Effect of grid resolution on tectonic regime in global-scale convection models

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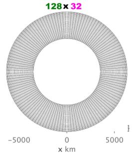
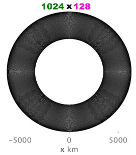
BGI Bayerisches Geoinstitut — Universität Bayreuth — EGU General Assembly 2020 — DeepEarthVolatileCycles — BGI Geodynamics

1. Motivation



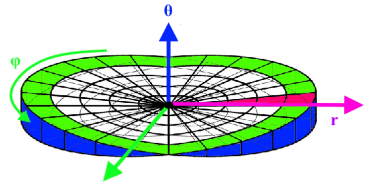
In numerical simulations four types of lid regimes can be obtained by varying the ***yield strength***.
Also numerical parameters, such as the ***grid resolution***, determines the outcome of a simulation.

Guiding question: What is the effect of grid resolution on the tectonic regime?



2. StagYY

- Code **StagYY** (*1*), data analysis **StagLab** (*2*)
- **Spherical annulus** geometry (3), equatorial slice of a planet
  - **Azimuthal resolution** (ϕ) in the y direction (longitude)
  - **Radial resolution** (r) in the z direction (radius)
  - **Zenithal resolution** (θ) in the x direction (latitude)



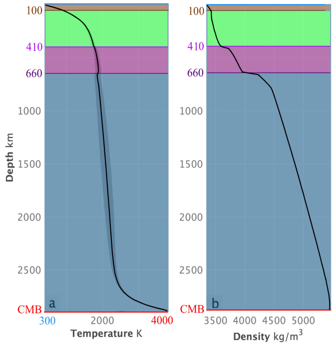
- **Stokes equations** solved for compressible material:

Continuity Equation	Energy Equation
$\frac{\partial\rho}{\partial t}+\frac{1}{r^d}\frac{\partial}{\partial r}(r^d\rho v_r)+\frac{\partial}{\partial\phi}\left[\rho\left(\frac{v_\phi}{r}\right)\right]=0$	$\frac{1}{r^d}\frac{\partial}{\partial r}(r^d\tau_{rr})+\frac{1}{r}\frac{\partial\tau_{r\phi}}{\partial\phi}-\frac{\tau_{\phi\phi}+\tau_{\theta\theta}}{r}-\frac{\partial p}{\partial r}-\rho g=0$

Angular Component of Momentum Equation	Radial Component of Momentum Equation
$\frac{1}{r^d}\frac{\partial}{\partial r}(r^d\tau_{r\phi})+\frac{1}{r}\frac{\partial\tau_{\phi\phi}}{\partial\phi}+\frac{\tau_{r\phi}}{r}-\frac{1}{r}\frac{\partial p}{\partial\phi}=0$	$\frac{\partial e}{\partial t}+v_r\frac{\partial e}{\partial r}+\left(\frac{v_\phi}{r}\right)\frac{\partial e}{\partial\phi}=\frac{1}{r^d}\frac{\partial}{\partial r}\left(r^dK\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial\phi}\left(K\frac{\partial T}{\partial\phi}\right)+H$

4. Model Assumptions

- Isothermal, free slip boundaries
- Constant radiogenic heating
- No melting
- Composition: 60% ol + 40% pxgt
- Exothermic phase change (Wd)
- Endothermic phase change (Pv)
- Upper/lower η cutoff: $10^{28}/10^{17}$ Pa s
- 15 Gyrs simulated time
- Initial Rayleigh Number: $8*10^7$
- **Constant yield strength**



3. Rheology

- **Arrhenius law:** strongly **T-dependent** viscosity (ηdiff)

$$\eta_{diff}(T,P)=\eta_0\,exp\left(\frac{E+PV}{RT}-\frac{E}{RT_0}\right)$$

- **Plastic rheology: Yield Stress limiter** (τ_y) restricts ηapp

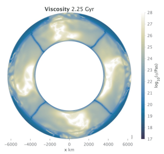
$$\eta_{app}=\frac{\tau_y}{2\dot{\varepsilon}_{II}}$$

- **Effective viscosity:** minimum between ηdiff and ηapp

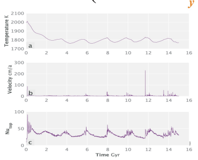
$$\eta_{eff}=\min\left[\eta_{diff}(T,P),\ \eta_{app}(\tau_y,\dot{\varepsilon}_{II})\right]$$

5. Lid Regimes

Dripping behaviour
(10 MPa < τ_y < 20 MPa)

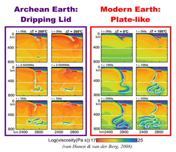


Snow-fall like subduction



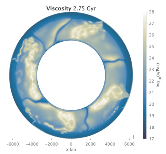
Time evolution profile

Colander lid

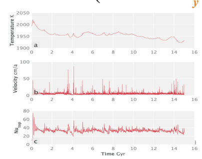


Archean Earth

Plate-like behaviour
(20 MPa < τ_y < 50 MPa)

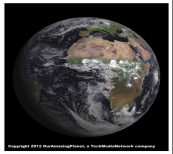


Continuous subduction



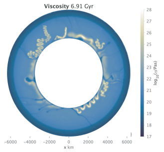
Time evolution profile

Vent holes lid

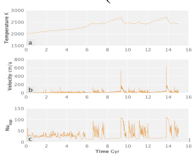


Present day Earth

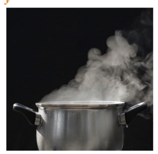
Episodic behaviour
(50 MPa < τ_y < 80 MPa)



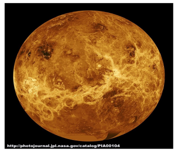
Mantle overturn



Time evolution profile

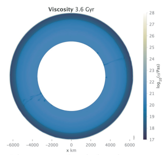


Steaming Pot

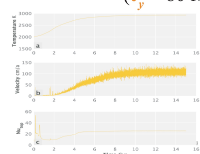


Venus

Stagnant lid behaviour
(τ_y > 80 MPa)



Absence of subduction



Time evolution profile

Sealed Pot

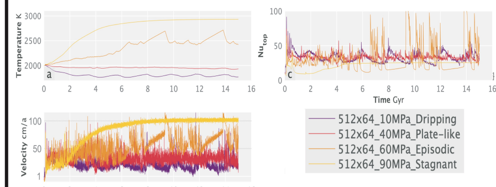
Moon

6. Nusselt Number

A very useful parameter to study the different lid behaviours

$$Nu=\frac{q_{tot}}{q_{cond}}=\frac{\text{total heat transport}}{\text{conductive heat transport}}$$

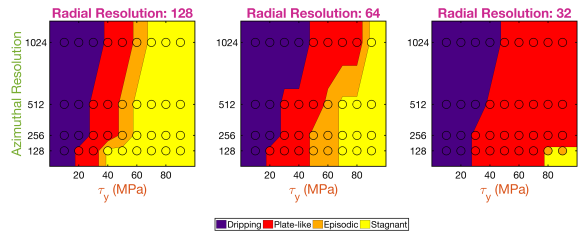
7. Resolution Tests



Different lid regimes can be distinguished by:

- Temperature profile
- Surface Nusselt number
- Average velocity profile

12 different **grid resolutions** (from **128**x**32** up to **1024**x**128**) over a range of 9 different τ_y (from 10 to 90 MPa)



8. Conclusions

- **Yield strength** controls the strength of the lithosphere leading to 4 different behaviours: **Dripping, Plate-like, Episodic, Stagnant**
- **Grid resolution** is a key numerical parameter since it affects the lid behaviour stability domain
- Critical τ_y that separates plate-like from episodic regime shifts toward higher τ_y, either if the **radial resolution** is low or the **azimuthal** is high

1. Tackley, P. J. *(2008) Phys. Earth Planet. Int., 171(1-4), 7-18;* ***2. Crameri, F.*** *(2018) Geosc. Mod. Dev., 11(6), 2541-2562.;* ***3. Hernlund, J. W., & Tackley, P. J.*** *(2008) Phys. Earth Planet.Int., 171(1-4), 48-54;* ***4.Van Hunen J. & Van Der Berg A. P.*** *(2008) Lithos 103(1-2), 217-235*