MANTLE CONVECTION: RAYLEIGH-BÉNARD PLUS PLUMES AND PLATES? OR PEKERIS WITH INTRINSIC SMALLER SCALES?

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ABSTRACT

There are three distinct mechanisms which might give rise to convection in the Earth's mantle. Rayleigh-Bénard takes place if the radial superadiabatic gradient exceeds a critical value, for a fluid heated from below. Convection may also be driven by internal heat sources or secular cooling. Convection grows from unstable perturbations to a static equilibrium. No equilibrium is possible if horizontal temperature gradients are present; convection will start if there is any horizontal thermal gradient no matter how small. There is no critical Rayleigh number. This type of convection was first discussed by Pekeris (1935) in the context of an irregular distribution of continental crust on the surface.

"Plume convection" is a hypothetical thermal mechanism which is smaller scale and independent of normal convection and which requires an abnormally hot and low-viscosity lower thermal boundary layer (TBL) that is not disrupted by background convection. Modern "plume theories" require that material be isolated in the TBL until it obtains temperatures and viscosities not normally available and then suddenly released to rise unimpeded through the mantle. Plumes, as currently used, must be distinguished from the normal hot upwellings, generally quite broad, that occur in any convecting system.

The Earth differs from idealized Rayleigh-Bénard (RB) convection in several important ways: 1. the mantle is not primarily heated from below. 2. plates and slabs cause the top and interior of the mantle to be cooled and driven in completely different ways than envisaged by RB theory. 3. The evolution of the surface TBL involves chemical buoyancy, strength and high-viscosity; it does not leave the surface on the same time or length scale as a normal TBL. 4. Lateral variations in plate thickness, in particular, the presence of thick Archean plates, cause horizontal motions which can exceed those created by RB convection. 5. The locations and dimensions of upwellings reaching the surface are controlled by plate properties, not the dimensions of the convecting system. 6. Lateral variations in temperature melt content, fertility and volatile content, caused by the history of subduction, insulation and melt extraction, cause the mantle not to be homogeneous, adiabatic or nearly isothermal; there are lateral changes in buoyancy.

Some of the above effects are so fundamental that they cannot be treated as small perturbations in an RB reference state, a homogeneous fluid heated from below. If the mantle were homogeneous, with no plates or phase changes, heated from below, with no secular cooling or internal heating, then hot upwellings would certainly represent instabilities from a lower TBL. Some other physics would have to be invoked, however, to generate a smaller scale (plume) instability that is not swept up in the background flow. This external physics can be superheated fluid released by hypodermic needles or punctured diaphragms but these experiments have not been done with background convection, phase changes or plates.

The largest temperature contrasts on Earth are related to subduction of cold slabs and the downwarping of cold isotherms by Archean cratons (Archons). Flux induced melting of the mantle wedge introduces an additional buoyancy gradient. It is not coincidental that large igneous provinces (LIPs) occur on edges of Archons or at time of ridge-trench collision. These are conditions for large lateral temperature (buoyancy) gradients.

The stream function and horizontal velocity for a sinusoidal temperature variation at the top of a convecting system is:

$$\psi = \frac{-g\alpha\Delta T}{8k^2\nu}\sin kx(ky^2 - y)e^{ky}$$

$$u = \frac{g\alpha\Delta T}{8k^2\nu}\sin kx$$

where symbols have their usual meaning; k is the wave-number of the surface inhomogeneity, ΔT is the horizontal temperature difference over 1/k (Allan et al., 1967).

Long wavelength temperature variations (craton to ocean) are more effective than short wavelengths (edge of craton) but 1 to 10 cm/yr convective velocities are easily obtained with reasonable parameters. Even higher velocities can be obtained if slab pull, trench roll-back and other extensional forces cause plate separation, or pull-apart. These pull-aparts, and the small-scale convection, will be focused at lateral lithospheric discontinuities.

Thus, plates, cratons and slabs can not only organize and modify mantle convection but can actually drive it, at all scales. The "small scale" convection will range from supercontinent, continent, cratonic separation scales down to slab and craton scales. Narrow surface manifestations of magmatism are a result of the smaller scales and the scale of plate controlled rifts, rather than by hypothetical "plume tails". Surface tectonics, geoid undulations and geochemical domains have dimensions of order 400-600 km. These are often attributed to the "radius of influence" of plumes but this is the natural scale length for upper mantle convection and of cratons.

Larger domains (Pacific hemisphere, DUPAL, Superswells) are related to past subduction, supercontinents and a possible lower mantle influence. For example l=1, 2 and 6 anomalies (geoid, tomography, heat flow, hotspots, residual topography) are related to, respectively, Pangea, post-Pangea subduction cooling and upper mantle convection (Tackley) modulated by cratons. The l=6 spherical harmonic hotspot map looks just like the l=6 craton expansion indicating that upwellings are not isolated plumes or superplumes but are part of a global pattern.

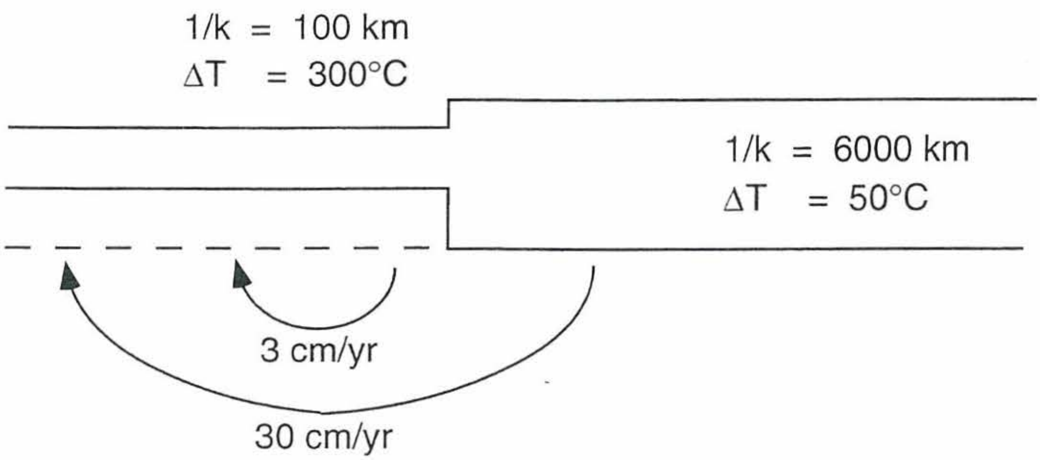

Figure 1: Mantle convection driven by lateral temperature gradients caused, for example, by thick craton lithosphere or cold slabs. Two scales of convection are illustrated; a 6000 km scale with ΔT of 50°C and an "edge" scale (100 km, 300°C). The convecting mantle is differentially cooled from above and there is no critical Rayleigh number.

PLUME 2

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