THE GROWTH OF GRAVITATIONAL INSTABILITIES DEVELOPED BY A BUOYANT HORIZONTAL CYLINDRICAL FLUID REGION

Catherine A. Mériaux*, John A. Mansour ** , Louis N. Moresi**, Ross C. Kerr ***& David A. May****
Instituto Dom Luiz, Faculdade de Ciencas, Universidade de Lisboa,Campo Grande 1749-016 Lisboa.
**School of Mathematical Sciences, Monash University, Victoria 3800, Australia.*
*** *Research School of Earth Sciences, Australian National University, Canberra, 0200 ACT, Australia.*
**** *Geophysical Fluid Dynamics, Department of Earth Sciences, ETH Zürich,*
Zürich, Switzerland.

Thermal plumes are an intrinsic feature of convection. Their long-lived shape can loosely be described by a cylindrical conduit. Provided that they are not subjected to a shearing current, plumes will rise opposite to gravity, whereas, in the presence of a velocity shear, they will tilt.

The idea that plumes are deflected from the vertical has especially been portrayed in the case of the Earth's mantle convection because of the large scale plate-driven shear flow [1]. In particular, laboratory experiments [2-5] showed that gravitational instabilities of compositional plume conduits could occur if the conduits were either horizontal or tilted by a background shear by more than 60 degree from the vertical. When thermal diffusion from plume conduits is considered, the development of the gravitational instabilities is not straightforward [6]. If the instability of a rising horizontal cylindrical region of buoyant viscous fluid is unaffected by diffusion when the thermal Rayleigh number Ra is greater than about 300, diffusion significantly increases the time for instability when Ra is less than 300. In this later case, the rising fluid region needs to grow substantially by both diffusion and entrainment before it becomes unstable.

The growth rate of instabilities developed by an initially horizontal, buoyant cylinder of fluid rising through a denser fluid at low Reynolds number was further investigated through three-dimensional numerical experiments. Two series of experiments were carried out and analyzed as a function of the Rayleigh number, the viscosity ratio between the inner cylinder fluid and the outer ambient fluid, and the dimensions of the domain. In the first series of numerical experiments, a hybrid particle-in-cell finite element method was used to examine non-diffusing plumes at infinite Rayleigh number. These experiments show that 1) the timescale of the fastest growing instability varies with viscosity ratio and 2) the growth rate slightly increases as the distance between the cylinder and the free-slip boundaries that are vertical and parallel to the cylinder axis decreases. In the second series of numerical experiments, the effect of thermal diffusion was investigated using a standard finite element method and an initial thermal disturbance condition. These experiments show that 1) initial disturbances grow with rates that vary with the Rayleigh number and the viscosity ratio and 2) a range of wavenumbers allows growth but one wavenumber, which depends on the viscosity ratio, is the most unstable.

Applied to the mantle, the results suggest that strongly tilted plume tails are likely to be gravitationally stable as estimates of the time for growth are larger than 16 Myr and 300 Myr for an instability that would develop in the upper and lower mantle, respectively.

References

[1] Steinberger, B., O'Connell, R. J. , 1998, Advection of plumes in mantle flow: Implications for hotspot motion, mantle viscosity and plume distribution, Geophys. J. Int., 132, 412.

[2] Skilbeck, J.N., Whitehead, J.A., 1978, Formation of discrete islands in linear island chains, Nature, 272, 499.

[3] Whitehead, J.A., 1982, Instabilities of fluid conduits in a flowing Earth- Are plates lubricated by the asthenosphere?, Geophys. J. R. Astron. Soc., 70 , 415.

[4] Olson, P., Singer, H., 1985, Creeping plumes, J. Fluid Mech., 158, 511.

[5] Kerr, R.C., Lister, J.R., 1988, Island arc and mid-ocean ridge volcanism, modelled by diapirism from linear source regions, Earth and Planet. Sci. Letters, 88, 143.

[6] Kerr, R.C., Mériaux, C., Lister, J.R. , 2008, Effect of thermal diffusion on the stability of strongly tilted mantle plume tails, J. Geophys. Res., 113, B09401, doi:10.1029/2007JB005510

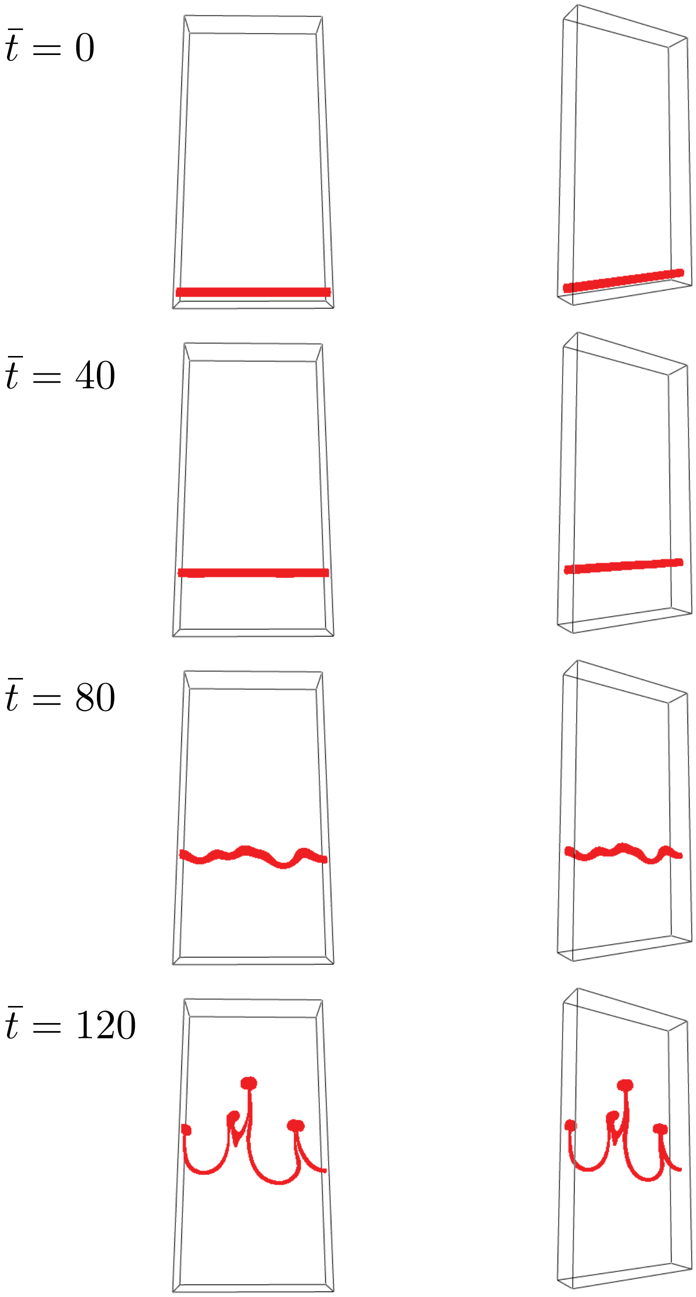

Figure 1. Snapshots at dimensionless times $\bar{t} = 0$, 40, 80 and 120 of the rise of an horizontal cylindrical region of buoyant viscous fluid at infinite Rayleigh number. A front and a perspective view are shown. The dimensionless wavelength $\bar{\lambda} = \lambda/a$, where a is the radius of the cylinder, is $\bar{\lambda} = 11.1 \pm 2.0$.