Lithosphere erosion and breakup due to the interaction between extension and plume upwelling*

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1 – INTRODUCTION

We have built up 2D numerical models of coupled continental lithosphere - upper mantle systems, where an external velocity fields acts and a mantle plume impinges the lithosphere. The models are designed to simulate the interaction between plumes and lithosphere in an extensional setting. A novel aspect is melt generation due to plume, upper mantle and lithospheric mantle partial melting. The main purpose of this study is to understand which conditions are more favorable for plate extension and breakup, and the melt role in the lithosphere weakening and thinning. This helps in evaluating the role of plumes during plate extension, and review the mechanism of active rifting in a more realistic light.

The models (Fig.2) have been built by using ELEFANT (Thieulot, 2011), a code designed for the solution of the Stokes and heat transport equations at various scale. A lithospheric heterogeneity (weak seed) is present at the lower crust-upper mantle boundary. Simulation sets have been carried out with and without partial melting incorporated, by varying the distance between the weak seed and the plume axis.

2 – GOVERNING EQUATIONS

- Momentum conservation equation:

$$\nabla \cdot \boldsymbol{\sigma} + \sigma \boldsymbol{g} = 0$$

- Mass conservation equation:

$$\nabla \cdot \boldsymbol{v} = 0$$

- Stress and strain tensors:

$$\boldsymbol{\sigma} = -p\mathbf{1} + \boldsymbol{s}\ ;\ \boldsymbol{s} = 2\mu\dot{\boldsymbol{\varepsilon}}\ ;\ \dot{\boldsymbol{\varepsilon}} = \frac{1}{2}\left(\nabla \boldsymbol{v} + (\nabla \boldsymbol{v})^T\right)$$

- Stokes equation:

$$\nabla \cdot (\mu \nabla \boldsymbol{v}) - \nabla p + \rho \boldsymbol{g} = 0$$

- Heat transport equation:

$$\rho C_p \left(\frac{\partial T}{\partial t} + \boldsymbol{v} \cdot \nabla T\right) = \nabla \cdot (k \nabla T) + H_r + H_s + H_m$$

3 – MELT P-T SOLIDUS AND LIQUIDUS

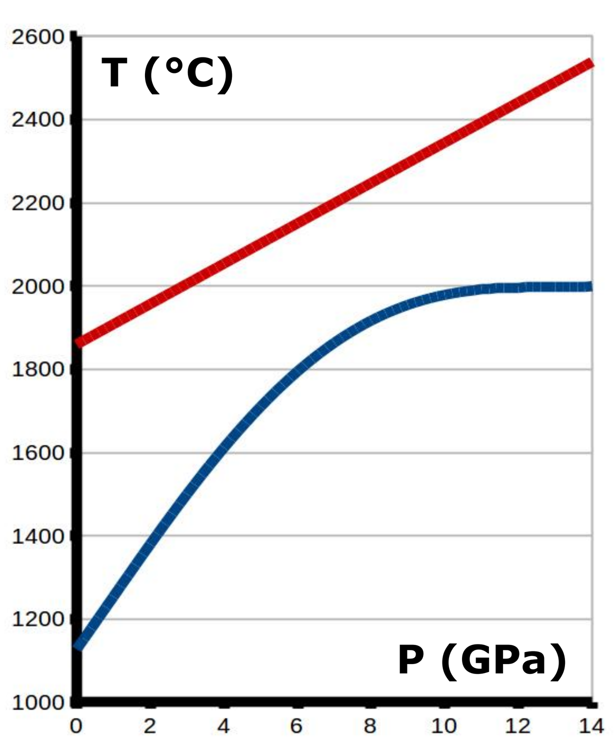


Fig.1 – Solidus and liquidus temperatures at different pressure values. P-T data points for the solidus curve are interpolated, basing on the results by Takahashi (1986) and Ueki & Iwamori (2014). Values for the liquidus curve are taken from Deer et al. (2013), and ref. therein.

4 – RESULTS

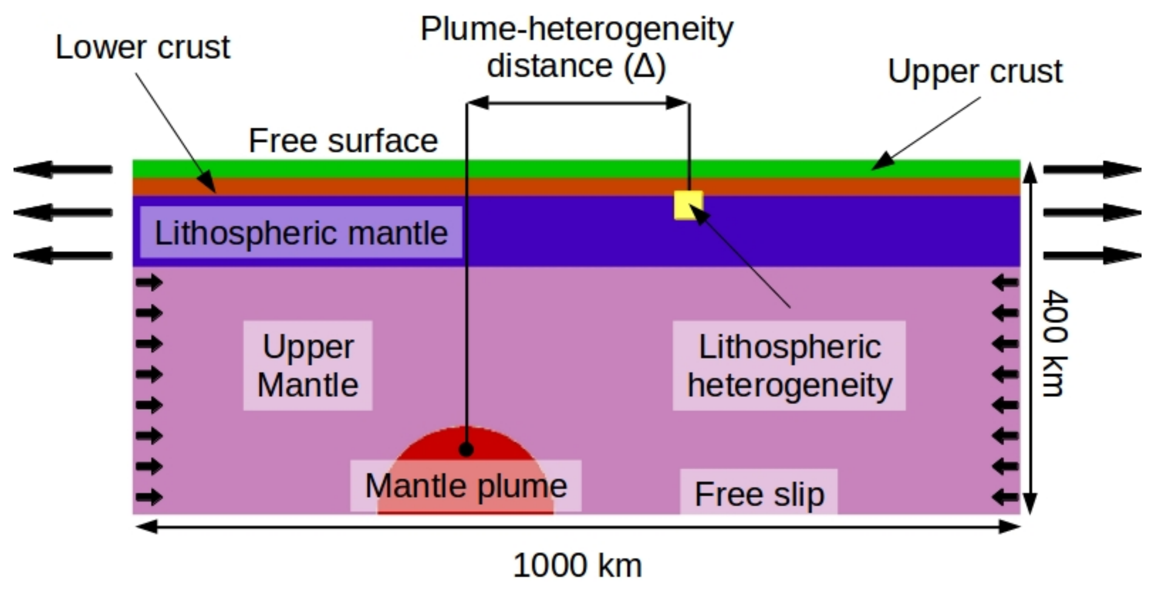
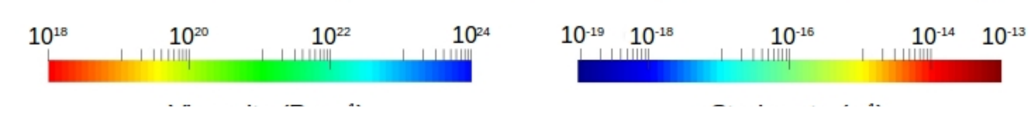


Fig.2 – Model geometry adopted at the initial stage of the simulation (t=0). The layering is as follows: upper crust (green), lower crust (orange), lithospheric mantle (violet), upper mantle (pink), mantle plume (red) and weak seed (yellow). Black arrows indicate directions of mass outflow and inflow (see Thieulot, 2011). The effect of Δ variations are investigated for each simulation set.



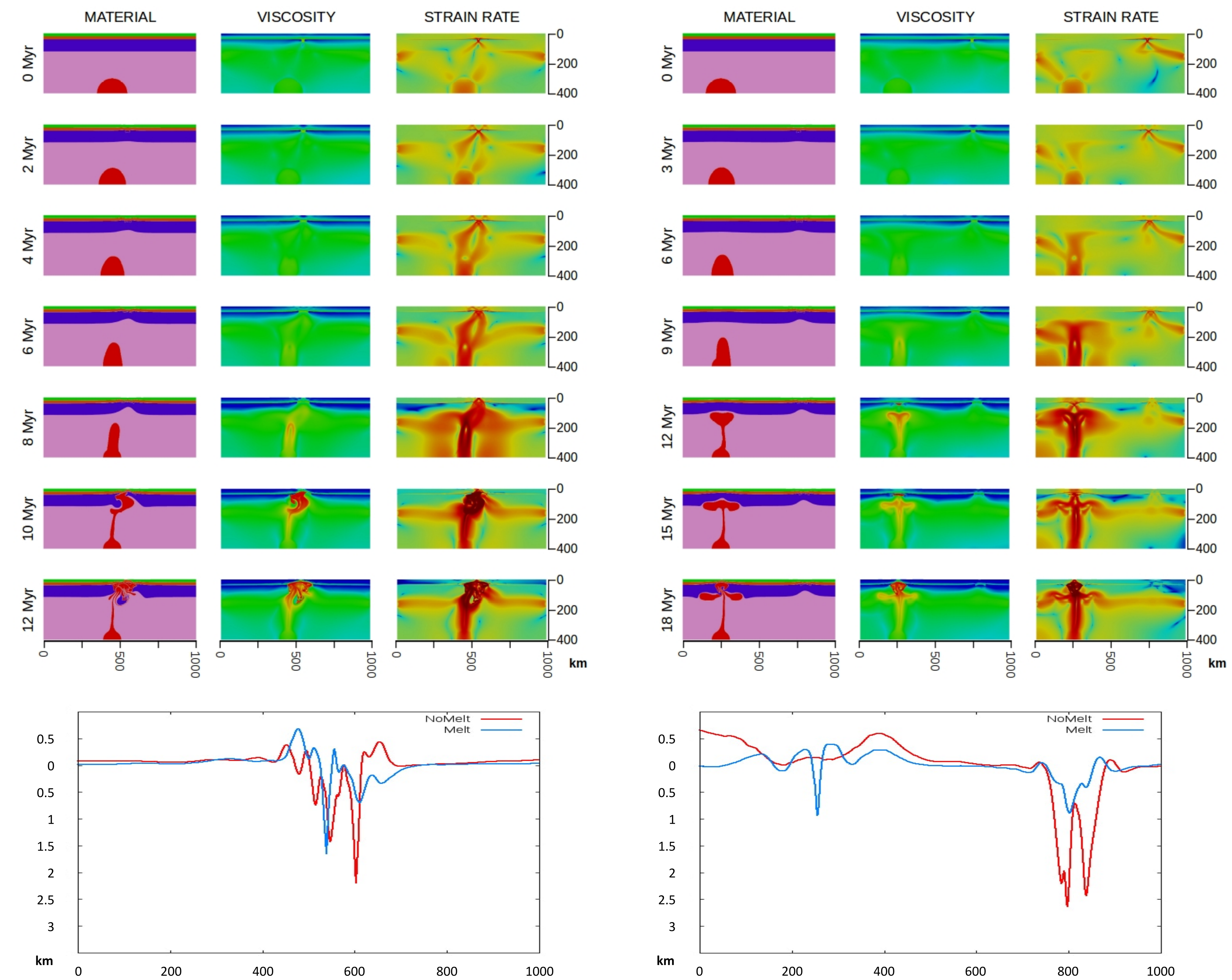


Fig.3 –Model results from the simulation set where Δ is 125 km (left simulation set) and 500 km (right simulation set). Dimensional values are expressed in km. Left column: material deformation (green: upper crust; orange: lower crust; violet: lithospheric mantle; pink: upper mantle; red: plume). Central column: viscosity values. Right column: strain rate values. Color scale in the central and right column is expressed as $\log_{10}$ of the obtained values. The bottom panels illustrate the topography variations obtained when partial melting of mantle materials is introduced in the model (blue line), and compare it with the topography obtained when partial melting is not included (red line).

	Upper crust	Lower crust	Lithospheric mantle	Upper mantle	Plume
ρ_0 [kg m^{-3}]	2800	2900	3325	3300	3275
k [W m^{-1} K^{-1}]	2.25	2.5	3	3	3
C_p [J kg^{-1} K^{-1}]	750	750	1200	1200	1200
A [Pa^{-n} s^{-1}]	1.1E-28	2.41E-16	2.41E-16	2.41E-16	2.41E-16
n	4	3	3.5	3.5	3.5
Q [kJ mol^{-1}]	223	356	540	540	540

Surface T	20 °C
Lithosphere base T	1300 °C
Model base T	1475 °C
ΔT Plume	200 °C
Extensional velocity	5 mm yr^{-1}
A_0	2 μW m^{-3}
D	14 km

Tab.1 – Thermal parameters adopted in the model and parameters adopted in the model for different layers. ΔT plume value refers to the temperature difference adopted at the beginning of the simulation (i.e. t=0) between the plume material and the surrounding upper mantle. This value is subjected to variations during the simulation, due to the combined effect of heat advection and diffusion. A_0 and D are parameters relative to the equation $A=A_0\exp(-z/D)$, calculating the radiogenic heat contribution in the crust.

5 - CONCLUSIONS

Our study shows that the presence of melts may have a great impact on the resulting characteristics of passive margins. The lateral distance between main areas of lithospheric heterogeneity and plumes is a parameter of primary importance for rifting evolution. Lithosphere weak zones determine the location for initial plate breakup, that may persist in the same area for an extended period. Subsequently, our model predicts a close interaction between the rift area generated by passive stresses and the presence of plumes.

When the plume is close enough to be channeled into the rift, the effects of active and passive stress fields sum up, resulting in an acceleration of lithosphere erosion. On the other hand, when a plume is not channeled into areas of lithospheric thinning, and in absence of melting, its presence does not cause main effects on lithospheric rifting evolution. Melts may substantially impact the evolution of passive continental margins, when the melt presence exceeds a threshold sufficient to cause a strength drop in the lithosphere, but their role also depends on the relative position of plumes with respect to the rifting area.

Melt underplating may favor the evolution of asymmetric passive margins, independently from the pre-existing structure of the lithosphere, and appears a key factor in the erosion of the lithosphere caused by plumes: this effect may be so intense that well delineated rifts may be abandoned and new areas of lithospheric breakup may develop over intensely underplated lithospheric intervals, with consequent jumps in rift formation.

REFERENCES

Takahashi E. (1986), Melting of a dry peridotite KLB-1 up to 14 Gpa: Implications on the origin of peridotitic upper mantle. J. Geophys. Res., 91, B9, 9367-9382.

Thieulot C. (2011), FANTOM. Two- and three-dimensional numerical modelling of creeping flows for the solution of geological problems. Phys. Earth Planet. Int., 188, 47-68, doi:10.1016/j.pepi.2011.06.011.

Ueki K. and Iwamori H. (2014), Thermodynamic calculations of the plybaric melting phase relations of spinel lherzolite. Geochem, Geophys. Geosis., 15, 5015-5033, doi:10.1002/2014AGC005546.

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