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Microwave-Based, Internally-Heated Convection: New Perspectives for the Heterogeneous Case

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Abstract. The thermal evolution of telluric planets is primarily controlled by the balance between internal heating - due to radioactive decay - and efficiency of convective heat transfer in their mantle. In the Earth, the problem is particularly complex due to the heterogeneous distribution of heat sources in the mantle and the non-linear coupling between this distribution and convective mixing. To tackle this issue, we have developed a new technology to produce internally-heated convection based on microwaves absorption. This technology has the unique capability to selectively heat different zones of a convective fluid (heterogeneous convection) through the careful control of the absorption properties of the different fluids. Here we illustrate with two examples the new geophysical perspectives offered by microwave-based internally-heated convection: the problem of lithosphere stability and the evolution of a hidden enriched reservoir in the lowermost mantle.

INTRODUCTION

The thermal evolution of telluric planets after differentiation is mainly governed by the gradual cooling of their rocky mantle. The slow convective motion of the silicate mantle depends on the transport properties of the rocks and on the amount and spatial distribution of internal heat sources. Long-lived radioactive isotopes (^{238}U, ^{235}U, ^{232}Th and ^{40}K) represent an important source of internal heating. The initial concentration of radioactive elements in the bulk silicate mantle can be estimated from chondritic material, although there is a lively debate on the type of chondrites that formed the Earth [1, 2]. Furthermore, the concentration of radioactive elements in the convective mantle also depends on the differentiation processes subsequent to planet formation. For example, multi-stage core formation [3] or the solidification of the primordial magma ocean [4] may have yield a vertically heterogeneous repartition of heat producing elements in the mantle. 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. Recent geochemical observations [5] indicate an early differentiation (4.53 Ga) of the mantle, leading to the formation of an enriched 'hidden' reservoir, which may have trapped incompatible and radioactive elements. However, no surface rock seems to carry this primitive fingerprint, and the enriched reservoir has remained 'hidden' so far. Hence many questions have to be answered: (a) Why has the enriched material never reached the surface? (b) Can we constrain its density, composition, temperature, and content in radioactive elements? (c) What is its origin? Primitive layering [3, 6, 7] or primordial recycled crust [8]? (d) What could be its present-day volume and geometry? A continuous basal layer, large scale piles or smaller scale blobs disseminated into the lowermost mantle?

To our knowledge, there is no experimental study combining chemical heterogeneities with internal heating. Experimentally, a technological barrier has limited up to now all the research teams: the ability to study the evolution of a convective system with an heterogeneous internal heating controlled by the fluid chemistry. To investigate the behavior of such systems, we have devised a new technology based on microwave heating that we have validated in previous studies [9, 10, 11]. Our specific microwave-based method offers the new perspective, out of experimental reach until now, to selectively heat different zones of a convecting liquid, analogue to heterogeneous convection in the

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presence of chemical reservoirs with distinct concentration of radioactive isotopes. To illustrate the potential of our technique to better model the evolution of the Earth′s mantle, we propose here to study experimentally convection in a system initially formed by two layers with different rates of internal heat production. The issues we tend to address with such set-ups are as follows:

1. Continental lithosphere is usually depicted as the upper conductive layer of the Earth. Its formation is achieved through melt depletion that generates a residue that is less dense and more viscous than the underlying convecting mantle. As it is cooled from above, continental lithosphere can develop its own convective currents and may become unstable depending on its thickness and density contrast with the mantle [12]. But chemical differentiation due to mantle magmatism also enriches continental lithosphere in heat producing elements. According to present estimates, the Earth′s mantle may have lost as much as half of its radioactive elements in favour of continental crust and this stratified redistribution of heat sources has two main effects [13]. First, mantle convection vigor decreases and becomes increasingly sensitive to heat supply from the core. Second, localized heat production at the top surface increases the continental insulating effects and competes against lithospheric instabilities. Our new technology will enable us to determine which amount of internal heating is required to keep the lithosphere stable for a given rate of cooling from the top.
2. The pattern of convection in Earth′s mantle is still controversial because of conflicting evidence from geophysics and geochemistry: seismic images that indicate convection and mixing throughout the mantle are in disagreement with chemical composition of erupted magma, which requires distinct reservoirs with different isotopic composition. The origin of these reservoirs is still the object of debate: they originate either from the subducting oceanic plates or from volumes of primitive mantle with an initially higher concentration in radioactive material. Regardless of their origin, they imply the existence of heterogeneities that persist for billion years, whose size, shape and physical characteristics are not well constrained. To study the stability of such reservoirs in the context of vigorous mantle convection, we carry out two-layer experiments in which the bottom layer contains a higher amount of internal heating.

RELEVANT DIMENSIONLESS NUMBERS FOR THERMAL CONVECTION

Convection generated by bottom heating and top cooling (Rayleigh-Bénard convection) is described by two dimensionless numbers: the Rayleigh number and the Prandtl number. The Rayleigh number, Ra, sets the vigor of convection. It is defined as the ratio of the driving thermal buoyancy forces over the thermal and viscous dissipation

$$Ra = \frac{\rho g \alpha \Delta T h^3}{\kappa \mu}, \tag{1}$$

where ρ is the density, g is the acceleration of gravity, α is the thermal expansion coefficient, κ is the thermal diffusivity, μ is the dynamic viscosity of the fluid, ΔT is the temperature difference between the top and bottom of the layer and h is the layer thickness. Convection starts when Ra exceeds a critical value depending on the mechanical boundary conditions [14], and then follows a sequence of transitions toward chaos as Ra increases. In the purely internally heated case, the temperature scale for convection is related to the internal heating rate

$$\Delta T_H = \frac{Hh^2}{\lambda}, \tag{2}$$

where H is the heat generated per unit volume and λ is the thermal conductivity. The resulting Rayleigh-Roberts number [15] is

$$Ra_H = \frac{\rho g \alpha H h^5}{\lambda \kappa \mu}. \tag{3}$$

The second parameter, the Prandtl number, represents the ratio of momentum diffusivity over heat diffusivity

$$Pr = \frac{\nu}{\kappa}, \tag{4}$$

where $\nu = \mu/\rho$ is the kinematic viscosity of the fluid. When $Pr >> 1$ inertial effects are negligible compared to viscous ones and the fluid motion stops as soon as the heat source is cut off. This is the case for telluric mantles, where $Pr \sim 10^{23}$. In experiments, the Pr number can be considered as infinite (*i.e.*, its exact value does not affect the dynamics of the system) as long as it is larger than 10^2 [16].

LABORATORY EXPERIMENTS IN A MICROWAVE OVEN

Experimental layout

A complete description of the experimental setup is given in previous studies [10, 11]. It includes a power generator driven by an embedded control system and an antenna through which the MW radiation propagates towards the working fluid where it is uniformly absorbed. Our innovative design of the MW circuits guiding the MW radiation into the fluid ensures that a laterally uniform MW field distribution is continuously maintained throughout the heating process. The volumetrically heated fluid is cooled from above with an aluminum heat exchanger, that is temperature-controlled by a thermostatic bath. The tank ($30\times30\times5$ cm^3) is made of poly(methyl methacrylate), so that bottom and sides boundaries are as close as possible to adiabatic. The experimental mechanical boundary conditions are rigid. Experimental fluids are transparent silicone oils and hydroxyethylcellulose - water mixtures. The viscosity of the hydroxyethylcellulose - water mixtures can be varied within a wide range, depending on polymer concentration and the density can be either increased by adding NaCl or decreased by adding isopropanol. The fluid rheology was characterized with a Thermo Scientific Haake rheometer RS600 and its density and thermal expansion were measured with a DMA 5000 Anton Paar densimeter [9]. Dielectric properties were measured using an Agilent N5230A vector network analyzer with an 85070E performance dielectric probe kit [10]. The values of microwaves attenuation were converted into heat generated power per volume. Values of the fluid properties are given in Table 1. During an

TABLE 1. Fluid properties for the two types of experiment. Subscript 1 refers to the bottom layer and 2 to the top layer. h is the layer thickness in 10^{-3}m, A is the attenuation in Np m^{-1}, H is the heat generated power per volume in W m^{-3}, ρ is the density in kg m^{-3} and μ the viscosity in Pa s. The values were obtained at 20 °C.

	h_1	h_2	A_1	A_2	H_1	H_2	ρ_1	ρ_2	μ_1	μ_2
”Lithosphere”	33	17	0.5	90	620	35970	964	948	0.081	2.287
”Deep mantle”	10	40	66	33	33370	2940	1003	1000	0.346	1.777

experiment, the convecting fluid is scanned with a laser sheet over half of the tank size. The scattered light is registered by a CCD E-lite monochrome camera (1.4 Mpixels, 12 bit, 17 Hz) from LaVision allowing the measurement of both temperature and velocity fields without perturbing the flow. To measure the temperature field we use thermochromic liquid crystals (TLC) and laser induced fluorescence (LIF). Using Particle Image Velocimetry (package DaVis from LaVision) we calculate the velocity field by cross-correlating successive images. A fluorescent dye (Rhodamine B) is used to highlight one of the layers and to measure the temperature field by LIF for the ”lithosphere” type of experiment.

”Lithosphere” two-layer convection experiment

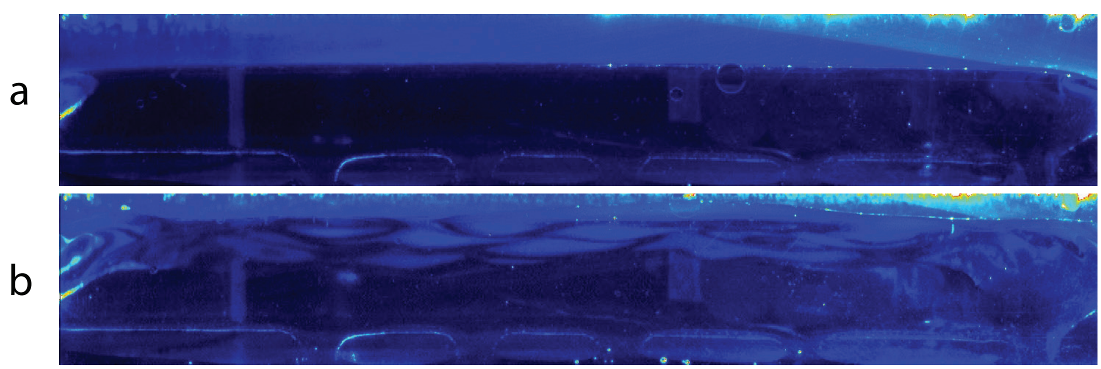

FIGURE 1. Cross-section of the experimental tank containing the optical image (arbitrary colors) a) initial, stable condition, b) two-layer convection.

In this group of experiments, we consider the stability of a less dense and more viscous top layer that is furthermore subject to a higher internal heating than the bottom layer. This set-up is thus suitable for the study of the stability of the continental lithosphere in the Earth. The experimental parameters are as follows: h_2=0.5*h_1; H_2=58*H_1;

μ_2/μ_1=28; $\Delta\rho$=1.7 %, where indices 1 and 2 refer to the bottom and top layer, respectively, see Table 1. The initially stable two-layer system (Fig. 1a) starts convecting when the internal heating is turned ON in both layers. The convection in the bottom layer is mainly due to lateral variations of temperature induced by interface deformation and to the low viscosity of the fluid, since its internal heat source is negligible. The convection into the top layer organizes in a typical "egg box" shape, with a characteristic wavelength (Fig. 1b). The stability of the top layer depends on its viscous contrast with the bottom one, the ratio between intrinsic and thermal density difference, the ratio of the two thicknesses and the ratio of heat production within the layers. Depending on this set of parameters, the top layer could remain stable with no deformation or could undergo instabilities leading to mixing between the two layers. The exploration within the parameters space is made possible via the in-situ fabrication of the adequate fluids. Further work will establish conditions for the stability regime of the upper layer depending on the parameters in the system and will confront experimental results to marginal stability analysis.

"Deep mantle" two-layer convection experiment

In this group of experiments, we consider the stability of a more dense and less viscous bottom layer that is furthermore subject to a higher internal heating than the top layer. This set-up is thus suitable for the study of the stability of a hidden enriched reservoir in the deep Earth's mantle. The experimental parameters are as follows: h_1=0.25*h_2; H_1=12*H_2; μ_1/μ_2=0.2; $\Delta\rho$=0.3 %, see Table 1. The two-layer fluid is initially stable at the temperature of the top heat exchanger (see Fig. 2a). When the internal heating is set ON the convection starts first into the top layer as indicated by the amplitude of the velocity field (see Fig. 2b), although the top layer contains a lower amount of internal heating. This is due to the larger thickness of the top layer since the Rayleigh-Roberts number (eq 3) representative of the vigor of convection, depends on power 5 of the thickness h and is only proportional to internal heating H. The bottom layer remains stable at the first stages of the experiment and only its upper interface is deformed by the cold instabilities of the top layer that dig and spread the bottom fluid on their surroundings. Because internal heating is maintained, convection eventually starts in the lower layer. Once convection is fully developed, we scan with the laser sheet half of the tank and we acquire images at different positions into the tank. Then we reconstruct by interpolation the 3D surface of the bottom layer (see Fig. 3). As one can notice, the bottom layer is not continuous anymore and forms some large scale piles. It is when the height of the piles is large enough that the bottom layer starts to convect and later on mixing occurred. Further work will establish conditions for the stability regime of convection into two separate layers with no mixing depending on the parameters in the system.

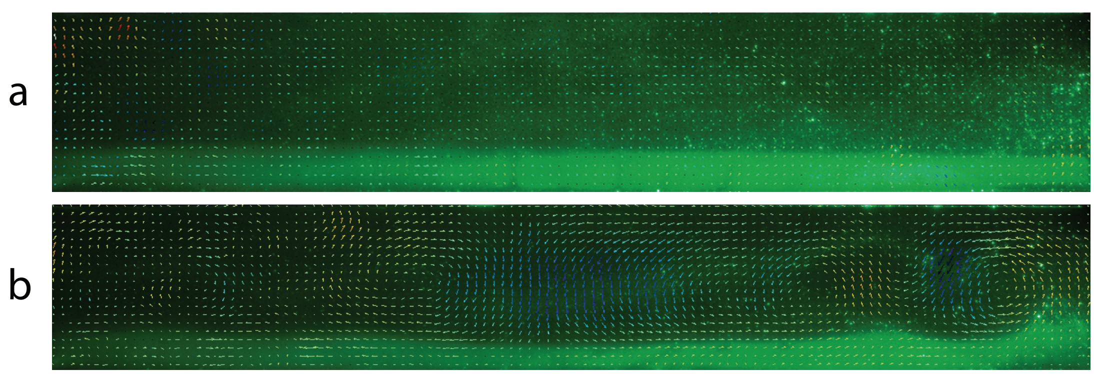

FIGURE 2. Cross-section of the experimental tank containing the optical image superposed on the 2D velocity field a) initial, stable condition, b) initiation of the two-layer convection.

CONCLUSION

We developed, to the best of our knowledge, the first prototype for convection experiments with internal heating produced by microwave absorption. This scientific and technological success now opens a huge field of applications for the study of internally-heated heterogeneous convection, that have so far remained experimentally out of reach.

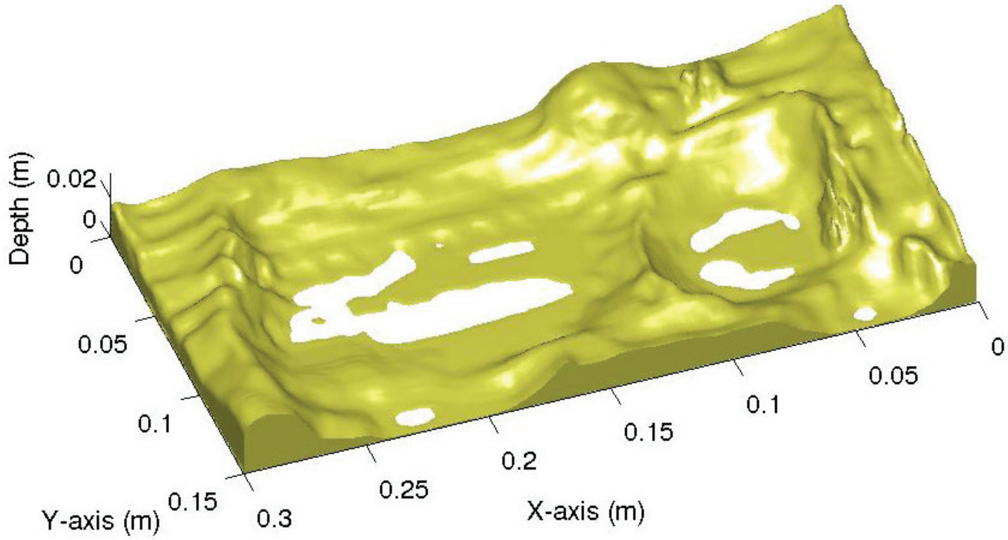

FIGURE 3. 3D map of the bottom layer with fully developed convection.

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