Multi-Agent Modelling of Earth's Dynamics: Towards a Virtual Laboratory of Plate Tectonics

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MACMA (Multi-Agent Convective MAntle) is a new tool developed to simulate plate tectonics and mantle convection in a 2-D cylindrical geometry (Combes et al., 2012).

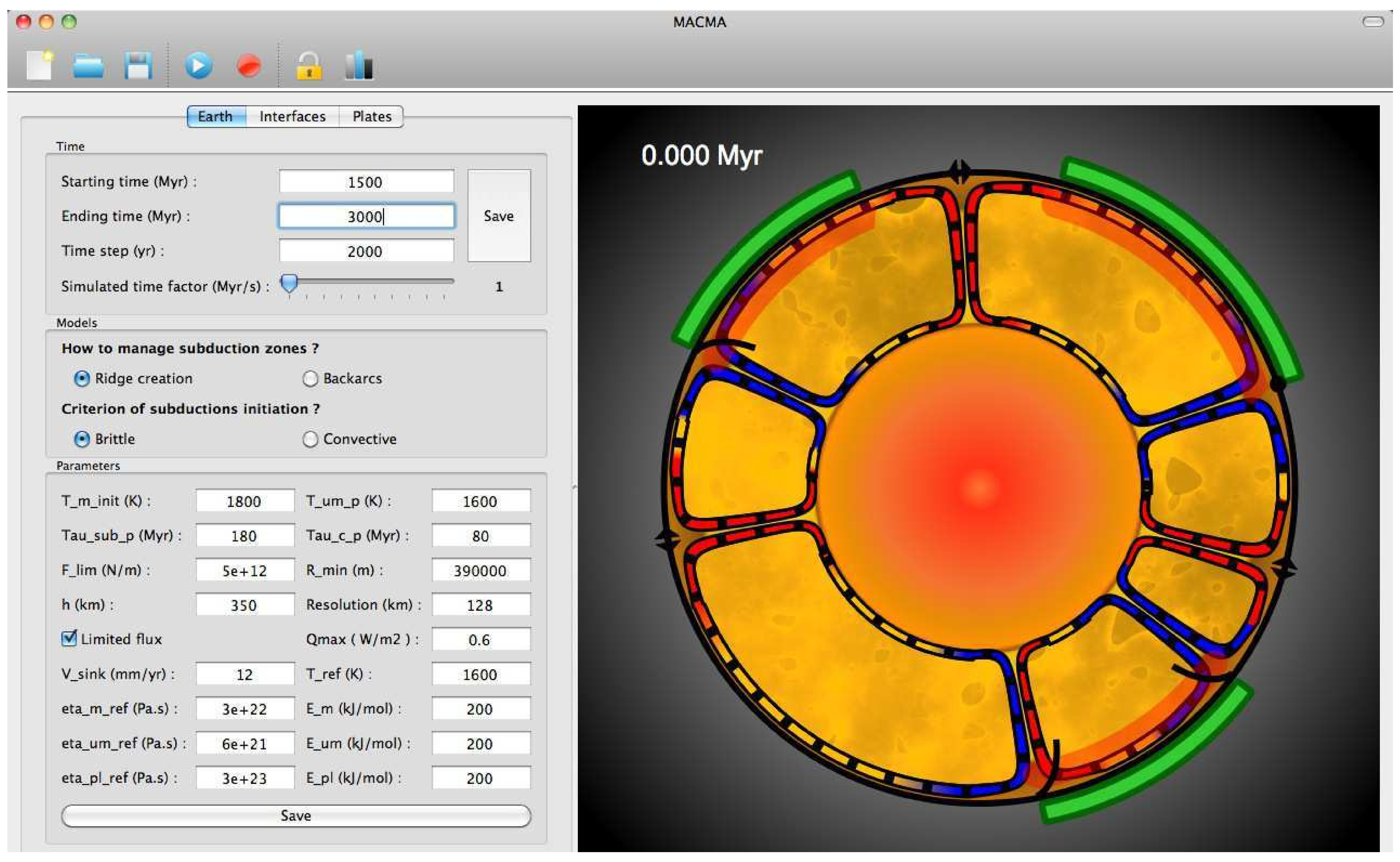


Fig. 1: Interface for MACMA: (left panel) geophysical input parameters and (right panel) evolutive geometry of plates, convective cells, plate boundaries and continents.

Four types of **agents** are considered: (1) plates, (2) plate boundaries, (3) convective cells and (4) continents.

These agents are **autonomous entities** which collect information from their environment and **interact with each other**. The dynamics of the system is mainly based on **a force balance** on each plate.

Force balance

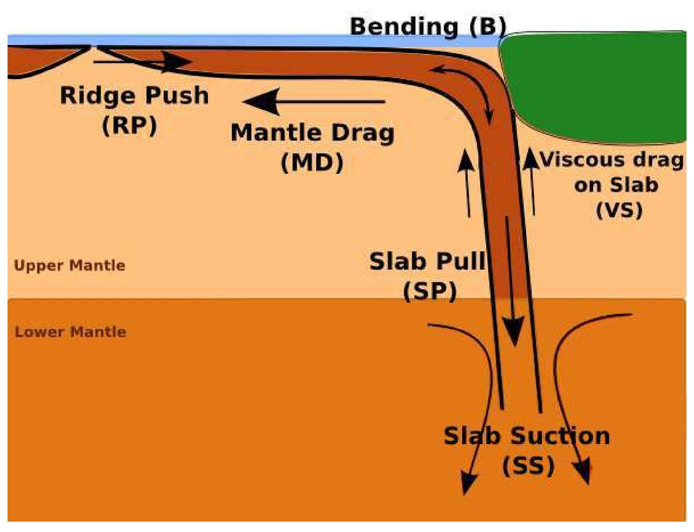


Fig. 2: Driving forces: RP, SP and SS; Resistive forces: MD, B and VS.

Writing RP + SP + SS + MD +B +VS = 0, we get the velocity of each plate as a function of

- its **length**,
- its **slab depth** and the curvature in the subduction zone (if the plate is subducting),
- its **maximum seafloor age**,
- the **viscosities** of the lithosphere and of the upper and lower mantles.

Thermal balance

The following thermal balance is used to compute the evolution of the mantle temperature $T_{\rm mantle}$:

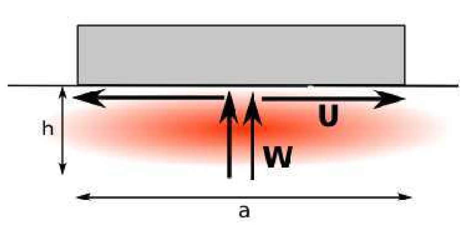
$$M_{\rm Earth}\, C_p\, \frac{dT_{\rm mantle}}{dt} \;=\; -Q_{\rm ocean}(t) \;+\; H_{\rm radiogenic}(t)$$

where $Q_{\rm ocean}$ is the oceanic heat flux derived from the seafloor age distribution (half-space cooling model) and $H_{\rm radiogenic}$ is the radiogenic internal heating of the mantle.

Phenomenological laws

The **interactions** between plates and the possible **changes in plate configuration** are controlled by analytical and empirical laws. For instance:

- Subductions are one-sided and are initiated along passive margins when a critical seafloor age is reached;
- Continental breakups occur in the middle of continents, when a critical diverging force due to subcontinental warming is reached;



- A structural criteria is used for the behavior of trenches:

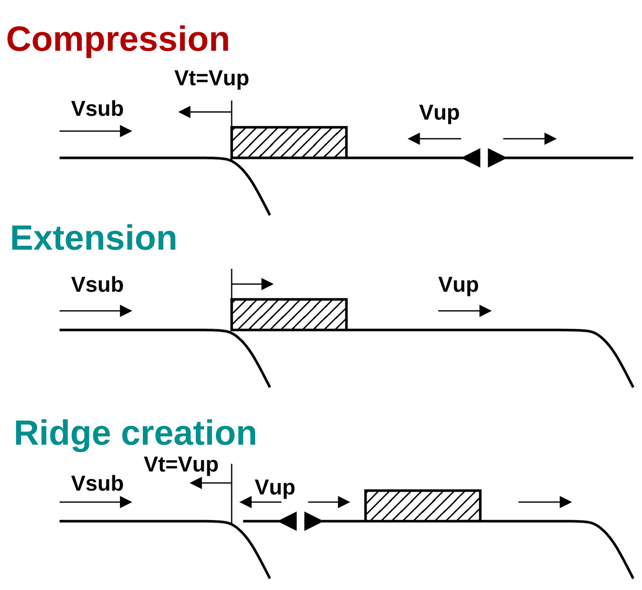


Fig. 3: When the upper plate is driven by ridge push, we assume a **compressive regime** and trench migration is prescribed by the upper plate motion (top).

When the upper plate is driven by subduction, we assume an **extensive regime** and a new ridge is created (middle and bottom).

Reference:

Combes, M., Grigné C., Husson L., Conrad C.P., Le Yaouanq S., Parenthoën M., Tisseau C. and J. Tisseau, 2012, *Multiagent simulation of evolutive plate tectonics applied to the thermal evolution of the Earth*, Geoch. Geophys. Geosyst., Vol. 13, No. 5, doi:10.1029/2011GC004014.

Evolutive plate tectonics

We obtain an **evolutive system** where the geometry and the number of plates are not imposed but **emerge naturally** from the dynamics of plate tectonics.

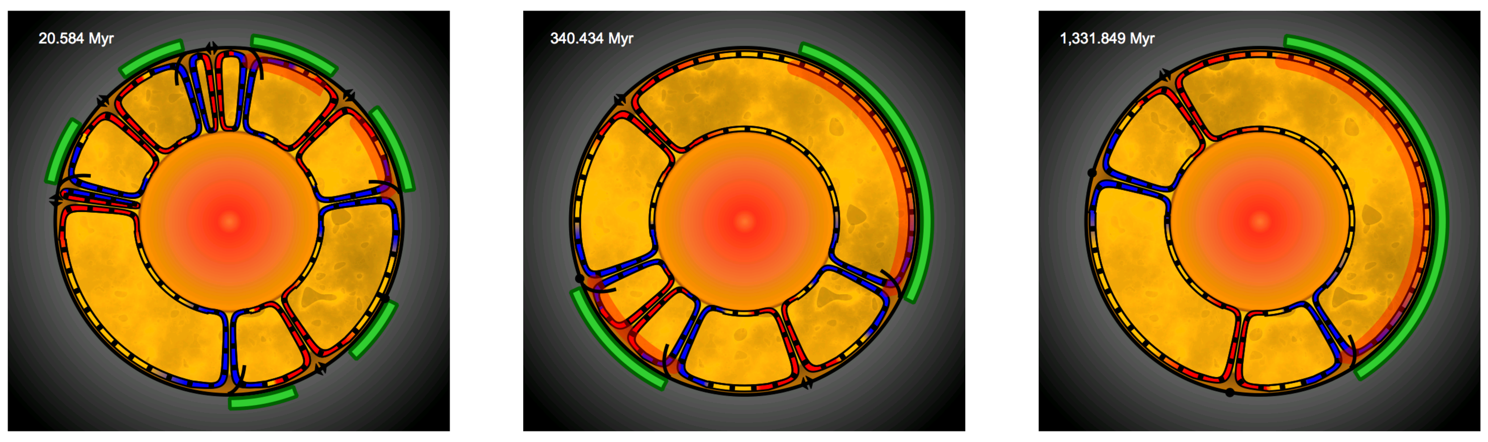


Fig. 4: Three configurations of plate tectonics obtained with the initial system shown in Fig. 1, showing the evolutive number of plates and continents.

Short-term thermal and dynamical evolution

In our model, Earth's total heat loss and the average velocity of tectonic plates show some sudden variations, that reflect the changes in plate configuration.

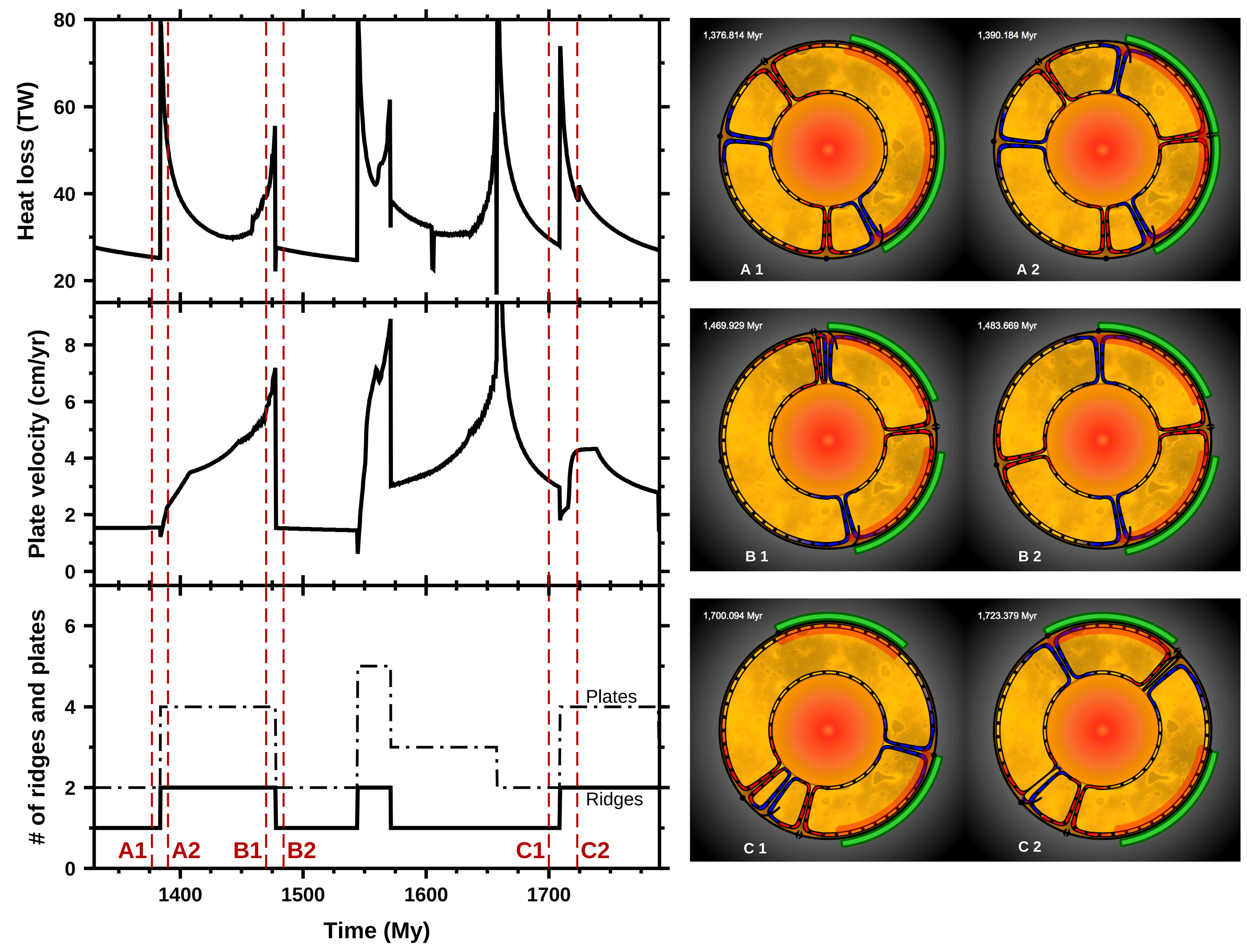


Fig. 5: Number of ridges and plates, average plate velocity and total heat loss of the Earth over time for the model presented in Fig. 1. (A) The peak of heat loss and the slowly increasing plate velocity are due to continental breakup, with the creation of a new ridge. (B) A ridge is subducted and a small plate disappears: the accelerating small plate causes a local peak of heat loss, followed by a sudden decrease when the small plate disappears. (C) A new subduction zone appears in an extensive context, and the subsequent new ridge (back-arc basin) induces a peak of heat loss.

Long-term thermal evolution

While the heat loss and plate velocity exhibit some sudden variations, the mantle temperature decreases in a smoother way. For a certain range of input parameters, we obtain an average cooling rate of the Earth compatible with geochemical, petrological and rheological constraints (around 40-80 K/Gyr).

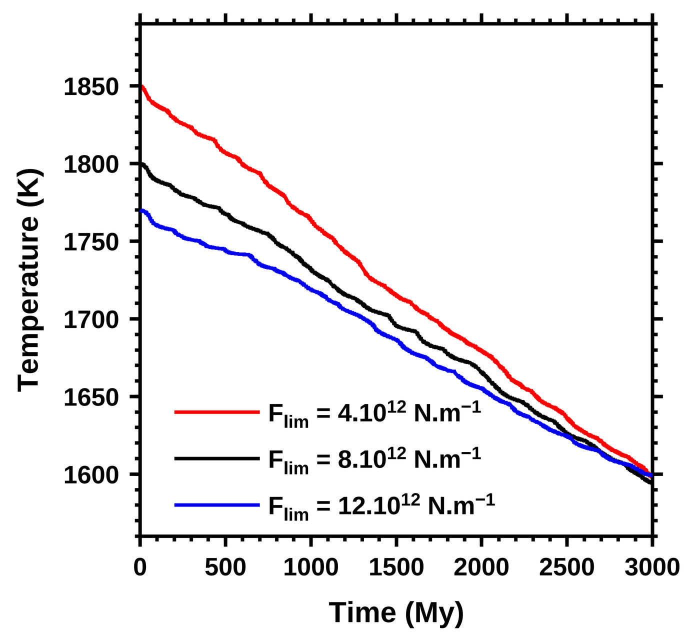


Fig. 6: Temperature obtained with different continental yield strength $F_{\rm lim}$.

A very important parameter **controlling Earth's cooling rate** in our model is the **continental yield strength**, which determines how fast, if at all, continents will break up.

Therefore, in our model, the cooling rate depends mainly on the ability of the Earth to **replace old insulating seafloor by young thin oceanic lithosphere**.

- Two timescales in heat flow evolution: sudden variations due to the creation and disappearance of ridges, and slow long term decrease in temperature.
- Long-term thermal evolution controlled by surface processes.

- MACMA: A new model to study Earth's evolution.
- An evolutive tool, that can easily integrate new behavioral laws, to test local and global processes and their interactions.