grow, and shrink in ways that do not resemble the behavior of more familiar convecting fluids. Various modes of convection have been proposed, some not closely related to the plates, the explanation for hot spots has been debated, and there has been a major controversy about whether the mantle convects as two separate layers or as one. There is still much disagreement on some of these questions.

A clearer view of the role of plates emerges if we go back to the basics of convection. Thermal convection is driven by one or both of two thermal boundary layers: a cold one at the top and a hot one at the bottom. Fluid motion is driven by buoyancy (positive or negative) of the fluid when a boundary layer becomes unstable and rises (or falls) away from the boundary. A distinctive feature of the mantle is the strongly temperature-dependent rheology of its silicate material. As a result, the cold upper boundary layer is stiff and strong. Also, as every geologist knows, cool rocks are brittle: they break and slide along faults or narrow shear zones. Apparently the internal stresses of the earth have been sufficient to break the strong surface boundary layer into the pieces that we call the plates. Their odd shapes and sizes can then be seen as arising from the mechanical properties of the strong lithosphere rather than from those of the underlying fluid mantle (*1*).

It follows of course that a strong downwelling will be driven where a subducting plate releases its negative buoyancy into the mantle, and there must be complementary upwellings at ridges, where plates pull apart. In other words, the plates "organize" the geometry of mantle flow. Measurements of the conducted heat flux through the sea floor show that the cycle of plate formation, cooling, subduction, and reheating accounts for more than 80% of the heat being lost from the mantle (*2*). Thermal contraction of the cooling, thickening plates also accounts for the dominant topographic feature of the sea floor, the mid-ocean ridges, which stand high relative to the subsiding top surface of the plates (*2*). This explanation implies, incidentally, that usually the upwelling under ridges is passive and not driven by local buoyant material (*2*).



Plunging plates. (**A**) Numerical model of convection with a plate as an integral part of the flow. The fluid is heated internally and cooled at the top, so there is no boundary layer at the base. The viscosity is temperature-dependent with a total variation by a factor of 1000 in this example. The cool, stiff "plate" moves to the right and descends at a low-viscosity "fault" beneath a stationary plate on the right. The (prescribed) weaknesses in the top, stiff boundary layer determine the locations of upwelling and downwelling, and hence the lateral size of the convection cells. (**B**) The viscosity structure in the model shown in (A) [adapted from (*17*)].

It follows also that away from plate boundaries much of the negative buoyancy of the plates will be trapped by their stiffness, and indeed there is a lack of evidence, in gravity and the topography of the sea floor, for "small-scale" (that is, sub–plate-scale) convection, except in some special places (*3*).

We are thus led, by fairly direct inferences from well-established observations, to conclude that there is a "plate-scale" flow that is the dominant flow in terms of heat and mass transport, at least near the top of the mantle, with the plates controlling the structure of this flow. In this view, the plates are a crucial part of the mantle convection system, comprising the upper driving boundary layer.

Is there a hot lower boundary layer? If there were, it should generate buoyant, low-viscosity upwellings that would elevate the top surface as they approached it, and might also cause anomalous melting and volcanism. Indeed, the anomalous, localized, mid-plate volcanism at Hawaii, the presence of a swell on the surrounding sea floor that is about 1 km high and 1000 km across, and the sharpness of the bend between the Hawaiian and Emperor seamount chains lead directly to the inference that there is beneath Hawaii a column of hot upwelling mantle, perhaps less than 100 km in diameter (*4*, *5*); this is just Morgan's (*4*) mantle plume proposal. There are 40 or more such volcanic hot spots scattered around the earth, and from the sizes of their swells we can deduce that their underlying plumes transport roughly 6% of the earth's heat budget through the mantle (*2*, *6*). This fits estimates of the heat that should be emerging from the slowly cooling metallic core of the earth, and supports the suggestion (*4*) that plumes come from the bottom of the mantle, nearly half-way to the center of the earth, though this conclusion is controversial.

Laboratory experiments have shown that when a new low-viscosity plume starts, it is led by a large spherical "head" that forces a path for a much narrower conduit or "tail" (*7*). Morgan (*8*) noted that some hot spot tracks emerge from flood basalt provinces and suggested that the latter may be caused by the arrival of a new plume head. After a slow gestation, this idea has recently been elaborated and better quantified, and seems to explain a variety of

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observations with considerable success (9). It has also been realized that plumes, because of their relatively high temperature and potential to uplift the surface, may have played a much more important role in the geology of continents than had been hitherto suspected (10).

There has been controversy over whether the transition zone of the mantle, where pressure-induced phase transformations occur near a depth of 650 km, prevents vertical flow and divides the mantle into separately convecting layers (11). It is argued, for example, that the composition of the lower mantle is different from that of the upper mantle or that local buoyancies associated with the phase transformations block lithosphere penetration, though these arguments are disputed (12). It is also argued that structural complications in subduction zones (13) imply that the descent of subducted lithosphere is being blocked there, and that chemical heterogeneities in the mantle sources of basalts require layering in order to explain their isolation in the mantle for up to 2 Ga. Both of these points may be as explicable with a viscosity increase across the transition zone as with a barrier to flow (14).

Two arguments against two-layered convection seem to be particularly robust. First, plumes or other upwellings originating in the transition zone would have to carry more than 70% of the earth's heat budget, instead of less than 10%, because there is not enough radioactivity in the upper mantle to account for the observed surface heat flux. Heat coming from deeper down would have to be conducted through the transition zone interface, above which a thermal boundary layer would develop, giving rise to strong plumes. There is no evidence in sea-floor topography or elsewhere for such strong upwellings (2). Second, the positive gravity and geoid anomalies over subduction zones require a large vertical separation between the dense subducted slabs and the balancing deflections of fluid surfaces required by the laws of mechanics. If there is a viscosity jump rather than a barrier to flow at 650 km, then the main compensating deflection occurs at the core-mantle boundary, so providing the required large separation. Other models do not seem to be capable of quantitatively satisfying the gravity constraints (15).

If the arguments for a single layer of convection are accepted, a relatively simple picture of mantle convection emerges in which plates comprise the top, dominant boundary layer, plumes come from a weaker bottom boundary layer, and viscosity increases by a factor of 100 or so from top to bottom. This picture seems, at this stage, to promise a satisfactory account of the dynamics of the plate-mantle system as it operates at present (16). It implies that plates cool the mantle while plumes cool the core, and it installs "plume tectonics" as an agent complementary to plate tectonics, and possibly nearly as important in the evolution of the continents.

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Nitric Oxide: First in a New Class of Neurotransmitters?

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Nitric oxide (NO) is a simple gas with free radical chemical properties, but it is often confused with the chemically distinct nitrous oxide, N_2O, which is used as an anesthetic and is chemically stable. In bacteria NO participates in nitrogen fixation and has recently been shown to function in mammals as well.

NO serves as the messenger whereby macrophages exert their tumoricidal and bactericidal effects (1). When macrophages are activated by endotoxin, a bacterial cell wall lipopolysaccharide that elicits inflammatory responses, the enzyme that makes NO, NO synthase (NOS), which transforms arginine into NO and citrulline, is markedly activated. Inhibition of NO formation by removal of arginine or by *N*-methyl-arginine, an NOS inhibitor, blocks the tumoricidal and bactericidal actions of macrophages.

NO is also a physiologic mediator of blood vessel relaxation. Stimuli that dilate blood vessels, such as acetylcholine, bradykinin, and adenosine triphosphate (ATP), lose their vasodilating activity in blood vessels stripped of endothelium (2). These mediators act upon receptors on endothelial cells to trigger the release of an "endothelial-derived relaxing factor" (EDRF), which diffuses to adjacent smooth muscle cells to elicit relaxation. EDRF has been definitively identified as NO or a close derivative that releases NO (3). Although normal release of NO mediates physiologic vasodilation, excessive release may play a role in septic shock, the symptoms of which can be relieved in animals (4) and in humans (5) by treatment with NOS inhibitors.

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The existence of NO in the brain was first suggested by demonstrations that cerebellar neuronal cultures release a factor with properties resembling NO (6), as well as by observations of NO-forming activity in brain extracts (7) and slices (8). NO acts as a messenger in the brain, where it can influence guanosine 3′,5′-monophosphate (cGMP) formation. In blood vessels NO relaxes smooth muscle by stimulating the formation of cGMP through activation of guanylyl cyclase. NO binds with very high affinity to iron in the heme of guanylyl cyclase, eliciting a conformational change that enhances the enzyme's catalytic activity. Cyclic GMP stimulates protein phosphorylation by cGMP-dependent protein kinase, leading to muscle relaxation, although the exact mechanisms are unclear. In the brain, the highest concentrations of cGMP occur in the cerebellum where glutamate, the major excitatory neurotransmitter in the brain, rapidly increases cGMP levels ten times via the *N*-methyl-D-aspartate (NMDA) subtype of the glutamate receptor (9). In these slices glutamate or NMDA triples NOS activity with concentration-response relations identical to those for the increases in cGMP (8). Moreover, selective inhibitors of NOS block the