Coupling between Thermo-Hydro-Chemical reactive transport and Gibbs minimisation: magma evolution in evolving multiphase porous media

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General context

How melts are extracted from its peridotite sources and how melts are transported to the surface are key questions in igneous petrology. Such processes have been intensively studied for the case of mid-ocean ridges, but less effort has been made for intraplate volcanoes where low degree partial melts need to be extracted from their sources and transported across thick and cold lithosphere to produce alkaline lavas at the surface.

Example of Petit-spot volcanoes

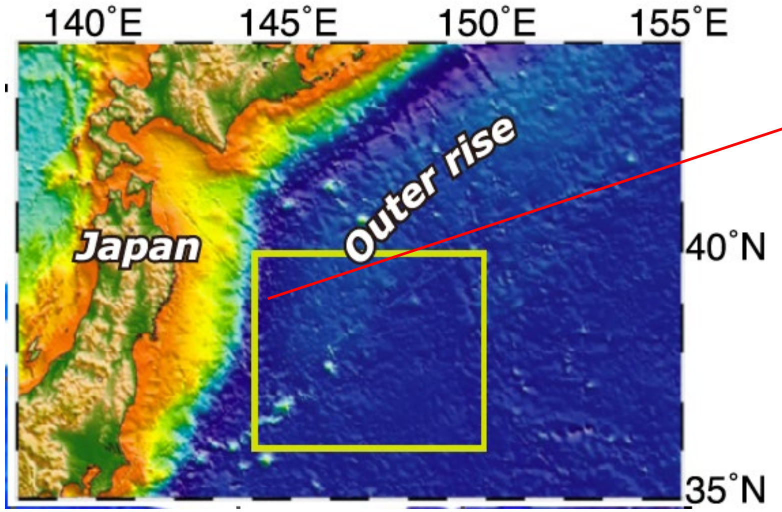


Figure from Machida *et al.* (2015) *EPSL*

To illustrates the problem of alkaline magma generation and transport, we will focus on the case of *Petit-spot* volcanoes.

Petit-spot volcanoes (~50 m high) were discovered on the subducting Pacific plate 600 km east of the Japan trench. (Hirano *et al.*, 2006).

Hypothesis for the generation of *Petit-spot* volcanoes

Petit-spots are interpreted as small intraplate volcanoes produced by the extraction of low degree melts from the base of the oceanic lithosphere. This melt extraction seems related to lithospheric stress variation linked to plate flexure in front of subduction zones

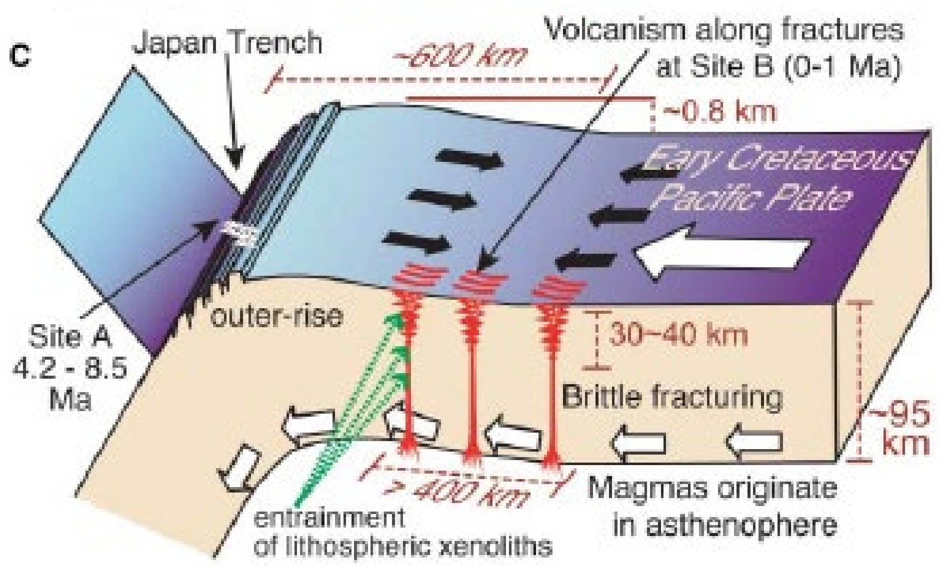


Figure from Hirano *et al.* (2006) *Science*

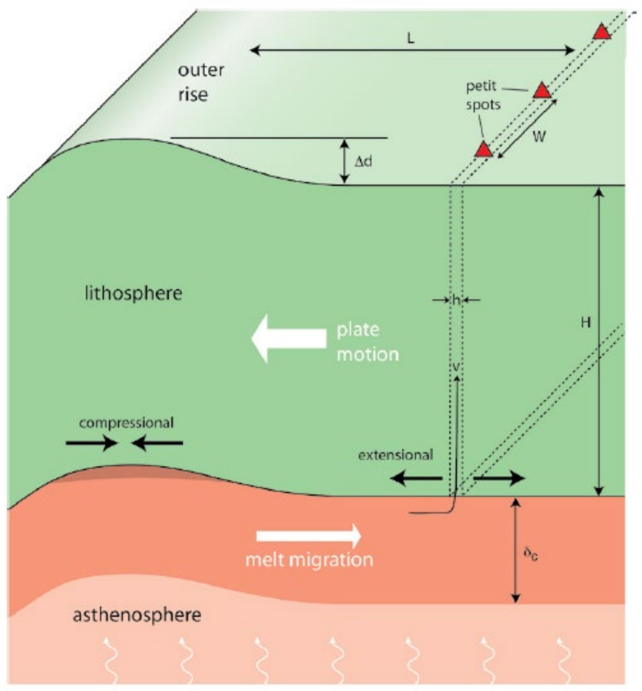


Figure from Yamamoto *et al.* (2014) *Geology*

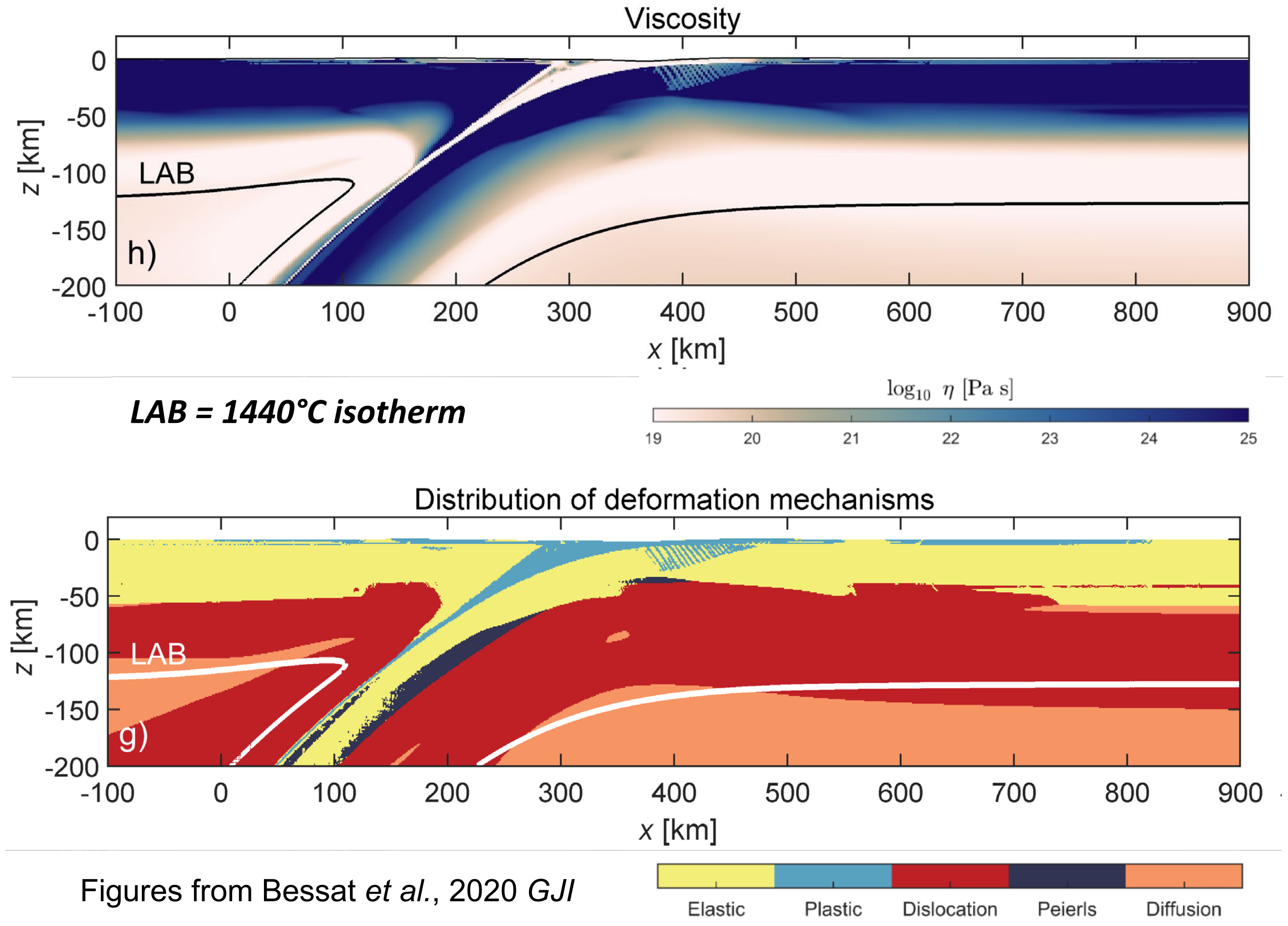
As illustrated by the figure of Yamamoto *et al.* (2014), the initial model for the formation of *Petit-spot* volcanoes suggests the presence of **small melt fraction at the base of the lithosphere**, i.e. within the low seismic velocity zone (LVZ), and the development of **fractures at the base of the lithosphere**.

If the presence of low degree melt within the LVZ is supported by geophysical studies (e.g. Kawakatsu *et al.* 2009, Stern *et al.* 2015), it is unclear if fracture could reach the base of the lithosphere.

Quantification of lithosphere deformation in subduction zone

To constrain the rheology and the lithospheric stresses associated to plate flexure, we performed numerical simulations (Bessat *et al.*, 2020). These simulations show :

- The viscosity of the mantle increases slowly from the asthenosphere to the middle of the lithosphere (where lithosphere and asthenosphere are distinct by their respective thermal regime)
- The vertical middle region of the lithosphere is associated to a change in the main deformation mechanisms, from ductile (dislocation & diffusion creeps) in the lower region to elasto-plastic in the upper region.



Figures from Bessat *et al.*, 2020 *GJI*

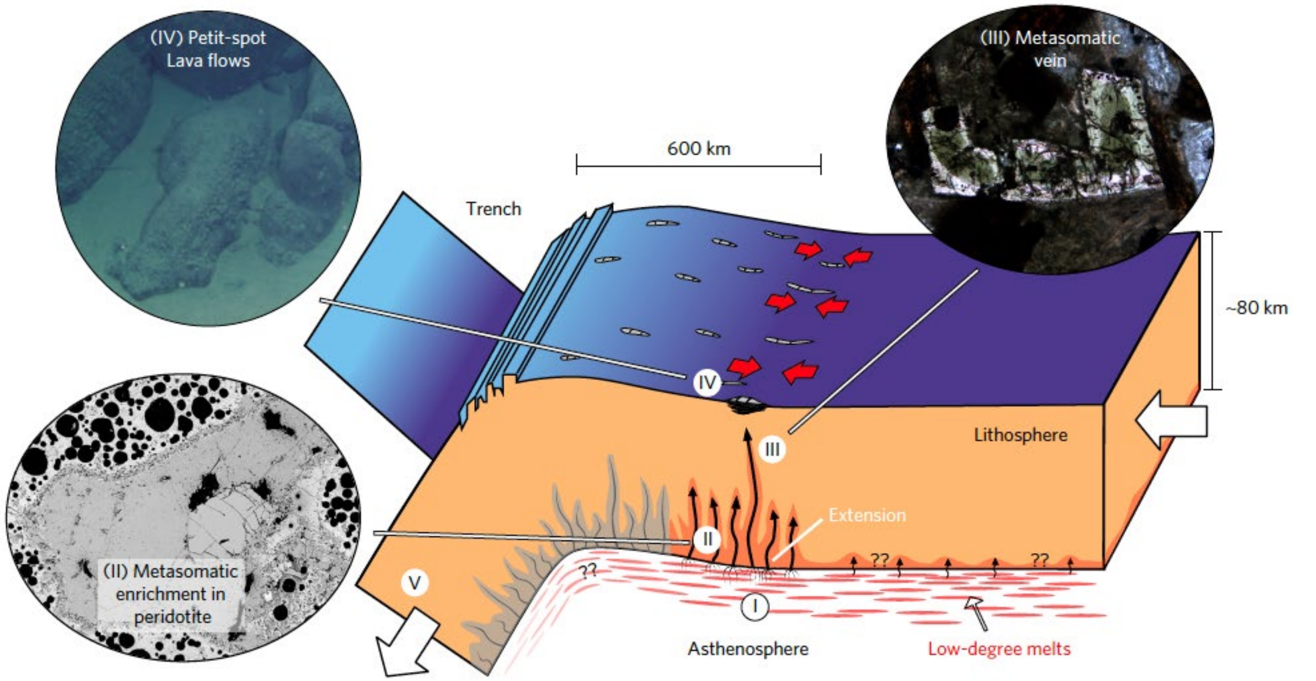
The simulation results show that at the base of the lithosphere viscous deformation is likely dominant and questions the fracture-driven mechanism of melt extraction from the LVZ.

New Hypothesis for the generation of *Petit-spot* volcanoes

An alternative model for *Petit-spot* formation suggests that melts from the LVZ do not form *Petit-spots* directly at the surface, but first metasomatize the base of the lithosphere before new pulses of magma from the LVZ produce *Petit-spot* lavas at the surface, after interaction with metasomatized lithosphere (Buchs *et al.*, 2013; Pilet *et al.*, 2016; Sato *et al.*, 2017).

This model is supported by:

1. Multiple saturation experiments showing that *Petit-spot* melts last equilibrate at lithospheric conditions (Machida *et al.*, 2017).
2. Mantle xenoliths enclosed in *Petit-spot* lavas showing evidence of metasomatic enrichment occurring at the base of the oceanic lithosphere similar to that observed in the cratonic lithosphere (Pilet *et al.*, 2016).



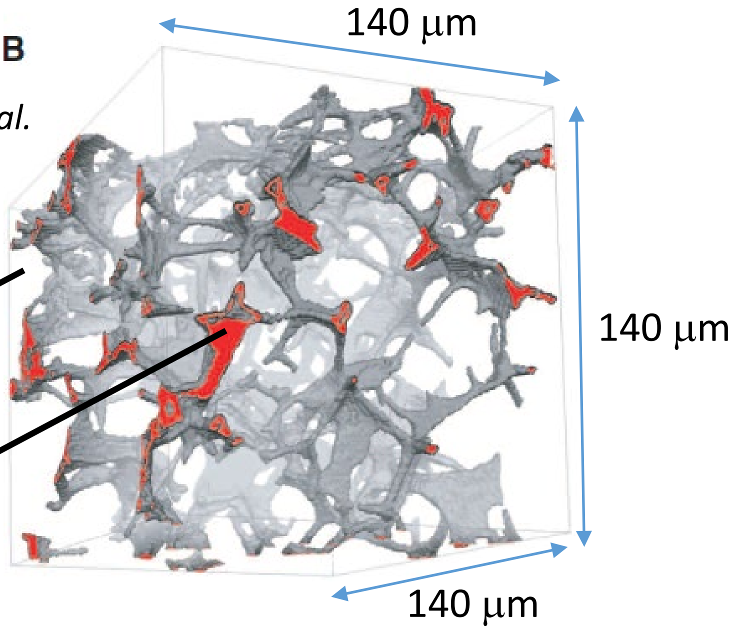
Schematic model illustrating the metasomatism of the oceanic lithospheric mantle associated to plate flexure. Extension at the base of the lithosphere created by plate flexure allows low-degree melts from the LVZ to percolate into the lithospheric mantle (I). The percolation and differentiation of these melts produce various (an-) hydrous metasomatic veins and cryptic metasomatism in oceanic lithosphere (II–III). In some cases, the reacting low-degree melts could reach the surface and generate the petit-spot sills and lavas (IV). Pilet *et al.* 2016, *Nature Geoscience*

Nevertheless, the physical aspects of this model remains mostly unconstraint. How 1-2% of partial melts are able to percolate across the base of the lithosphere and how these melts interact and metasomatize the lithospheric mantle are some questions we would like to investigate using a Thermo-Hydro-Chemical reactive transport model

Schematic model of magma migration in pores

Figure from Zhu *et al.* (2011) *Science*

Here melt volume fraction is 0.05. Gray: interface between melt and olivine crystals.



We create a Thermo-Hydro-Chemical reactive transport code with Matlab to study the magma evolution in evolving multiphase porous media.

- 2 phase model -> 2 fluids
  - a viscous rock with pores (olivine crystals – hollow space)
  - a magma flowing in the pores (interior of melt channels – in red)

- THERMO: diffusion and advection of temperature are considered
- HYDRO: we assume that the magma flows in the pores following Darcy's law and that the solid is immobile (solid velocity $v_s = 0$)
- CHEMICAL: Considering first the chemistry of a very simple system of "Forsterite-Fayalite"

To solve the equations (next slide) we use the pseudo-transient finite difference method.
(see method in Duretz *et al.*,GJI, 2019 and Räss *et al.*,GJI, 2019)

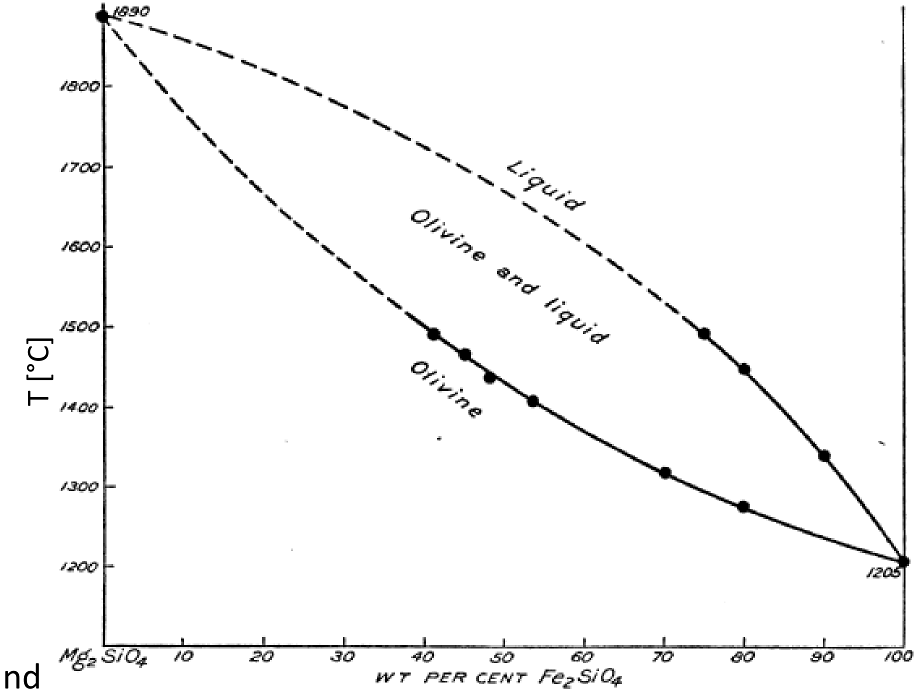


Fig. 7. Equilibrium diagram of the system, Mg_2SiO_4-Fe_2SiO_4.

Figure from Bowen and Schairer (1935) *Am J Sci*

Equations and thermodynamic database

We use 3 equations of conservation and 1 equation for the melt velocity following Darcy's law:

Total mass

$$\frac{\partial}{\partial t}\left(\rho_\mathrm{m}\varphi + \rho_\mathrm{s}(1-\varphi)\right) = -\frac{\partial}{\partial x}\left(\rho_\mathrm{m}\varphi v_\mathrm{m}\right)$$

Mass of forsterite

$$\frac{\partial}{\partial t}\left(C_\mathrm{m}\rho_\mathrm{m}\varphi + C_\mathrm{s}\rho_\mathrm{s}(1-\varphi)\right) = -\frac{\partial}{\partial x}\left(C_\mathrm{m}\rho_\mathrm{m}\varphi v_\mathrm{m} - D_\mathrm{m}\rho_\mathrm{m}\varphi\frac{\partial C_\mathrm{m}}{\partial x} - D_\mathrm{s}\rho_\mathrm{s}(1-\varphi)\frac{\partial C_\mathrm{s}}{\partial x}\right)$$

Energy

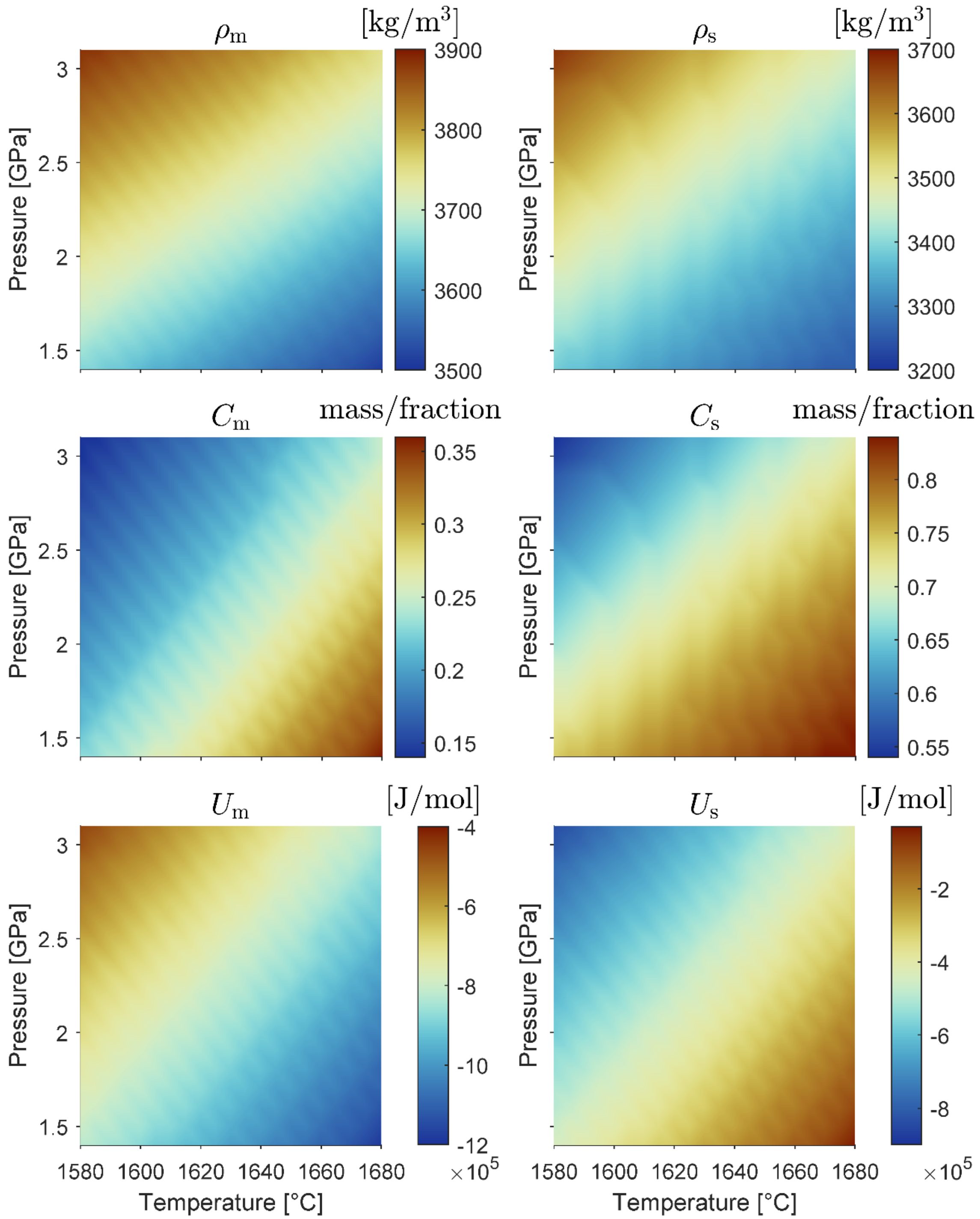
$$\frac{\partial}{\partial t}\left(U_m\varphi + U_s(1-\varphi)\right) = -\frac{\partial}{\partial x}\left(U_\mathrm{m}\varphi v_\mathrm{m} - \lambda_\mathrm{tot}\frac{\partial T}{\partial x}\right)$$

Darcy's law

$$\varphi(v_\mathrm{m}) = -\frac{k\varphi^3}{\eta_\mathrm{m}}\left(\frac{\partial P_\mathrm{m}}{\partial x} + \rho_\mathrm{m} g\right)$$

(assuming $v_s = 0$)

We have 10 unknowns. To determine them, we have 4 equations and 6 thermodynamic databases, for ρ_m, ρ_s, C_m, C_s, U_m and U_s, obtained by Gibbs minimisation to solve the system of equation.
Formulation with thermal energy, U_m and U_s, has the advantage to include directly the effect of variable specific heat.



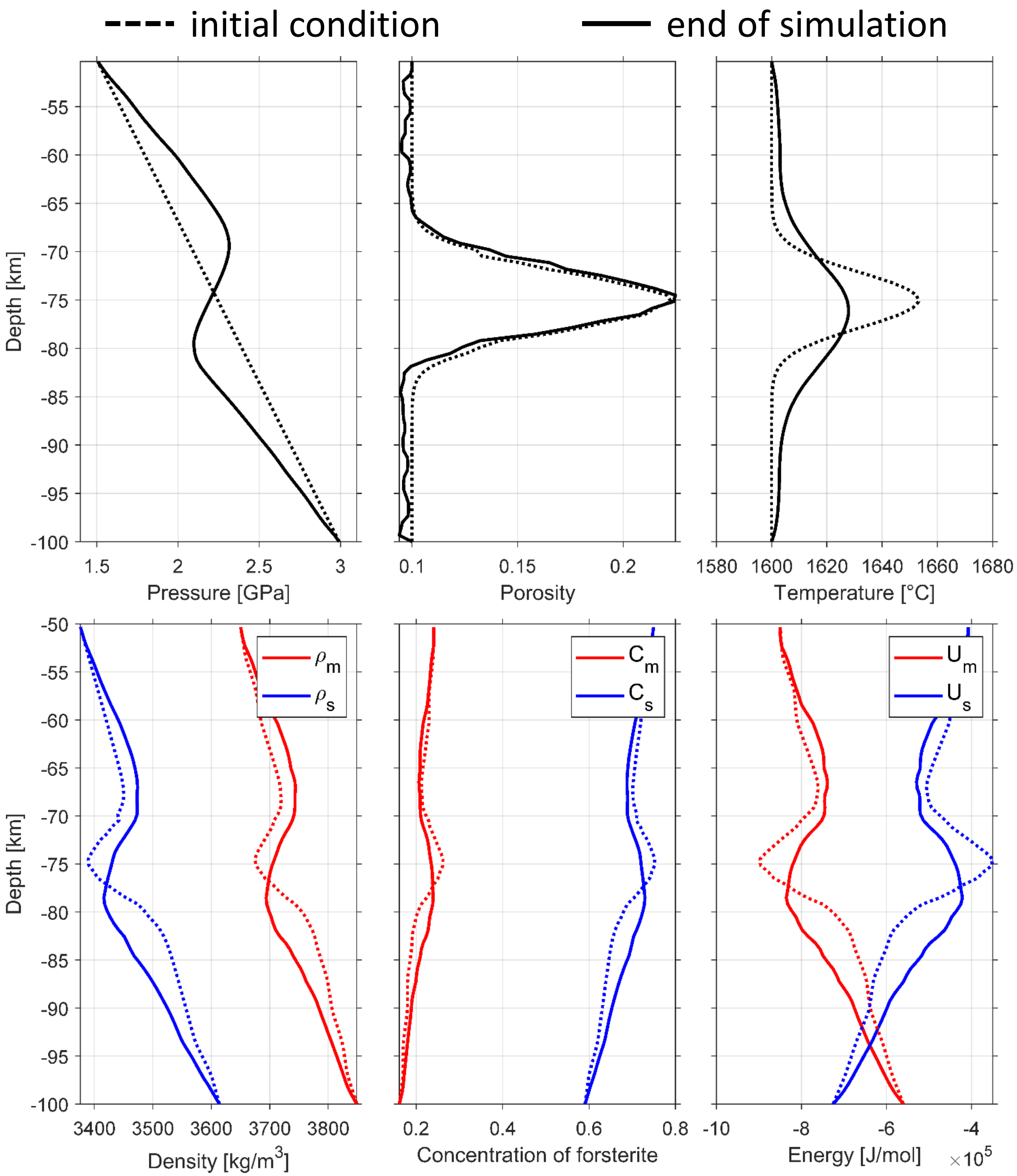
First results: Parameters and model configuration

All parameters are chosen to be applicable to the base of the lithosphere.

- Pressure of the rock is lithostatic without any mechanical deformation (solid velocity, Vs, = 0)
- Melt velocity, Vm, is calculated with Darcy's law and is relative to the solid
- Density, concentration in mass fraction and thermal energy are determined from the thermodynamic database

First result with simple chemical system to test the coupling between all the processes… work in progress!

Next steps: Using more complex chemical system (include pyroxene) and more realistic T profile to study upward melt migration through the lithosphere.



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