Electronic supplement

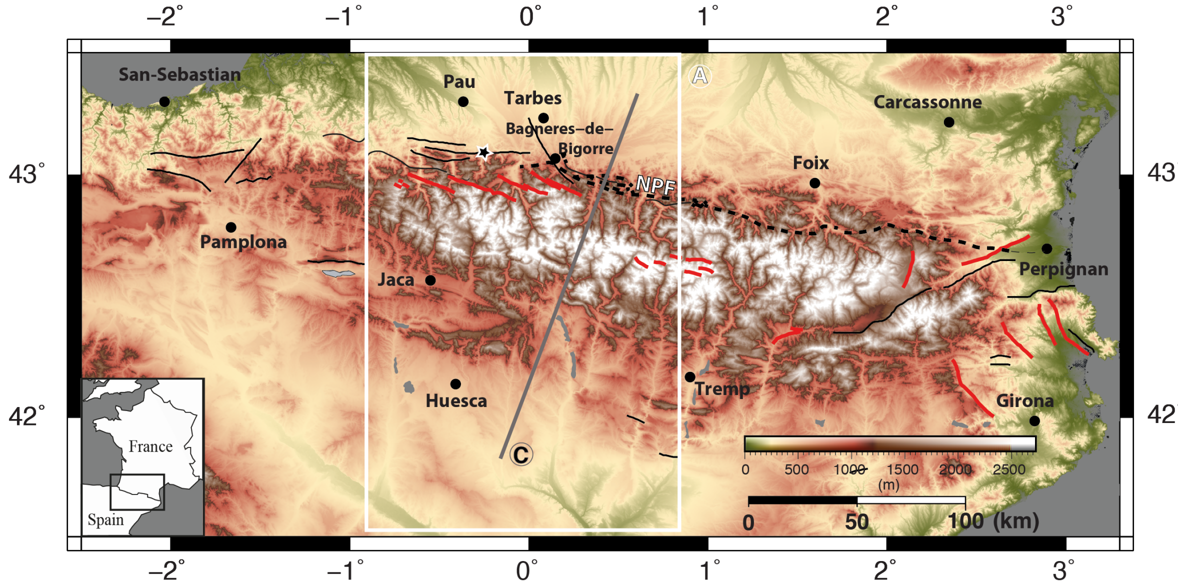

Figure 1.bis :

Topographic map of the Pyrenees. Solid lines are for faults with evidence of post-orogenic activity and red lines highlight normal faults (from Lacan & Ortuno, 2012). The dashed line is for the North Pyrenean Fault (NPF) which is not reported as an active fault. White box gives the location of figure 1A.

Three models geometry and their boundary conditions:

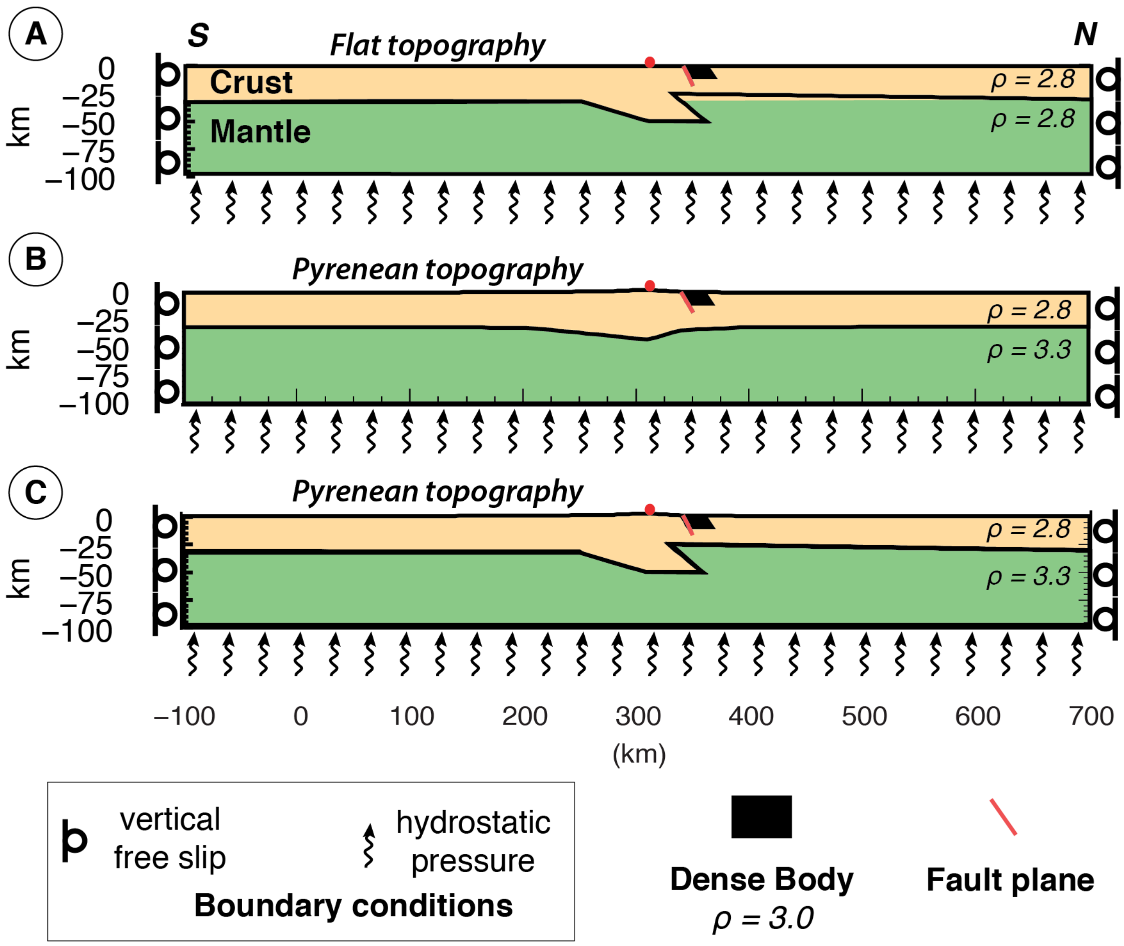

Figure 2.bis: model setting:
(A) Flat Topography model (**FLAT**) with the same density for the crust and mantle, (B) Isostatic Pyrenean Model (**ISO**), the moho depth locally compensates the topography, and (C) Pyrenean Model (**PYR**) based on Fig. 1D. Horizontal boundary conditions are set to 0 mm/yr but vertical motions are allowed, hydrostatic pressure is applied at the base of the model. The red point is the reference mark shown in Figure 1 and used to extract the evolution of the position versus time in Fig. 3.

Rheological layering

We divide the lithosphere in two layers: the crustal and the upper mantle (Fig. 2.bis A-C). We use seismologically derived parameters to model the elastic deformation (Table 1). Beyond the elastic limit, we assume that the anelastic stress-strain relations in the lithosphere are controlled by frictional and viscous processes (Brace and Kohlstedt 1980). Therefore, we use the same generic elasto-plastic-viscous rheology for the crust and the mantle. Average values of rheological parameters for the continental lithosphere are used (Table 1). At low temperature, activation of frictional processes is modelled by a Drucker-Prager flow law with an internal friction angle of 15°. In this case, the limit stress of the medium is mostly dependent from the average stress. Non-linear viscous relation is assumed at higher temperature using experimentally derived parameters for quartz-rich rock (crust) and olivine rich-rocks (mantle). Following the concept of stress envelope (Brace and Kohlstedt, 1980), we choose among viscoelastic and elastic frictional behaviors considering that the rheology with the minimum deviatoric stress invariant controls the deformation process (Chery et al. 2001). According to this dual behavior, our rheological model naturally reflects parameter variations such as strain-rate, stress and temperature.

In order to mimic the localized strain associated with crustal faulting, we also use material discontinuities with a frictional criterion inside the crust. This makes possible to explore the consequences of inherited fault weakness on the present-day strain.

Parameters and units	Crust (quartz-rich)	Mantle (olivine-rich)
ρ, $kg.m^{-3}$	2800	3300
E, GPa	10	10
ν	0.25	0.25
c, MPa	10	10
f	15	15
g_0, $Pa^{-n}.s^{-1}$	$6.03\ 10^{-24}$	$7.0\ 10^{-14}$
n	2.72	3.0
Ea, $kJ.mol^{-1}$	134	510

Table 2. Parameters values used for crustal and mantle materials. These parameters are density (ρ), Young modulus (E), Poisson ratio (ν), cohesion (c), internal friction angle (f), pre-exponential term of the power law (g_0), exponent of the power law (n), activation energy (Ea).

Temperature field

Because of the strong dependence of rheology with temperature, the definition of the temperature field of the model has a large impact on the model deformation (Kirby 1987). Unfortunately, surface heat flow measurements in mountainous areas weakly reflect conductive processes occurring in the lithosphere. Indeed, meteoritic water circulation associated with topography largely alters heat transport (Cabal and Fernàndez 1995) as attested by hydrothermal features of the north Pyrenean zone (e.g. Levet et al., 2002). We therefore define a temperature model for the Pyrenees based on simple considerations. We choose a temperature field outside of the Pyrenees associated with a surface heat flow of 60 mW/m^2, a radiogenic heat production of 1 mW/m^3 in the crust and a mantle heat flow of 15 mW/m^2. These parameters are roughly consistent with the heat flow knowledge in the Pyrenean surroundings (Lucazeau and Vasseur 1989) and lead to a Moho temperature of 650°C. Because of the lack of reliable conductive heat flow data in the Pyrenees, we simply assume that the radiogenic heat production in the thickened Pyrenean crust should lead to a surface heat flow of 80 mW/m^2. We model the heat flow anomaly of the Pyrenean root by imposing a thermal anomaly located in the crustal root (Fig. 2D). This leads to a temperature of 650°C at 30 km depth in the foreland and 1000°C at the root bottom in central part of the range.

Boundary conditions

The lack of detectable horizontal motions in western Europe (Nocquet 2012) forces us to set the differential velocity across the profile to zero. However, we do not prescribe the vertical motion on the lateral sides of the model for allowing a possible flexural response of the foreland. All models are supported at their bottom by hydrostatic pressure representing the interaction with an asthenosphere having a density of mantle. Because of these boundary conditions, deformation should occur only in response from body forces and surface processes.

Initial conditions and time-stepping

The problem of initial conditions of a geodynamical model is mostly associated with the lack of knowledge of the initial stress state and geometry. In a simple configuration associated with horizontal layering and no lateral density variation, it is possible to compute a lithostatic stress field that exactly balances body forces and boundary conditions. This is the case of FLAT experiments that are in a perfect self-equilibrium. For ISO and PYR experiments, lateral density contrast induces transient motions allowing for the deviatoric stress to build up. We experimentally observe that a period of time of 2Ma and 20Ma are necessary to obtain a nearly complete strain relaxation for respectively ISO and PYR experiments. Therefore, FLAT and ISO experiments are conducted during 2Ma without imposing additional loading. For PYR experiments this time is extended to 20 Ma. After this initial stress building, additional loading (dense body and/or surface processes) is applied during 1 Ma and the friction fault is reduced to 0.02.

References:

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