Fluid Overpressures and Decollements in Source Rocks – Application of Thermo-mechanical Models to the Subalpine Chains*

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Abstract

A key question with respect to the petroleum exploration of Fold and Thrust Belts (FTB) is to determine the calendar of the formation, the expulsion and the migration of the hydrocarbon products in relation with the development of structural traps. The geometry of the successive deformation steps from the restored geologic cross sections until the present-day cross section must be predicted taking into account the mechanical behavior of the sedimentary basin materials. A study case in the Subalpine Chartreuse FTB is documented. Hydrocarbon-related fluids generated in the source rock decollement could have influenced its propagation and the development of thrust-related folds. In order to better predict the Chartreuse FTB scenario of evolution and to study the impact of the fluid pressure, it is necessary to incorporate a formulation of rock mechanics in basin models. Several simple mechanical models performed with the code FLAMAR show that it is possible to provide useful data with thermo-mechanical models. The localization, activation, and propagation of decollements in a simulated mechanical stratigraphy could be explained only by the variation of several key parameters, such as the internal friction angle and the cohesion of decollement rocks.

Introduction

Many petroleum exploration studies of fold-and-thrust belts (FTB) have shown that the source rock levels under the frontal-most folds are crossing the oil window maturity level (Roure and Sassi, 1995; Moretti et al., 1996; Grelaud et al., 2002; Faure et al., 2004; Deville and Sassi, 2006; Sassi et al., 2007). A key question for the geologist is to determine the calendar of the formation, the expulsion and the migration of the hydrocarbon products in relation with the development of these structural traps. To answer these questions it is necessary to reconstruct in detail the sequential geometries of the geologic system. The geometry of the successive deformation steps until the present-day geologic cross section must be predicted, such as to determine the restored cross sections taking into account the mechanical behavior of the sedimentary basin materials.

Forward kinematic models integrating balanced cross-section principles combined with thermal and geochemical elements (Roure and Sassi, 1995; Sassi and Rudkiewicz, 2000) often show the progression of the frontal thrust synchronous to the generation of hydrocarbon within shale source-rock decollements (e.g., Moretti et al., 1996; Faure et al., 2004; Deville and Sassi, 2006). The high fluid pressure generated during the source rock maturation could have facilitated the formation of thrust-related folds and the propagation of decollement levels, and therefore impact the tectonic deformations and the fold styles (Mourgues and Cobbold, 2006; Zanella et al., 2014; Aydin and Engelder, 2014). Still, a major difficulty is that currently balanced cross sections are obtained with mathematical geometric models and not with mechanical models. In order to better predict the scenario of structural evolution and to study the impact of the fluid pressure, it is necessary to incorporate a formulation of the rock mechanics of the sediments in basin models.

The Chartreuse FTB in the Western Alps provides constraints on a geological system where the propagation of the decollement and the development of the structural style could have been facilitated by fluid pressure in the main source rock (Deville and Sassi, 2006). In order to introduce mechanical concepts in the scenario of structural evolution, we use the thermomechanical code FLAMAR (Burov et al., 2014, and reference therein). We run a parametrical study to investigate the onset of thrust development and localization with boundary conditions close to that of the Chartreuse. Different rheological parameters are tested, along with the introduction of a simple mechanical stratigraphy.

Geologic Setting

The Chartreuse FTB is located in the external part of the Western Alps (Figure 1). The tectonic structures result from the last step of deformation of the Subalpine Chains during the Miocene (Bellahsen et al., 2014 and references therein). The Chartreuse FTB is formed by a narrow succession of thrust faults that root within a Liassic-Aalenian decollement level (Figure 1).

The thrusts ramp-up from the Lias-Aalenian shale without employing the potential decollement of the Middle Jurassic “Terres Noires” shales and Berrasian marls (Figure 2). The decollement level is localized within the Toarcian-Aalenian black shales, interpreted as a good quality source rock in the Subalpine chains (Deville and Sassi, 2006). While petrophysics and geochemistry studies provide good knowledge on the type and distribution of organic content and on the stratigraphy of the Liassic organic-rich intervals, the precise localization of the decollement level with respect to the shale mineralogy and the organic content is still poorly described and understood (Figure 2). Questions remain on the thickness of the decollement level and the impact of fluid circulations within and out of limit of the shale organic-rich formation.

Thrustpack forward kinematic models (Sassi and Rudkiewicz, 2000) performed in the Chartreuse FTB propose that the timing of generation of hydrocarbons in the Lias is synchronous with the propagation of the decollement (Deville and Sassi, 2006). Moreover, the Paladru well in the frontal-most thrust block evidenced hydrocarbon overpressures in the Toarcian, still in the oil-window in this area (Deville et al., 1994). Therefore, several observations seem to indicate that hydrocarbon-related overpressure has a strong impact in the emplacement of the stacked thrust horses of the Chartreuse FTB. An integrated mechanical approach should in practice be used to explain the relationship between regional structural style differences as observed between the closely located Chartreuse FTB, Vercors FTB, and Bauges FTB (Deville and Sassi, 2006; Bellahsen et al., 2014).

Insight from Mechanical Modelling

FLAMAR is a hybrid finite-element/finite difference code. It solves simultaneously Newtonian equations of motion in a Lagrangian formulation, coupled with visco-elasto-plastic rheology, heat transport equations and state equation (see Burov et al., 2014 and reference therein). Several models are set according to a simple set-up (Figure 3), that respect the elastic and elasto-plastic solutions provided by previous analytical and numerical models (Sassi and Faure, 1997; Gerbault et al., 1998).

The point is to understand and constrain the onset of deformation with respect to specific boundary conditions supplied by the study of the Chartreuse FTB, in order to discuss and predict mechanical results. Sensitivity tests on physical parameters such as the internal friction angle and the basal friction of the material are performed (Figure 3). While only these basic mechanical rock properties are modified, important variations are observed on where the localization of the shear zone takes place (Figure 3) and how the future fault geometry will lead to new structural blocks, including their location and vergence (Figure 3).

The introduction of a single weak layer in the model simulates a secondary decollement level that is able to modify both the stress field and the style of the deformation (Figure 4). These exercises of modified Hafner problem (Hafner, 1951) show that different mechanical answers can be displayed and an internal decollement can be developed using only simple hypotheses on the internal friction angle and the basal shear strength.

In further attempt to integrate more complexity in the exercises, several models are run with different mechanical stratigraphy (Figure 5a) and integrating a simple erosion/sedimentation law (Figure 5b). It is shown that a secondary decollement is activated only for a very low value of friction angle and cohesion (Figure 5a). When it does, the simulated fold adopts a geometry and kinematics close to that of a fault-bend fold (Suppe, 1983). However, for a value of friction angle and cohesion similar to that of natural shale, the secondary decollement is not activated (Figure 5a); the resulting geometry of the simulated fold is that of a fault propagation fold (Suppe and Medwedeff, 1984).

When a simple erosion/sedimentation law is integrated in the model, both stress and strain fields are deeply modified (Figure 5b). The decollement level activation is facilitated, leading to its progression toward the foreland, and a small transported piggy-back basin is formed in front of the main fault-related fold. Additional structural blocks are accounted for in the frontal part of the model (Figure 5b).

Conclusions

A study case in the Chartreuse FTB is documented, where hydrocarbon-related fluids generated in a source-rock decollement could have influenced its propagation and the development of thrust-related folds. However, currently the relation between source-rock thermal maturation, fluid circulations, and deformations cannot be considered in the building of a structural scenario of deformation, because no tools exist to provide mechanical insight in basin models. Several simple mechanical models run with FLAMAR show that it is possible to provide useful data with thermomechanical model. The localization, activation, and propagation of decollements in a mechanical stratigraphy can be explained only by the variation on several key parameters of the mechanical stratigraphy, such as the internal friction angle and the cohesion of the decollement rocks. The critical values needed to activate a decollement in shale levels is shown to be very low, which may indicate the need for important fluid pressures to allow the development of such geologic structure. However, these critical values still need to be constrained with laboratory experiments. Also, external factors, such as the erosion and the sedimentation, strongly modify the distribution of the deformation in a mechanical stratigraphy, and therefore must be taken in those kinds of modeling approach.

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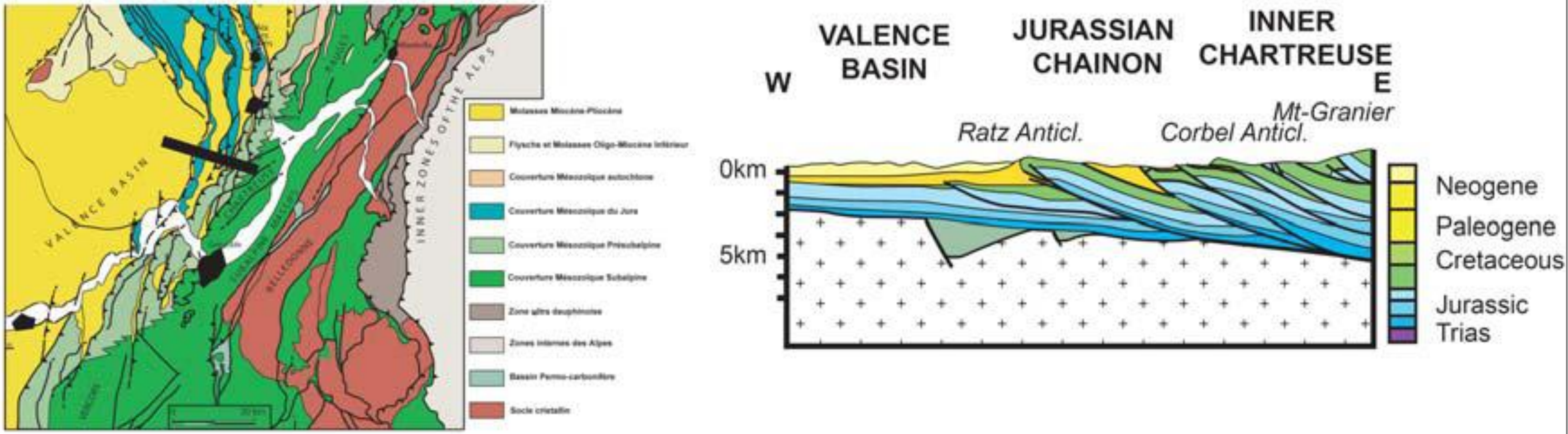

Figure 1. Location and cross section of the Chartreuse FTB.

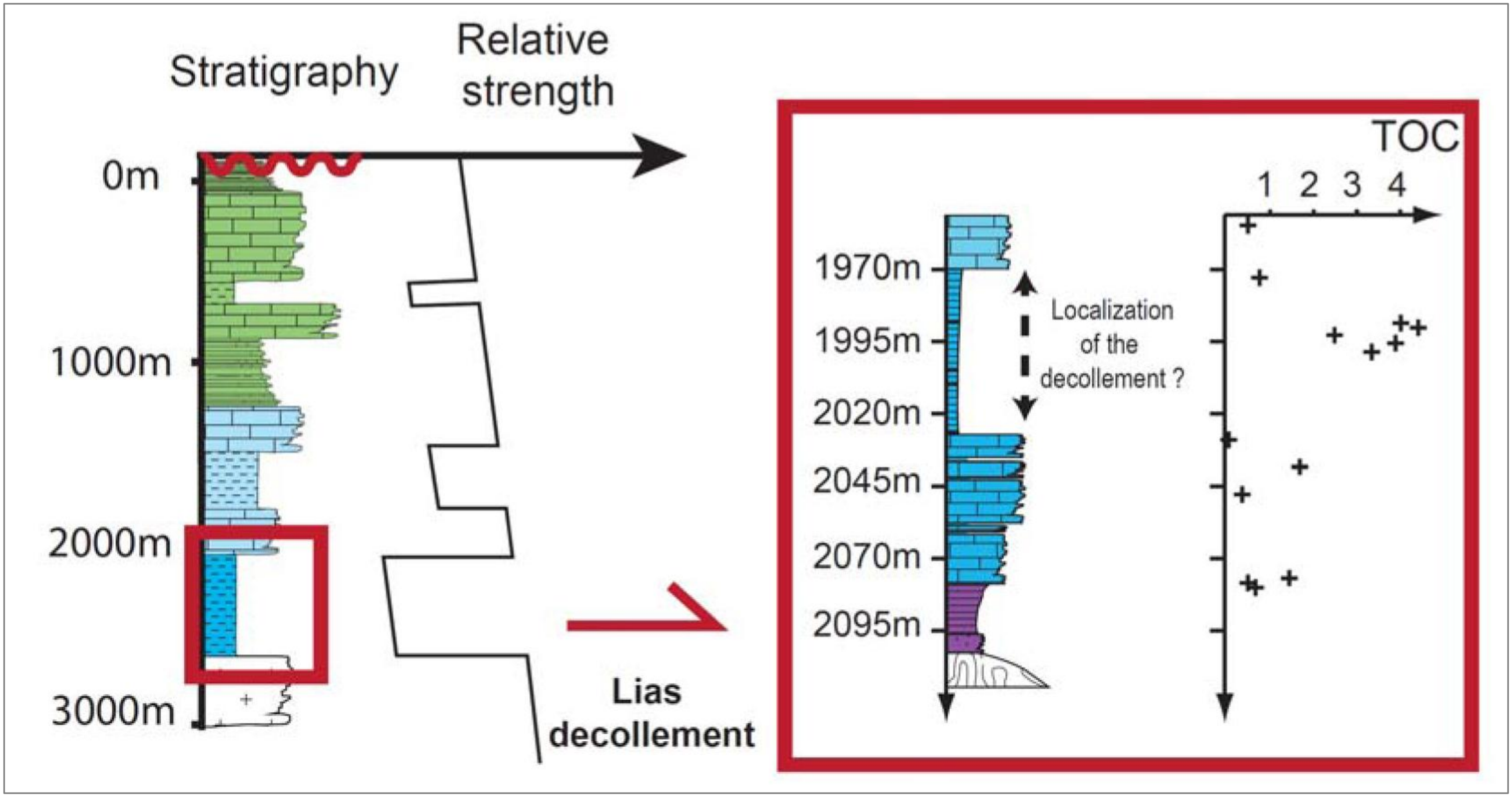

Figure 2. Stratigraphy of the Inner Chartreuse, with its relative strength. The zoom details the stratigraphy of the Lias and its TOC content, based on the Paladru well located west of the Ratz Anticline (Figure 1).

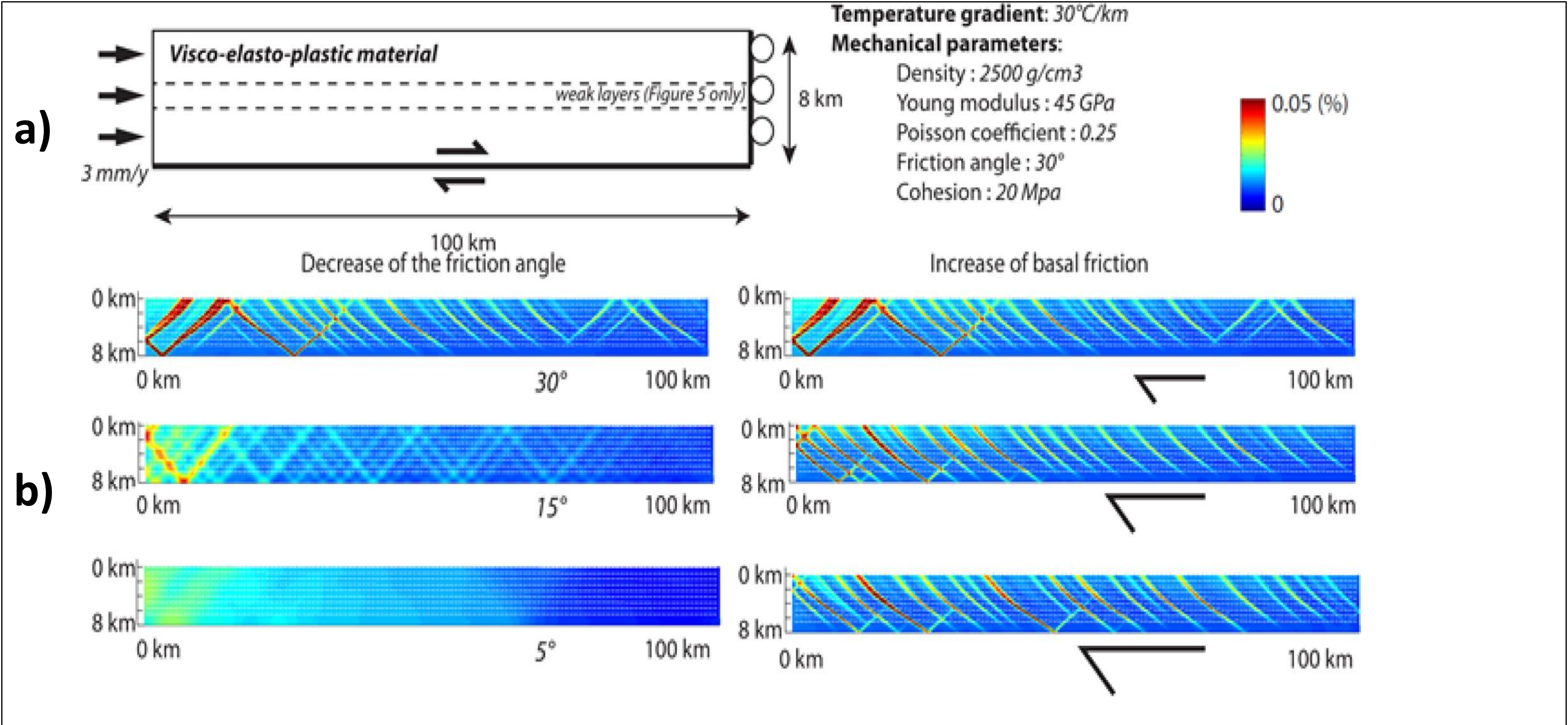

Figure 3. a) Set-up of the numerical experiments. The rheological laws are set according to Burov et al. (2014). b) Sensitive tests of the friction angle and the basal friction. Each picture represents the computed strain at 1km of shortening, with different friction angle and basal friction. Vectors indicate the orientation of the principal stress σ_1.

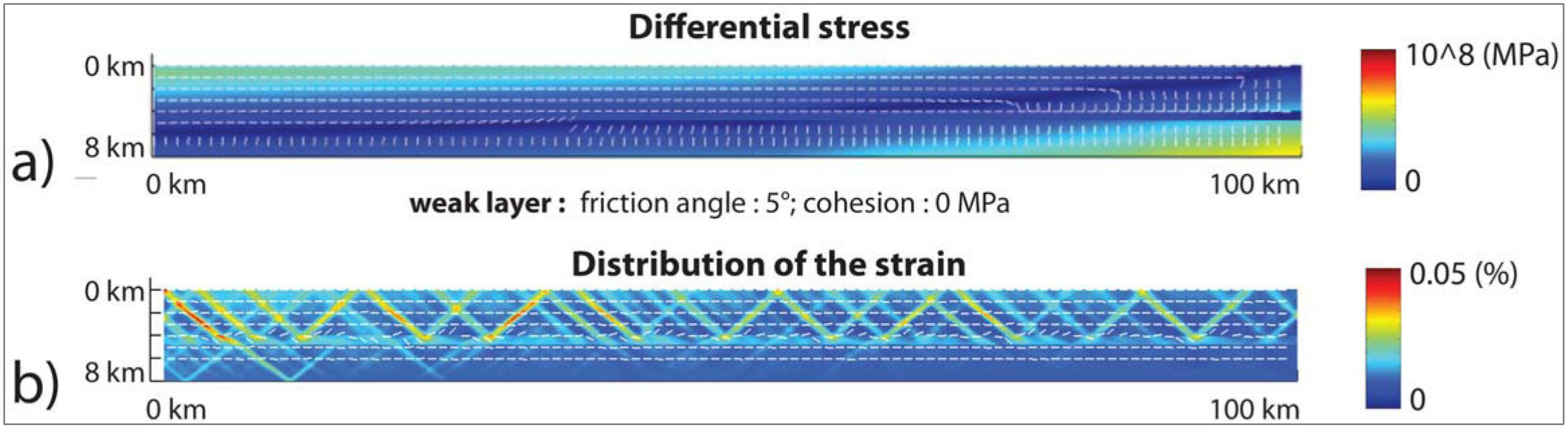

Figure 4. Numerical results of the set-up with the introduction of mechanical stratigraphy. The picture represents the differential stresses at 100m of shortening (a) and the computed strain at 1km of shortening (b).

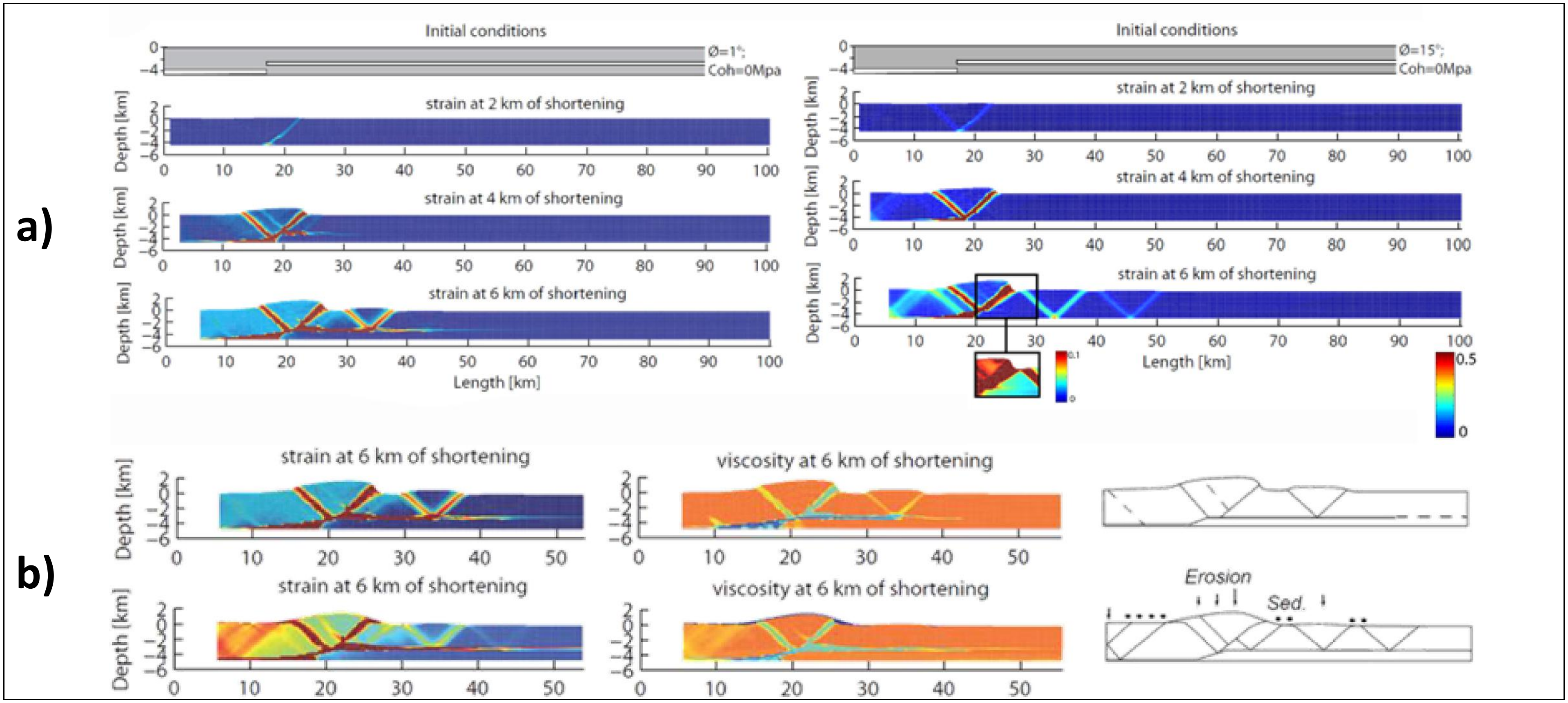

Figure 5. a) Numerical results indicating the critical need of low friction angle and cohesion to activate and propagate a secondary decollement level. b) Effect of a simple erosion/sedimentation law on the strain distribution.