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Crustal shortening in the External French Alps: thermo-mechanical modelling

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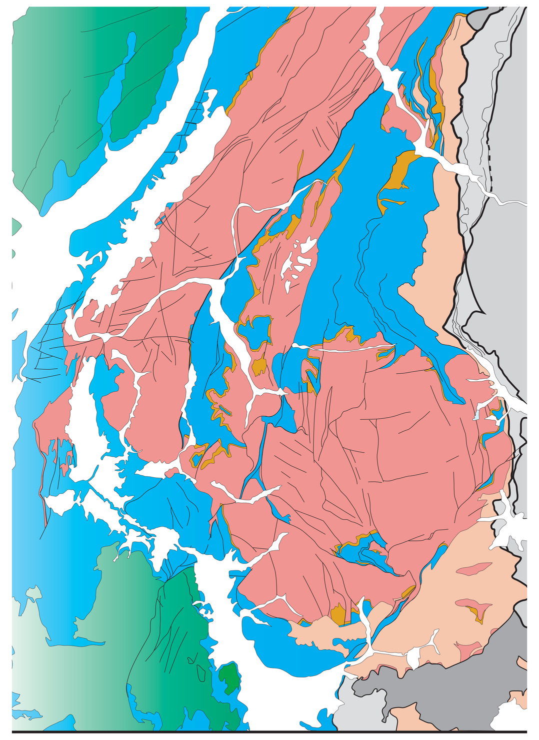
!! or attend to Nicolas's related talk today at 16:45 room 5/EGU2009-2060 !!

Introduction

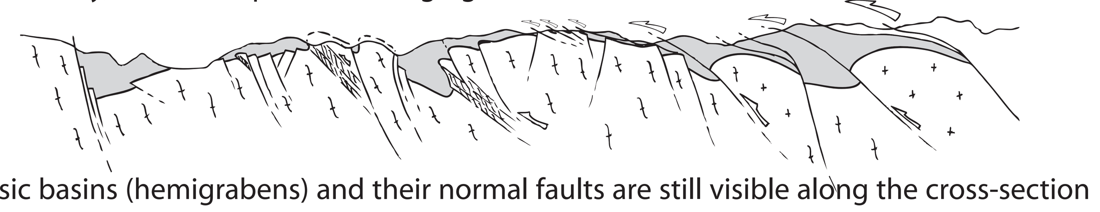
Geological Setting



Structural map
of the Ecrins Massif

The External Crystalline Massifs (and the Taillefer-Grandes Rousses-North Pelvoux (Emparis)) in particular are located west of the so-called alpine Penninic Front. These massifs are made of crystalline hercynian basement covered by Triassic and the Jurassic (syn-rift Lias, mainly marls) sequences.

We here consider the post-Priabonian, west-verging, alpine deformations (mainly Oligocene) contemporaneous with the overthrusting of internal units. The Dauphinois (European proximal continental margin) crust subducted below the internal units and started to thicken. The presence of pyrophylite and cookeite in the Liassic sediments from west to East, respectively, record temperatures ranging from 280 to 350°C.



Liassic basins (hemigrabens) and their normal faults are still visible along the cross-section and thus have not been completely inverted. In the field, we could not find any evidence in favor of a reverse reactivation of those normal faults, either at small or large scale. In the hanging-wall of many of those, compressional deformation can be observed and is described in the following:

- In the basins, the Liassic sediments are deformed and present a penetrative schistosity and a clear dip-slip stretching lineation (around E-W in strike) marked by elongated and boudinaged objects such as belemnites. This schistosity shows sigmoidal features between East-dipping shear bands.
- The main structural insight is the presence of "basement folds". These fold has a radius of curvature of about a few hundreds of meters, associated to west-verging thick shear zones in the basement

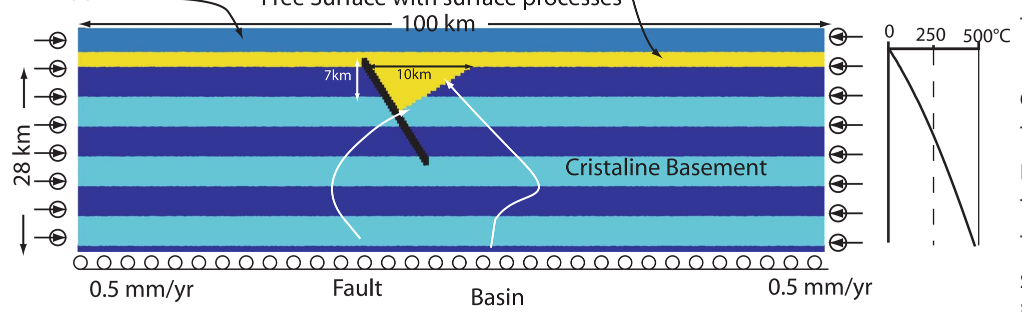
Modeling hypothesis

The rifting happened back in the Lias (270Myr) so that at the moment of the inversion, one can suppose the geotherm was back at steady state. Initial temperature at top and bottom are maintained constant throughout the computation while the lateral heat flow is maintain to zero on the lateral wall.

We seek to understand inverted passive margins. At crustal scale, those objects are constituted of faulted basement rocks which have been in filled by syn rift sediments. Hence, we find two types of mechanical heterogeneities: the basins and the pre-existing faults.

The pre-existing faults are old and although they did cumulate large amount of shear strain during the rifting, it is not clear wether they are indeed weaker of stronger than the basement at the moment of the inversion. Either, the faults have completely recovered regular properties of rocks (Byerlee friction 1978). Either, they are indeed weaker because of their anisotropy or their low permeability.

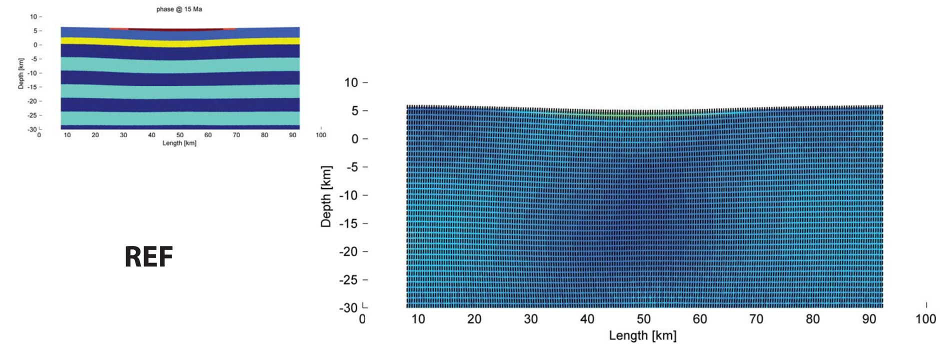
Similarly, the syn-rift basins are constituted of indurate sediments which mechanical properties may be quite similar to the basement after lithification or they may have kept a relatively lower effective viscosity because of small scale folding and/or intense pressure dissolution.



NB: The stripes in the basement are only meant to highlight the mode of deformation by folding or faulting.

* Post and Synrift sediments have the same rheology.
* Velocity at boundary condition is given to reach 15% bulk shortening after 15 Ma according to geological estimates.
* The bottom boundary condition is fixe vertically reflecting the Moho is not deforming.
* Bottom and lateral wall are free to slip
* Faults are included as 60° dipping relatively thin slabs (2 elements) of frictionaly weaker material in the models
* geothem reach 250-300°C at the base of the syn-rift according to geological constrains

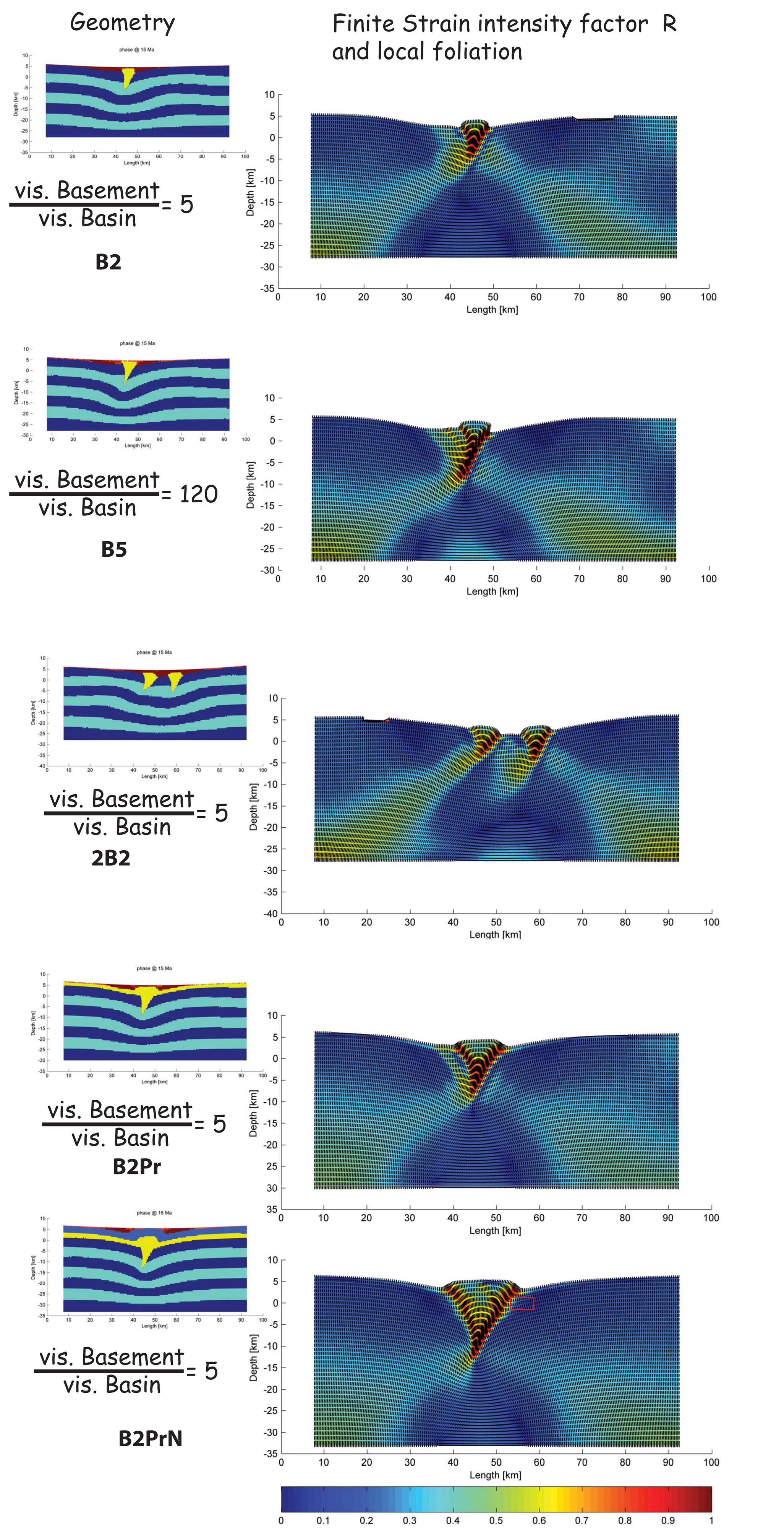
Homogenous Models



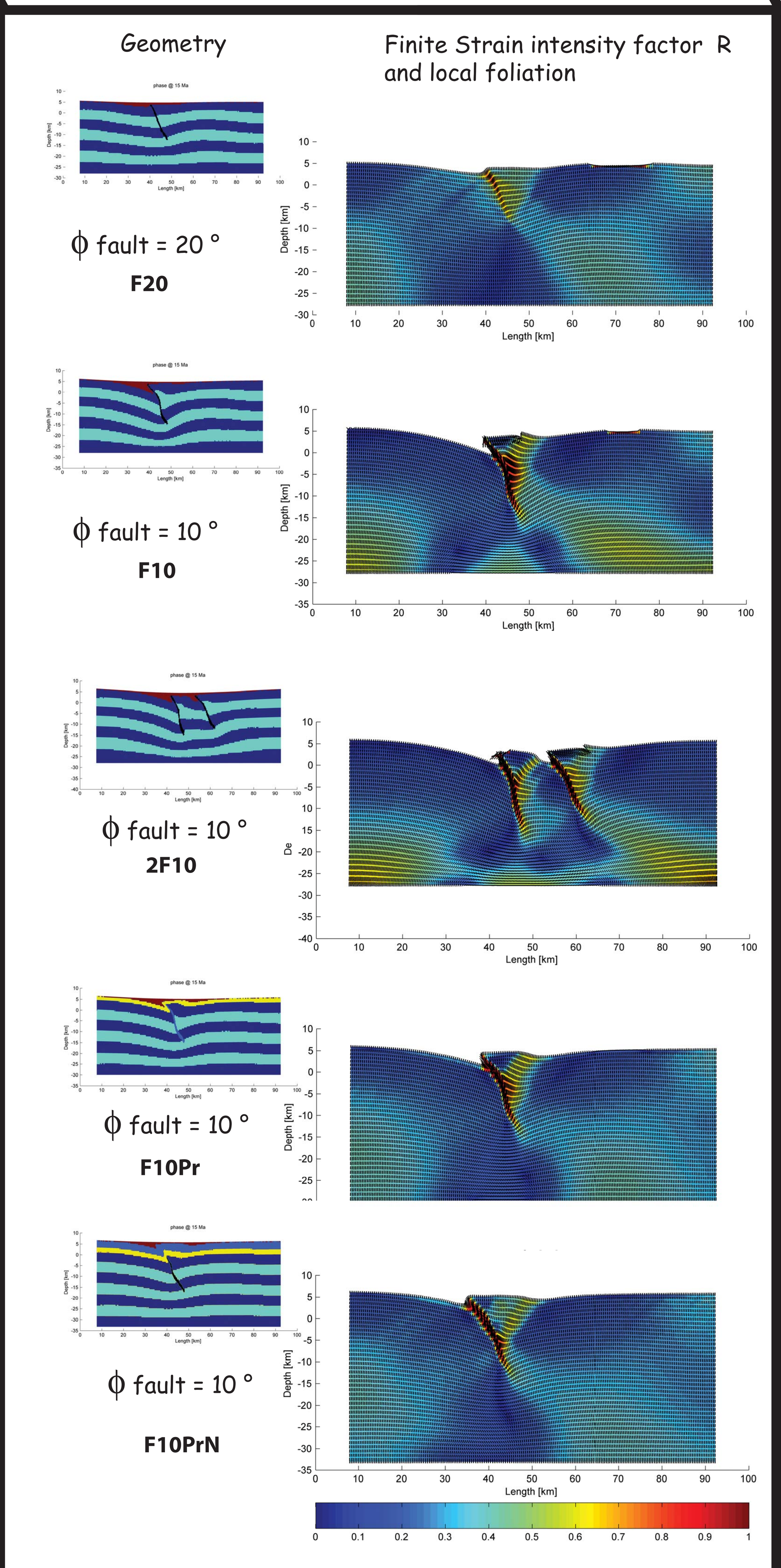
At **very small shortening rate**, a crystalline basement alone made of granitic type rock deforms without any localize deformation.
Instead, the gradient of viscosity within the crust allows for strain to be mainly accommodated by **crustal scale buckling**.
The folding is nearly **isopack** and the ratio folding versus pure thickening decreases with depth.
It is accompanied by relatively more deformation along principal shear direction that links the extrados at depth to the intrados of the folds at the surface but **no real localization**.

Numerical experiments

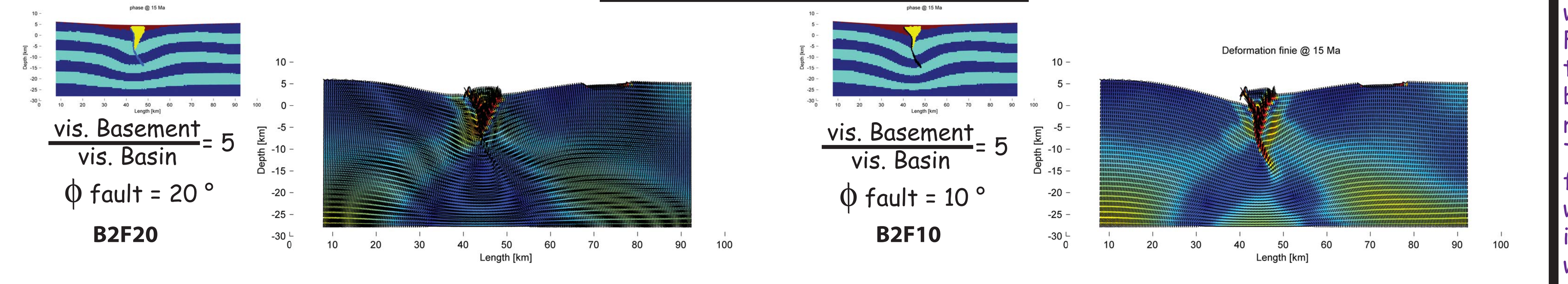
Weak Basins ϕ fault = ϕ basement =30°



Weak Faults η basin = η basement = f(T)



Basins & Faults



Comments

Basins localize pop down structures in the basement because they reduce of the elastic strength at the top of the upper crust.

Interestingly enough, the relative weakness of the basin influences only slightly the mode of deformation (B2 vs B5). This implies that the folding is controlled by the viscosity of the basement.

Oppositely, inherited weak faults tend to push the basins upward.
Very weak fault (F10) induces pop up structure and very intense stretching of the basement parallel to the fault at the brittle ductile transition. At the end of the inversion the fault becomes sigmoidal.

Slightly weak fault (F20) induce short cut fault and downward fexure of the hanging wall.

In both case, folding is predominant at depth but compare to REF, it is much less isopack.

These two models intend to highlight the impact of interaction between tilted blocks on the geometry.

For basins, the repeated pattern of tilted block tends to minimise the strain along the fault. A short cut shear zone forms between the bottom of the right basin and the top of the left one.

For very weak fault no similar short cut shear zone forms

In both case the wavelength of folding is reduced to a 10th of kilometers because the basement is weaker.

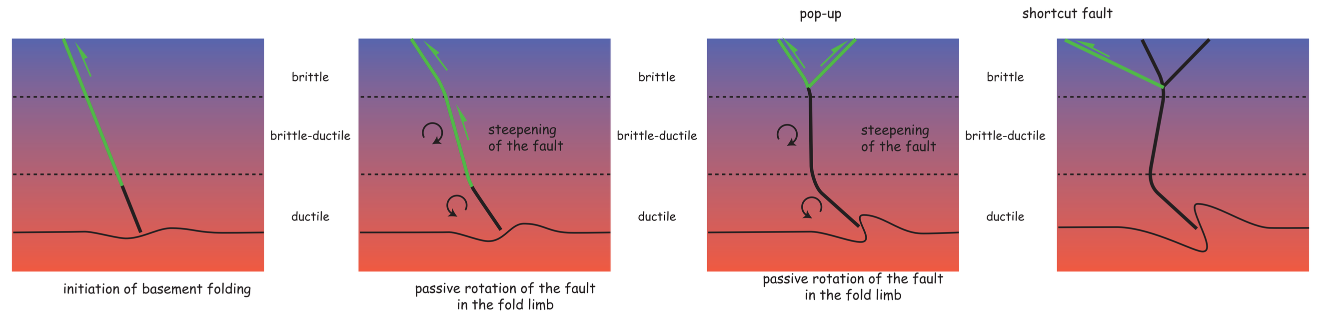
Post rift sediments and possible nappe stacked throught the orogenic process affects the inversion of passive margin by 1) changing the thermal regime within the tilted block zone at the initiation of the inversion and 2) changing the burial depth of the faults.

For very weak faults, the burial does not anhilate plastic deformation in the upper part. However, in the deeper part, with the rise of the temperature, the viscous relaxation becomes predominant.

Basin type of weakness are not sensitive to burial, but the fact that they happend deeper within the upper crust tends actually to reinforce their large scale weaking capacity. Detailed observation show that shear zone may form at the top of the basement within the post rift sediments.

The interaction between faults and basins leads to more important differential rotation of the fault with depth.
For reasonably weak fault, the basin controls completely the deformation as highlighted by the similarity between models B2 and B2F20 and the fault is not reactivated at all.
The sigmoidal shape being increased, one notice the formation of a short cut fault at the front of B2F10 which roots at the base of the "S". Also, the sigmoid is so much rotated that reverse play on the fault would appear as normal.

Discussion



The fault is reactivated in the brittle field.

At depth, the fault is prologated into a fold

The fault rotate passively into the fold limb at depth.
At the surface, it continue to play in the brittle field.
Within the BDT it rotate counterclockwise in response to viscous drag

the kink in the fault causes the localization of a small back thrust and the formation of a pop up structure while the fault continues to verticalieze at middle depth.

In extreme case, particulary in presence of the basin adjacent to the fault which maximizes viscous relaxation,, the fault may dip in opposit direction. At that moment, the pop up is abandoned in favour of a short cut fault.

Conclusions

The basins are as much and maybe even more important than the faults when it comes to invert passive margin.

In all the cases, even without heterogeneities, the thermal gradient implies a mechanical layering of the crust which favors buckling at the at crustal scale. However, adding weak zone in the upper crust results in a diminution of the effective elastic thickness of the model resulting in smaller wavelength and increased disharmonic folding.

Increasing the thickness of the overburden by stacking post rift sediments or nappe on top of the passive margin diminishes the effects of the faults and maximizes the effect of the basins.

In the model all the faults happend to be deformed even the weak ones. This is generally generally not accounted in restoring cross sections. This appoximation maybe correct for shallow fold and thrust belts but our models show that it should be taken with care when restoring cross section where the basement is involved.

Numerics

The numerical experiments were run using Flamar / parovoz (Yamato 2007, Poliakov 1992) . This code solves the momentum conservation equation (1) and heat transfer equation (2) using a FLAC (Cundall) type algorithm.

(1) $$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho g_i \approx 0$$

2) $$\frac{DT}{Dt} = \mathbf{div}\left(\frac{\kappa}{\rho Cp}\nabla T\right) + \frac{H}{\rho Cp}$$

Each brick elements of the mesh are 400m x 400m for a total number of elements which varies between 28000 and 33000 depending on the experiment.

All the elements behave as visco-elasto-plastic bodies. Their viscous properties depends on the temperature and an add hoc parameters C that fixes the viscosity contrast. The peak friction of the elements is reduced only in the weak faults and no plastic softening was used during the experiments. The thermal and mechanical are listed here

param	G	K	A	E	n	Co	ρ	κ
unit	GPa	GPa	$MPa^{-n} s^{-1}$	kJ	~	MPa	kgm^{-3}	m^2s^{-2}
value	3	5	$Cx6.x10^{-6}$	156	3	20	2700	10^{-6}

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Poliakov. A., Cundall P., Podladchkov Yu., Laykhovsky V. 1993. An explicit inertial method for the simulation of visco-elastic flow: an evaluation of elastic effects on diapiric flow in two- and three- layers models. In: D.B.Stone and S.K.Runcorn (eds.), Flow and Creep in the Solar System: observations, modelsing and Theory, Proceeding of NATO Advanced Study. Institute, 175-195.