DRIVING MECHANISMS FOR PLATE TECTONICS

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RESUMEN

Está generalmente aceptada la idea de que el motor de la tectónica de placas sea algún tipo de convección térmica. La fuerza impelente puede aplicarse dentro de la placa, o bien puede transmitirse a la placa desde abajo. Las siguientes fuerzas actúan sobre una placa: 1) el exceso de peso específico y la mayor elevación de los límites de fase en la placa descendente, 2) el deslizamiento gravitacional de la placa desde las crestas oceánicas. Ambas fuerzas pueden calcularse con relativa precisión. Las fuerzas transmitidas a la placa por esfuerzos de corte aplicados en la base son mucho más difíciles de estimar. No se conoce la forma del flujo convectivo en el manto y las cifras estimativas sobre la viscosidad pueden variar en órdenes de magnitud. La posibilidad de que tales fuerzas contribuyan al mecanismo motriz de la tectónica de placas pertenece al dominio de la especulación.

ABSTRACT

It is generally accepted that some form of thermal convection drives plate tectonics. The driving force can act within the plate or can be transmitted to the plate from below. Forces acting within the plate are: 1) the negative buoyancy and elevated phase boundary in the descending plate and 2) gravitational sliding of the plate off the ocean ridge. Both of these forces can be calculated with reasonable accuracy. Forces transmitted to the plate by shear stresses acting on its base are much more difficult to evaluate. The form of the convective flow in the mantle is not known and estimates of viscosity may be in error by orders of magnitude. It is only possible to speculate whether such forces contribute significantly to driving plate tectonics.

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INTRODUCTION

Relative motions of the surface plates are now well established. It is also accepted that the surface plates are created at ocean ridges and are destroyed by descending into the mantle at ocean trenches. However there is still considerable controversy regarding the driving mechanism for the motion of the plates.

When considering the driving mechanism the first question that must be answered is the energy source. The energy source must be larger than the energy dissipated in seismicity and volcanism; this is estimated to be 10^{18} ergs/sec. Two possible energy sources have been suggested. The first is the energy being lost by the slowing of the earth's rotation and the increase in the radius of the lunar orbit. This is estimated to be 3×10^{19} ergs/sec. The second source is radioactive heat production within the earth. This is estimated to be 3×10^{20} ergs/sec.

Having found adequate energy sources it is necessary to find mechanisms for converting energy into motion. No satisfactory mechanisms have been proposed for converting rotational energy into mantle flows. On the other hand thermal energy is readily converted into motion through thermal convection. A number of authors have shown that the estimated Rayleigh number for the mantle is several orders of magnitude larger than the critical value required for thermal convection.

The other nondimensional parameter that governs thermal convection is the Prandtl number. For the mantle the Prandtl number is very large, diffusion of vorticity is much more rapid than conduction of heat. Thermal convection for large values of the Rayleigh and Prandtl numbers has a boundary layer character. This is illustrated in Fig. 1 for two-dimensional convection of a fluid layer heated from below. The flow takes the form of counterrotating cells. Thermal boundary layers form on the hot and cold boundaries. These boundary layers become gravitationally unstable and separate from the boundaries to form hot ascending and cold descending plumes.

The gravitational body forces in the plumes drive the highly viscous core flow.

BODY FORCES

Although mantle convection can only be approximated by a constant viscosity theory, our knowledge of the structure of the earth's lithosphere is consistent with the boundary layer theory. As shown in Fig. 2 the lithosphere behaves like the cold thermal boundary layer of a mantle convection cell. The isotherm at which rock behaves as a rigid material defines the lower boundary of the lithosphere. The lithosphere becomes gravitationally unstable and sinks into the mantle at ocean trenches. The gravitational body force on the descending lithosphere is a primary mechanism for driving plate tectonics.

In addition to the body force due to thermal contraction in the descending lithosphere, there is also a body force due to the elevation of the olivine-spinel phase boundary. For a typical descending lithosphere these body forces have been determined by Turcotte and Schubert (1971) and the results are given in Table 1. The values are probably accurate to a factor of two.

There is also a body force on the lithosphere due to the presence of the midocean ridge. This body force is the component of the gravitational body force due to the slope of the topography, i.e. gravitational sliding. The hydrostatic pressure associated with the change in topography gives an equivalent horizontal pressure gradient. In terms of laboratory convection this body force is due to the horizontal pressure gradient associated with ascending convection. The body force for a typical ridge has been determined by Turcotte and Oxburgh (1969) and is given in Table 1.

OTHER FORCES

In the boundary layer theory for thermal convection the fluid below the cold thermal boundary layer resists the flow through viscous interaction with the boundary layers and plumes. If we assume that this is also the case in mantle convection we can estimate the viscosity of the mantle below the lithosphere. An approximate expression for the drag on the lithosphere is

$$f_v = L\,\eta\frac{\Delta\mu}{h} \tag{1}$$

where L is the horizontal dimension of the lithosphere, η the viscosity, $\Delta\mu$ the velocity of the lithosphere, and h the vertical extent of the flow. From the previous estimates we take $f_v = 10^{17}$ dynes/cm, also $\Delta\mu = 10^{-7}$ cm/sec and $L/h = 10$. Substitution of these values into Eq. (1) gives $\eta = 10^{23}$ poise. Since it is estimated that the viscosity of the upper mantle is in the range $10^{21} - 10^{22}$ poise it is clear that the body forces on the lithosphere are sufficient to overcome the viscous drag on its base.

Studies of earthquake focal mechanism (Isacks and Molnar, 1971) indicate that the lower part of the descending lithosphere is often in compression. The conclusion is that the deep lithosphere is encountering a large resistance to its motion. This is probably due to the increase in viscosity with depth expected from the pressure dependence of solid state viscosity. This resistance may place an upper limit on plate velocities.

CONCLUSION

In the absence of evidence to the contrary it seems reasonable to conclude that mantle convection is similar to laboratory convection; that the lithosphere as the cold thermal boundary layer plays a dominant role in the convection pattern; that the body forces on the lithosphere are the dominant driving mechanisms for plate tectonics; and that the mantle plays a passive role in the convection, resisting the motion through viscous interaction and closing the streamlines with slow flows.

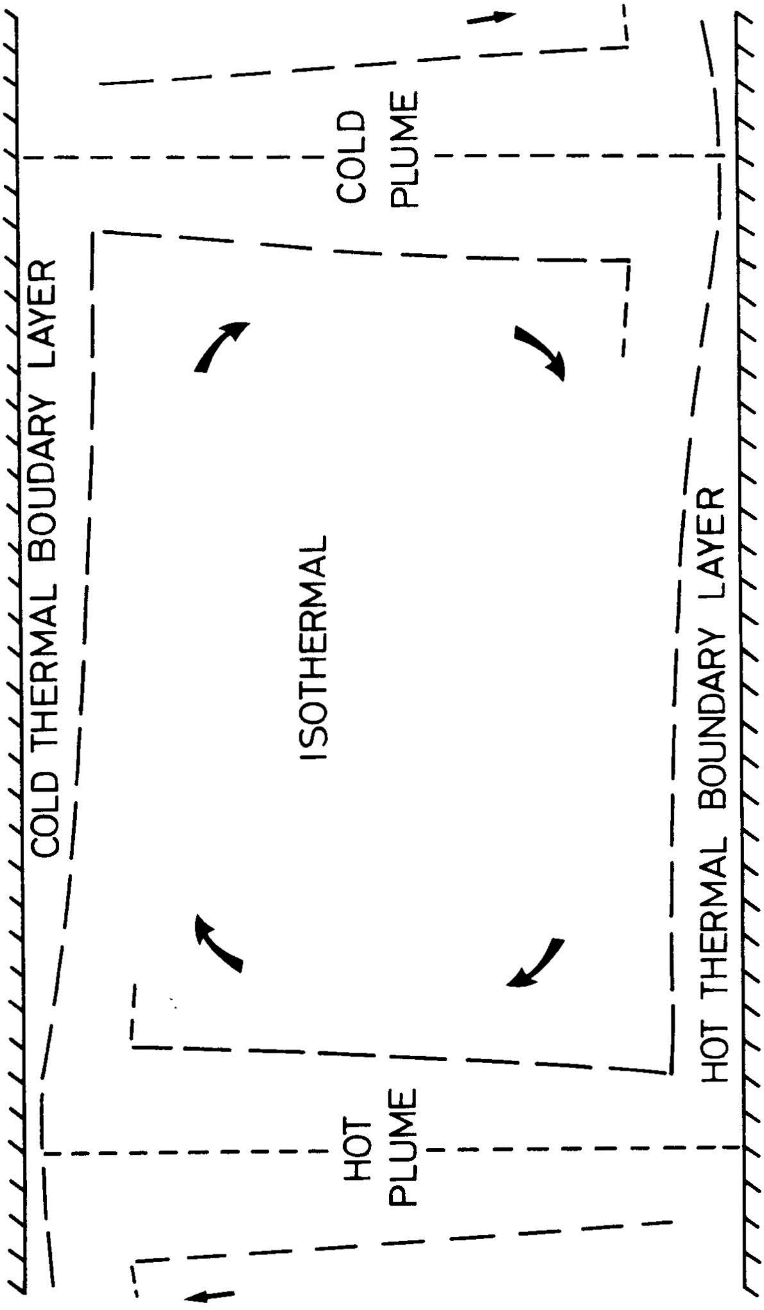

Figure 1. Boundary layer structure of thermal convection cells at large Rayleigh and Prandtl numbers.

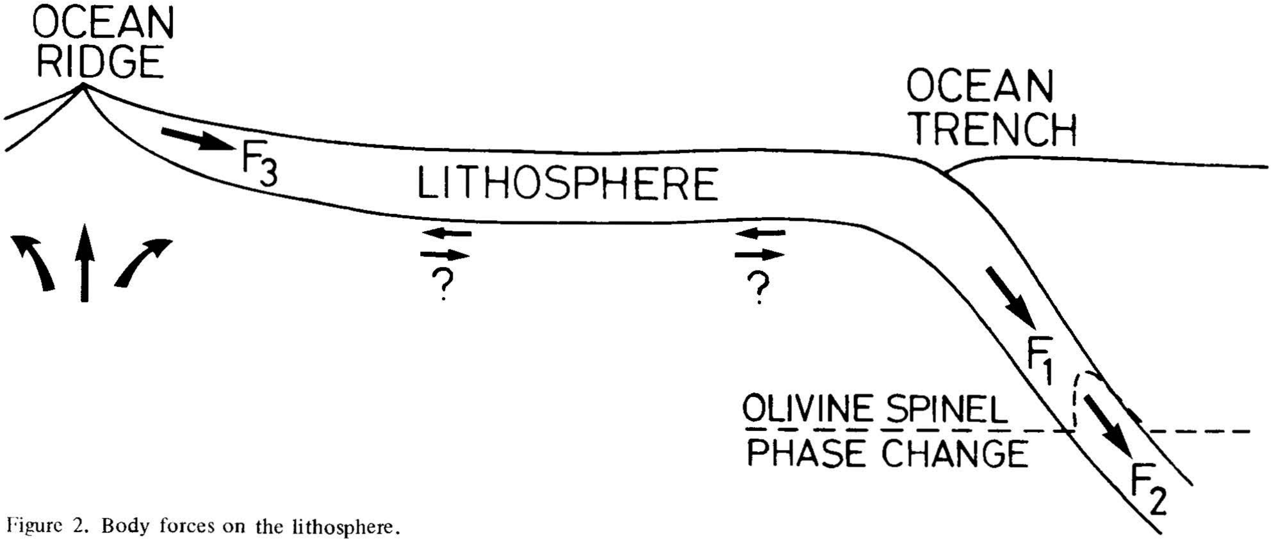

Figure 2. Body forces on the lithosphere.

TABLE 1

BODY FORCES ON THE LITHOSPHERE

Body forces on the descending lithosphere due to:	
1. Thermal contraction	15 x 10^{16} dynes/cm
2. Elevation of the olivine-spinel phase boundary	5 x 10^{16} dynes/cm
Body forces on the lithosphere at an ocean ridge due to:	
3. Gravitational sliding	4 x 10^{15} dynes/cm

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