Convection in an Internally-Heated Two-Layer System*

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Abstract   The Earth's mantle is chemically heterogeneous and includes primordial material inherited from early planetary processes, which probably led to an initial depth-dependent composition of radioactive elements. One consequence is that its internal heat sources are not distributed homogeneously. Mantle convection induces mixing, such that the flow pattern, the distribution of heterogeneities and the thermal structure are continuously evolving. We studied these phenomena in the laboratory using a unique microwave-based experimental set-up for convection in internally-heated systems. We characterize the development of convection and the progression of mixing in an initially stratified fluid made of two layers with different physical properties and heat production rates. In analogy to the Earth's mantle, the upper layer is thicker and depleted in heat sources compared to the lower one. Two different convection regimes are identified, a dome regime and a stratified regime. In the dome regime, large domes of lower fluid protrude into the upper layer and remain stable for long time-intervals due to their enhanced heat production. In the stratified regime, cusp-like upwellings develop in association with deformation of the interface separating the two fluids. Upwellings are similar in size and morphology to those that would be generated by heating through the tank base, implying that mantle plumes are not necessarily due to heating by the Earth's core. These plumes are made of heated upper layer fluid and enriched lower fluid in variable proportions giving rise to a range of plume compositions. Mixing proceeds by two mechanisms: shearing of thin slivers by viscous coupling at the interface between the two fluids, and trapping of upper fluid within the lower fluid through folding. Empirical scaling law for the mixing rate allows extrapolation to planetary mantles.

Keywords: Microwave heating, Laser induced fluorescence, Mixing, Scaling law, Mantle, Radiogenic heat

1. Introduction  
Solid state thermal convection, which controls the dynamics of planetary mantles, is generated by both internal heating and heating at the base of the mantle. The internal heating is due to the radioactive decay of $^{238}$U, $^{235}$U, $^{232}$Th and $^{40}$K in the mantle rocks. The initial concentration of these long-lived radiogenic isotopes in the bulk silicate mantle can be estimated from chondritic material, although there remains some debate on the type of chondrites that formed the Earth [1, 2]. The initial concentration of radiogenic elements in the convective mantle depends on differentiation processes that were active during and after planet formation. In particular, partial melting efficiently concentrates incompatible elements, such as U, Th and K, in the melts that will form the crust, thereby leaving a depleted residual mantle on one hand and an enriched mantle unaffected by crust extraction on the other hand.

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The second source of internal heat is secular cooling, which can be treated as a volumetric heat source. For terrestrial planets, cooling and solidification of the iron-rich core is the main source of heating from below. Heat flow from the core, which depends on convection in the very viscous mantle, controls the strength of the magnetic field and the rate of solidification of the core. The respective amounts of these two heat sources are poorly known [3, 4].

The anomalous isotopic compositions of lavas from mantle plumes support the existence of deep mantle heterogeneities [5] and have been linked by some authors to primordial mantle material [6, 7]. Little is known about how such material was generated in early phases of planetary evolution. The formation mechanisms include the sedimentation of iron-bearing phases and crystallization in a primordial magma ocean [7]. These mechanisms operated over a wide range of temperature and pressure and probably led to an initial depth-dependent composition [8,9]. Regardless of its origin, such primordial material contains higher concentrations of radioactive elements than today's upper mantle [10-13]. Enhanced heat source in the lower mantle can generate motions that can be interpreted as due to heat supplied by the Earth’s core. These two types of heating depend on different parameters and are not likely to follow the same evolution over time. Thus, discriminating between them is a difficult challenge.

The consequences of early differentiation phases following accretion have been largely erased by subsequent evolution due to mantle convection. However, some remnants may lie in the deep Earth, as evidenced by seismology [14, 15, 16]. Seismic wave velocities are unusually low in two broad regions called large low-shear-velocity provinces (LLSVPs) and cannot be explained by purely thermal anomalies [17]. LLSVPs appear to be located below hotspots and appear to be stable over hundreds of million years [18, 19, 20]. At a smaller scale, ultra-low velocity zones (ULVZs) located at the core-mantle boundary may be due to the presence of iron rich [21] or partially molten [22] material. How these anomalies were generated and how they influence mantle motions is needed to improve our understanding of the dynamics of Earth's interior. Our approach aims to go beyond the conceptual models of mantle convection that the community is currently debating [17].

We intend to bring answers to an important question: how a compositionally stratified mantle evolves quantitatively in the presence of convective motions. These motions act to deform the boundaries of chemically distinct domains and induce mixing. It is therefore essential to determine which conditions allow the long-term survival of primordial material at the base of the mantle and, more specifically, how this depends on intrinsic density and heat production contrasts between the different types of mantle material.

So far, this problem has been mainly tackled by numerical simulations [23-26]. These calculations, however, suffer from limitations on the accuracy of mixing processes, especially in 3D [27, 28, 29]. Quantitative laboratory studies were carried out in Rayleigh-Bénard type setups with fixed temperatures or fixed heat flows at the top and bottom of the tank [30-34]. These studies reveal a wealth of phenomena such as the oscillatory movements of domes, the overturning of layers, or the anchoring of plumes by deformation of the lower layer. The missing ingredient, necessary to achieve a more accurate picture of the mantle, is the internal heating, which has never been explored experimentally for lack of suitable technology.

To our knowledge, there has been no experimental study combining chemical heterogeneities with internal heating differences. Our method is based on microwave heating with a heat source that can be varied in space and time [35-39]. This method offers the new perspective, unattained up to now experimentally, to selectively heat different zones of a convecting liquid, allowing the study of heterogeneous convection in the presence of chemical reservoirs with distinct concentration of radiogenic isotopes [40]. Our state-of-the-art visualization system allows the non-invasive, simultaneous determination of the temperature, velocity and compositional fields [41]. We have studied extensively convection in a stratified system involving two fluids with different intrinsic densities and heat production rates and we have
determined scaling laws relating all the dynamical characteristics of convection to the relevant dimensionless numbers [42]. These scaling laws will be used to upscale the experimental results to mantle convection in agreement with the geophysical and geochemical observations.

2. Theoretical framework

We have first focused on internal heating only and have studied a stratified system above an adiabatic base. Using standard scales for time, velocity and length, the governing Boussinesq equations for homogeneous internally-heated convection lead to two dimensionless numbers, the Rayleigh-Roberts number \( Ra_H \) and the Prandtl number \( Pr \) [43]:

\[
Ra_H = \frac{\rho g a H h^5}{\lambda \kappa \mu},
\]

\[
Pr = \frac{v}{\kappa},
\]

where \( \rho \) is the density at some reference temperature, \( g \) is the acceleration of gravity, \( a \) is the thermal expansion coefficient, \( H \) is the rate of heat generation per unit volume, \( h \) is the reservoir thickness, \( \lambda \) is the thermal conductivity, \( \kappa \) is the thermal diffusivity, \( \mu \) is the dynamic viscosity and \( v = \mu / \rho \) is the kinematic viscosity. For sufficiently large values of \( Pr \), inertial effects are negligible compared to viscous effects and one can work in the infinite Prandtl limit [44]. In these conditions, which are certainly those of telluric planets mantles with \( Pr > 10^{23} \), the characteristics of convection depend only on \( Ra_H \).

Here, we investigate convection in an initially two-layer reservoir involving two miscible fluids, which differ by their intrinsic densities, viscosities and heat generation rates and have identical coefficients of thermal expansion, thermal conductivities and heat capacities. In the following indices 1 and 2 refer to the lower and upper layers, respectively. Other dimensionless numbers are needed to characterize the two-layer system. The thickness ratio \( a = h_1 / h \) is equal to the volume fraction of the lower fluid and remains a key control variable even when the layered structure has been destroyed. The bulk rate of internal heat production is: \( H h = H_1 h_1 / H_2 h_2 \). The viscosity of the final homogenized fluid can be estimated from the following expression [45]: \( \mu = \mu_1 \mu_2^{1-a}. \) These allow calculation of a ‘bulk’ Rayleigh-Roberts number for the homogenized reservoir, denoted by \( Ra_H \) as above. The enrichment factor for the lower fluid is defined as follows:

\[
F = \frac{H_1}{H}.
\]

The other dimensionless numbers are the viscosity ratio:

\[
\gamma = \frac{\mu_1}{\mu_2},
\]

and the buoyancy number (i.e. the ratio of the stabilizing density anomaly to the destabilizing thermal anomaly):

\[
B = \frac{\Delta \rho}{\alpha \rho \Delta T},
\]

where \( \Delta T \) is the temperature difference between the two fluids. In our setup, this temperature difference is initially zero and changes as mixing proceeds. It eventually decreases to zero and it may be shown that the relevant value is the maximum value that is reached in an experiment.

We seek scaling laws: i.e. functional relationships that relate the parameters of interest to the relevant dimensionless numbers of the system: \( Ra_H, a, F, \gamma, \) and \( B \). This parameters space is available through in situ fluid preparation and fine-tuning of the heating rate.

2. Experimental method

The prototype using a unique setup of microwave (MW) internal heating of aqueous fluids [37, 39] is shown in Fig. 1. A commercial microwave oven (Whirlpool AMW 848IX, cavity volume 40 l) was entirely modified to perform lab-scale experiments suited for mantle convection studies. Laterally homogeneous internal heating of the sample (contained in an optically and MW transparent tank covered with a cooling plate) was achieved via a specially designed MW waveguide - homogenizer system. A proprietary, feedback based command and control hardware and software compensated for the magnetron output power variations [46]. A specially designed heat-sink system ensured a stable output power dissipated into the sample as heat. Flow
visualization and thermostated bath circulation were achieved through special openings equipped by MW filters that ensure user safety against microwave radiation leakage.

The experiments were performed in a $30 \times 30 \times 5$ cm$^3$ and $1$ cm thick poly (methyl-methacrylate) tank so the bottom and lateral boundaries are insulating. The top surface was a thermostated aluminium plate. Working fluids were aqueous solutions of salt and hydroxyl-methylcellulose, whose intrinsic densities and viscosities could be varied within large ranges. Sodium chloride salt was used to increase both microwave absorption and density. The physical properties were determined over the relevant temperature range.

Fig. 1  Microwave heating prototype.

The experimental methods are presented in detail elsewhere [41] and here we give only a few key aspects. A laser sheet scans half of the tank whilst two CCD cameras acquired images in different spectral ranges allowing simultaneous measurement of the temperature and composition fields via a two-dyes Laser Induced Fluorescence (LIF) method. Dye concentrations in the lower layer were three times larger than in the upper one, allowing us to track the interface that separates them. In addition, we determined the velocity field via a Particle Image Velocimetry (PIV) algorithm. 3D distributions were constructed by interpolation of the 2D data sets. We acquired images at a spacing of $1$ cm over half of the tank width ($15$ cm), which provided a representative sampling of the different fields.

3. Results

We performed 38 experiments that covered a large parameter space [42]. We describe in the following the main conclusions we drew from the experiments in relation with Earth’s mantle dynamics.

3.1 Large-scale convective features

The topography of the interface that separates the two fluids provides a natural marker of flow structure and is of particular interest for comparison with tomographic images of the Earth’s mantle. Two convection regimes can be observed and can be defined rigorously based on the statistics of the topography: a stratified regime for large $B$ and a dome regime for low $B$ (Fig. 2(a), (b) respectively).

Fig. 2  Examples of the lower layer topography in the two convection regimes: stratified (a) and dome (b) (experiments $18$ and $3$ in [42]).

Fig. 3 shows a cross-section of a convection experiment in the dome regime. We notice that the temperature field is more diffused than the composition field, because the fluid that generates the largest amount of heat (at the bottom of the tank) also heats the surrounding fluid. The domes generally remain heavier than the surrounding liquid, except for small zones in their head; they are part of a larger upwelling structure involving surrounding fluid that...
has been heated and that rises buoyantly. For application to Earth, this is in agreement with tidal tomography data [47], indicates the presence of a denser zone at the base of LLSVPs.

3.2 Small-scale convective features

Mixing proceeds through two mechanisms. Fig. 4(a) illustrates the how entrainment is driven by viscous coupling between the two layers, which is most effective in cusps that form at the interface. Fig. 4(b) shows the velocity field on top of the composition and emphasizes cusps formation in the zones of maximum shear. Fig. 4(c) illustrates the second mixing mechanism that occurs when a dome reaches the top isothermal surface, cools down and collapses with a fast downward movement visible in the velocity field (Fig. 4(d)). In this case the lower fluid traps the upper fluid through folding and encapsulating.

Fig. 3 Example of an internally heated heterogeneous convection experiment in the dome regime (experiment 4 in [42]). Composition (a) and temperature (b) maps can be used to calculate the density contrast (b). Vertical velocity map (d). Black contours in all figures represent the composition threshold value used to determine the enriched layer topography. Yellow contour in (c) represents a neutral density contrast.

Laboratory and numerical studies of convection in homogeneous internally-heated fluid [38, 48] showed that convection is organized in strong, localized downwellings and passive, diffuse return flow. For heterogeneous convection, when domes are formed, we observe that upwellings in the top layer are more focused and preferentially localized along steep slopes of the deformed interface that separates the two fluids (as one can see at x = 100 mm in Fig. 3(d)). Such an upwelling could well be mistaken for a thermal plume. In geological context, this plume can give rise to volcanism at the surface. Its composition would be variable in time and would contain various proportions of heated surrounding fluid and entrained, enriched material.

Fig. 4 Illustration of the two mixing mechanisms for experiment 3 in [42]. Composition and velocity maps for entrainment ((a) and (b)) and for folding ((c) and (d)).

Fig. 5 shows histograms of intensity levels in the tank (obtained from the individual pixel values) at several times during experiment 18. The two fluids are initially well separated (light green curve), with the first and second peaks corresponding to the top and bottom layers, respectively. Mixing of the two fluids can be tracked by the migration of the two peaks towards intermediate values and eventually by the generation of a single peak (a situation almost reached at the time lapse illustrated by the black curve). By using this type of histograms we can characterize the amount of mixing for a convecting system starting from two end-member reservoirs.
4. Conclusion

We identified two convection regimes for internally-heated convection in a two-layer system. For low buoyancy numbers, large domes of lower fluid protrude into the upper layer and remain stable for long time-intervals. Smaller upwellings are generated at the edges of these domes. For large buoyancy numbers, in the stratified regime, cusp-like upwellings develop at the edges of large basins in the lower layer. In both cases, upwellings cannot be distinguished from those that would be generated by heating at the base of the tank. These plumes are made of two components: heated upper fluid and entrained, enriched lower fluid. The two components can have variable proportions, giving rise to a range of plume compositions. Mixing occurs through two mechanisms: entrainment of thin slivers at the interface between the two fluids and more rarely the trapping of one fluid through folding of the other fluid. The entrainment model developed for two-layer Rayleigh-Bénard convection [31, 49] account for our data well provided we take into account the experimentally derived temperature contrast between the layers. We are able to relate the survival of a reservoir to the vigor of convection, as measured by $R_{aH}$, the viscosity ratio, the buoyancy factor $B$, the thickness ratio $a$ and the heat production contrast $F$.

We plan to use our experimental method in other configurations to investigate mixing phenomena in a systematic manner. However, they already provide strong insights for the interpretation of convection in the deep Earth and its geophysical signatures.

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