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# At least three scales of convection in a mantle with strongly temperature-dependent viscosity

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## ABSTRACT

We studied the convective patterns developing at high Rayleigh numbers and intermediate viscosity ratios in a fluid with a strongly temperature-dependent viscosity. Within this sluggish lid regime, three different scales of convection develop. The largest convective scale is cellular, with cold downwelling sheets of viscous fluid encasing hotter, less viscous, parts of the tank. Within each of those cells develop several (typically 3–7) hot 3D upwelling plumes. Upon impinging under the cold thermal boundary layer, each plume in turn generates locally a small ring of cold material which does not reach the bottom of the tank.

Applying those results to the Earth's mantle, we suggest that the large-scale features of mantle convection and the co-existence of several scales of convection, i.e. slabs and plumes, are produced by thermal convection in a mantle with high Rayleigh number and a strongly temperature-dependent viscosity material. This generates a convective pattern in two large-scale cells : the Pacific and the Indo-Atlantic "boxes". Our experiments further suggest that what has been named the two hot superplumes, i.e. the two seismically slow regions encased within the subduction rings, are in fact each constituted of several hot instabilities. Moreover, plumes impacts under the lithosphere should be surrounded by cold rings of small extent. The asthenosphere appears therefore as the graveyard of both small-scale convection and hot plumes generated in the system.

## 1. Introduction

Owing to the presence of continents and to the chemical heterogeneity and complex rheology of mantle material, several scales of convection co-exist in the Earth's mantle, producing cold linear slabs, mid-ocean ridges, 3D superswells and hot spots. Tomographic images (Fig. 1) show that the Earth's mantle and the hot spots population is divided in two large boxes by subduction (Masters et al., 1982; Molnar and Stock, 1987; Weinstein and Olson, 1989; Grand et al., 1997). In terms of convection, mantle cold downwellings are therefore sheet-like and are delimiting two large-scale cells, in which several hot instabilities are generated to produce hot spots and superswells (e.g. Davaille et al., 2002, 2005; Jellinek et al., 2003; Gonnermann et al., 2004; Schubert et al., 2004; McNamara and Zhong, 2005). However, even though these features have individually been generated and studied in numerical and laboratory experiments, the exact conditions for their co-existence in a self-consistent convective model have remained elusive.

Numerical studies (e.g. Bercovici, 1996, 1998, 2003; Moresi and Solomatov, 1995; Trompert and Hansen, 1998; Gurnis et al., 1998, 2000; Tackley, 2000a,b,c; Ricard et al., 2001; Stein et al., 2004) have shown that the presence of rigid plates and the strong localization of deformation typical of plate tectonics on Earth are obtained only in fluids with complex rheology (yield-stress, strongly temperature-dependent, and self-lubricating). Nevertheless, if we consider the large-scale feature, that is the upper cold more viscous thermal boundary layer of the mantle (i.e. the lithosphere) participating in the convective overturn of the whole mantle, plate tectonics convection appears like an example of the mobile-lid regime featured in convection in a strongly temperature-dependent viscosity fluid at intermediate viscosity ratios (e.g. Weinstein and Christensen, 1991; Solomatov, 1995; Moresi and Solomatov, 1995; Ratcliff et al., 1997; Kameyama and Ogawa, 2000; Stemmer et al., 2006). But the question is then whether this rheology is sufficient to produce several scales of convection, and under which conditions.

We have therefore run laboratory experiments to explore the influence of a strongly temperature-dependent rheology on the

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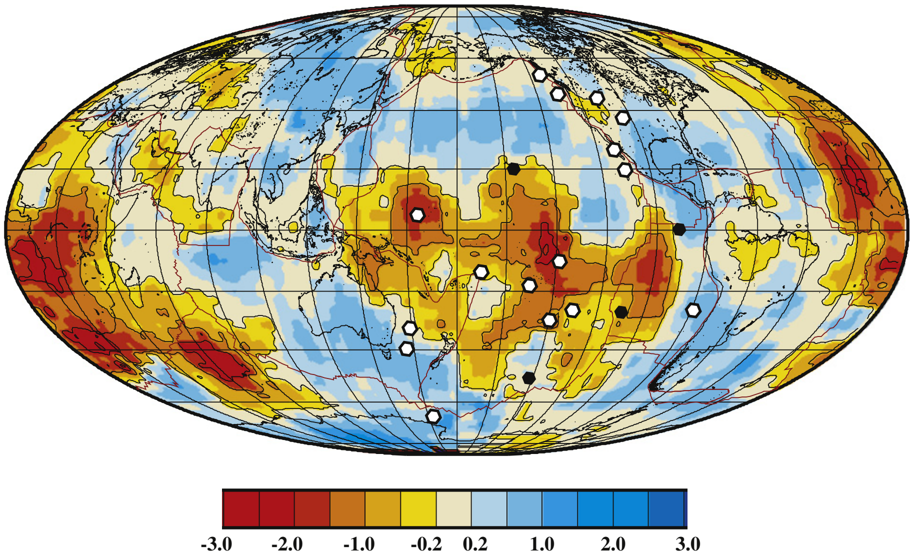

**Fig. 1.** Variations of S-waves seismic velocities at 2700 km depth, extracted from tomographic model TXBM (Grand, 2002). The circles show the hot spots on the Earth surface. The subduction ring around the Pacific seems to divide the mantle in two "boxes": Indo-Atlantic and Pacific. However, note that the slow seismic velocity anomaly (in orange–red) under the Pacific is not uniform but presents at least 5 local maxima. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

pattern of thermal convection when the intensity of convection is mantle-like (i.e. high Rayleigh number, $10^6$–$10^8$). New visualization techniques (Davaille and Limare, 2007) allowed us to measure the detailed structure of the temperature and velocity fields. This work complements previous studies run either in 2D geometry (Christensen, 1984a,b, 1985; Hansen and Yuen, 1993; Moresi and Solomatov, 1995; Kameyama and Ogawa, 2000), or in 3D geometry at lower Rayleigh numbers (Olson et al., 1988; Richter et al., 1983; White, 1988; Ogawa et al., 1991; Christensen and Harder, 1991; Weinstein and Christensen, 1991; Giannandrea and Christensen, 1993; Tackley et al., 1994; Tackley, 1996; Ratcliff et al., 1997; Yoshida and Kageyama, 2006; Stemmer et al., 2006), or with no strongly temperature-dependent viscosity (Davies, 2005; Davies and Davies, 2009), or with less detailed information on the temperature and velocity fields (Weeraratne and Manga, 1998; Manga and Weeraratne, 1999; Manga et al., 2001; Schaeffer and Manga, 2001). We were able to expand the regime diagram of the different convective regimes, which then allows us to explain in a same framework a number of terrestrial observations. The laboratory experiments are described in Section 2, while the implications for the style of mantle convection, and the nature of the asthenosphere are presented in Sections 3 and 4.

## 2. Laboratory experiments

### 2.1. Experimental set-up

Layers of sugar syrup were cooled from above and heated from below at constant temperatures in square-based (30 cm × 30 cm) plexiglas tanks of aspect ratios 2 and 5. The top and bottom boundaries are copper exchangers within which thermostated liquids (cold ethanol and hot water) were circulated. Each experiment was run during several days in order to reach quasi-steady state. To simultaneously measure in situ the temperature and velocity fields, the fluid was seeded with glass spheres (10-μm diameter) and four types of thermochromic liquid crystals (TLC). Each type of TLC brightens at a different temperature. So, we visualize four isotherms which appear as bright lines (39.50 ± 0.25, 31.10 ± 0.25, 24.35 ± 0.30, 10.70 ± 0.60 °C, labelled, respectively A, B, C and D in the figures) when vertical cross-sections of the tank are illuminated with a 532-μm laser sheet (Davaille and Limare, 2007). Images were taken every half-second by a CCD camera (1280 × 1020 pixels). Thanks to the glass spheres, the velocity field was calculated by cross-correlation between images, using the PIV package Davis from LaVision. We can also scan the tank with the laser sheet in order to determine the 3D structure of the instabilities. In addition, a vertical probe (labelled "T" on the figures) containing 14 thermocouples was used to measure a vertical temperature profile at a given location. Thermocouples were also placed in the lower and the upper plates. We verified that temperature was homogeneous in each copper plate within 0.05 °C. All temperatures were read every 30 s through a scanning voltmeter connected to a computer. The thermocouples allow us to take very long time series (e.g. Fig. 7).

Twenty-six experiments were performed, using three fluids (differing by the amount of solid matter dissolved in water). Their physical properties are given in Annex 1 and Tables 2 and 3. All fluids are in the limit $\nu/\kappa \gg 1$ relevant to the Earth, where $\kappa$ is the thermal diffusivity and $\nu$ is the kinematic viscosity (i.e. momentum diffusivity). The intensity of convection is related to the global Rayleigh number, which compares the driving thermal buoyancy forces to the resisting effects of thermal diffusion and viscous dissipation:

$$Ra(\nu) = \frac{\alpha \rho g \Delta T H^3}{\kappa \nu} \qquad (1)$$

where $H$ is the layer depth, $\Delta T$ is the temperature difference applied across it, $\alpha$ is the thermal expansivity, $\rho$ is the density, $g$ is the gravity acceleration, and $\nu$, the kinematic viscosity. Since the viscosity of the fluids depends strongly on temperature, the temperature at which the viscosity is taken in Eq. (1) has to be defined; several choices are possible: $Ra_{\mathrm{hot}} = Ra(\nu_{\mathrm{hot}})$ with the viscosity taken at the temperature of the bottom hot boundary, $Ra_{\mathrm{cold}} = Ra(\nu_{\mathrm{cold}})$ with the viscosity taken at the temperature of the top cold boundary, $Ra_{1/2} = Ra(\nu_{1/2})$ with the viscosity taken at the averaged temperature between the two boundaries, and $Ra_m = Ra(\nu_m)$ with the viscosity taken at the mean temperature of the convecting bulk interior of the tank.

In the limit $\nu/\kappa \gg 1$, the system dynamics depend on only two parameters, one of the Rayleigh numbers, -here we shall take $Ra_{hot}$-, and the viscosity ratio across the tank defined as the ratio of the viscosity of the cold (top) fluid to the hot (bottom) one $\gamma = \frac{\nu_{cold}}{\nu_{hot}}$. The