FINITE ELEMENT MODEL FOR LITHOSPHERIC THINNING BY A MANTLE PLUME

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Continental hot spots on Earth are often associated with uplift and rifting. Uplifted and rifted structures are also found on other terrestrial planets (the Beta Regio and the Aphirodite-Beta linear on Venus, the Tharsis plateau and the Valles Marineris on Mars) and they suggest the possible past or present existence of hot spots on these bodies. It has been proposed that hot spots are the surface manifestations of mantle plumes, possibly of deep origin. A hot plume, incident at the base of the lithosphere, is able to erode the lithosphere by heating it and carrying away material made mobile by virtue of its higher temperature. The thinning of the lithosphere causes isostatic uplift and the possible initiation of rifting.

Lithospheric thinning by a mantle plume is a coupled thermal and mechanical phenomenon and it is essential to model both aspects of the process self-consistently. Turcotte and Emerman (1) and Emerman and Turcotte (2) have approached the problem using a similarity solution of a stagnation point flow. We have studied the problem from a numerical point of view. We use a finite element code originally developed by Thompson (3) and modified by Schubert and Anderson (4) in a recent study of thermal convection. In order to simulate lithospheric thinning by a hot rising plume we consider the temporal evolution of flow and temperature in a convective cell whose bottom temperature is abruptly increased.

The equations of mass, momentum and energy conservation for an incompressible, Boussinesq, infinite Prandtl number fluid with Newtonian temperature dependent viscosity are solved for a square box geometry. The free-slip condition is specified on all boundaries; the top and bottom boundaries are isothermal and the vertical sides are insulated. The dependence of viscosity μ on temperature T is assumed to have the exponential form

$$\mu(T) = \mu_0 \exp[A/(RT)],$$

where R is the gas constant, A is the activation energy, and μ_0 is a constant. The values of μ_0 and A were chosen to give $\mu = 10^{21}$ Pa s and $\mu = 10^{23}$ Pa s for T = 2200 °C and T = 1000 °C, respectively. With this form of the viscosity function, the change in temperature between the surface and the base of the lithosphere produces a variation in μ of 17 orders of magnitude. The numerical procedure accounts for this large viscosity variation across the lithosphere.

We first obtain steady state solutions for convection beneath lithospheres of different thickness. Lithospheres with a variety of thicknesses are obtained self-consistently by varying the bottom temperature. We next investigate the transient process that leads from one steady state to another, with particular attention on the thinning of the lithosphere directly above the warm rising plume. The transient solution is obtained using a Crank-Nicholson algorithm with a time step $\Delta t \leq \Delta L/V_{max}$, where ΔL is the grid spacing and V_{max} is the maximum value of the material velocity in the cell. The steady state solution with the lowest bottom temperature is the initial condition for the transient analysis; a sudden increase of the bottom temperature causes the formation of a new hot plume that rises along the vertical boundary. This method allows us to simulate the emplacement of a high temperature, high velocity, high heat flux plume beneath the lithosphere. When the hot plume reaches the base of the lithosphere, it warms and carries away the formerly rigid material, thereby causing the thinning of the lithosphere.

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We have obtained preliminary results for a bottom temperature increased from 1600 to 2000 °C at t=0. The process of thinning starts after an interval of time (Δt_0) in which the hot plume is formed and rises toward the lithosphere. We have found that the lithosphere thickness (ℓ) decreases with the square root of time [$\ell \propto (t - \Delta t_0)^{-1/2}$], in agreement with the results found by Spohn and Schubert (5). The vertical velocity of the lithosphere-asthenosphere boundary is ≈ 0.12 km Ma^{-1} at $t = \Delta t_0$; it decreases to about 0.06 km Ma^{-1} when half of the thinning is completed. These small values of the thinning rate are a consequence of the relatively small initial heat flow (11.9 mW m^{-1}) and the small increase in plume heat flux by only a factor of ≈ 2. Additional results will be presented for the dependence of lithospheric thinning rate on the increase of plume heat flux between the initial and the final steady states, on the initial lithospheric thickness, and on the rheological parameters of the material.

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