MACMA User Manual

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Contents

1 The MACMA Model

MACMA (Multi Agent Convective MAntle) is a simulation tool for 2-D cylindrical plate tectonics, with evolutive plate boundaries, and a dynamics that relies mainly on a force balance applied on each plate (Combes et al., 2012).

1.1 General approach

We consider a 2D cylindrical planet covered by mobile plates, with evolutive plate boundaries that can be created and eliminated. The conservation of heat is written as Eq. (1), using a uniform temperature for the mantle.

$$M\ c_p\ \frac{dT_m}{dt} = H(t)\ -\ Q(t), \tag{1}$$

where T_m is the mantle potential temperature, M the mass of the Earth, and c_p its average thermal capacity, accounting for the isentropic thermal gradient in the mantle and the coupling with core, assuming that mantle and core have similar cooling rates. H is the internal heat production due to a radioactive decay and Q is surface heat loss, computed at each time step using the distribution of seafloor ages (see section 1.4).

Mass and momentum conservations are imposed with a force balance for each plate, considering a total of 3 driving forces and 3 resistive forces. The general framework of MACMA is presented in Figure 1. Plate boundaries may be ridges or trenches. Other elements are continents and staples, which are discontinuities in oceanic lithosphere ages appearing when two plate boundaries collide.

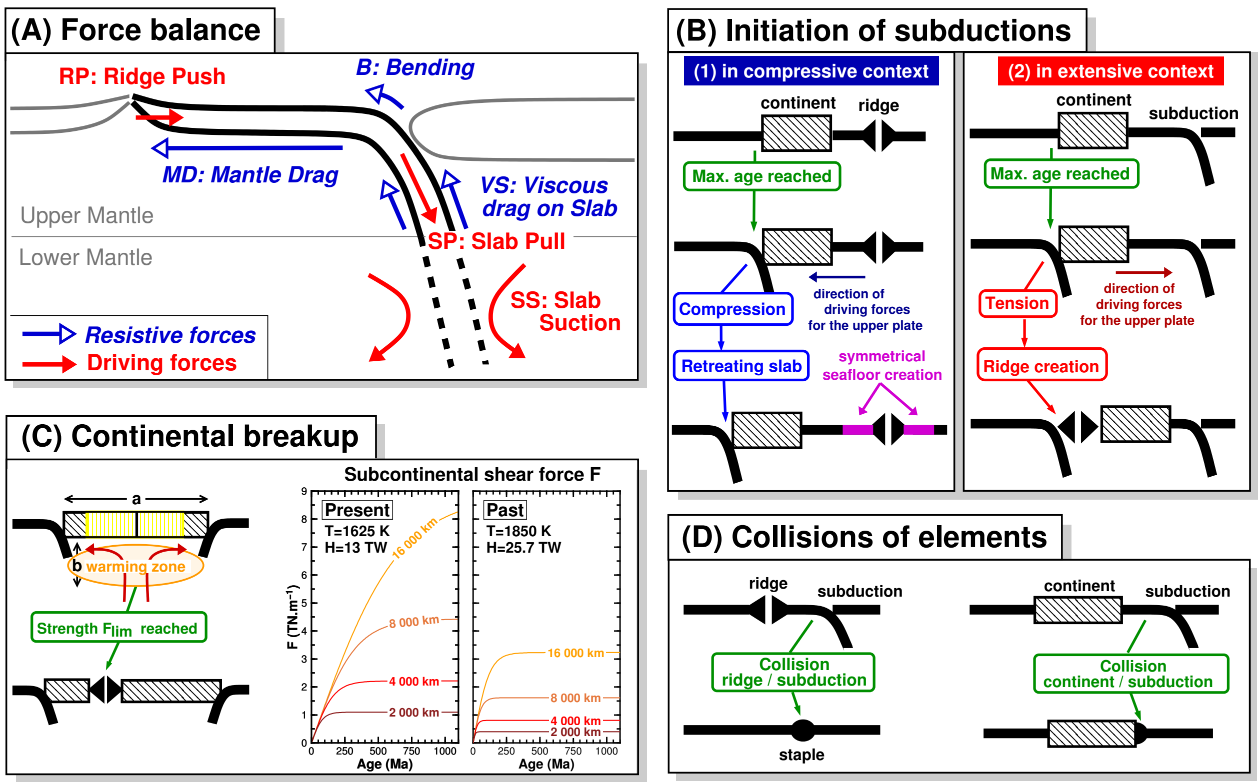

Figure 1: (A) Force balance used in this study. (B) Initiation of subductions in compressive (B1) and extensive context (B2). When the ocean seafloor age at the passive margin reaches the limit age $\tau_{\max}$, a subduction is created. The compressive case (B1) occurs when the upper plate moves towards the trench. The symmetrical accretion around the ridge is also schematized. The extensive case (B2) occurs when the upper plate moves away from the trench: a ridge is created to compensate for the diverging motion of the two plates. (C) Continental breakup: an advective shear force F below the continent is computed and compared to a fixed continental strength $F_{\lim}$. If $F > F_{\lim}$ the continent can open, at a position that is randomly picked in the yellow zone.

Fixed parameters used in MACMA are given in Table 1.

Parameter	Symbol	Value	
Earth's mass	M	5.9736×10^{24}	kg
Mantle's mass	M_m	4.079×10^{24}	kg
Continental crust's mass	M_cont	2.201×10^{22}	kg
Earth's radius	R_E	6370	km
Upper mantle thickness	d_um	670	km
Lower mantle thickness	d_lm	2230	km
Gravitational acceleration	g	10	$\mathrm{m.s^{-2}}$
Earth's average thermal capacity	c_p	1200	$\mathrm{J.kg^{-1}.K^{-1}}$
Mantle's thermal diffusivity	κ	8.0×10^{-7}	$\mathrm{m^2.s^{-1}}$
Surface temperature	T_s	273	K

Table 1: Parameters used in this study.

Plate velocities are deduced from a force balance, using a layered mantle (lithosphere, upper mantle and lower mantle). Each layer has a newtonian temperature-dependent viscosity, written as an Arrhenius law using reference values for present-day Earth. Hereafter, the subscript 0 stands for present-day values:

$$\eta_i(T) = \eta_{i_0}\ \exp\left(\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right). \tag{2}$$

The subscript i stands for the different layers in Earth ($i = \mathrm{pl}$, um or lm for oceanic plates, upper mantle and lower mantle respectively), E is the activation energy and $R = 8.314\ \mathrm{J.K^{-1}.mol^{-1}}$ is the gas constant.

The thickness of plates δ as a function of the seafloor age τ is needed in the expressions of several forces hereafter. From the halfspace cooling model (e.g. Turcotte and Schubert, 2002), we use

$$\delta(\tau) = c\sqrt{\kappa\tau} \tag{3}$$

with $c = 2.1$. This yields an oceanic lithospheric thickness of ~10 km for $\tau = 1$ Myr and ~95 km for $\tau = 80$ Myr.

1.2 Force balance

The force balance used in this study is presented in Figure 1A. With a 2D geometry, we express the forces in $\mathrm{N.m^{-1}}$.

1.2.1 Driving forces

The driving forces are the following: (1) ridge push (RP), (2) slab pull (SP) and (3) slab suction (SS).
Following Parsons and Richter (1980), we write

$$\mathrm{RP} = \alpha\rho g\ (T_m - T_s)\ \kappa\ \tau_\mathrm{max} \tag{4}$$

where τ_max is the maximum age of the plate.

Slab pull is due to the excess weight of the cold slab, and we consider this force in the upper mantle only, as was done by Conrad and Lithgow-Bertelloni (2002):

$$\mathrm{SP} = \Delta\rho\ g\ \delta(\tau_\mathrm{max})\ \min(Z, d_\mathrm{um}), \tag{5}$$

where Z is the depth reached by the slab and $\delta(\tau_\mathrm{max})$ is the thickness of the slab (Eq. 3).
We consider slab suction (SS) in the lower mantle: sinking slabs induce mantle flow that pulls both the subducting plate and the overriding plate towards the subduction zone. SS is expressed as a shear stress exerted on the slab and transmitted to the horizontal plates on both sides of the trench:

$$\mathrm{SS}\ =\ \eta_{\mathrm{lm}_0}\left(\frac{V_{s_0}}{d_\mathrm{lm}/2}\right)\ \max(0, Z - d_\mathrm{um}) \tag{6}$$

Only the height of the slab in the lower mantle is considered here. V_{s_0} is the present-day vertical velocity of the slab in the lower mantle, described as a Stokes velocity, so that at each time $\eta_\mathrm{lm}\ V_s = \eta_{\mathrm{lm}_0}\ V_{s_0}$. Eq. (6) is therefore written with present-day values. Grigné et al. (2005) showed that the width over which shear stress is exerted equals the half depth of the layer, and we thus express the strain rate as $V_{s_0}/(d_{\mathrm{lm}}/2)$, where d_{lm} is the thickness of the lower mantle.

The three driving forces RP, SP and SS depend on the depth of slabs and on seafloor ages, but not on the velocities of plates. SP is taken into account only for subducting plates, while SS is considered for both the subducting and the overriding plates.

1.2.2 Resistive forces

The resistive forces are: (1) the vertical shear stress on the slabs in the upper mantle (VS), (2) the horizontal mantle drag under the plates (MD) and (3) the bending dissipation (B) (see Figure 1A). These three forces can all be expressed as shear forces, equal to the product of an effective viscosity that accounts for the geometry of the plate, and of the velocity U of the plate. The equivalent viscosities are denoted hereafter by η_{VS}, η_{MD} and η_{B}.

The vertical viscous shear VS on descending slabs is taken into account in the upper mantle only (this option can be modified), and the characteristic width of the sheared zone is $d_{\mathrm{um}}/2$ (Grigné et al., 2005), which gives

$$\mathrm{VS} \;=\; -\eta_{\mathrm{um}} \left(\frac{U}{d_{\mathrm{um}}/2}\right) \, \min(Z, d_{\mathrm{um}}). \tag{7}$$

Writing $\mathrm{VS} = -\eta_{\mathrm{VS}}\, U$ yields

$$\eta_{\mathrm{VS}} \;=\; 2\left(\frac{\min(Z, d_{\mathrm{um}})}{d_{\mathrm{um}}}\right)\eta_{\mathrm{um}} \tag{8}$$

where Z is the depth reached by the slab.

For the horizontal mantle drag MD, we consider that the whole mantle is sheared. We denote by U_i the horizontal velocity at the interface between the upper and lower mantle. Considering that the viscous shear is continuous across this interface, we have

$$\eta_{\mathrm{um}}\left(\frac{U-U_i}{d_{\mathrm{um}}}\right) = \eta_{\mathrm{lm}}\left(\frac{U_i}{d_{\mathrm{lm}}}\right). \tag{9}$$

The horizontal drag is

$$\mathrm{MD} = -\eta_{\mathrm{um}}\left(\frac{U-U_i}{d_{\mathrm{um}}}\right) L \tag{10}$$

where L is the length of the plate. Eliminating U_i with Eq. (9) and writing $\mathrm{MD} = -\eta_{\mathrm{MD}}\, U$ gives an equivalent viscosity

$$\eta_{\mathrm{MD}} \;=\; \left(\frac{d_{\mathrm{um}}}{\eta_{\mathrm{um}}} + \frac{d_{\mathrm{lm}}}{\eta_{\mathrm{lm}}}\right)^{-1} L \tag{11}$$

We use the expression for bending dissipation given by Buffett (2006):

$$\mathrm{B} \;=\; -\frac{2}{3}\,\eta_{pl}\left(\frac{\delta(\tau_{\max})}{R_{\min}}\right)^{3} U \tag{12}$$

where $\delta(\tau_{\max})$ is the thickness of the lithosphere at the trench, given by Eq. (3). $R_{\min}$ is the minimum radius of curvature of the plate, that is to say at the trench, which we set to $R_{\min} = 390$ km (e.g. Wu et al., 2008). Writing $\mathrm{B} = -\eta_{\mathrm{B}}\, U$ yields

$$\eta_{\mathrm{B}} \;=\; \frac{2}{3}\left(\frac{\delta(\tau_{\max})}{R_{\min}}\right)^{3}\eta_{\mathrm{pl}} \tag{13}$$

The sum of the resistive forces is

$$\mathrm{VS} + \mathrm{MD} + \mathrm{B} = \,-\,\big(\eta_{\mathrm{VS}} + \eta_{\mathrm{MD}} + \eta_{\mathrm{B}}\big)\, U \tag{14}$$

1.2.3 Plate velocities

Considering a mantle with infinite Prandtl number, the forces exerted on a plate must cancel out:

$$(RP + SP + SS) \;+\; (MD + VS + B) \;=\; 0. \tag{15}$$

With Eq. (14), U is directly obtained:

$$U = \frac{\mathrm{RP} + \mathrm{SP} + \mathrm{SS}}{\eta_{\mathrm{MD}} + \eta_{\mathrm{VS}} + \eta_{\mathrm{B}}} \tag{16}$$

1.3 Dynamics of plate boundaries

1.3.1 Velocity of trenches and ridges

Simple laws are used to account for the mobility of plate boundaries. Trenches are given the velocity of their overriding plates, which undergo the resistive forces acting on the slab. Only plates limited by two ridges have $\eta_{\rm VS} = \eta_{\rm B} = 0$. As for ridges, we consider symmetric spreading: ridges are given a velocity equal to half the sum of the velocities of the two diverging plates.

1.3.2 Elimination of plate boundaries

When collisions occur between two plate boundaries (trench-ridge or trench-trench), both of them disappear and are replaced by a so-called staple, which marks a former plate boundary that becomes an age discontinuity in the middle of a plate upon collision (see Figure 1D).

1.3.3 Creation of new ridges

New ridges may be created in two circumstances: when tension appears in an upper plate over a subduction zone, and during continental break-up. The former case is illustrated in Figure 1B: when the upper plate is driven away from the trench, we impose the creation of a new ridge which represents a simplified back-arc basin.
Continental break-up is shown in Figure 1C: we consider that continents have an insulating effect and derive a parameterization of the warming rate and subsequent advective motion in a shallow layer below a continent as a function of its width and of the radiogenic heating rate in the mantle. The resulting shear force F, which also depends on mantle viscosity has to overcome a fixed yield strength $F_{\rm lim}$ in order for the continent to break up (see Combes et al. (2012) for calculation details).

Additionally, continental break-ups occur only if the plate that contains the continent is limited by at least one subduction zone. Its direction and position do not matter, i.e. it is not required that the continent is bordered by an active margin. Without this condition in our 2D setting, the new ridge created by continental break-up, which exhibits initially a null ridge push force (seafloor of age zero), would immediately reclose because of the two opposing ridge push forces on either side of the plate. Furthermore, in order to avoid symmetrical configurations that may arise from breaking up the continent right in its middle, the rifting position can be randomly chosen (see Figure 1C).

1.3.4 Creation of new subductions

We make the assumption that subduction occurs at a certain critical age $\tau_{\rm subd}$. This critical age may be computed with three different criteria (see section 3.2.2, Eqs. 21 to 23). An additional condition is used: subductions are created only at discontinuities in lithospheric ages (passive margins and staples).

1.4 Thermal balance and time evolution

The age of the oceanic lithosphere is tracked using a given resolution (recommended value: 0.25° (27.8 km)). New age points are created at ridges, and they are consumed by subduction. At each time step and for every point of the oceanic lithosphere, the seafloor age τ is used to compute the local heat flux $q_{\rm loc}(\tau)$:

$$q_{\rm loc}(\tau) = \frac{k\ (T_m - T_s)}{\sqrt{\pi \kappa\ \tau}}. \tag{17}$$

This is integrated over the oceanic surface to compute the total heat flow Q. To convert from an angular distance β in our 2D setting to a surface area, we consider the total area A between two meridians separated by β: $A = 2\beta R_E^2$. Mantle temperature T_m is updated using Eq. 1.

An explicit method is used for the time evolution of the model. First, each point (oceanic ages, plate boundaries, staples and continental borders) is advanced using its velocity. If a collision between two plate boundaries should occur over one time step, its value dt is reduced so that a perfect collision is reached without any overlap between elements. A finite difference form of Eq. 1 is used to update T_m, and new temperature-dependent viscosities are computed. Driving and resistive forces are assessed using the new positions and viscosities. Eq. 16 and criteria described in section 1.3 are then used to move points for the next time step.

2 Using MACMA

2.1 Getting started

MACMA software is written in C++ and uses the open source libraries **Boost** and **Qt**, as cross-platform tools, to deal respectively with multithreading and with the design of the graphical user interface.

The MACMA folder contains C++ sources in the subfolder `src/`, while headers are in the `inc/` subfolder. The Qt file containing the user interface `MACMA.ui` is in the `ihm/` subfolder (see `http://qt-project.org/` for the construction of a Qt user interface).

One example of input file is given in `configs/`.

2.2 Installing MACMA

The program MACMA is built in the folder `build/`.
For a first installation, in `build/`, type:

(1) `cmake ..` (uses the file `../CMakeLists.txt`)

(2) `make`

If you install MACMA on a new architecture and the `build/` folder is not empty, type in the folder `build/`:

(1) `make clean`

(2) `rm -r *` (⚠ make sure you are actually inside the folder `build/`)

(3) `cmake ..`

(4) `make`

To re-compile MACMA after having made modifications to a file in `src` (`src/*.cpp`), simply type `make` inside `build/`. If headers in `inc/` (`*/*.h` files) were modified, it is recommended to first clean and empty the folder `build/` before compiling.

2.3 Launching MACMA with its Graphic Interface

To launch MACMA, in the `build/` folder, type `./MACMA` or click on the MACMA icon.

A window will first ask you to choose the folder where outputs will be written. Four subfolders are created in this folder: `logs/`, `images/`, `ages/` and `elements`. The different type of results will be described in section 5.

If you choose a folder that already contains these four subfolders, the latter will be emptied and former results will be lost. A window prompts the user to agree or not on destroying the existing folders. If no output folder is selected, results will be written in `/tmp/MACMA/`.

Once the output folder is defined, a user interface window opens. This user interface is shown in Fig. 2. The left part of the interface contains four tabs (*Earth*, *Model*, *Interfaces* and *Plates*), where input parameters are entered and where the initial plate tectonics configuration is created. The right window helps to visualize the construction of a new initial plate configuration.

The role of the four tabs will be described in sections 3.1 to 3.4.

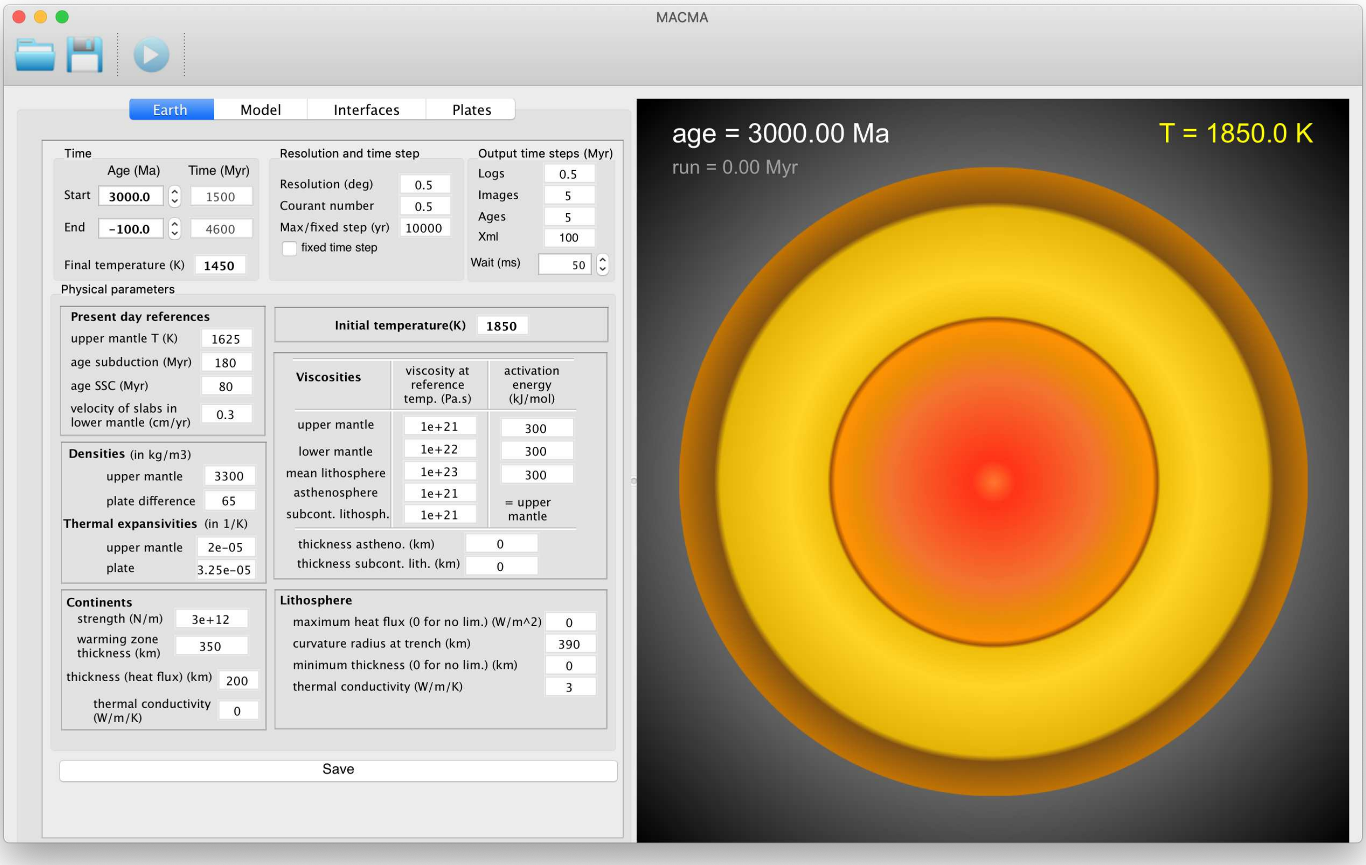

Figure 2: User interface for MACMA, with default parameters and empty configuration.

The top three icons in the toolbar are, from left to right:

- Open an existing configuration.
- Save the current configuration.
- Start/stop the run.

3 Building a new plate configuration

This section describes how to define parameters for the run and how to create a new initial plate configuration. Four tabs in the left part of the user interface window (see Fig. 2) are used. They are described hereafter.

3.1 Earth tab

The *Earth* tab is divided into four boxes, whose input parameters are described hereafter:

3.1.1 Time

The starting age (*Start*) in million years (Ma) is used to define the duration of the simulation and to compute the initial radioactive heat production. To start a run at present time, enter **Start = 4550 Ma**. The corresponding time after Earth's formation is shown in the right box.

There are two ways to define the ending time of a simulation:

- Enter the ending age in Ma (negative ages are for the future).

- Enter the final temperature in K.

The run is stopped either when the final age is reached or when the temperature is below the final one.

3.1.2 Resolution and time step

- **Resolution (deg):** The resolution is the spacing between two points of seafloor for defining their age. As long as the resolution is smaller than 1 degree (∼111 km), its choice has no effect on the obtained plate dynamics, but a smaller resolution yields a smoother heat flow evolution (computed from seafloor age distribution). (todo: add resolution tests in appendix)

- **Courant number:** MACMA does not rely on partial differential equations in an Eulerian description and it does not need to obey a Courant condition (Courant et al., 1928): ages are simply translated with the plate they belong to. However, ocean seafloor is subducted and ages points are then deleted, while new ages points are created on both sides of a ridge. For a good accuracy of age distribution, no more than one age point should disappear or be created at each time step at a plate boundary, which can be expressed as a Courant condition: $V_{\max} dt/dx < C$, where $V_{\max}$ is the maximum plate speed at a given time, dt is the time step, dx is the resolution and C is the Courant number.

  The Courant number entered in this field is thus used to compute the time step dt as $dt = C\ dx/V_{\max}$, which is evolving over time as a function of $V_{\max}$.

- **Max/fixed step (yr):** this field is either a fixed imposed time step, or when the "**Fixed time step**" box is unchecked, it is the maximum value $dt_{\max}$ given to the time step dt: $dt = \min\Big(C\ dx/V_{\max},\ dt_{\max}\Big)$, in order to avoid very large time steps when plate velocities are very small.

- **Fixed time step check box:** if this box is checked, the time step dt is not computed but has the fixed value given in the field "**Max/fixed step (yr)**".

3.1.3 Output time steps (Myr)

The user enters here the writing intervals (in Myr) for the different types of outputs (detailed in section 5).

- **Logs:** time interval for writing average values, such as the mantle mean temperature, Earth's total heat loss, plate velocity, etc. The corresponding files are written in the folder `logs/`.

- **Ages:** time interval for writing seafloor ages expressed as a function of position, as well as other position-dependent values (velocity, heat flux...), in the folder `ages/`. Ages files are named `ages*Ma.log` (e.g. `ages00015.0Ma.log`, `ages00015.5Ma.log`, `ages0016.0Ma.log`... for an age interval of 0.5 Myr). The minimum time interval that can be chosen is 0.1 Myr.

- **Images:** time interval for writing PNG images of the plate configuration in the folder `images/`, with names with the pattern `MACMA_00015.5Ma.png`, `MACMA_00016.0Ma.png`..., which indicates the time at which one image was written.

  Note that since MACMA uses multithreading, background physical computation and graphic processing are done on different threads. Therefore a slight delay may exist between the moment when the physical computation reaches the time interval for saving an image and the moment when the image is actually drawn and saved. For instance, when asking for a time interval of 5 Myr, we may get files named `MACMA_00194.9Ma.log`, `MACMA_00200.1Ma.log` etc. with actual times indicated on the figures that are respectively 195.1 Myr and 200.4 Myr. In order to obtain an exact timing for the writing of images, the physical computation would need to be stopped while the graphic interface is updated, which would unnecessarily slow down the run in a drastic way.

- **Wait (ms):** Saving images may result in synchronization problem between the physical computation and the graphic thread that creates images. This can result in graphic lags in the ongoing animation in the right window of MACMA (note that the actual run and the writing of images still go on in the background even if the animation is completely stuck). To avoid this problem, we impose a little delay for the computation thread each time an image is saved (set by default to 50 ms). Depending on your processor and graphic card, this value may be too high and you can improve performance with lowering this waiting time to 5 or even 0 ms.

3.1.4 Physical parameters

There are a total of 27 physical parameters that can be modified by the user. The meaning and units are explicitely written in the graphic interface of MACMA. Corresponding symbols that are used in articles using MACMA (Combes et al., 2012; Grigné and Combes, 2017), C++ variables and additional notes are given in Table 2.

Physical parameter	Symbol	C++ variable	Note
Initial temperature	-	`T_m_init`	
Present-day references			
upper mantle T	T_{m_0}	`T_p`	present-day reference temperature (1)
age subduction	τ_{subd_0}	`tau_sub_p`	present-day critical age for subduction (2)
age SSC	τ_{SSC_0}	`tau_ssc_p`	present-day critical age for SSC (3)
velocity of slabs in lower mantle	V_{s_0}	`V_sink_p`	velocity for slab-suction (4)
Densities and thermal expansivities			
upper mantle density	ρ	`rho_um`	
plate difference	$\Delta\rho$	`DeltaRho_p`	excess density of slabs for slab pull
upper mantle thermal expansivity	α	`alpha_um`	
plate thermal expansivity	α_{pl}	`alpha_pl`	
Viscosities			(5)
upper mantle viscosity	η_{um_0}	`eta_um_p`	
upper mantle activation energy	E	`E_um`	
lower mantle viscosity	η_{lm_0}	`eta_m_p`	
lower mantle activation energy	E	`E_m`	
plates viscosity	η_{pl_0}	`eta_pl_p`	
plates activation energy	E	`E_pl`	(6)
asthenosphere viscosity	-	`eta_ast_p`	
subcont. lith. viscosity	-	`eta_subcont_p`	
thickness astheno.	-	`thick_ast`	(7)
thickness subcont. lith.	-	`thick_subcont`	
Continents			
strength	F_{lim}	`F_lim`	maximum continental resistance (8)
warming zone thickness	b	`subcont_warming_H`	
thickness	d_{cont}	`thick_continent`	thickness for conductive heat flux (9)
thermal conductivity	k_{cont}	`k_continent`	
Lithosphere			
maximum heat flux	Q_{max}	`Qmax`	(10)
curvature radius at trench	R_{min}	`R_min`	(11)
minimum thickness	δ_{min}	`min_plate_thick`	(12)
thermal conductivity	k_{oc}	`k_ocean`	Thermal conductivity for oceanic heat flux

Table 2: Physical parameters used in MACMA, with the symbols used in Combes et al. (2012); Grigné and Combes (2017) and in this guide. C++ variables are the notations used in the sources of MACMA.

Notes in Table 2:

(1) The present-day reference mantle temperature T_{m_0} is used to compute the temperature-dependent parameters with using a reference value for present day (always denoted by the subscript “0”) (See Eq. 2).

(2) Criteria for subduction initiation rely on a temperature-dependent critical age τ_{subd} for the onset of subduction. As for the viscosity, the critical age τ_{subd} for any T_m is written as function of the present-day value τ_{subd_0} (see section 3.2.2).

(3) Small-Scale Convection (SSC) is a possible cause for the flattening of bathymetry and the almost constant heat flux observed for ages older than 80 Myr (e.g. Parsons and McKenzie, 1978). If SSC starts from a convective destabilization of the oceanic lithosphere (critical fixed Rayleigh number), it can be shown that τ_{SSC} depends on the present-day critical age for the onset of SSC and on mantle temperature T_m:

$$\tau_{\mathrm{SSC}} = \tau_{\mathrm{SSC}_0} \left(\frac{\eta(T_m)}{\eta(T_{m_0})}\right)^{2/3} \left(\frac{T_{m_0} - T_s}{T_m - T_s}\right)^{2/3}, \tag{18}$$

where $T_s = 273$ K is the surface temperature.

(4) V_{s_0} is the present-day velocity of slabs in the lower mantle, used to compute the driving “slab suction” force on plates (see Conrad and Lithgow-Bertelloni (2004)).

(5) We consider up to four concentric layers for the mantle, as described in Fig. 3. The thickness of the total upper mantle (D) and of the whole mantle (d) are fixed (D=670 km and d=2900 km). Two more layers can be added in the upper mantle: the asthenosphere and a subcontinental lithosphere (see note (7)). Each layer can have its own reference viscosity for present-day.

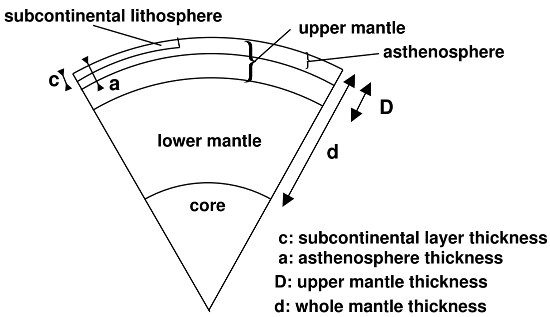

Figure 3: Possible mantle layers in MACMA.

(6) In simulations done so far, we considered the same activation energy for all layers of mantle (E), but the possibility of different values of E is implemented.

(7) The two extra layers (subcontinental lithosphere and asthenosphere) can be added when entering non-zero values here.

(8) The parameterization for continental breakup is presented in Grigné and Combes (2017). $F_{\rm lim}$ is the continental strength. Recommended values should be equal to a few TN/m.

(9) By default the heat flux through continents is zero. This is set with using a zero thermal conductivity k_cont ($k_{\rm cont}$ hereafter). If a non-zero value for $k_{\rm cont}$ is entered, the thickness of the continent thick_cont ($d_{\rm cont}$ hereafter) is used to compute a mean heat flux $q_{\rm cont}$ through continents:

$$q_{\rm cont} = k\left(\frac{T_m - T_s}{d_{\rm cont}}\right) \tag{19}$$

(10) If $Q_{\max}$ is set to zero, there is no limitation on local heat flux, which can be very high along ridges. It is possible to set a limit on heat loss with using $Q_{\max} > 0$.

(11) $R_{\min}$ is the curvature of plates entering a subduction zone and is used to compute the viscous dissipation due to bending, using the formulation by Buffett (2006).

(12) The thickness δ of the oceanic lithosphere is computed using

$$\delta \;=\; c\,\sqrt{\kappa\,\tau} \tag{20}$$

with $c = 2.1$. This yields an oceanic lithosphere that goes from a thickness $\delta = 0$ at the ridge to $\delta \approx 105$ km for $\tau = 100$ Myr. A zero thickness at the ridge is actually unrealistic, and here one can set the minimum thickness $\delta_{\min}$ for the oceanic lithosphere (crust thickness for instance).

Important: any changes in the Earth tab will be taken into account only if the bottom “save” button is pushed.

3.2 Model tab

The second tab (see Fig. 4) is used for changing laws that control several dynamic processes.

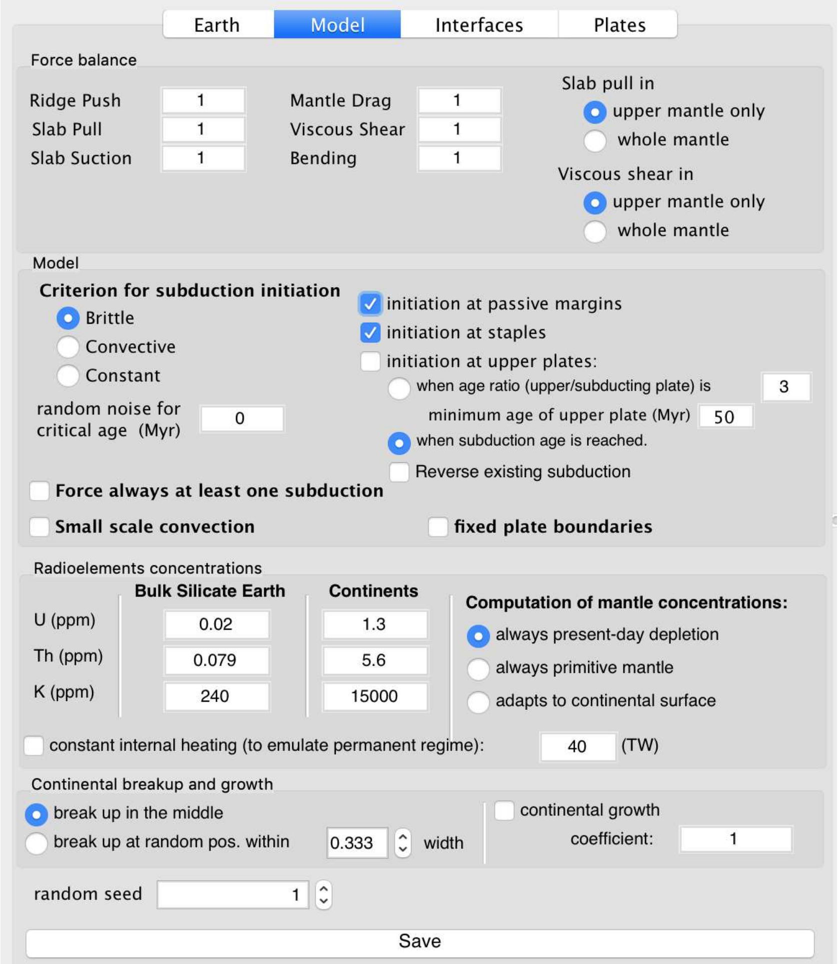

Figure 4: Model tab

3.2.1 Force balance

In the top group "Force balance", one can increase or lower the intensity of the different forces: the value in the box corresponding to each force is a multiplying coefficient. Default formulations are given in section 1.2 and in Grigné and Combes (2017).

One can also choose to consider slab pull and viscous shear only in the upper mantle (default) or through the whole mantle.

3.2.2 Model

- Criterion for subduction initiation: a new subduction is created on the border of a continent and/or at a staple (depending on the checked button), when the local seafloor age reaches a critical age $\tau_{\rm subd}$.

  When the **Brittle** button is clicked, this critical age is computed at each time step using

$$\tau_{\rm subd} = \tau_{{\rm subd}_0} \left(\frac{T_{m_0} - T_s}{T_m - T_s} \right)^2 \tag{21}$$

  If the **Convective** button is clicked, $\tau_{\rm subd}$ is computed as

$$\tau_{\rm subd} = \tau_{{\rm subd}_0} \left(\frac{\eta}{\eta_0} \right)^{2/3} \left(\frac{T_{m_0} - T_s}{T_m - T_s} \right)^{2/3} \tag{22}$$

  See Combes et al. (2012) to check how Eqs. 21 and 22 were derived.

If the **Constant** button is clicked, we have simply

$$\tau_{\mathrm{subd}} = \tau_{\mathrm{subd}_0} \tag{23}$$

In order to avoid too symmetrical situations, some noise can be added to the critical age for subduction (changing at each time step), within the range given in the corresponding field. Default is zero (no noise).

- Initiation at passive margins, at staples, at upper plates: defines where subduction initiation is allowed. All boxes can be unchecked. In this case, once all subductions have disappeared, oceanic seafloors are aging and the lithosphere is unlimitedly thickening. Without continents, subduction initiation should be allowed at staples to avoid this.

  Subduction at upper plates (beta) is implemented in order to avoid that upper plates exhibit very old ages. Some situtations may arise (especially for a cold mantle) when the seafloor age for the upper plate is larger than 400 Myr. Two criteria are possible to force this old plate to subduct, relying either on the ratio between the age of the upper and the subducting plates (top button, not recommended), or on the absolute age of this upper plate (lower button).

  Two different behaviors for the creation of the new subduction at the upper plate are possible depending on the “reverse existing subduction” box (see Figure 5).

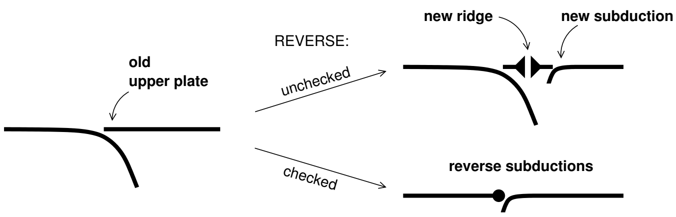

Figure 5: Initiation of a subduction for an old upper plate, with checking or not the "Reverse existing subduction" box.

- Force always at least one subduction: when plate boundaries are migrating fast (for a hot mantle), all subductions may disappear before the critical age for a new subduction to appear is reached anywhere in the model. Plate tectonics then stops until the critical age is reached. This effect may be related to the 2D restriction of MACMA. In order to test how continuous plate tectonics affects mantle cooling, it is possible to force at least one subduction zone to be present in the model with checking the box. The new subduction is created where the seafloor is the oldest (at a passive margin and/or staple depending on the location of possible initiations defined above).

- Small Scale Convection: SSC is taken into account only if the button is checked. The effective seafloor age τ_{eff} for computing plate thickness and heat flux is then such that

$$\tau_{\mathrm{eff}} = \min\big(\tau, \tau_{\mathrm{SSC}}\big) \tag{24}$$

- Fixed plate boundaries: for testing the effect of fixed plate boundaries on the cooling of the mantle, this box can be checked. This may not be possible depending on the initial configuration (an error will be raised at the start of the run).

3.2.3 Radioelements concentrations

Concentrations in U, Th and K for the Bulk Silicate Earth and the continental crust are entered here. Default values are from McDonough and Sun (1995) and Rudnick and Gao (2003).

The user can choose one of three options:

- always present-day depletion: radioactive heating is computed with concentrations corresponding to the present-day surface area of continents (40% of Earth’s surface), whatever the total size of continents in the actual model (e.g. depleted mantle even if there are no continents).

- always primitive mantle: radioactive heating is computed with concentrations for a primitive mantle (i.e. as if there are no continents).

- adapts to continental surface: considering a constant thickness of continental crust, the level of depletion is computed at all time with considering the continental surface area.

The last checkbox is obviously the most adapted for a simulation with continental growth or when varying the size of continents between different runs. The two other cases are implemented for comparison.

A constant internal heating rate may also be chosen (last line).

3.2.4 Continental breakup and growth

Continental breakup occurs when the advective shear force F below continents (see Grigné and Combes (2017) for computation details) is such that $F > F_{\rm lim}$ and when the plate containing the continent is bordered by at least one subduction.

- break up in the middle: the continent is separated in two continents of equal size. This may result in a very symmetrical plate organization where continents all have the same size and are aggregating and separating in rhythm.
- break up at random pos. (...): to avoid this symmetrical regular situation, the position for continental breakup can be randomly chosen at a certain distance d from the middle of the continent. This distance d is defined as $d = x \times a$ where a is the continental width and x is the ratio given in the box (default value is 0.333).

  The code uses a pseudorandom number each time a continent is breaking up, and the **random seed** can be changed in the last field (i.e. using twice the same random seed yields the same exact series of randomly pulled numbers).

Note that the same random seed is used for the noise for the critical age for subduction initiation.

Changing the random seed number (if continental breakups occur at randomized positions and/or if subduction initiations occur at a slightly randomized critical ages) is an easy way to obtain different plate tectonics histories while starting runs with the same parameters and configuration.

Continental growth is possible when the box is checked. The coefficient is a multiplying factor for the default parameterization (added continental volume depends on the temperature of the mantle and on the velocity of the subducting plate) (very beta...).

3.3 Interfaces tab

We denote by the term interface here the plate boundaries (ridges and subductions) and the staples. Staples are markers of seafloor age discontinuities.

The positions on the graphic interface are increasing counterclockwise and the position $0°$ is on the right. Examples of setting up a ridge and a subduction zone are shown in Figures 6 and 7. The choice for the type of the new interface is obtained with the drop down menu (see inset in Figure 6) and then clicking on “Add”. The position of the interface can then be chosen.

For ridges, only the position is required (default seafloor ages on each side are zero).

For subductions, the initial depth of the slab must also be entered as well as the seafloor ages on each side of the trench.

For staples, the position and the seafloor ages on both sides are required.

For subductions and staples, press “Save” before adding another interface.

⚠ Seafloor ages must be chosen so that ages are increasing along a plate from a ridge to a subudction zone. An error will most likely be raised otherwise.

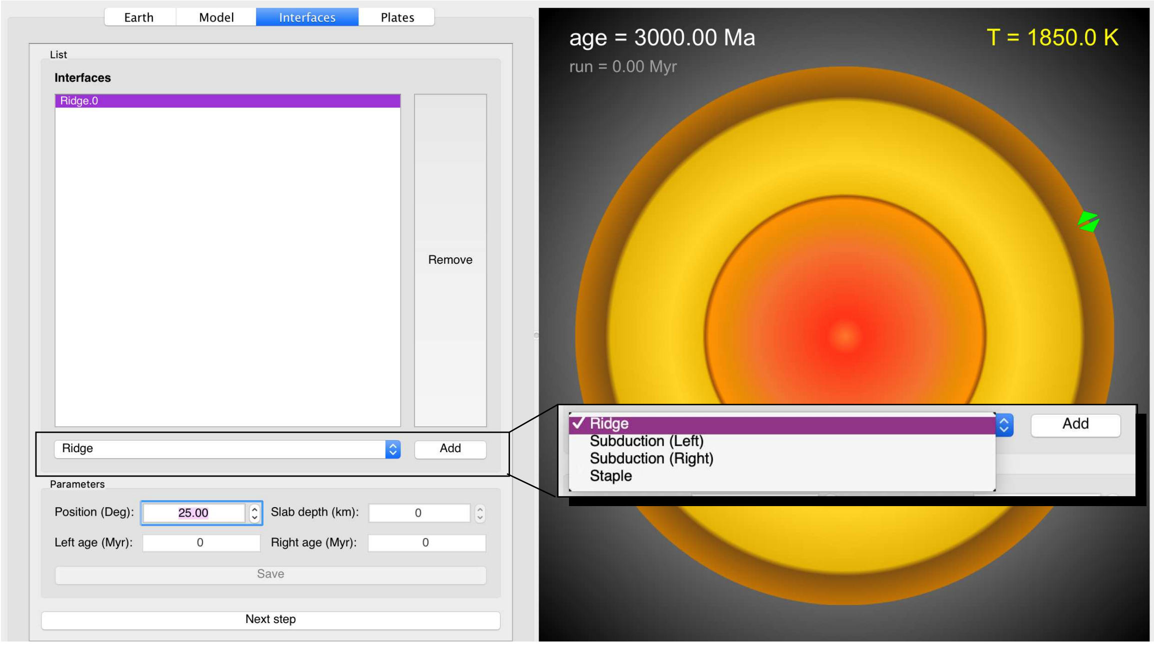

Figure 6: Set up of a ridge: the chosen position here is 25°. Ages on the left and right sides of the ridge are equal to 0 Myr.

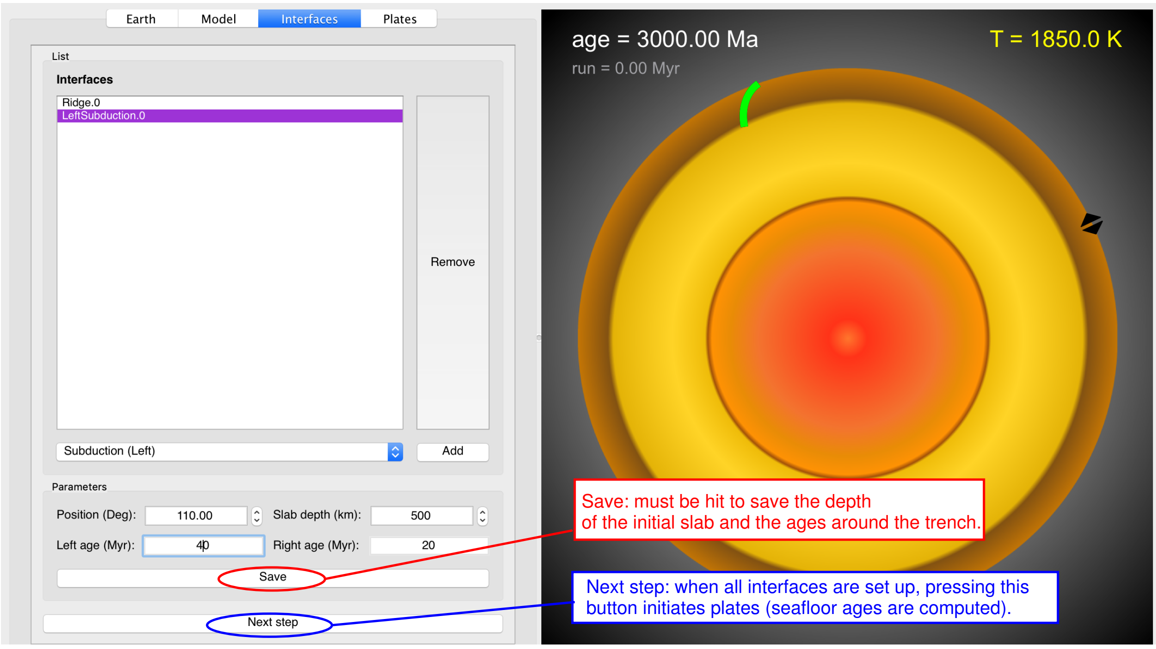

Figure 7: Set up of a left subduction at a position of 110°, with an initial depth of 500 km, and seafloor ages initially equal to 40 and 20 Myr on the left and right sides of the trench.

Seafloor ages along an oceanic plate are initialized so that they vary linearly from an interface to the next. Staples can be added in between two plate boundaries of the same type in order for ages to be correctly set up. For instance, creating a plate limited by two ridges, whose ages are zero, will raise an error as it would imply creating a lithosphere with an age equal everywhere to 0 Myr. Adding a staple with strictly positive ages on its sides between the two ridges will solve the problem.

Hereafter and in the sources, we denote by the term **plateSection** every piece of plates where the seafloor age increases or decreases continuously.

Once all the interfaces are set up: press "Next step". The seafloor ages are then initialized between interfaces. Convective cells appear on the graphic interface. These cells are for viewing purposes only, to help following plate boundaries during the run. They have no effect in the computation.

3.4 Plates tab

The plates tab is used for adding continents within plate sections. The user must first choose the plate, and then the plateSection on which the continent will be added. An example is shown in Figure 8.

When choosing a plateSection, the default right position of the continent is the right limit of the plate section, and its default length is zero. Only a length equal to or shorter than the total length of the plateSection is allowed. The ages on the sides of the continents must be carefully set (see subsection 3.3).

Figure 8: Set up of a continent, placed on Plate.1, on plateSection.1.

3.5 Format of *.macma* files

The files containing the input parameters and the geometrical configuration are XML files (and therefore ascii). One examples is given the `config/` folder.
(TO COMPLETE...)

4 Running MACMA without the GUI

Note : We recommend that users first create and save (second icon from the left within the top toolbar) their configuration through the graphic interface in order to check the correctness of the geometry.

When a configuration file has been created, a run with no graphic interface can be launched with typing " `$MACMAFOLDER/build/MACMA config.macma`" in a terminal, where `$MACMAFOLDER` is the folder containing the sources for MACMA and `config.macma` here is the configuration file.

Folders `ages/`, `logs/` and `elements/` are then created in the current folder.
If these folders already exist and are not empty, the users will be asked if present folders should be deleted or not.

No images are saved with this mode.

5 MACMA outputs

(TO DO)

6 Remarks on the code

MACMA relies on an object-oriented approach.

The class `MACMA` (see `src/MACMA/graphics/macma.cpp`) initializes parameters and sets up either the graphic interface ("calling" `macmaGui.cpp`) or the inline run (`macmaNonGui.cpp`).

The main "physical" class is `Earth`, which is defined by its physical parameters and contains the methods used to compute the evolution of plate tectonics and the thermal history of the Earth. The header for this class is `inc/MACMA/physics/earth.h` and the methods are defined in `src/MACMA/physics/earth.cpp`.

The method controlling the evolution of the model is `Earth::_timeLoop()`. Over one timestep, the main methods do the following:

- modify the positions of plate boundaries using mainly the velocities of plates (`updatePositions()`)
- check for the possible initiation of subduction zones (`_checkDiving()`),
- check if the condition for continental breakup is met (`_checkOceanOpening()`),
- create new ridges above subduction zones if an extensive context is noted (`_checkRidgeCreation()`),
- update the velocities of plates, taking into account the possible creation or disappearance of plate boundaries and the consequent reorganization of plates (`_computeVelocities()`),
- heat conservation is used to modify the temperature of the mantle (`updateQtot()`, `updateRadioHeatTW()`, `updateT()`, `updateTData()`).

(TO COMPLETE...)

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