Dynamical transport processes in the Earth's mantle

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Over the last two decades it has become widely accepted that convective flows within the Earth's mantle form the mechanism which turns heat from the Earth interior into mechanical work, thus providing ultimately the mechanism behind all tectonic activities on Earth. Mantle material, while reacting elastically upon short term loads and forces like earthquakes, acts like a viscous fluid in response to forces which are applied over geological time scales. Having recognized the 'fluid' nature of the Earth's mantle, a new dynamic picture of the mantle emerged from the application of concepts from fluid mechanics to the Earth's Interior. Computer models have been designed which allow to study the dynamic transport processes in the Mantle and from which possible evolutionary models of the Mantle can be inferred. From those studies it appears that the flow in the Mantle does not take place in the form of regular convection cells. Complex flow patterns ,fluctuating in time and space seem to be the characteristic style of convection within the Earth's mantle. Slow gradual changes in the flow pattern coexist with spontaneous changes on shorter time scales. The thermal structure of the Earth's interior and also its chemical composition will be widely determined by these dynamical phenomena. An understanding of mixing properties of mantle convection is of key importance in order to be able to interpret results as obtained from geochemical investigations in terms of their geodynamical implications. Recent seismological investigations indicate that at least a strict layering of the upper and lower mantle does not exist (Van der Hilst *et al.*, 1997). The prime candidates for at least two different reservoirs may not be that clear anymore and further questions have to be answered. Does the existence of geochemically distinct reservoirs necessarily mean that convection currents are strictly separated in the mantle. Or, conversely, does an essentially non-layered mantle imply that the mantle is well mixed? From previous work on convection two different domains in a convective flow have been identified. One, is the central part of the (quasistationary) convection cell, the other is made up by the boundary layers of the flow. The boundary layers have been identified with the lithosphere (on top), the Core-mantle-Boundary and the associated D''-layer (at the bottom of the mantle) and possibly an internal boundary at a depth of 670-km, separating the upper and the lower mantle. On the basis of 2 dimensional models of mantle convection the idea has been put forward that material within the thermal boundary layers of the flow would hardly come into contact with material from the inner part of the flow, thus providing an explanation for keeping heterogeneities intact in a globally convecting mantle. According to this picture subducted lithosphere would sink to the core-mantle boundary where it would accumulate and form possibly detectable anomalies. After being sufficiently heated the material would rise again. Especially the D''-layer has been considered to form a reservoir in which either rests of subducted slabs or material which has been left over from core formation has accumulated thus forming a region which shows disitinct seismological, geochemical and also topographical signatures (Hansen and Yuen, 1988). The investigation of full three-dimensional convection provides a more complex picture (Schmalzl *et al.*, 1996). Mixing in three-dimensional flow can be complex, even if the underlying fluid pattern is rather simple. In a realistic situation of time-dependent 3D flow several convection-cell-like structures develop and persist for significant time. Within each of the cells mixing is rather effective. In each of the circulation cell the material performs a spiraling motion. There are periods during which the material travels on paths which connect the lower and the upper boundary (like in the 2D picture). During other periods the radius of the spiral decreases and the material is kept for some time in the central region of the circulation cell. This mechanism leads to efficient destruction of heterogeneities within the convection cell. However hardly any material escapes from one circulation cell to the neighbouring cell. The up-and downflows between the different cells act as separatrices allowing only for diffusive flux between the cells. Thus this 'cross-cell mixing' is not efficient as compare to the 'inner-cell mixing' which is described about. While heterogneities are homogenized within a cell on the scale of several overturns, heterogeneities between neighbouring cells can persist for tens of overturns.

Plumes from the core-mantle boundary have been proposed to sample the mantle during ascent and thus lead to chemical signatures being between the one of lower and upper mantle. The ideas are largely based on experiments in which isolated plumes were generated by injection of less dense and less viscous material into denser, more viscous material (Griffiths and Campbell, 1990). Differently from these laboratory set ups, plumes within the Earth mantle are believed to develop as critical phenomena from a thermal boundary layer. Once the boundary layer becomes unstable plumes can detach. In a series of numerical experiments we have investigated both scenarios. Plumes which were started artificially by injection entrain surrounding material.Those plumes which are developing selfconsistently from a boundary layer do show significant internal convection within the plume-head. The intensity of the internal convection is a function of the viscosity contrast between the plume head and the surrounding mantle. However all selfconsistent plumes do not show any evidence for entrainment. Upon arrival of the plume at the surface the plumehead consists virtually of pure boundary layer material. Mantle material can only get into the plume if it is processed through the bottom boundary layer. According to this models plumes resemble the material of the boundary layer from which they originate. If the viscosity is a strong function of temperature, as it is believed to be in the Earth's mantle, instabilities develop as patches traveling in a wave-like fashion through previously established paths, rather than as connected mushroom like plumes. Thus, episodicity seems to be a generic feature of plumes in fluids with strongly temperature dependent viscosity.

In most studies on plumes only such plumes have been considered which have developed in an otherwise quiescent mantle. This is most likely an unrealistic setting. Plumes will develop with a convecting mantle and will be influenced by a 'mantle wind'. Under such, hardly investigated conditions, complex evolutions of plumes can result from the interaction of a plume with the large scale mantle flow. It seems, for example, quite possible that the plumehead is detached from the conduit by the background flow. In such a way the plumehead and the conduit can be separated and may appear at the surface at different places. Under such circumstances the evolution of each plume will not only depend on material properties but also on the individual history of each plume.

References

Griffiths, R.W. and Campbell, I.H. (1990) *Earth Planet. Sci. Lett.*, **136**, 507–16.

Hansen, U. and Yuen, D.A. (1988) *Nature*, **334**, 237–40.

Schmalzl, J., Houseman, G.A. and Hansen, U. (1995) *Physics of Fluids*, **21**, 1027–33.

Schmalzl, J., Houseman, G.A. and Hansen, U. (1996) *J. Geophys. Res.*, **101**, 847–58.

Van der Hilst, R.D., Widiyantoro, S. and Engdahl, E.R. (1997) *Nature*, **386**, 578–84.