Mantle Convection and Plate Tectonics

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Basic Features of Plates

Convection in the mantle is bounded above by mechanically strong plates. These plates move coherently, with uniform velocity within each plate and strong derivitives in velocity at plate boundaries. These derivitives manifest themselves in plate convergence (subduction, thrust faulting), divergence (ridges, normal faulting), or horizontal sliding (strike-slip, transform faulting). The first two motions produce poloidal (convergence) motion, while the latter produces toroidal (spin) motion. Toroidal motion is possible because the surface boundary layer is strong. Plate boundaries can migrate with respect to the mantle and each other as the plates are consumed or produced, meaning that the plates change in shape and size with time. The size of the plates, as a result, is highly variable. Small plates such as the Cocos or Juan de Fuca plates have length scales of 1000 km or less while the Pacific plate is over 10000 km wide. The large plates mean that in some parts of the mantle, convection is occurring with a large aspect ratio. Because an aspect ratio of one is energetically favorable for convection, we can ask the question: Why do we have large plates? The answer certainly lies in the strength of the plates.

Plate Rheology

It is of interest to try to apply a rheology to the lithosphere which will generate plate-tectonic behavior. If we simply use highly temperature-dependent viscosity, the cold upper thermal boundary layer will freeze and convection will occur only under a "rigid lid". If the temperature dependence is not strong enough, however, upwellings and downwellings are not sufficiently localized at the surface and divergence and convergence occurs in the interior of a plate. Stress-dependent (non-Newtonian power law) rheology is a possibity, but this rheology also allows divergence and convergence which is not completely localized at the plate boundaries. Another possibility is to impose weak zones at plate boundaries, but this requires that the location of these plate boundaries be determined before the calculation begins. It is also difficult to determine how these plate boundaries can evolve with time, and how new plate boundaries can be generated. Thus, imposing plate boundaries with a different rheology than that of the plate interior is somewhat ad-hoc and not as satisfying as the achievement of a rheology which produces dynamically generated plate boundaries, as the Earth does.

Dynamically Generated Plate Boundaries

Another rheology which can be used to generate plate tectonics is a stick-slip rheology, which is simply a non-Newtonian power law rheology with a power law exponent of -1. This allows stress to decrease with increasing strain rate, so when stresses build up beyond a certain point, the material is weakened and allows strain rates to increase, which further weakens the material. As a result, localized plate boundaries are formed, and the plates between them behave in a plate-like way. One problem with this rheology is that it is an instantaneous rheology - the plate boundaries have no memory of their past history. We would expect real faults to be weaker than the surrounding material and to stay that way over long periods of time. The reimposition of stress on these faults should reactivate the fault. Thus, by imposing weak zones and by allowing these weak zones to continue to be weak and to move with the plates, we should be able to generate plate tectonics. Thus, we have two rheologies which give platelike behavior - one in which faults are permanently weak (imposed weak zones) and one in which faults temporarily weak while they are being deformed (stick-slip rheology) but can be healed instantaneously if the stresses go away. Reality probably lies somewhere in between, with faults healing over some long period of time. How fault healing affects the style of plate tectonics is a somewhat open question.

The Dynamics of Slab Penetration of a Phase Change at 670 km

The endothermic phase change at 670 km depth (for slabs going downwards) offers resistance to slab penetration . Because the slab is colder than the surrounding mantle, it does not go through the phase change until it is deeper than 670 km. As a result, the portion of the slab below 670 km should slow the slab penetration. If this effect is strong enough, it could prevent slabs from penetrating the 670 seismic discontinuity and force the upper and lower mantles to convect separately. The ability of a plate to descend past 670 km depends on several quantities. First, a strong plate can more easily push through the boundary because it will not be easily deflected at the phase change. Second, small aspect ratio convection will be more affected by the phase change because small plates have less negative driving buoyancy than do large plates due to the short cooling period they have at the surface. Large plates have time to acquire thick thermal boundary layers, so their driving buoyancy may be enough to penetrate the boundary layer. An intermediate case between penetration and no penetration of the phase change is intermittent penetration in the form of "avalanches". Finally, the pattern of layered convection has important implications for the interpretation of seismic tomography data. If the cold temperatures at the base of slabs in the upper mantle are sufficient to generate a downwelling in the lower mantle below the downwelling in the upper mantle, cold temperatures should occur in an unbroken line which extends through the depth of the mantle. This line of cold material should show up in seismic tomography and could be incorrectly interpreted as whole mantle convection. This pattern of convection, however, requires the upper and lower mantles to flow in opposite directions on either side of the phase change, a pattern which requires significant shearing of highly viscous mantle material. As a result, we expect downwellings in the upper mantle to overly upwellings in the lower mantle, which would be more energetically favorable and would not require shear across the phase change. If this layered convection pattern were to occur in the earth, it should be evident from seismic tomography, which does not appear to be.