MACMA : Mantle cooling mechanisms simulated by agents

Manuel Combes, C. Grigné, Laurent Husson, Sébastien Le Yaouanq, Marc Parenthoën, Chantal Tisseau, Jacques Tisseau

To cite this version:

Manuel Combes, C. Grigné, Laurent Husson, Sébastien Le Yaouanq, Marc Parenthoën, et al.. MACMA : Mantle cooling mechanisms simulated by agents. European Geophysical Union - General Assembly 2011, Mar 2011, Austria. 13, 1 p., 2011. <hal-00874980>

HAL Id: hal-00874980
https://hal.archives-ouvertes.fr/hal-00874980

Submitted on 24 Oct 2013

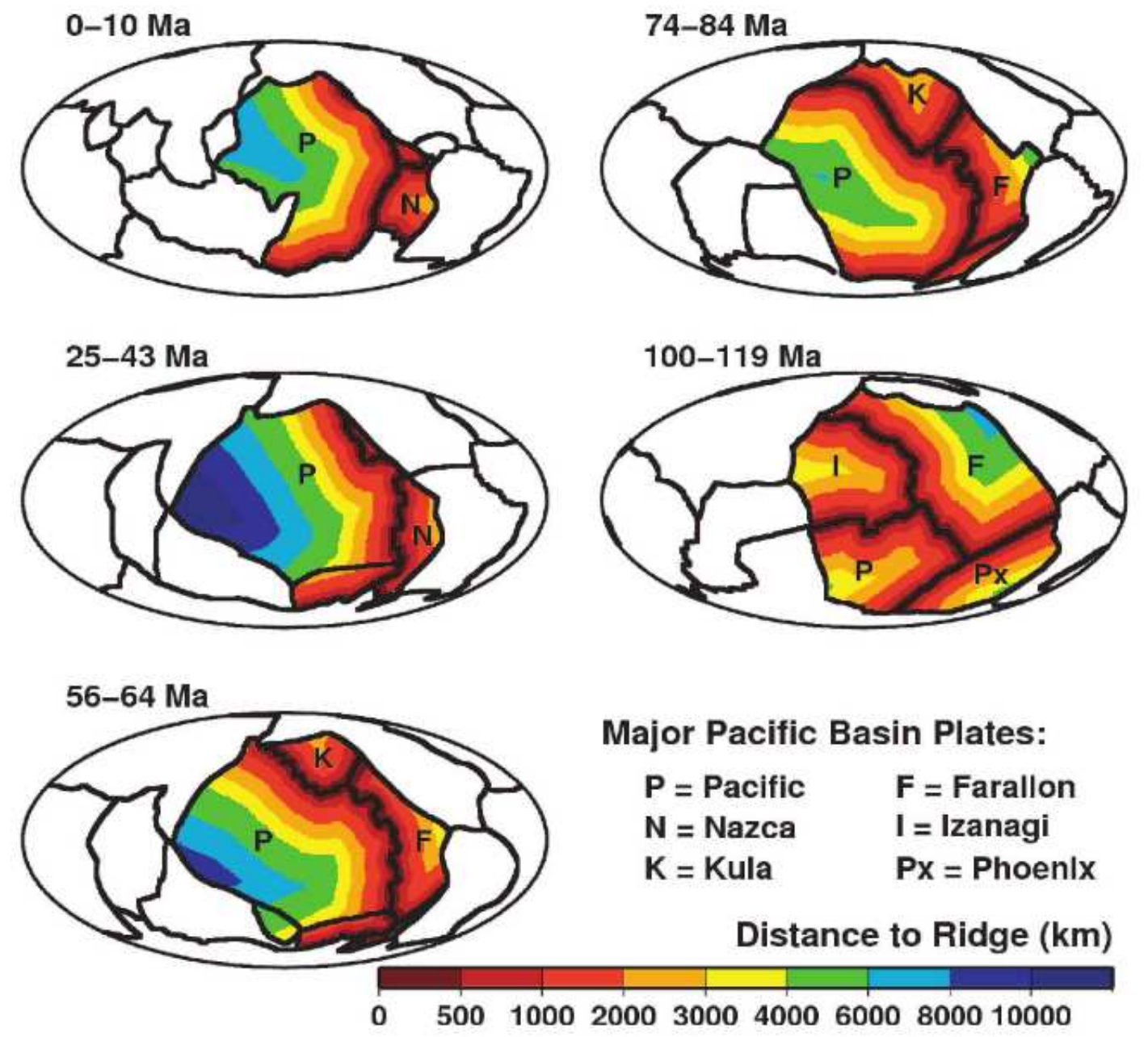
MACMA : Mantle cooling mechanisms simulated by agents.

Manuel Combes (1), Cécile Grigné (2), Laurent Husson (3), Sébastien Le Yaouanq (4), Marc Parenthoën (1), Chantal Tisseau (2), and Jacques Tisseau (1)
(1) European Center for Virtual Reality (CERV, EA3883), European University of Brittany, Plouzané, France (**combes@enib.fr**).
(2) European Institute for Marine Studies (IUEM, UMR 6538), European University of Brittany, Plouzané, France.
(3) Géosciences-Rennes (UMR 6118), European University of Brittany, Rennes, France.
(4) CERVVAL, Plouzané, France.

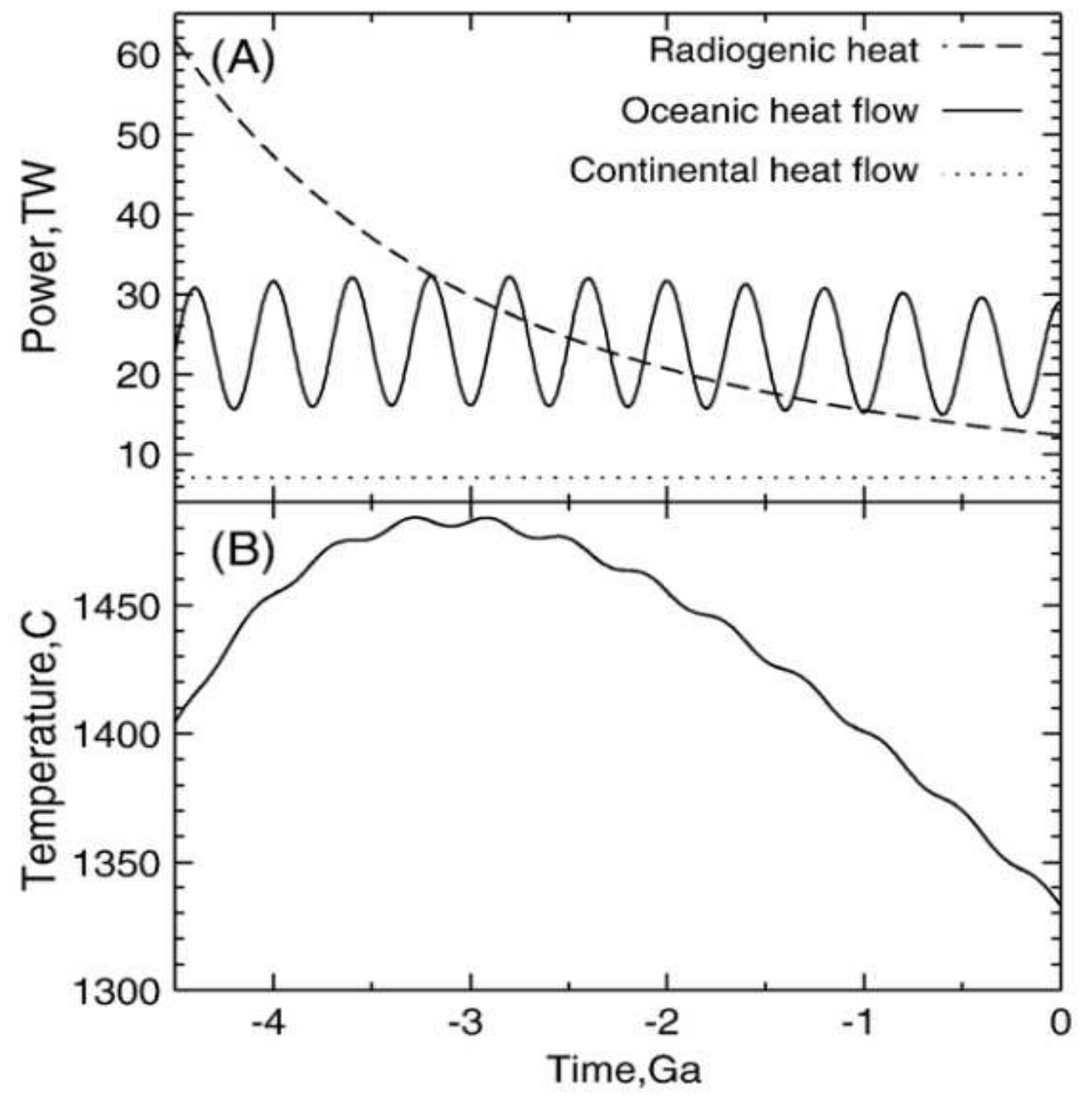
1. Motivation

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.



Data from Labrosse and Jaupart, 2007.

Multiagent proposition

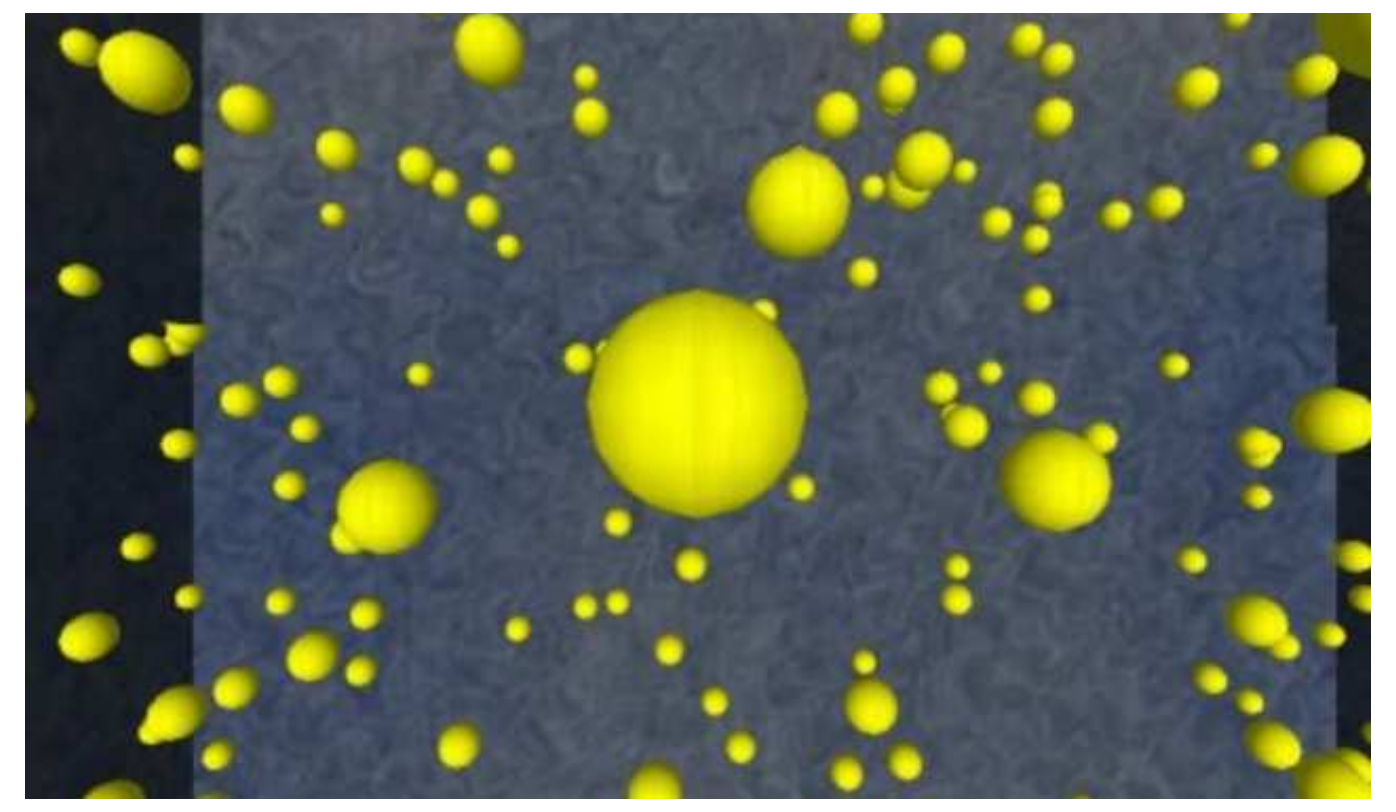
We aim at simulating time-dependent tectonics coupled with mantle convection over a variety of timescales.

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.

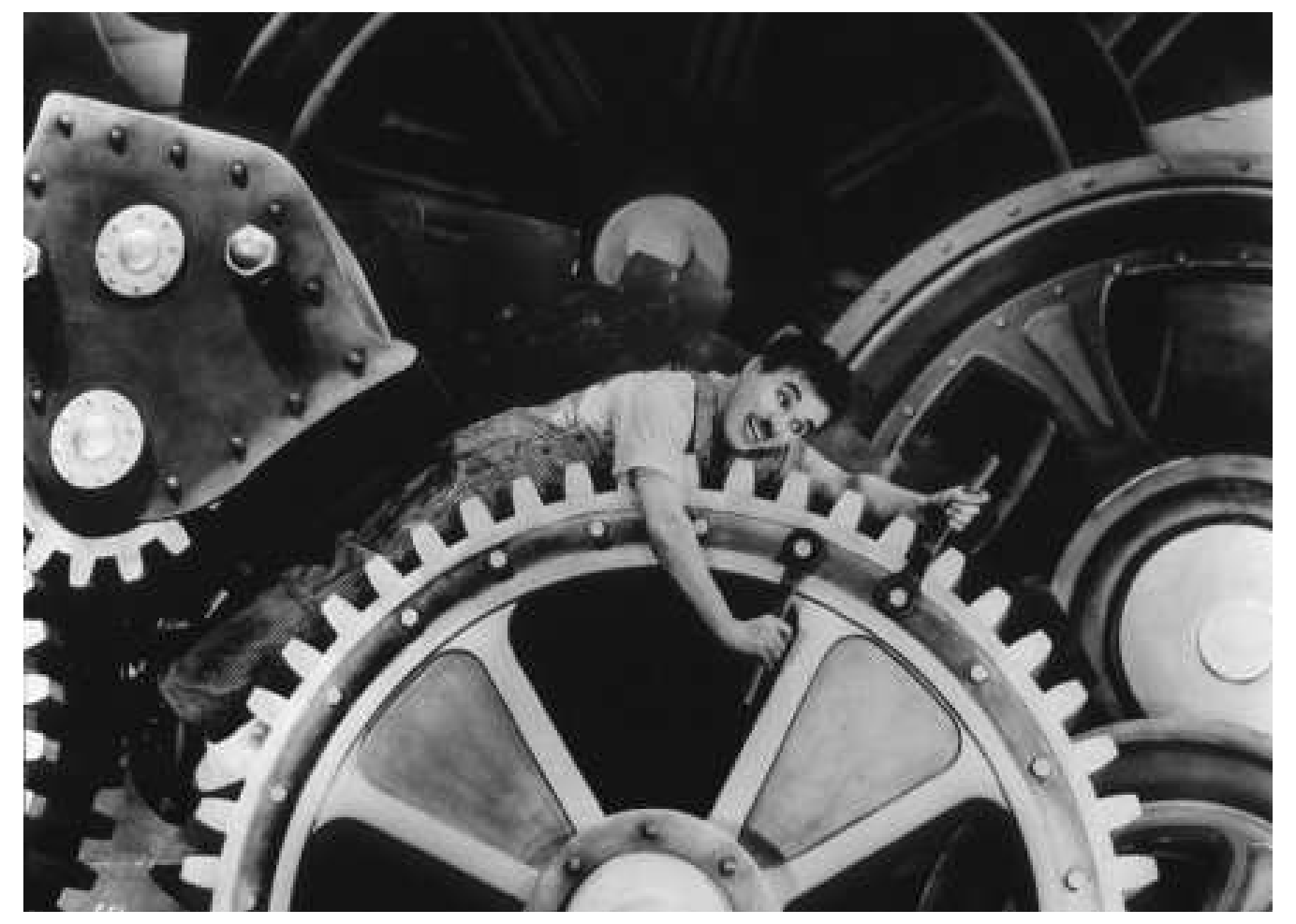
2. Multiagent systems

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).



Snapshot from Combes et al., 2010



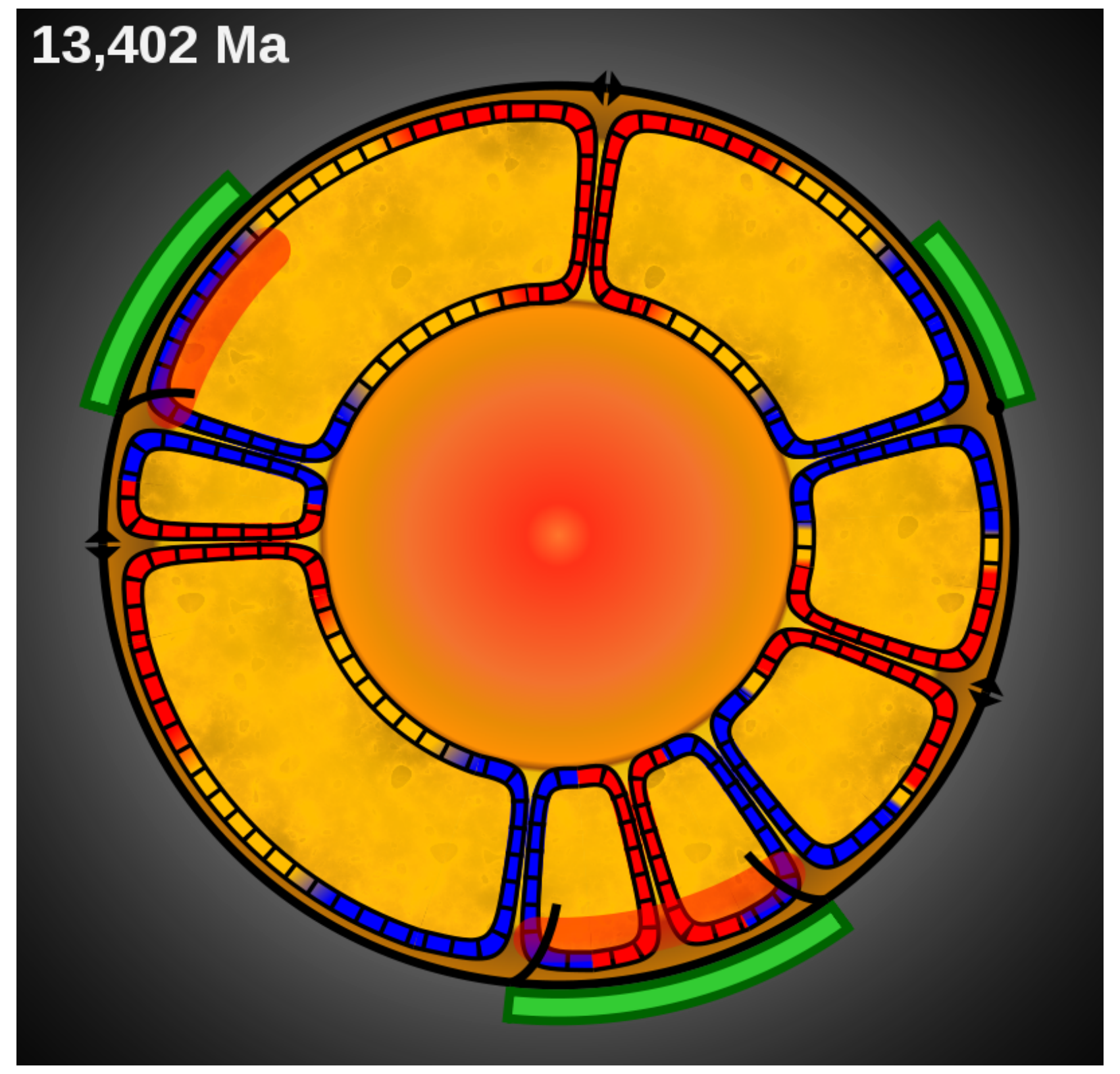
Our agents are convection cells, lithospheric plates, plate interfaces (subduction zones and ridges), and insulating continents that define the continental sections of the plates. Such multiagent simulations aim at experimenting physical models : any user can test hypotheses and investigate underlying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

3. Model

Force balance

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

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



Empirical laws

- **Limited plate thickening** : $H(\tau) < H_{\mathbf{max}}(T_m)$
- **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 $V_s = V_o\ \eta_o/\eta(T_m)$

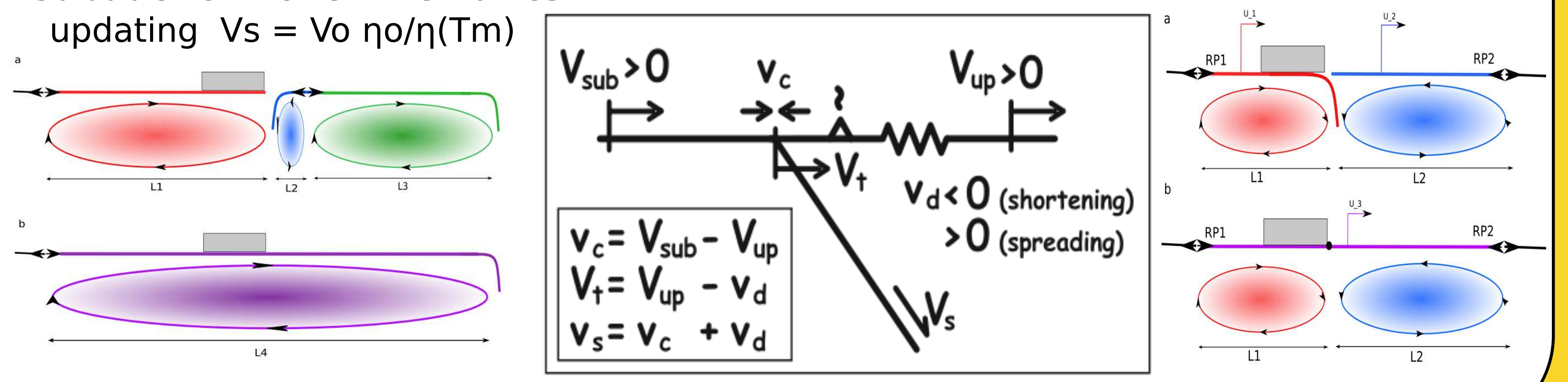


Figure from Lallemand et al., 2008.

Thermal behavior

- **Half-space cooling model** : (Turcotte and Schubert 2002)

$$q_{oc}(t,\tau) = \frac{k\big(T_m(t) - T_o\big)}{\sqrt{\pi\kappa\tau}} \quad \text{and} \quad H(\tau) = 2.32\sqrt{\kappa\tau}$$

- **Temperature-dependent viscosity** : (Karato and Wu 1993)

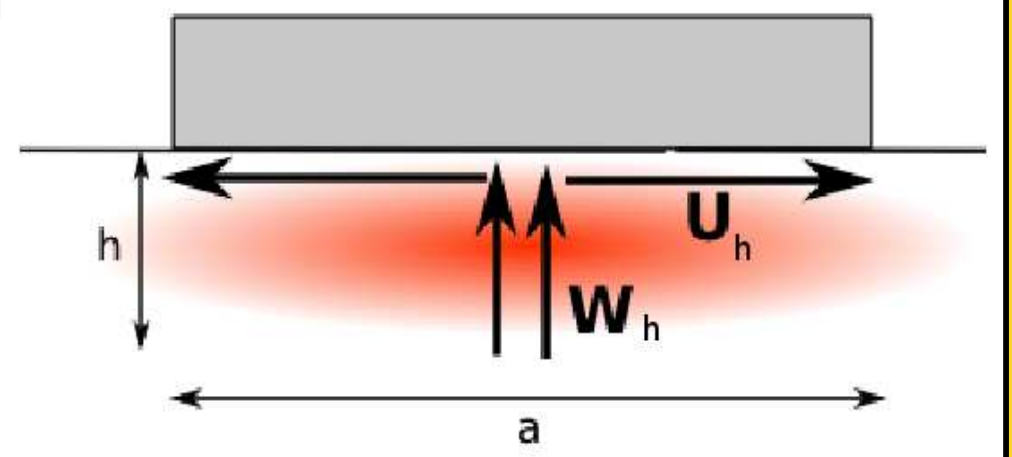
$$\eta(T_m) = \eta^o \exp\left[\frac{E}{R}\left(\frac{1}{T_m} - \frac{1}{T^o}\right)\right]$$

- **Global heat balance** :

$$M.C_p\frac{dT_m}{dt} = - < q_{oc} > S_{oc} + \sum_i H_i e^{-t/\tau_i}$$

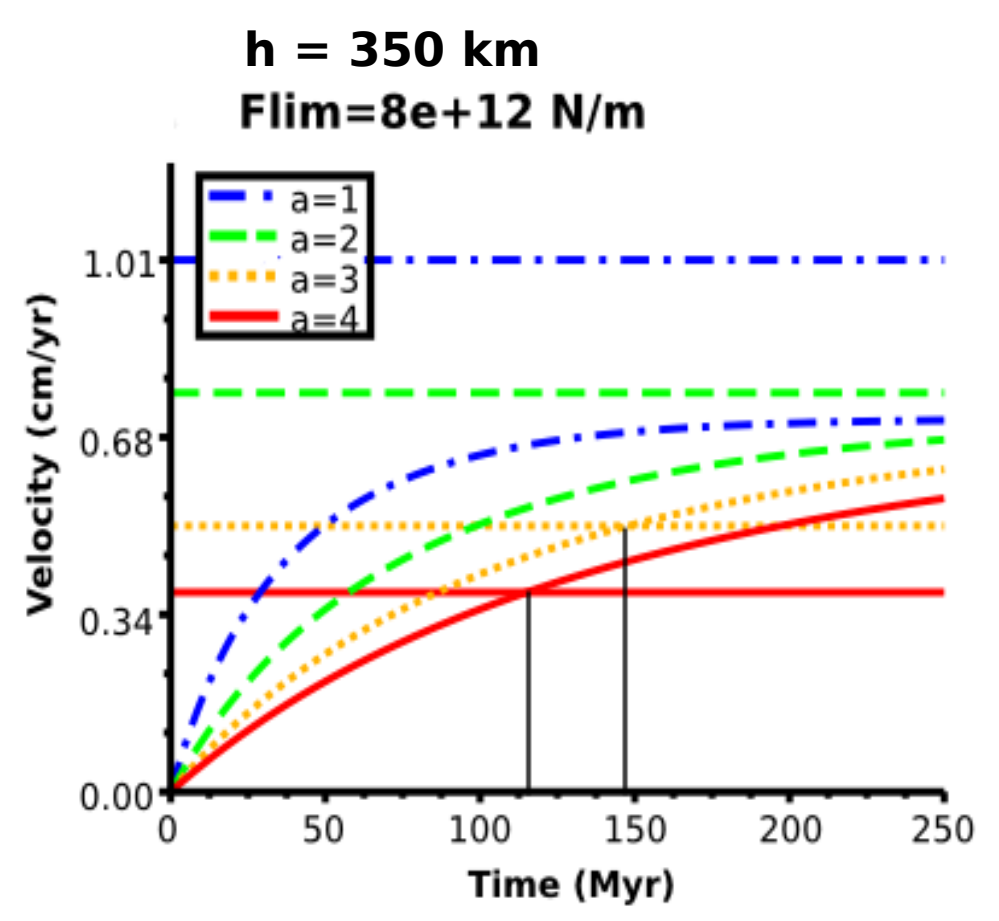
Continental breakup and oceanization

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



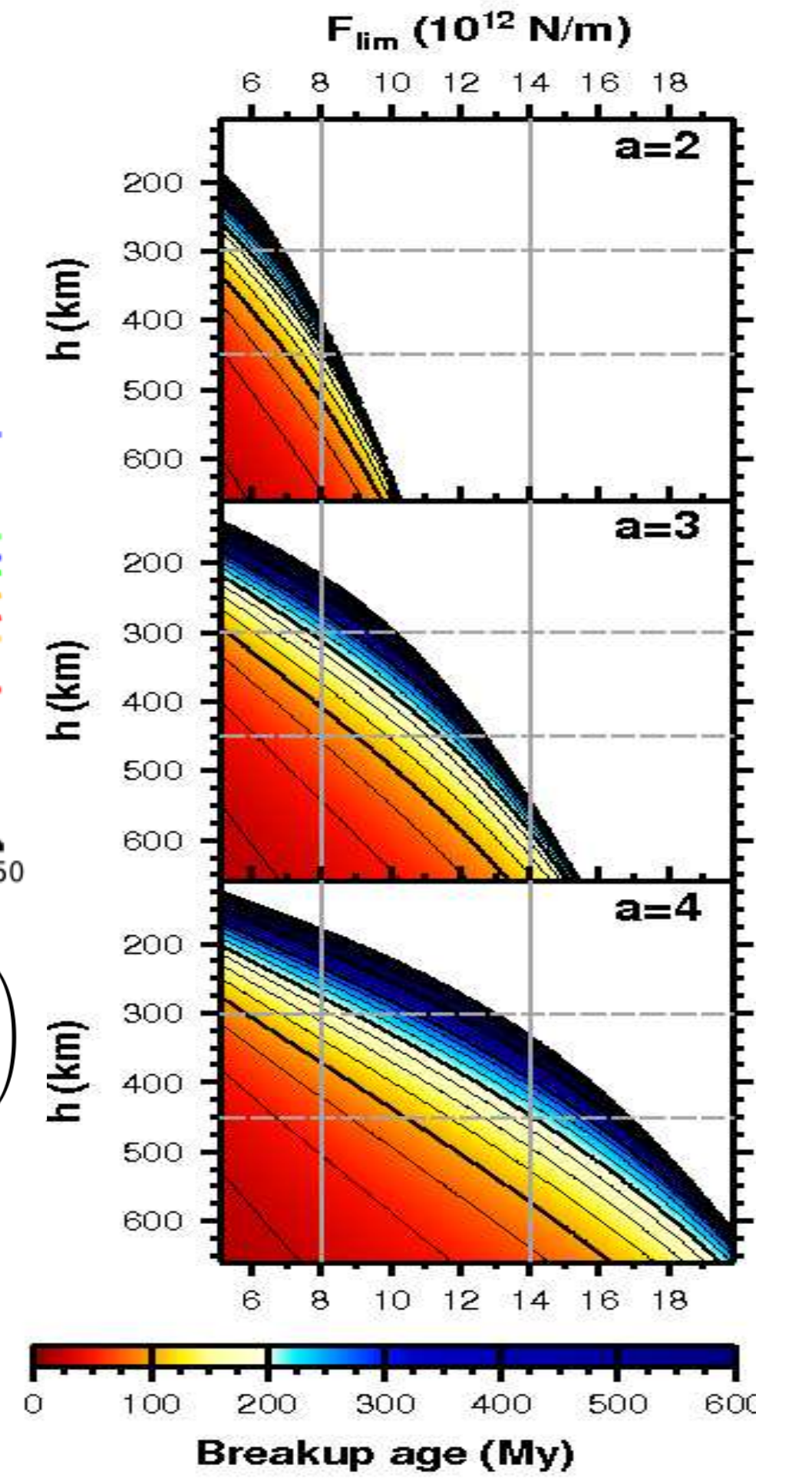
$$\frac{dT_h}{dt} + \frac{2h\alpha\rho_m g}{\eta_m}\frac{(T_h - T_h^o)^2}{\left(\frac{a}{2h}\right)^{-2} + \left(\frac{a}{2h}\right)^2} = \frac{H_{radio}}{C_p}$$

Parameter	Value
α, thermal expansivity	$2,5.10^{-5}\,K^{-1}$
H_{radio}, internal heating rate	$3.10^{-12}\,W/kg$
$\Delta\rho$, mass excess for a slab	$65\,kg/m^3$
T^o, initial mantle temperature	$1600\,K$
η_m^o, average mantle viscosity	$1 - 3.10^{22}\,Pa.s$
η_{um}^o, 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	$390\,km$
Ra, Rayleigh Number	2.10^7
τ, lithosphere age	
H, plate thickness	
L, plate extent	
Z, depth reached	
a, continental aspect ratio	
h, advection thickness	
F_{lim}, continental strength	



$$T_h(t) = T_h^o + T_c\left(1 - \frac{2}{1 + \exp(2T_c.\gamma.t)}\right)$$

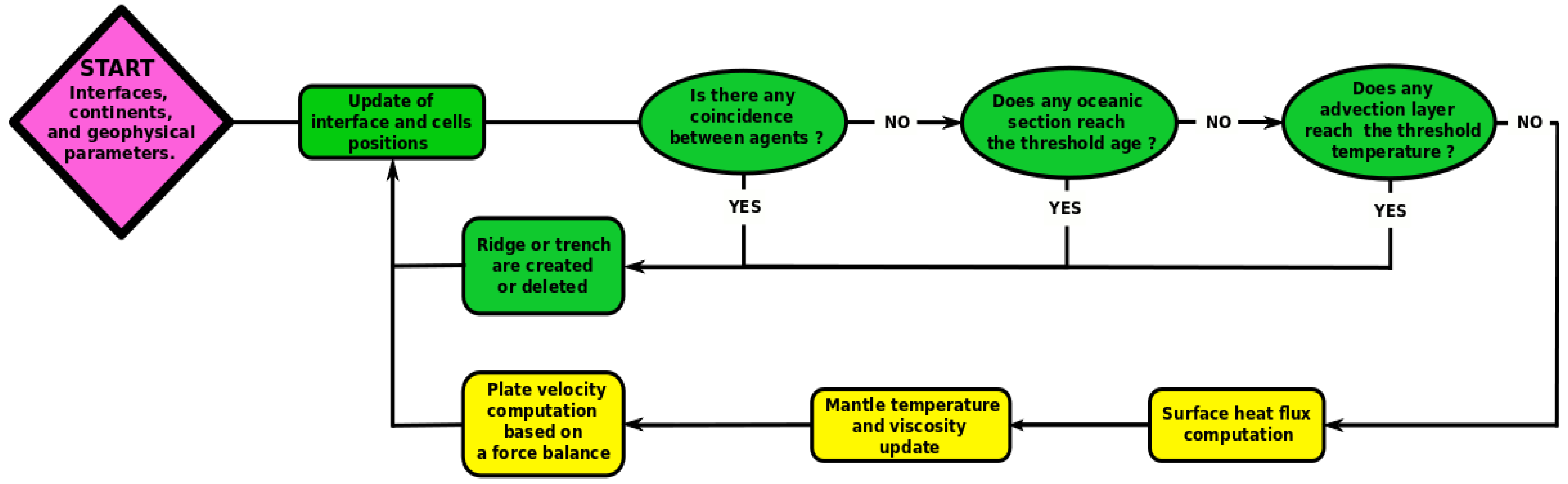
$$T_c = \sqrt{\frac{H_{radio}}{\rho_m C_p \gamma}}$$



+ 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



START Interfaces, continents, and geophysical parameters.

Update of interface and cells positions

Is there any coincidence between agents ?

NO

Does any oceanic section reach the threshold age ?

NO

Does any advection layer reach the threshold temperature ?

NO

YES

YES

YES

Ridge or trench are created or deleted

Surface heat flux computation

Mantle temperature and viscosity update

Plate velocity computation based on a force balance

5. Experiments

Mimicking current Earth's tectonics

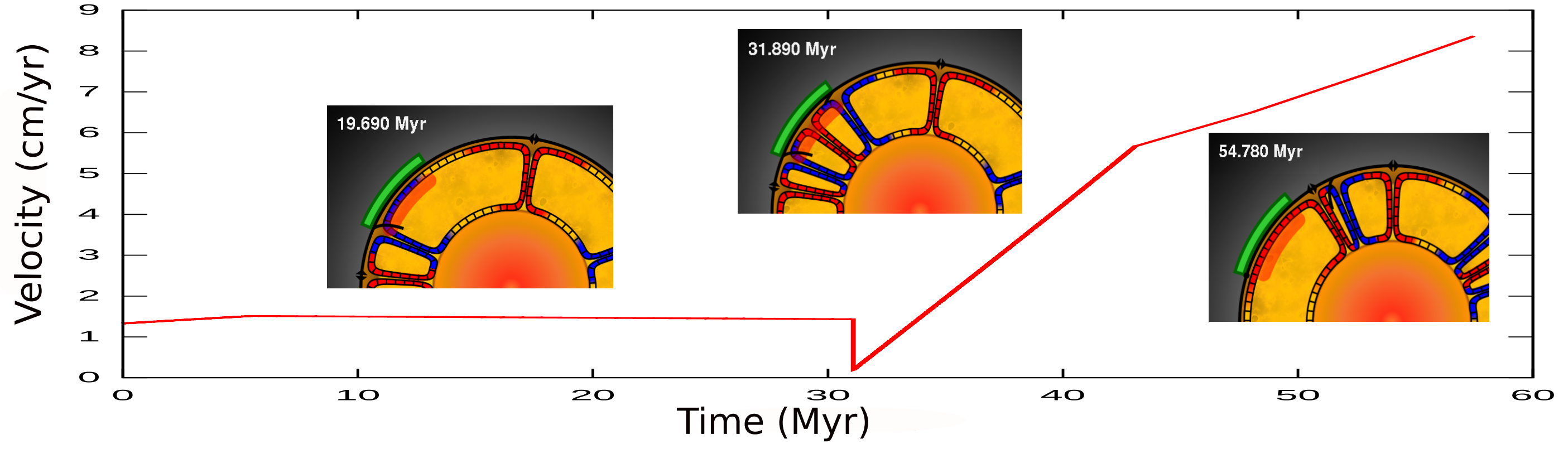
Computed plate velocities (cm/yr)

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

Average velocities in NNR

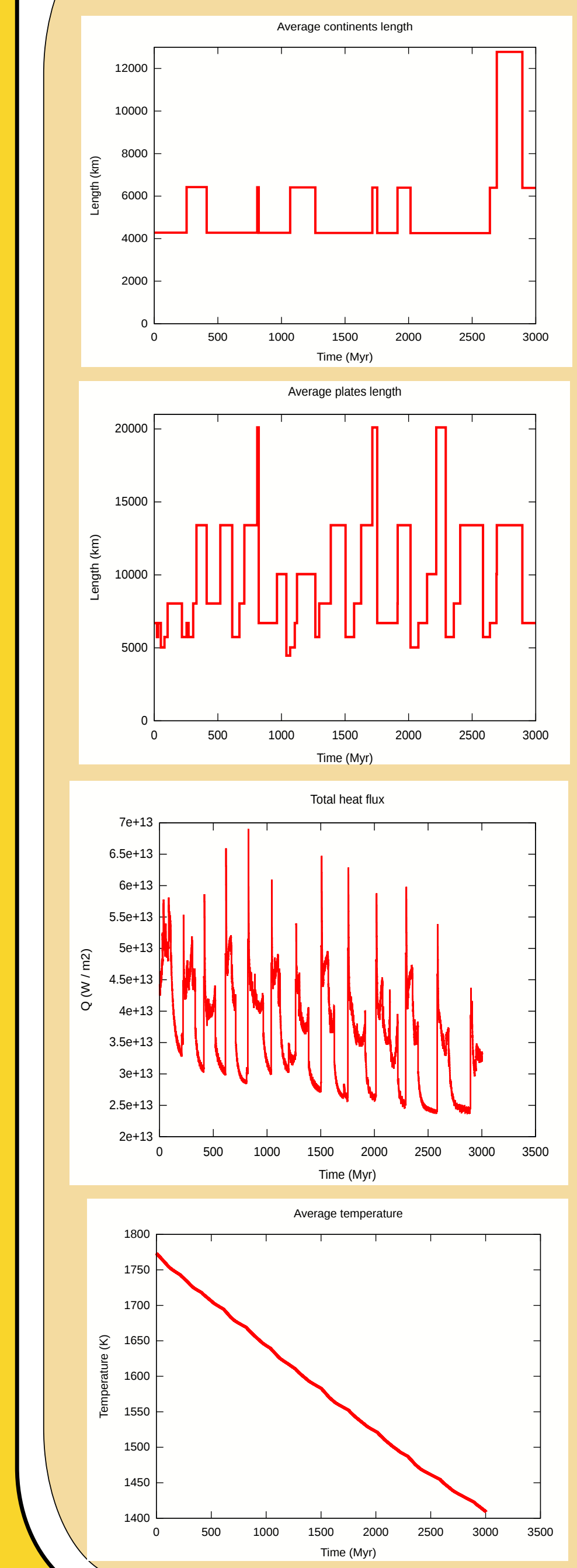
NZ	SA	P
7.0	0.4	5.5

Plate velocity through structure changes

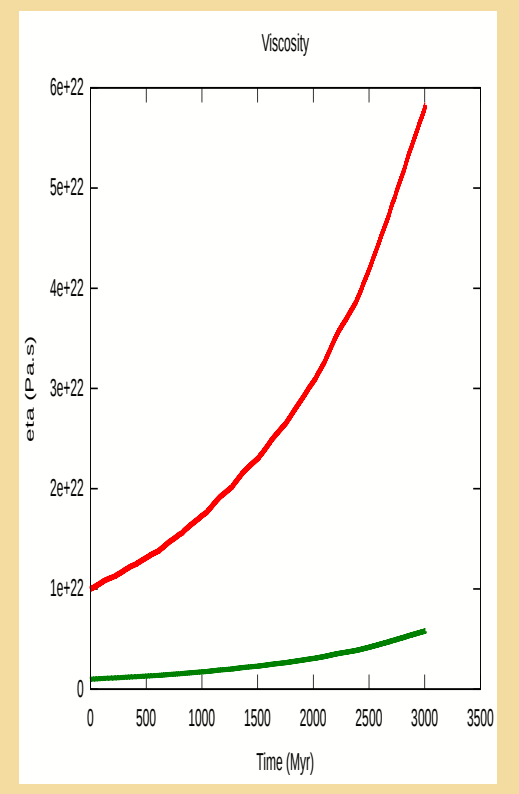


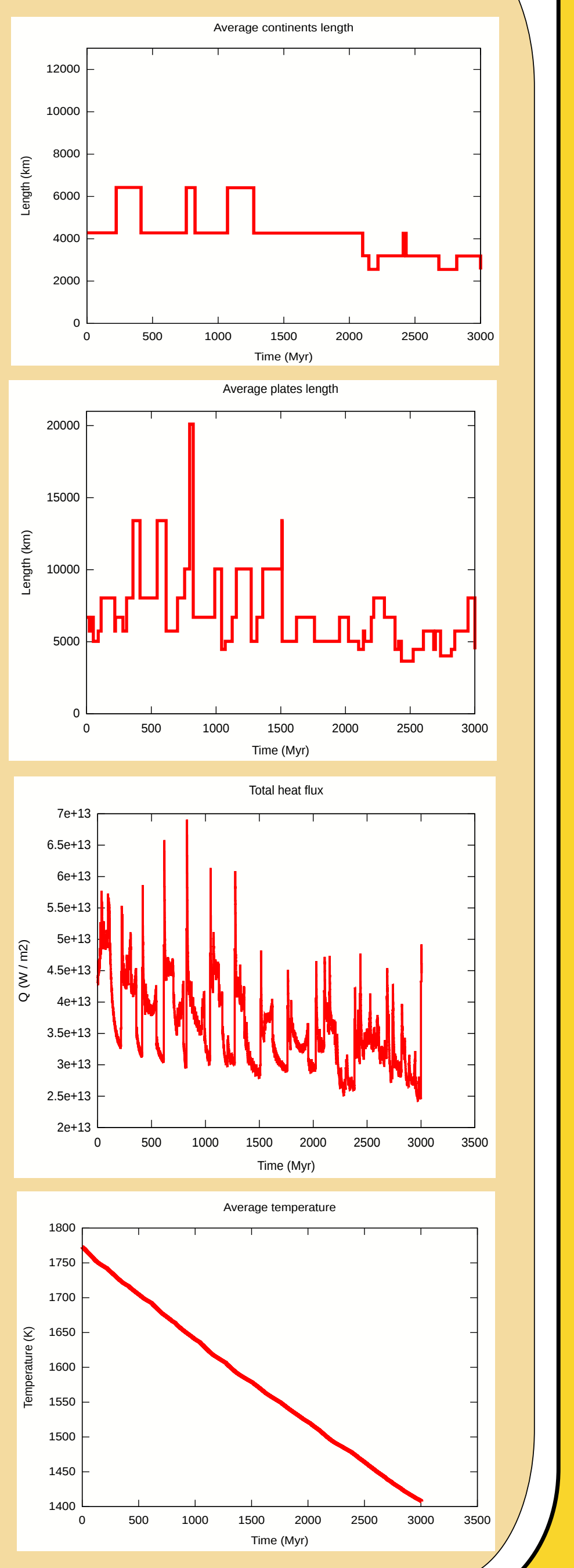
Viscosity laws and continental cycles

Constant viscosity



Temperature-dependent viscosity





Continental cycles depend on viscosity evolution in our model

Thermal history does not depend on viscosity evolution in our model