Towards a consistent thermo-mechanical model of plate tectonics for oceanic-lithosphere steady flows

Thibaut Putelat[1] **and Julien F. Scott**[1], **François Sidoroff**[2] **and Stéphane Guillot**[3]

[1] *Laboratoire de Mécanique des Fluides et d'Acoustique CNRS — UMR 5509*
UCB-Lyon 1 & École Centrale de Lyon, BP 163, F-69131 Écully Cedex, France
[2] *Laboratoire de Tribologie et de Dynamique des Systèmes CNRS — UMR 5513,*
École Centrale de Lyon, BP 163, F-69131 Écully Cedex, France
[3] *Laboratoire de Dynamique de la Lithosphère, UCB-Lyon 1, & Laboratoire des Sciences de la Terre, ENS-Lyon, CNRS — UMR 5570, F-69622*
Villeurbanne France

Thermal mantle convection is often put forward as the driving mechanism of plate tectonics. However, the nature of the coupling between the lithosphere and the underlying mantle is still not clearly understood. To this end, we are aiming to develop an analytical theory plate tectonics, allowing coupled treatment of the thermomechanics of both regions and incoporating rock constitutive models. The goal of our poster will be to illustrate such an analysis in the particular case of the seafloor-spreading dynamics.

In our analysis, as intuition and previous works suggest, seafloor spreading is accompanied by cooling of the upwelling flow of hot mantle as it moves towards the surface and separates on either side of the stagnation point corresponding to the ocean ridge. No a priori distinction is made between the lithosphere and underlying mantle, both being modelled as having the same homogeneous composition. The distinct properties of the two regions appears later as natural consequence of the model. A plastic/viscoplastic incompressible constitutive relation is used, based on the rheological profile and whose behaviour is either brittle and pressure dependent, or ductile and strongly temperature sensitive. Thus, expressing mechanical equilibrium and advection-diffusion of temperature, together with boundary conditions at the free interface with the water, a complex problem which couples flow, stress and temperature fields is obtained.

Approximate solutions of this thermo-mechanical problem can be constructed using a thermal boundary layer hypothesis suggested by the order of magnitude of the Péclet number. This non-dimensional number is defined as $Pe = U\,L/\kappa$, where κ, U and L are respectively the thermal diffusivity, velocity and length scales. Choosing geodynamical orders of magnitude, i.e. for U the surface velocity and for L the distance x to the ridge, it is found that $Pe \gg 1$.

As a result, the flow can be divided into at least three regions:

1. a thin thermal boundary layer (the lithosphere) whose thickness is of order $Pe^{-1/2}\,x$ and in which variations take place over horizontal distances much greater than vertical ones;
2. an external region beneath the thermal layer, characterised by horizontal and vertical length scales of the same order (x) and in which thermal diffusion is negligible;
3. and finally, a comparatively small region near the ridge in which the flow description is more complicated and a numerical approach would be needed.

As will be explained in the poster, the existence of two different length scales in the boundary layer implies that its dynamics is controlled by the horizontal strain rate $D_{xx}(x)$. Knowledge of D_{xx} determines indeed the temperature profile, the overall horizontal force acting on the layer and the position of brittle-ductile transition. By matching stresses and velocity with the external region, D_{xx} is determined at any distance x. As a result, one obtains non-local, nonlinear relations between D_{xx} and the shear stress just outside the layer. In principle, these provide boundary conditions for the flow external to the layer expressing the coupling between the external and surface-layer problems.

In attempt to obtain a consistent solution of the coupled problem, we consider ductile flow at constant temperature T_0 in the external region. Assuming different constant surface velocities on the two sides of the ridge, a hypothesis which is justified a posteriori, a self-similar external solution is obtained. The shear stress calculated from this solution is then used to determine the D_{xx} from the boundary layer problem. It is found that, at high enough external temperatures, the variations in surface velocity are indeed negligible. Significantly, it is found that the upwelling of the mantle in the external region is driven by the motion of the surface (plate), rather than the converse, and that the flow should be symmetric about the ridge. Apart from material properties of the rocks, the solution is uniquely determined by the surface velocity at the ridge and the upwelling temperature T_0, parameters which may depend on the particular ridge considered. Thermal definition of the lithosphere is then upheld and the plate imposes a constant-velocity boundary condition on the external convection.

Validity of the above description supposes sufficiently high T_0, otherwise we find rapid and significant variations of the surface velocity with x, rendering invalid both the assumption of constant surface velocity in the external problem and that of slow horizontal variations in the boundary layer. Furthermore, order of magnitude estimates suggest that the supposed incompressibility of the flow is questionable. Both points will be addressed in the poster and suggest directions for future work.