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# MACMA : Mantle cooling mechanisms simulated by agents.

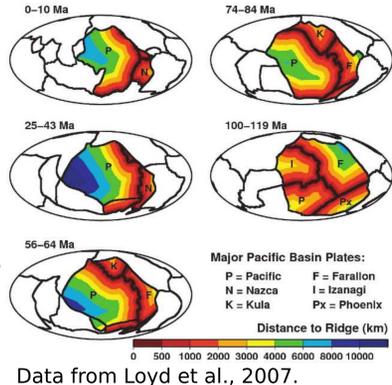
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## 1. Motivation

### Mantle cooling and tectonics

Earth's thermal history has long been studied with monotonous laws (Davies 1980, Labrosse and Jaupart 2007) but short-term mechanisms were demonstrated to influence the global heat balance on Earth : Becker et al. 2009 showed that the heat flux decreased by ~25% over 100 Myr during the Cenozoic because of plate tectonics. Hence, short timescales cannot be neglected to investigate mantle cooling mechanisms.

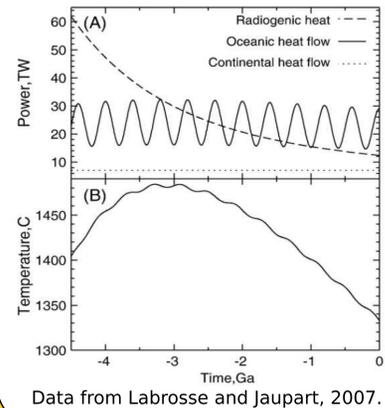


Data from Loyd et al., 2007.

### Multiagent proposition

We aim at simulating time-dependent tectonics coupled with mantle convection over a variety of timescales.

We develop a new approach based on multiagent systems that accounts for both analytical and empirical laws to examine the impact of evolutive plate boundaries on the geometrical and thermal evolution of the Earth. The number of plates is not fixed in our simulations, and any additional process (analytical or empirical) can be easily incorporated into the model.



Data from Labrosse and Jaupart, 2007.

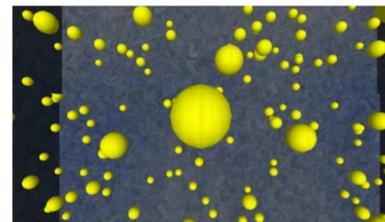
## 2. Multiagent systems

### Autonomous entities

Agents are autonomous entities that collect information from their environment to make a decision controlled by behavior laws. The thermal and mechanical interaction of these agents allows us to simulate a dynamical complex system by superimposition of various phenomena. Our approach has been previously applied to molecular dynamics (Combes et al. 2010).



Our agents are convection cells, lithospheric plates, plate interfaces (subduction zones and ridges), and insulating continents that define the continental sections of the plates. Such multiagent simulations aim at experimenting physical models : any user can test hypotheses and investigate underlying mechanisms.



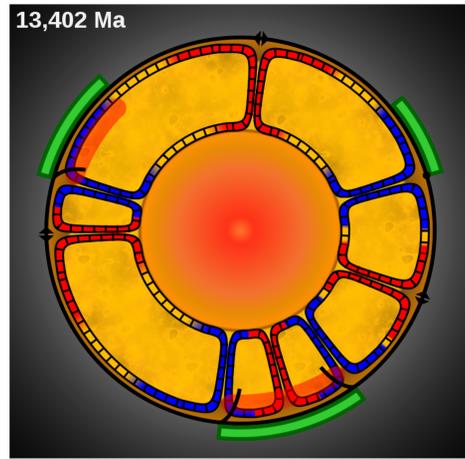
Snapshot from Combes et al., 2010

## 3. Model

### Force balance

Plate velocities are based upon a force balance (Pr~10^25):

- Ridge push =  $\alpha \cdot K \cdot g \cdot \rho \cdot T_m \cdot \tau$
- Slab pull =  $\Delta \rho \cdot g \cdot H(\tau) \cdot Z$
- Bending =  $-2/3 \eta_{pl} \cdot U \cdot (H/R_{min})^3$
- Slab resistance =  $-2\eta_{um} \cdot U \cdot Z/d$
- Mantle drag =  $-2\eta_m \cdot U \cdot L/d$
- Slab suction =  $2\eta_m \cdot V_s \cdot (Z-D)/d$



### Empirical laws

- Limited plate thickening :  $H(\tau) < H_{max}(T_m)$
- Spontaneous plate sinking : subduction initiation at 180 Myr (today)
- Plate suturing : continental collision, subduction of a ridge, back-arc basin creation.
- Subduction zone kinematics : updating  $V_s = V_o \eta_0 / \eta(T_m)$

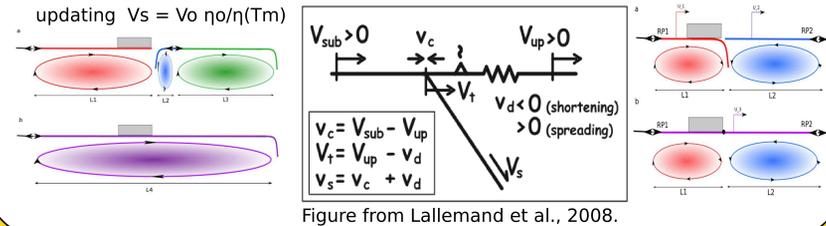


Figure from Lallemand et al., 2008.

### Thermal behavior

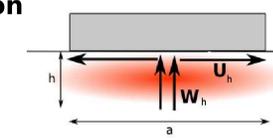
- Half-space cooling model :  $q_{oc}(t, \tau) = \frac{k(T_m(t) - T_o)}{\sqrt{\pi \kappa \tau}}$  and  $H(\tau) = 2.32 \sqrt{\kappa \tau}$  (Turcotte and Schubert 2002)

- Temperature-dependent viscosity :  $\eta(T_m) = \eta^0 \exp\left[\frac{E}{R} \left(\frac{1}{T_m} - \frac{1}{T^0}\right)\right]$  (Karato and Wu 1993)

- Global heat balance :  $M \cdot C_p \frac{dT_m}{dt} = - \langle q_{oc} \rangle S_{oc} + \sum_i H_i e^{-t/\tau_i}$

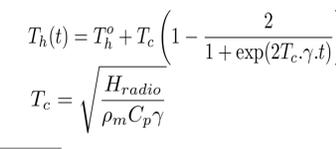
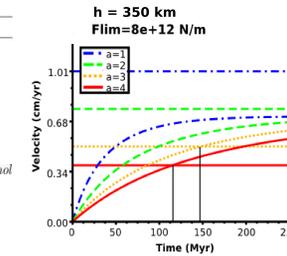
### Continental breakup and oceanization

Shallow advecting layers (a;h) are warmed beneath insulating supercontinents, implying :  
 - local heat balance  
 - mass conservation  
 - momentum conservation



$$\frac{dT_h}{dt} + \frac{2h\alpha\rho_m g}{\eta_m} \frac{(T_h - T_h^0)^2}{\left(\frac{a}{2h}\right)^{-2} + \left(\frac{a}{2h}\right)^2} = \frac{H_{radio}}{C_p}$$

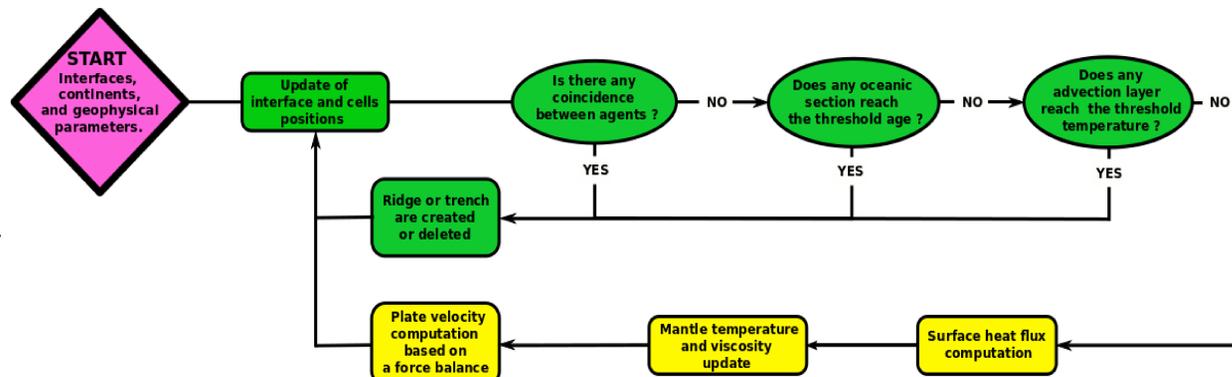
Parameter	Value
$\alpha$ , thermal expansivity	$2.5 \cdot 10^{-5} K^{-1}$
$H_{radio}$ , internal heating rate	$3.10 \cdot 10^{12} W/kg$
$\Delta\rho$ , mass excess for a slab	$65 kg/m^3$
$T^0$ , initial mantle temperature	$1600 K$
$\eta_m^0$ , average mantle viscosity	$1 - 3 \cdot 10^{22} Pa.s$
$\eta_{um}^0$ , upper mantle viscosity	$10^{21} Pa.s$
$E$ , activation energy	$250 - 400 kJ/mol$
$d$ , total mantle thickness	$2900 km$
$D$ , upper mantle thickness	$670 km$
$R_{min}$ , radius of curvature	$300 km$
$Ra$ , Rayleigh Number	$2.10^7$
$\tau$ , lithosphere age	
$h$ , plate thickness	
$L$ , plate extent	
$Z$ , depth reached	
$a$ , continental aspect ratio	
$h_c$ , advection thickness	
$F_{lim}$ , continental strength	



+ Newtonian threshold stress  $F_{lim}$ .

## 4. Algorithm

- Alternation dynamics / structure update
- 3 Gyr simulated in 12 minutes
- Flexibility through options :
  - temperature-dependent viscosity
  - back-arc basin existence
  - slab suction existence
  - oceanization parameters



## 5. Experiments

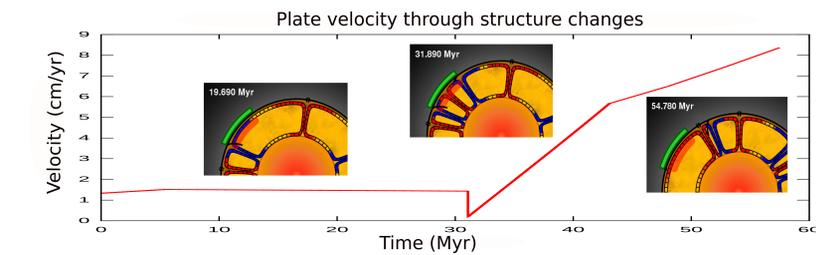
### Mimicking current Earth's tectonics

Computed plate velocities (cm/yr)

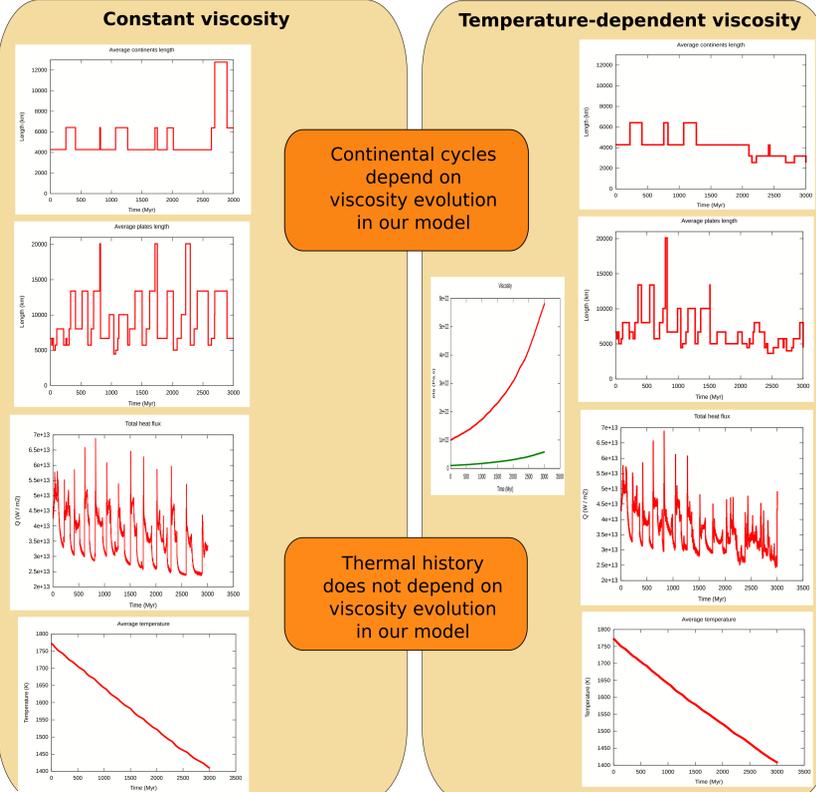
$\eta_m$	$d/2$	Z	NZ	SA	P
$1 \times 10^{22}$	1450	670	3.8	0.2	2.0
$1 \times 10^{22}$	1450	1300	4.6	0.78	2.3
$1 \times 10^{22}$	1450	2800	7.1	1.9	3.4

Average velocities in NNR

NZ	SA	P
7.0	0.4	5.5



### Viscosity laws and continental cycles



Continental cycles depend on viscosity evolution in our model

Thermal history does not depend on viscosity evolution in our model