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Convective regimes in "soft matter": implications for the dynamics of planetary interiors

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Abstract

The morphology and characteristics of convective patterns strongly depends on the mantle physical properties. Using laboratory experiments and quantitative techniques of visualization, we have therefore studied systematically the characteristics of thermal convection in viscous fluids with complex rheologies (strongly temperature-dependent, yield stress, visco-elastic, brittle). We show that strongly temperature-dependent viscosity at high Rayleigh number is sufficient to produce at least three scales of convection in mantle interiors with sheet-like cold downwellings encasing several 3D hot plumes. But it is the soft matter character of silicate materials (elastic and/or brittle on short time scales, viscous on long time scales), which is essential in producing asymmetric subduction, episodic whole surface rejuvenation, and/or Plate Tectonics. Moreover, the experiments reveal that as a planet cools, it can undergoes a succession of different regimes. Scenarios for the evolutions of Venus, Mars and the Earth can then be proposed.

1. Introduction

Planets long-term cooling, from their accretion to the present-day, as well as surface phenomena such as plate tectonics, volcanoes and earthquakes, are mainly controlled by the existence and patterns of convective motions in their solid-state mantle. Mars, Venus and the Earth presently show three different types of convective regims: convection under a very old and stagnant lithosphere (Mars), complete rejuvenation of the planet surface about 600 Ma ago (Venus), and continuous plate tectonics with asymmetric subduction and hot plumes (Earth). Using laboratory experiments, we explore here the necessary conditions to obtain the different regimes. The rheology of the fluid appears as the key parameter.

2. Temperature-dependent viscosity

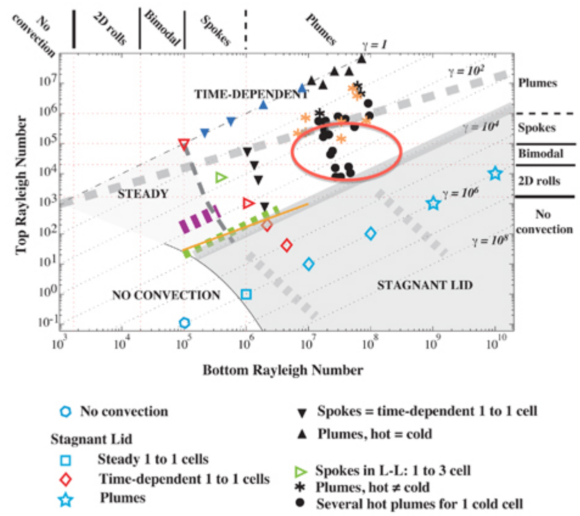

Figure 1: Newtonian but strongly temperature-dependent viscosity fluid. Convective pattern as a function of the Rayleigh numbers at the top and bottom boundaries for 3D experiments in a cartesian box. Numbers in italic indicate the viscosity ratio. Regims in the constant viscosity cases are indicated in the top and right bars. Open symbols designate experiments run with free surfaces (mostly numerical simulations) and solid symbols designate experiments run with solid boundaries. In black, our new data. The red ellipse represents the domain where several scales of convection with cold sheets encasing 3D hot plumes, a regime similar to the Earth, are observed.

Layers of sugar syrup were cooled from above and heated from below at constant temperatures in square-based plexiglas tanks of aspect ratios 2 and 5. The velocity fields were measured by Particle Image Velocimetry and the temperature fields by Thermochromic Liquid Crystals. Rayleigh number ($Ra =$

$\alpha g T H^3/\kappa\nu$) up to 10^8 and viscosity ratios γ up to 4200 were obtained (fig.1). For high Ra and intermediateγ, a sluggish lid regim, with three different scales of convection, develops. 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 to 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 (fig.2). For the Earth to be in this regime, the effective viscosity contrast between the lithosphere and the mantle should be between 300 and 3000. This implies that there is a mechanism to fragilize the lithosphere and reduce its viscosity.

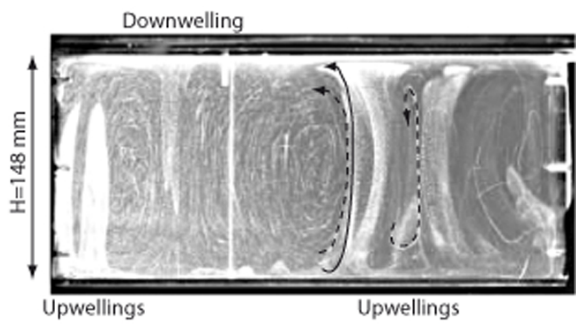

Figure 2: Experiment with sugar syrup at $Ra_{hot} = 5.310^7$ and $\gamma = 142$: Snapshot of a vertical cross-section. The bright lines are isotherms. Several hot plumes are seen while only one cold downwelling is observed. This situation resembles what is observed on Earth for exemple under the Pacific.

3. Complex fluids

The rheology of polymer gels and colloidal suspensions depends strongly on solid particle fraction ϕ_p, being newtonian at low ϕ_p, and presenting yield stress, elasticity, and brittle properties as ϕ_p increases. So a layer of fluid is dried from above. If drying is sufficently rapid, a skin forms on the surface. Four regimes were obtained: the one described in section 2, convection under a stagnant skin, episodic subduction of the skin and complete resurfacing, and finally a regime similar to continuous plate tectonics: the surface is constituted of several plates, moving and subducting. The subduction is always asymmetric, with one plate sinking beneath another one (fig.3). The brittle character of the skin is essential to produce this type of subduction. Moreover, the layer always evolves through different regimes during an experiment.

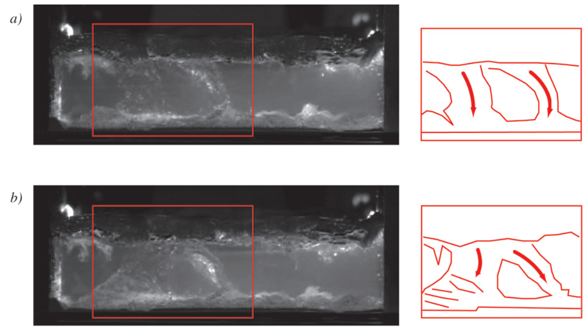

Figure 3: Convection in a colloidal solution dryed from above and heated from below. Two plates are continuously subducting in front of us below another plate. 20 minutes separate the two snapshots. On b) a pile is forming by folding of the subducted skin.

4. Summary and Conclusions

Depending on material rheology, several convective regimes have been obtained: the superposition of several scales of convection at high Ra and intermediate γ, convection under a stagnant lid, episodic surface rejuvenation with asymmetric subduction, and continuous plate tectonics. The different convective regimes observed in planets can now be studied in the laboratory.

Acknowledgements

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References

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