Feasibilities of GeoFlow as Thermal Convection Experiment for Modelling Mantle Dynamics

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Workshop on Geodynamics 2008

Overview

GeoFlow - Topical Team

Science Team

- BTU Cottbus, Germany
- University of Potsdam, Germany
- University of Leeds, U.K.
- CIRM, Marseille, France
- ESPCI, Paris, France

Space Industries

- EADS Astrium GmbH, Friedrichshafen, Germany
- MARS, Naples, Italy
- Alcatel Alenia Space, Turin, Italy
- E-USOC, Madrid, Spain

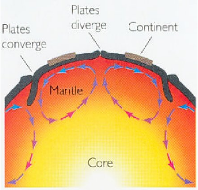
Space Agencies

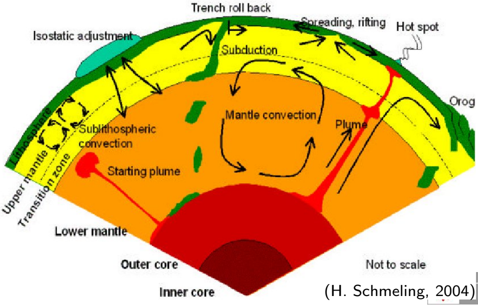
- ESA, Noordwijk, Netherlands
- DLR, Bonn, Germany

Mantle convection

- Thermal convection in the Earth mantle is driving mechanism of the plate tectonics.
- Earth's mantle behaves like an extremely viscous fluid on large time scales ⇒ approx. as a Stokes flow
- The only force that drives the convective flow is buoyancy force. Coriolis and Lorentz forces do not play any significant role.
- The mantle convection is thermally and compositionally driven
- The strong dependence of the fluid rheology on temperature and/or depth (pressure) has a great impact on the style of convection.
- The rheology of mantle materials is not simply Newtonian → a multi-component system

- convective upstreams
  - superplumes
  - hot spot volcanism
  - oceanic ridges
- convective downstreams
  - subduction





(H. Schmeling, 2004)

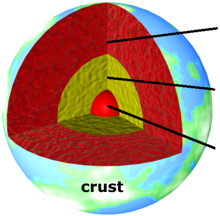
Motivation

- thermal convection in rotating spherical shells
- central force field
- Microgravity environment $\longrightarrow$ ISS

(DLR)

Fluid dynamics

- stability of flow states
- pattern formation
- transition to turbulence



- **GeoFlow I**
  fluid with low, nearly constant viscosity
  $\longrightarrow$ liquid outer core
- **GeoFlow II**
  fluid with non-uniform viscosity $\longrightarrow$ liquid mantle
- **Mantle properties**
  the viscosity of the mantle strongly depends on
  - temperature
  - pressure / depth
  - stress

State of the art

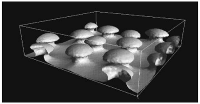
2D or 3D Cartesian domain → rectangular box heated from the bottom boundary

- M. Ogawa: *Mantle convection: A review*, Fluid Dynamic Research (2008)
- R. A. Trompert and U.Hansen: *On the Rayleigh number dependence of convection with strongly temperature-dependent viscosity*, Physics of Fluids (1998)
- U. Christensen and H. Harder: *Three-dimensional convection with variable viscosity*, Geophys. J. Int. (1991)

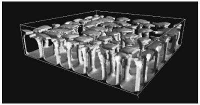
3D spherical convection model, $r_i/r_o = 0.55$ **→ effects of basal and internal heating**

- H. Bunge, M. A. Richards and J. R. Baumgardner: *Effect of depth-dependent viscosity on the planform of mantle convection*, Letters to Nature (1996)
- J. T. Ratcliff, G. Schubert and A. Zebib: *Effects of temperature-dependent viscosity on thermal convection in a spherical shell*, Physica D (1996)
- Louise H. Kellogg, S. D. King: *The effect of temperature dependent viscosity on the structure of new plumes in the mantle: Results of a finite element model in a spherical, axisymmetric shell*, Earth and Planetary Science Letters (1997)
- K. Stemmer, H.Harder and U.Hansen: *A new method to simulate convection with strongly temperature- and pressure-dependent vicosity in a spherical shell: Applications to the Earth´s mantle*, Physics of the Earth and Planetary Interiors (2006)

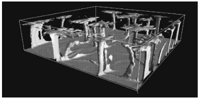
- **Tropert & Hansen (1998)** $\rightarrow$ rising and falling blobs at viscosity contrast $\Delta\eta = 10^6$



$\mathrm{Ra} = 1$



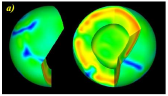
$\mathrm{Ra} = 100$



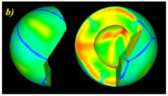
$\mathrm{Ra} = 1000$

- **Bunge, Richards & J. R. Baumgardner (1996)** $\rightarrow$ temperature distribution

Results: a modest increase in a mantle viscosity with depth has a dramatic effect on the planform of convection.



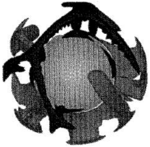
isoviscous



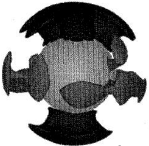
$\Delta\eta = 30$

- **Ratcliff, Schubert & Zebib (1996)** $\rightarrow$ plume-like upwellings
$\rightarrow$ mobile lid, sluggish lid and stagnant lid convective regimes

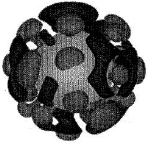
Results: the strong dependence of the fluid rheology on temperature has a great impact on the style of convection



isoviscous



$\Delta\eta = 10^3$



$\Delta\eta = 10^4$

Viscosity laws

- Mantle materials modeled by a Newtonian rheology $\longrightarrow$ Arrhenius relation

Temperature-dependent viscosity law

$\eta(T) = \eta_0 exp[-E(T - T_{ref})]$

E activation parameter
T_{ref} reference temperature
$\eta_0 = \eta(T_{ref})$

Temperature- and pressure-/depth-dependent viscosity law

$\eta(p, T) = \eta_0 exp[-E(T - T_{ref}) + V(r_o - r)]$

E, V are constants

- In a simple Newtonian lithosphere, ruptures cannot take place
  $\Rightarrow$ non-Newtonian rheology, mantle materials are a multi-component system (Ogawa 2008)

Stress-dependent viscosity law

$\eta(p, T, \omega) = \eta_0(p) exp[-E(T - T_{ref}) - F\omega/(1 + \omega)]$

$\longrightarrow$ dependence of eff. viscosity on the stress history

E, F are constants
ω damage parameter

The damage parameter: $\dfrac{d\omega}{dt} = \Gamma \sigma_{ij} \dot{\varepsilon}_{ij} - \dfrac{\omega}{\tau}$

$\longrightarrow$ to realize a multi-valued nature of eff. viscosity

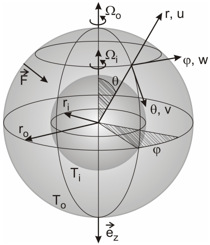
Γ a constant, τ decay time
σ_{ij} stress, $\dot{\varepsilon}_{ij}$ strain rate

Model geometry and general parameters

- rotating spherical annulus
- inner sphere heated, outer sphere cooled
- high voltage $\Rightarrow$ central artificial force field

Dynamic viscosity

- Geoflow I $\eta \approx const$
- Geoflow II $\eta(T)$



Nomenclature

gap width	$d = r_o - r_i$
reference dynamic viscosity	η_0
viscosity contrast	$\Delta\eta = \eta_{max}/\eta_{min}$
thermal diffusivity	κ
dielectric thermal coeff. of expansion	γ
angular velocity	$\Omega = 2\pi n$

Parameters

geometry	radius ratio	$\mu = \frac{r_i}{r_o}$
physical property of fluid	Prandtl number	$Pr = \frac{\eta_0}{\rho\kappa}$
buoyancy to central gravity (artificial)	Rayleigh number	$\mathrm{Ra} = \frac{\rho\gamma\Delta T g_e d^3}{\eta_0\kappa}$
Coriolis force	Taylor number	$\mathrm{Ta} = \left(2\rho\Omega d^2/\eta_0\right)^2$

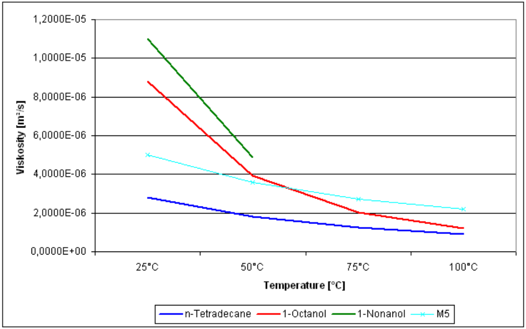
BTU

Identification of the fluid viscosity

Temperature dependency for different experiment fluids possible filling the spherical shell system of GeoFlow

- Bayer silicone oil M5 $\rightarrow$ experimental fluid of GeoFlow I
- alkane (paraffins) and alkanole fluids:

  Tetradecane ($C_{14}H_{30}$), Octanol ($C_8H_{18}O$), Nonanol ($C_9H_{20}O$)



(Handbook of Chemistry and Physics, B&T, 2008)

Study of the parameters according to technical requirements

- flashpoint
- transparency $\longrightarrow$ index of refraction
- safety guidelines $\longrightarrow$ Material Safety Data Sheet

Study of the parameters according to scientific requirements

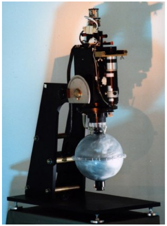
- temperature dependent viscosity
- dielectrical properties $\longrightarrow$ for setting up the high voltage potential

$\Rightarrow$ the alkanes offer the better dielectric performance than the alkanoles

$\Rightarrow$ the alkanoles show a significant percentage increase of temperature dependency of viscosity in the relevant thermal working regime

fluid	*Pr*	*Ra*	*Ta*
Baysilone M5	64.6	$2.86 \cdot 10^3 - 1.43 \cdot 10^5$	$5.37 \cdot 10^1 - 3.36 \cdot 10^6$
Nonanol $C_9H_{20}O$	142	$1.67 \cdot 10^3 - 8.17 \cdot 10^4$	$2.77 \cdot 10^0 - 1.73 \cdot 10^5$
Octanol $C_8H_{18}O$	108	$9.59 \cdot 10^3 - 4.80 \cdot 10^5$	$6.90 \cdot 10^1 - 4.31 \cdot 10^6$
Tetradecane $C_{14}H_{30}$	35.9	$2.57 \cdot 10^3 - 1.29 \cdot 10^5$	$6.83 \cdot 10^2 - 4.27 \cdot 10^7$

BTU



Experiment preparation

- GeoFlow refurbishment with low costs
- preliminary experiments
  → characteristics of the flow in a rectangular cavity
- preparation of accompanying laboratory experiments
  → under terrestrial conditions
  → spherical gap flow approaches

Experiment realization

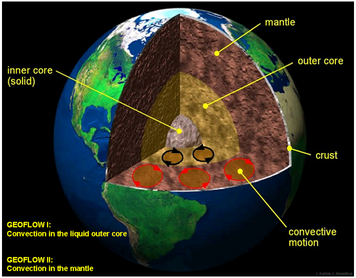
- experiment strategy → Experiment Science Requirements (ESR), . . .
- experiment realization → comparison with GeoFlow I

Numerical simulations

- extension of the pseudo-spectral code used for GeoFlow I
  → R. Hollerbach: *A spectral solution of the magneto-convection equations in spherical geometry*, Int. J. Numer. Meth. Fluids 32 (2000)
- implementation of temperature dependent viscosity
  → choose of an adequate temperature dependent viscosity law
  → implementation of the viscosity law in the numerical code
  → accomplishment of numerical simulations in the experiment parameters range

Outlook - GeoFlow II

- reflight planned for 2009/2010
- for GeoFlow II similar experiment procedure like GeoFlow I
- the experimental fluid is substitute with a strong temperature dependent fluid for simulate mantle convection (Nonanol ($C_9H_{20}O$) or Octanol ($C_8H_{18}O$))
- scientific analyses are comparable to those for GeoFlow I, but convective behavior is expected different to the results by GeoFlow I



GeoFlow experiment is available

→ loocking for the best fluid model to verify the experimental results

→ to verify with the experiment existing numerical results from mantle dynamics

→ next Topical-Team meeting: beginning of November