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Gouge compaction as softening process? Clues from analytical solution and 2D mechanical modelling.

A number of field observations suggest that sliding on fault planes may occur at very shallow dip in the brittle field. The existence of active low angle normal faults is much debated because (1) the classical theory of fault mechanics implies that faults are locked when the dip is less than 30°and (2) shallow dipping fault planes do not produce large earthquakes (M > 5.5). To reconcile observations and theory,we propose a new model for fault reactivation by introducing an elasto-plastic frictional fault gouge as an alternative to the classical dislocation models with frictional properties. Contrary to the classical model which implies that the dilation angle ψ equals the friction angle ϕ, our model accounts for $\psi < \phi$ and permits $\psi < 0$ in the fault gouge as deduced from laboratory and field observations. Whilst the predicted locking angles differ in most cases by less than 10° from the classical model, a significant amount of plastic strain (strain occurring in elasto-plastic regime) is predicted to occur on badly oriented faults prior to locking when the fault gouge is allowed to compact.

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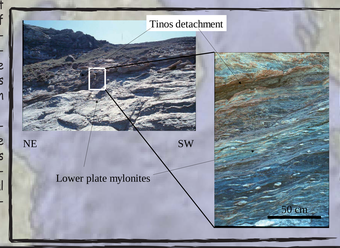
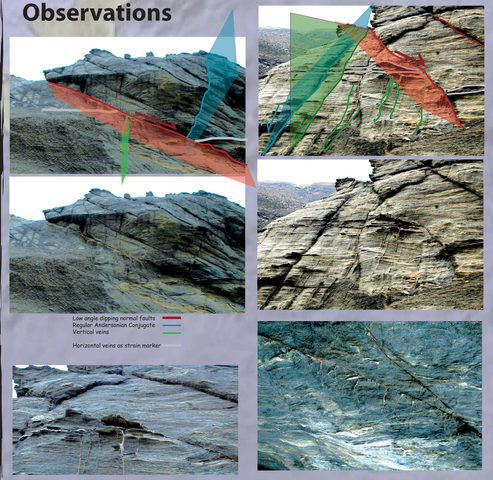
1. Initial Problematic

The Oligo-Miocene detachment of Tinos island is an example of detachment which has the particularity to highlight into a continuum of deformation the moment ductile mylonites cross the brittle ductile transition during their exhumation.
Detail mapping and stress inversions (Melh et al 2005) have shown that brittle structures marking extension are shallow- and steeply dipping normal faults associated with subvertical extensional joints and veins.

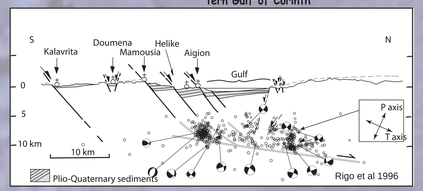


Observations



CORINTH GULF ?

This "abnormal" Normal fault activity is also suspected to happend in the Western Gulf of Corinth



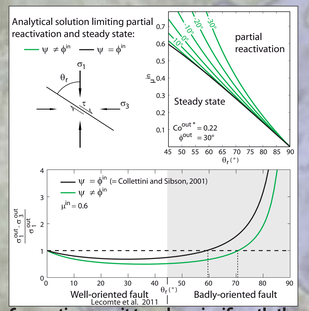
Take Away Message

Fault zone are thick and the stress may rotate within the fault zone when the dilatation angle of the Fault is smaller than the friction leading to reduction of the effective friction

Before locking faults can play in the brittle regime.

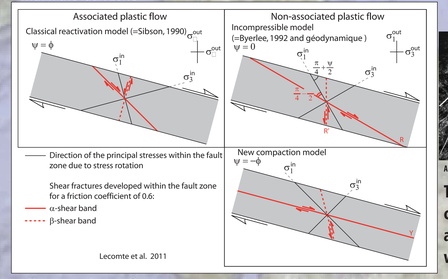
Badly oriented faults always play in hardening regime and therefore plastic yielding always occurs in stable slip.

Comparison to the classical brittle models



Compaction permit to reduce significantly the locking friction of low angle normal Fault...
It allows a fault with a peak friction of 0.3-0.4 to play at dip of 20°

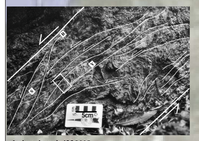
Predicted newly formed micro/meso-structures after the stress rotation within the fault zone



Non associated flow not only reduce the effective friction but also predict the neoformation of micro-structure within the fault that are observed on the field, i.e. Riedel shear for an incompressible flow and X-Y shear for a compacting flow.

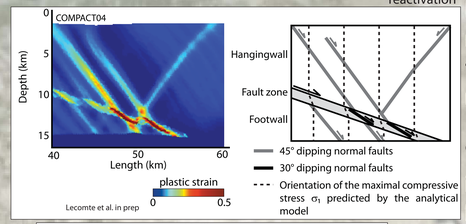
Associated flow predicts structures that are not observed in nature.

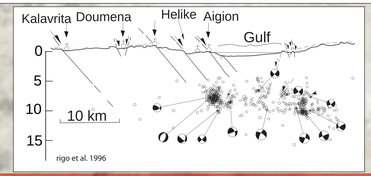
Riedel and Y shear



The orientation of the microstructures informs us about the state of stress withing the fault zone

Introduction of the compaction flow model in 2D numerical models of fault reactivation





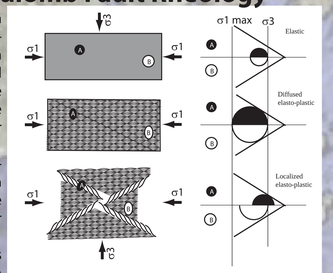
It possible to reproduce the neoformation of microstructure within fault zone within high resolution mechanical numerical models.

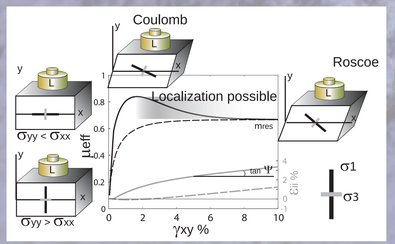
The microstructures are neoformed in softening regime so that slip may become unstable on local patches.

Microstructures are a possible explanation for the microseismic activity recorded on low angle normal faults.

2. Mohr Coulomb Fault Rheology

Mohr Coulomb flow rule is a rheology which allows deriving plastic strain rate from a potential function multiplied by a scalar so that in the elasto-plastic gouge the state of stress respects the Mohr Coulomb criteria.
This rheology reproduces typical aspects of stress-strain curves obtained for simple shear test in the Lab (Vermer 1990).
For badly oriented shear bands the faults strengthens with shear and reaches steady states without passing any peak (dashed line).





For well oriented shear bands (plain line), the peak of stress which occurs when maximum principal stresses form a Coulomb ($\pi/4-\Phi/2$) angle with the direction of shear at orientation allows for strain localization as principal stress rotate towards steady state orientation (i.e. Roscoe shear bands $q=p/4+\Psi/2$).

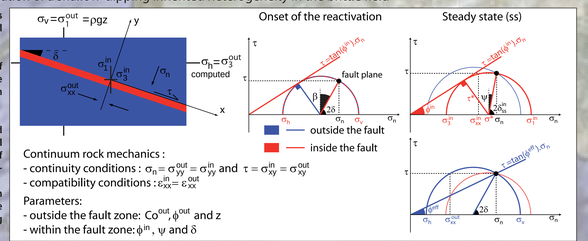
3. Punctual analytical and semi-analytical approach

Setup: extensional reactivation of a shallow-dipping inherited heterogeneity in the brittle field

Reactivation of badly oriented faults always occur in hardening regime for geometrical reason.

In a perfectly elastic embedding, the rate of hardening diminish with slip and the state of stress reaches a steady state solution which can be derived analytically.

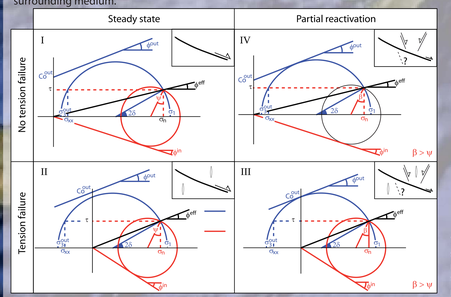
In nature the embeding may also break and a new, better oriented fault form. Analytical solution have been dervide for the state of stress at each branching of four modes of deformation described below.
A semi-analytical approach developped in Lecomte et al 2001 allows computing the amount of plastic strain before locking occurs.



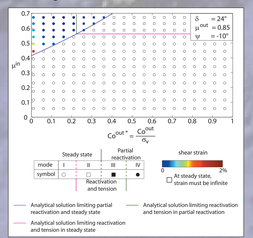
Continuum rock mechanics :
- continuity conditions : $\sigma_n = \sigma_{yy}^{out} = \sigma_{yy}^{in}$ and $\tau = \sigma_{xy}^{in} = \sigma_{xy}^{out}$
- compatibility conditions : $\varepsilon_{xx}^{in} = \varepsilon_{xx}^{out}$

Parameters:
- outside the fault zone: Co^{out}, ϕ^{out} and z
- within the fault zone: ϕ^{in}, ψ and δ

Four possible modes of reactivation including a complete or partial reactivation of the shear zone with or without tensile failure in the surrounding medium.



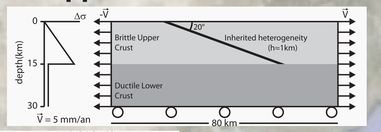
Plastic strain obtained in partial reactivation before locking

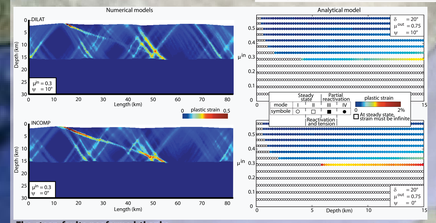


The amount of brittle strain authorised before locking rises with confining pressure while locking is favoured at confining pressure... It is necessary to run 2D models to ensure 1) that the analytical solution applies when faults neoforms in the background 2) to evaluate the cumulative effect kilometric scale displacements overhundreds of thousand years.

4. 2D Numerical Approach

	ρ	η	G	ν	Co	μ	ψ
Heterogeneity	2700		30	0.25	0	var	var
Upper Crust	2700		30	0.25	10	0.6	0
Lower Crust	2700	10^{21}	30	0.25			





Model	μ	ψ (°)	Reactivation
COMP03	0.3	-10	Complete
COMP04	0.4	-10	Partial
DILAT	0.3	10	Partial
INCOMP	0.3	0	Partial

The steep faults neoformed thanks to incompressible flow rule.

The numerical models are in good agreement with the analytical solution with a reactivation favoured at the surface and at depth.

It is possible to observe the neoformation of microstructure within the fault zone in some case.

Those patches where unstable slip is favoured are about 5km long taking a 25 km^2 rupture it would correspond to Mw 2.7 to 4.7 for a slip of 1mm to 10 cm .