Role of in situ stress and fluid compressibility on Slow Slip Events (SSE) & instability triggering (EQ) Derived from a Poro-Plastic Fault Core Model

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Purpose of the research:

- **Propose an original model of fault core behaviour accounting for the coupled effects of:**
  - **in situ stresses**
  - **tectonic displacements**
  - **fault core deformation**
  - **fluid properties**
  - **drained or undrained conditions**
- **Show how, when and why a (long-extended) fault core panel can be stable (SSE) or instable (EQ ?)**

Bases of the considered (Piau's) model[1,2] :

- **Poro-mechanical transient analytical model**

(→ simplifications, but that could be improved latter on, with numerical models)

- **Interface (fault core) between 2 elastic pads (cf. Tanaka et al.)**
- **Poro-plastic interface constitutive law**

  (no viscosity considered as in the Rate & State models [3])
- **Dilatant/contractant behaviour (sometimes considered in R &S models)**
- **(Tectonic) Far-field displacement conditions**
- **Possibility of a link between the fault core and a « pressure reservoir » →undrained or switch to drained conditions**

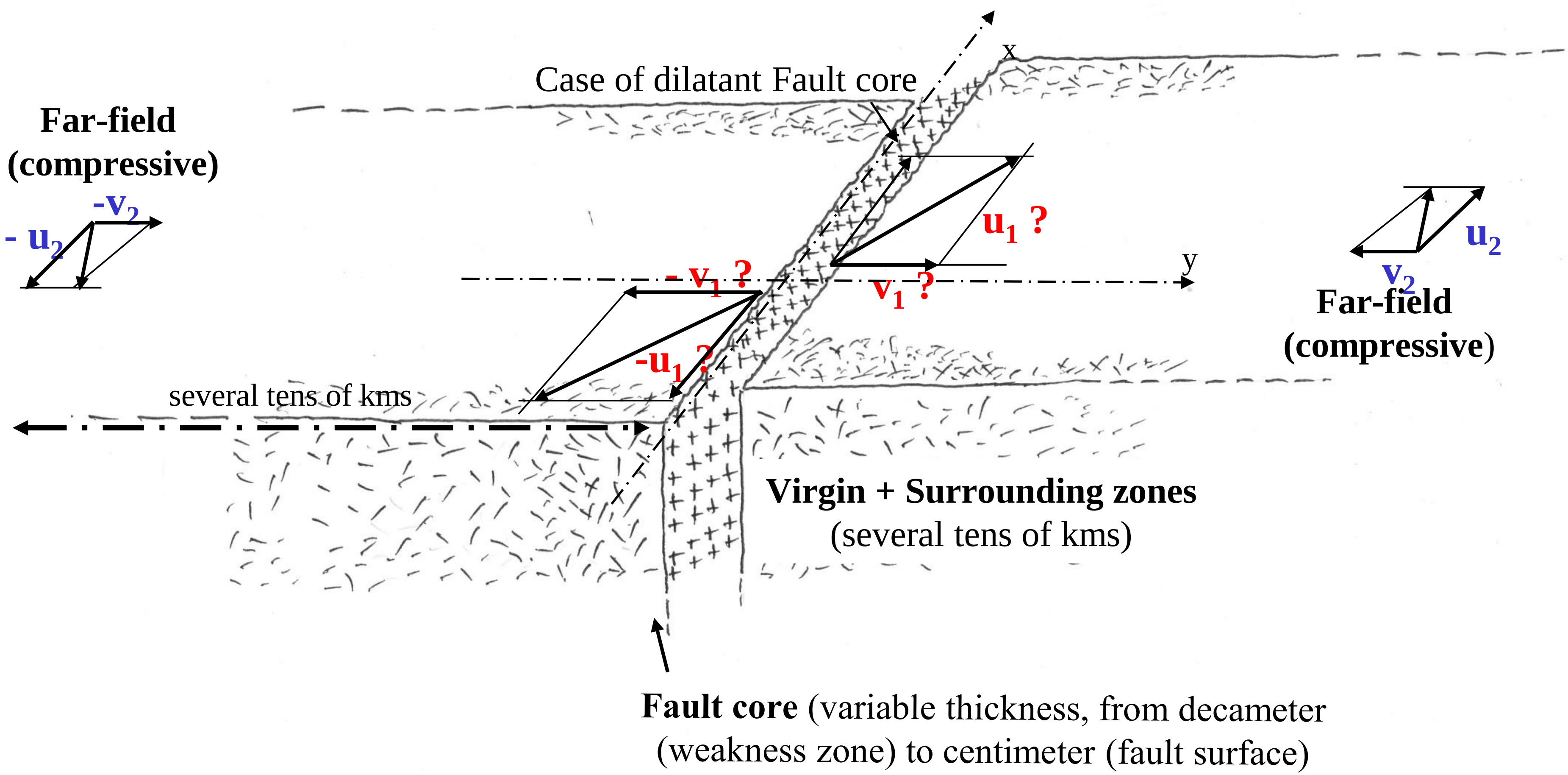
(1) Piau App. 3 in Géli Nature 2016

(2) See also Maury and al, ISRM Intern. Cong. 2011 Beijin, and Erice 2013

(3) Dietrich,1972,1978, Ruina, 1983, Scholtz,1998, Segall and Rice,1995, Dieterich, J., (1972), Segall et al. (2010)

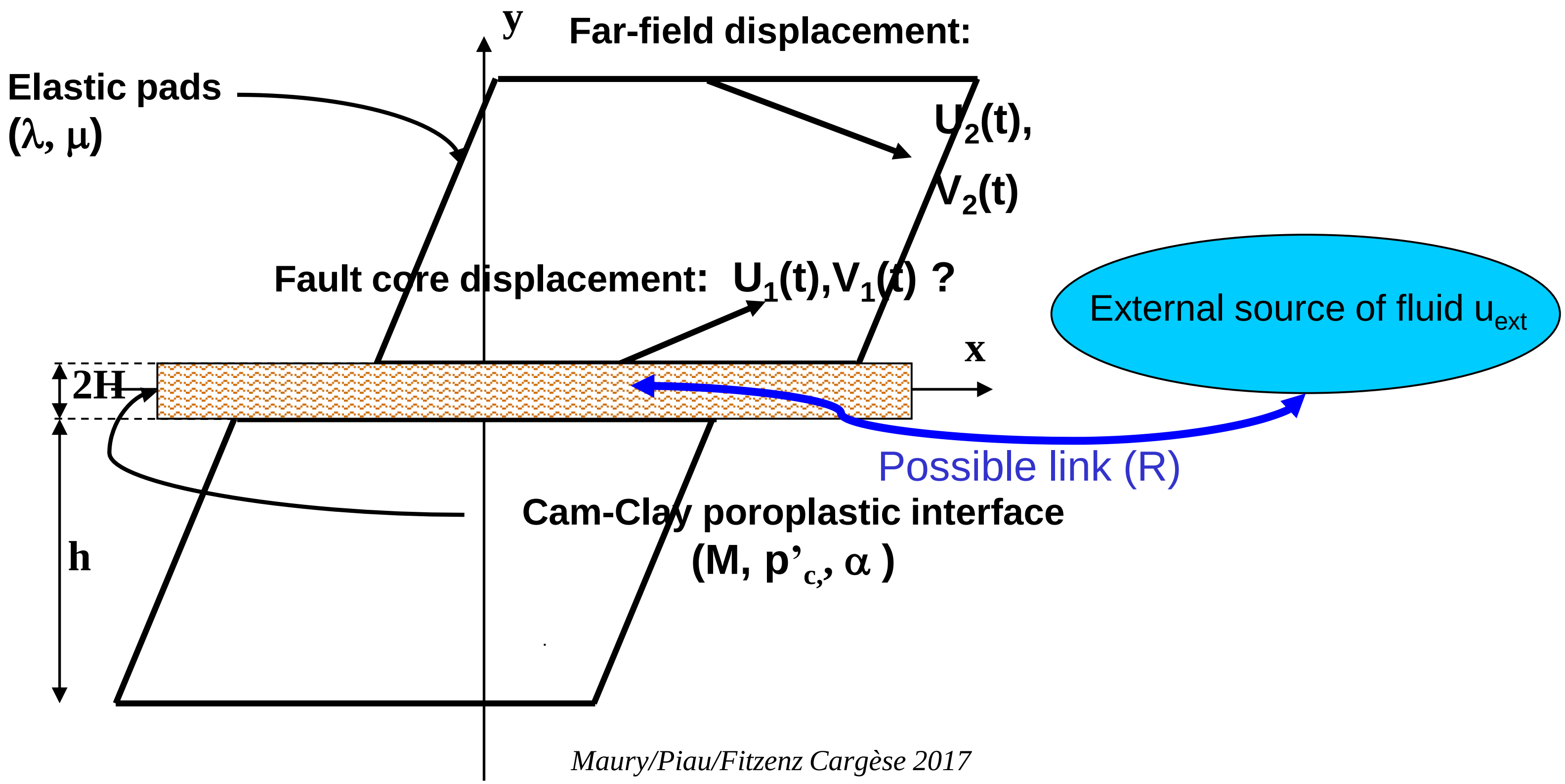
Geological structure of active faults : simplified model

after Tanaka (2001) for the Nojima fault (Japan), used by Fitzenz and Miller (2003, 2004)



Main features of the model

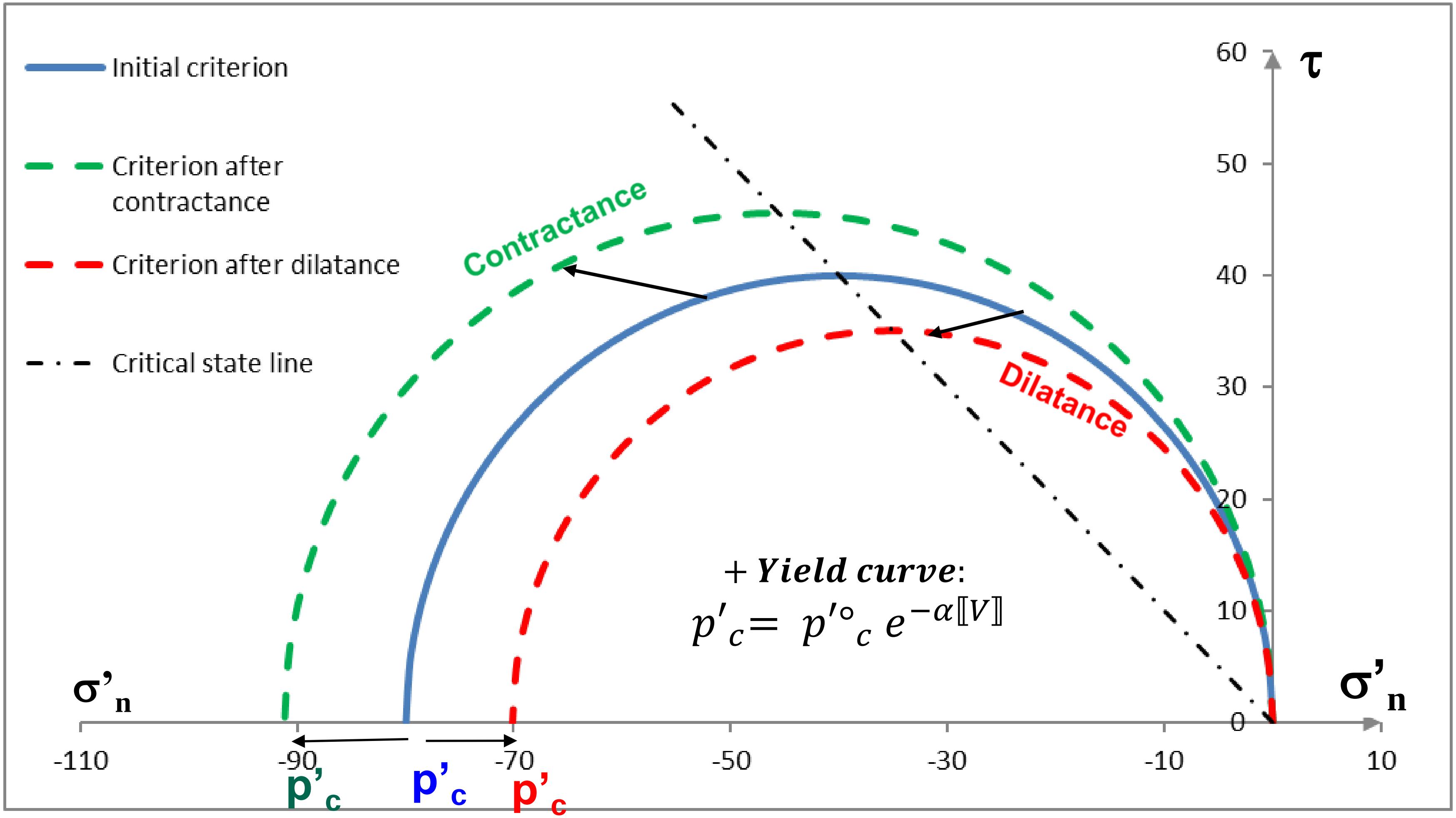
- **Fault core (metric thickness), (analytically modelled as zero thickness interface)**
- **Elastic pads (Km thick) driven by far-field tectonic shear and normal displacements**
- **Drained or undrained behaviour of the fault core with fluid pressure reservoir u_{ext}**
- **Current section of the fault, homogeneous along x (expansion of the fault not addressed here)**



Interface standard poro-plastic law (2D)

with positive & negative yield, deduced from Cam-Clay framework (3D)

(conv.: compressive stresses negative)



+ Yield curve:

$$p'_c = p'^{\circ}_c \, e^{-\alpha [\![V]\!]}$$

Values of parameters for typical case (Depth ~ 4000m)

- **Pad thickness : 10 000m**
  - **E: 40000 MPa, ν: 0.3, ρ: 2500 kg/m3**
  - **Initial horizontal stress : S_{YY0} = - 48 MPa, S_{XY0}= 12 MPa**
- **Fault core « physical thickness » : 20 m**
  - **Initial consolidation pressure : 80 MPa**
  - **Critical state line friction angle: 45°**
  - **Coeff. Consolidation Law (α): 26**
- **Fault core fluid Compressibility (Cfl): $8x10^{-3}$ MPa^{-1}**
  - **Initial pressure: 40 MPa**
- **Farfield displacement rate**
  - **U_2= 10 cm/yr, V_2= - 2 cm/yr (compressive)**
- **External pressure: 50 MPa**

Equation for the plastic multiplier $\dot\kappa$ during slow evolution

Failure criterion: $f(\sigma'_{yy},\sigma_{xy},p'_c)=\sigma'^2_{yy}+\sigma'_{yy}\,p'_c+\frac{3}{M^2}\sigma_{xy}^2$

Standard plastic flow rule: $\dot V_1=\dot\kappa(2\sigma'_{yy}+p'_c)$, $\dot U_1=\dot\kappa\frac{6}{M^2}\sigma_{xy}$

Yield curve : $p'_c=p'^{\,i}_c\,e^{-aV_1}\rightarrow \dot p'_c=-ap'_c\dot V_1=-\dot\kappa\,ap'_c\,(2\sigma'_{yy}+p'_c)$

Fault fluid pressure evolution: $\dot u=R(u_{ext}-u)-S\dot V_1=R(u_{ext}-u)-\dot\kappa S(2\sigma'_{yy}+p'_c)$

Elastic stress evolution in the upper pad (inertia forces being negligible):

- $\dot\sigma'_{yy}=(\lambda+2\mu)\frac{\dot V_2-\dot V_1}{h}+\dot u=(\lambda+2\mu)\frac{\dot V_2}{h}+R(u_{ext}-u)-\dot\kappa(2\sigma'_{yy}+p'_c)\left(\frac{\lambda+2\mu}{h}+S\right)$
- $\dot\sigma_{xy}=\mu\frac{\dot U_2-\dot U_1}{h}=\mu\frac{\dot U_2}{h}-\dot\kappa\,\mu\frac{6}{M^2h}\sigma_{xy}$

❖

In case of plastic evolution, $f(t)=0\rightarrow df/dt=0$:

$$\frac{\partial f}{\partial\sigma'_{yy}}\dot\sigma'_{yy}+\frac{\partial f}{\partial\sigma_{xy}}\dot\sigma_{xy}+\frac{\partial f}{\partial p'_c}\dot p'_c=(2\sigma'_{yy}+p'_c)\dot\sigma'_{yy}+\frac{6}{M^2}\sigma_{xy}\dot\sigma_{xy}+\sigma'_{yy}\,\dot p'_c=0$$

wherefrom: $\dot\kappa=N/D$

with :

$$N=(2\sigma'_{yy}+p'_c)\left(R(u_{ext}-u)+(\lambda+2\mu)\frac{\dot V_2}{h}\right)+\frac{6\mu}{M^2h}\sigma_{xy}\dot U_2$$ (positive value)

$$D=\underbrace{\frac{\lambda+2\mu}{h}(2\sigma'_{yy}+p'_c)^2+\frac{36\mu}{M^4h}\sigma_{xy}^2}_{>0}+\underbrace{(2\sigma'_{yy}+p'_c)^2S}_{\substack{\geq 0\\ \text{Pore pressure stiffening effect}}}+\underbrace{(2\sigma'_{yy}+p'_c)\sigma'_{yy}\,p'_c\,a}_{\substack{\leq 0\ \text{for}\ 2\sigma'_n+p'_c\geq 0\\ \text{Mechanical softening effect}}}$$

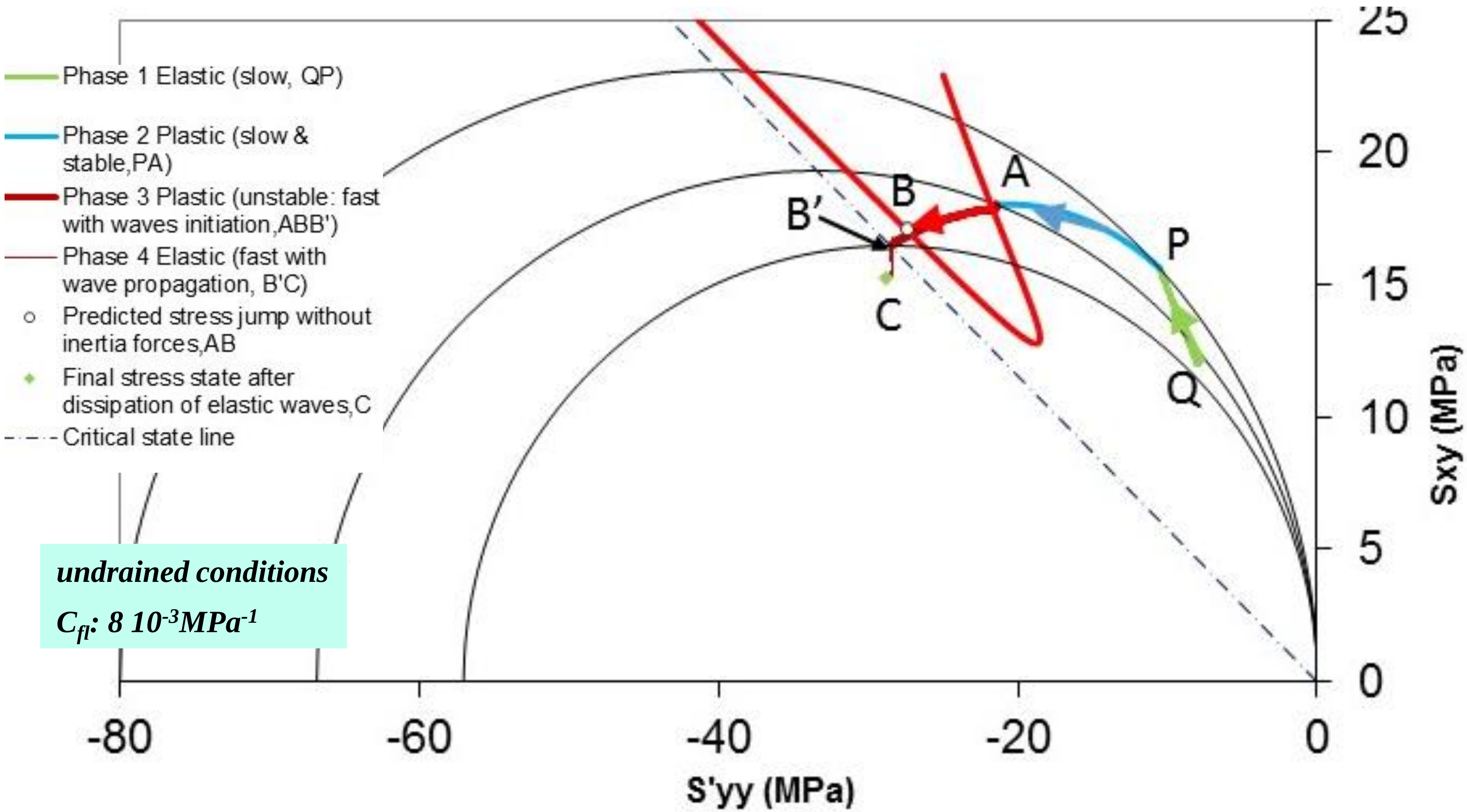
D must be positive or nil

➔ Instability, if D becomes negative

➔ Need to consider inertia forces in the pads to solve the problem

Typical response from the model

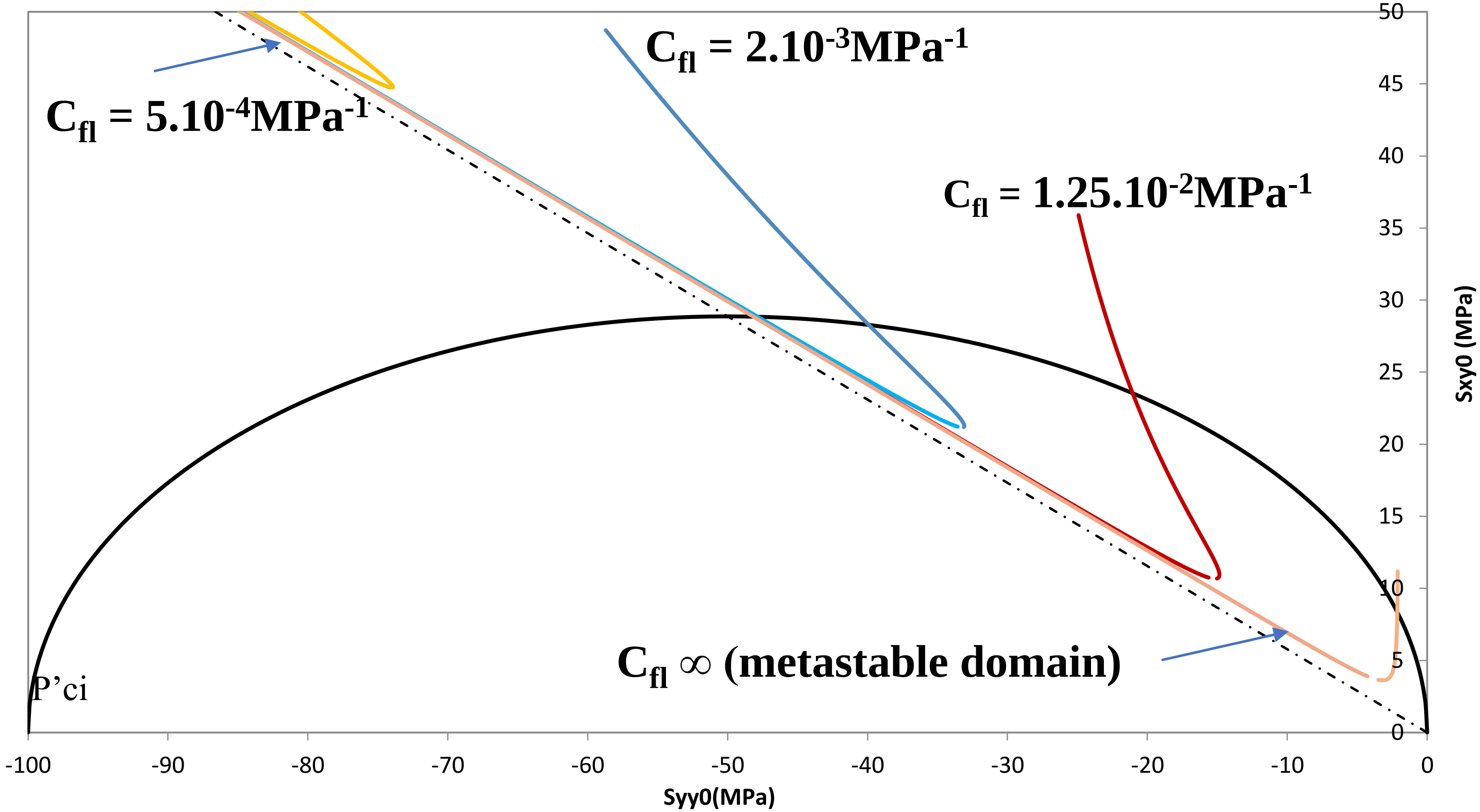
Typical stress path derived from the model with SSE and instability (EQ ?)



Slow Slip Event (SSE) (PA, ~ 10 years, ΔU_1~20 cm, $\mathring{U}_1$ ~ 2cm/yr)

before mainshock (EQ) (ABB' ~ 20 seconds, ΔU_1 ~ 2m)

Zone of instability for various fluid compressibilities C_{fl}



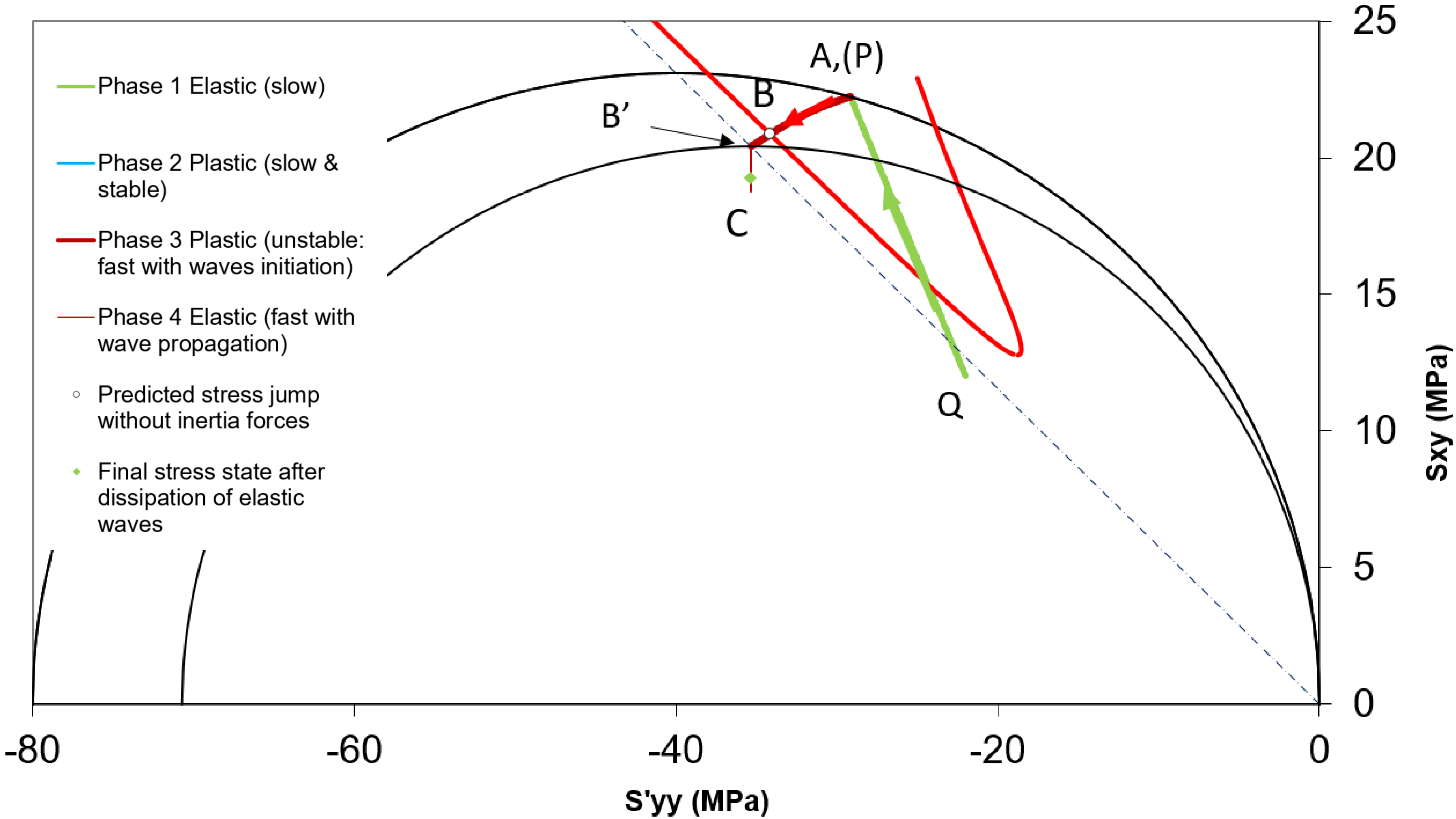
Cfl = 5.10^{-4}MPa^{-1} pure water at ambiant conditions

Cfl ∞ (~ dry condit. ; also metastable domain in drained conditions)

Scenarios

with different initial stress, tectonic loading, fluid compressibility, and drainage conditions

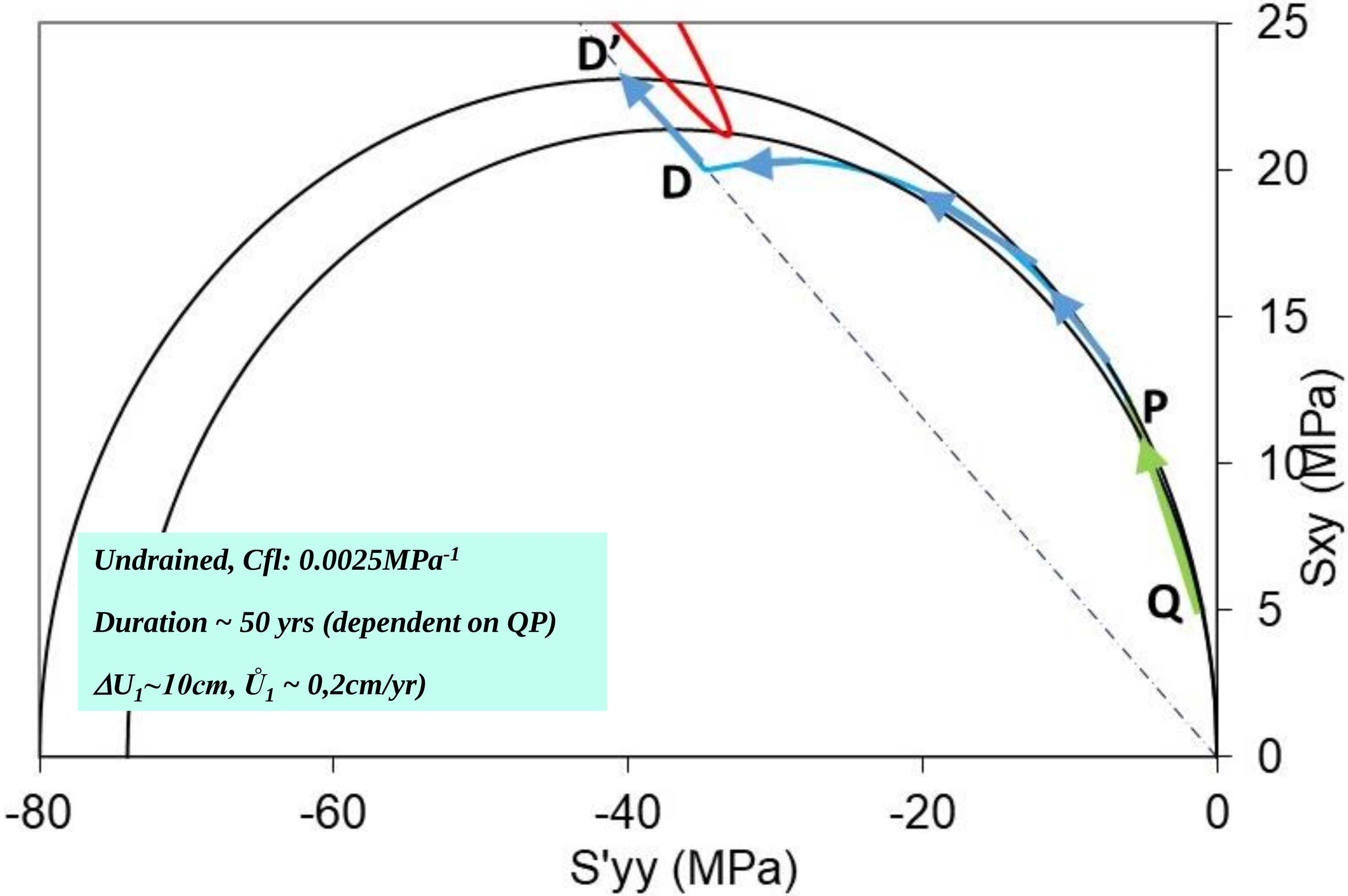
(a) Mainshock without previous slow deformation (SSE)



Elastic phase QA(P), and unstable plastic seismic phase (ABB’C)

(b) Stable SSE (PD 50 yrs) without instability (EQ)

and SSE (DD') along the critical state line (silent EQ ?)

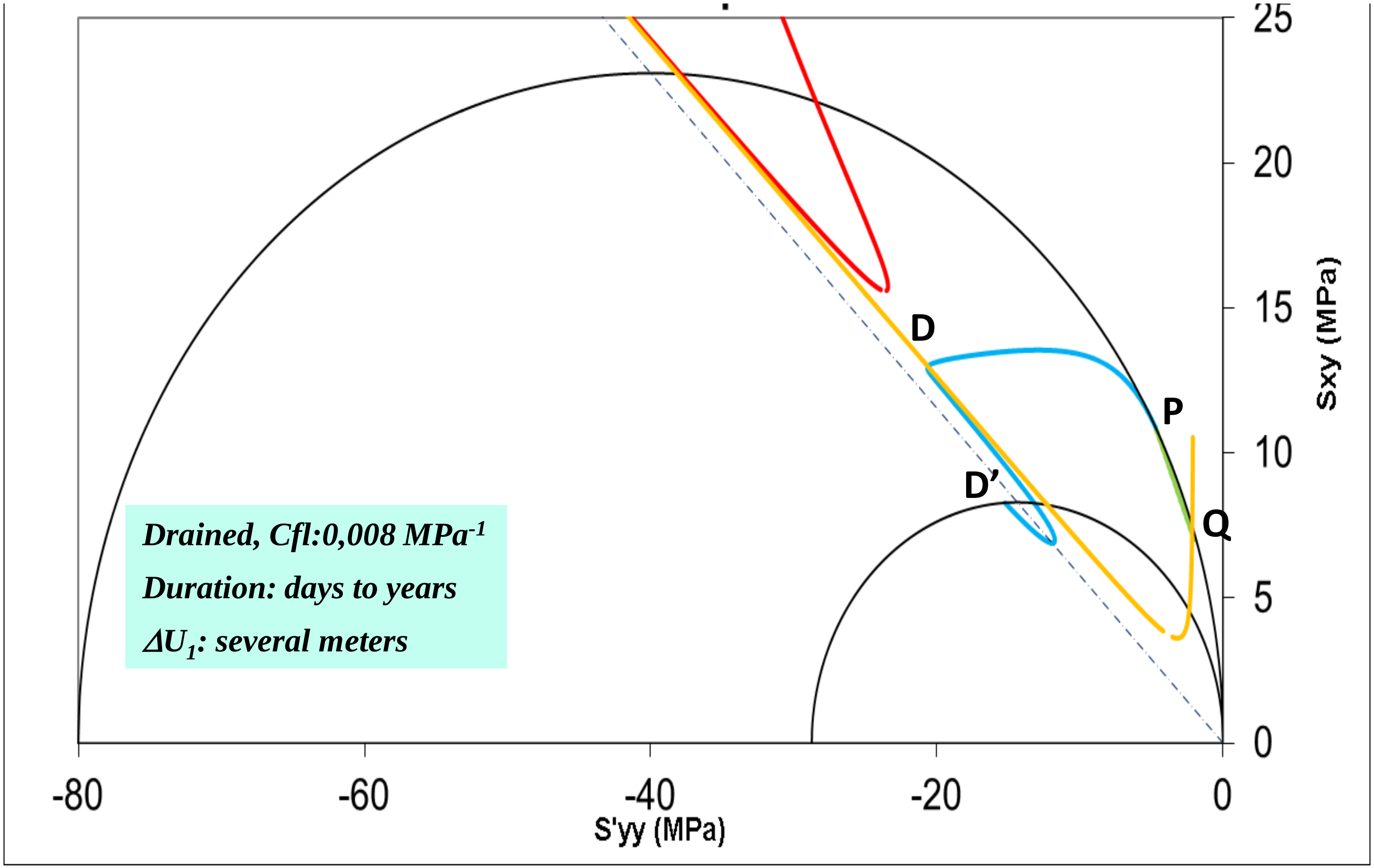


Undrained, Cfl: 0.0025MPa^{-1}

Duration ~ 50 yrs (dependent on QP)

ΔU_1~10cm, $\mathring{U}_1$ ~ 0,2cm/yr)

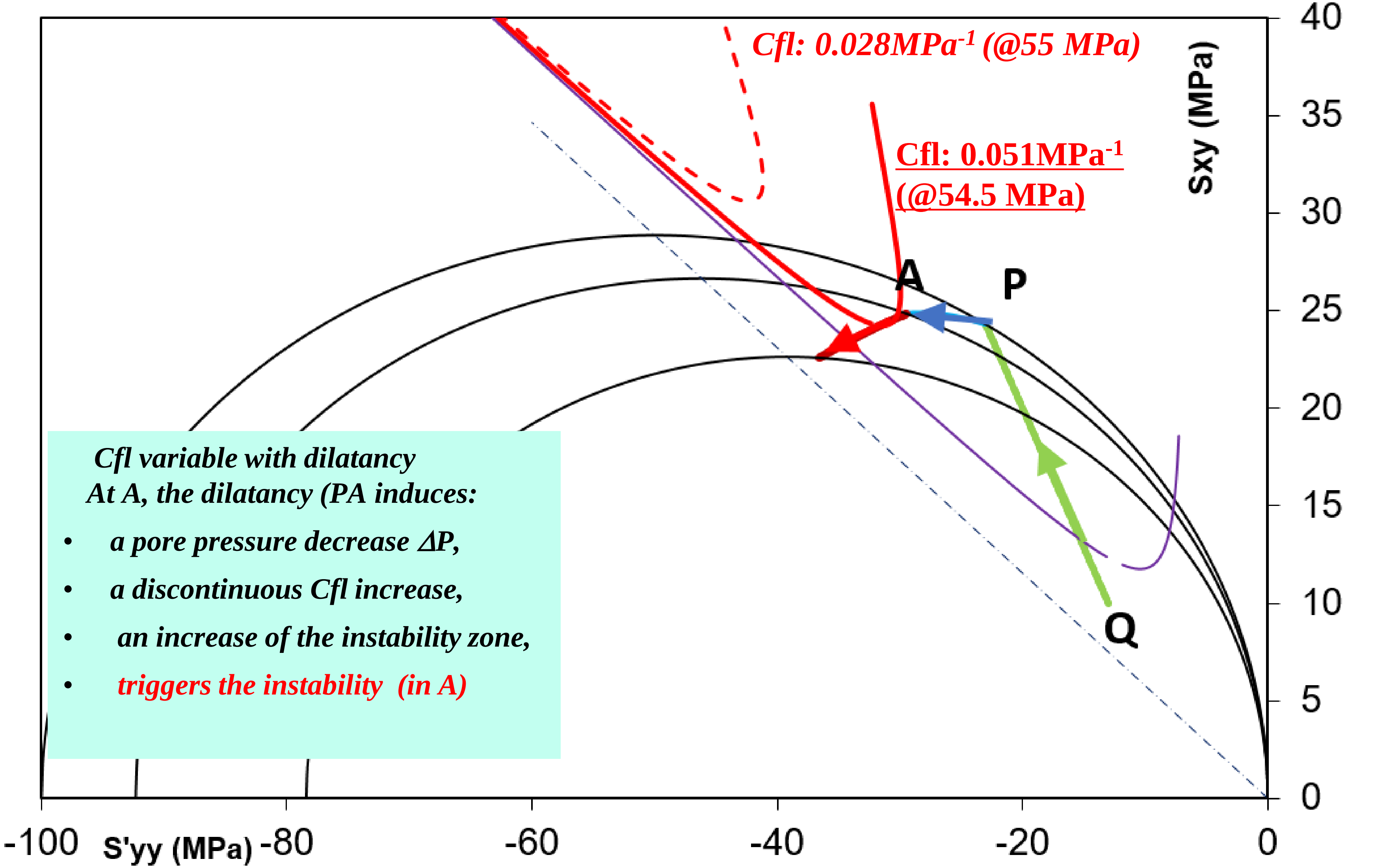
(c) Metastable plastic phase PD (SSE), and stable phase DD' (silent EQ ?) without mainshock



Beyond D', behaviour joining the critical state line

(d) Dilatancy inducing pore pressure decrease, phase change, and Cfl increase, resulting in an increase of the instable area & instability

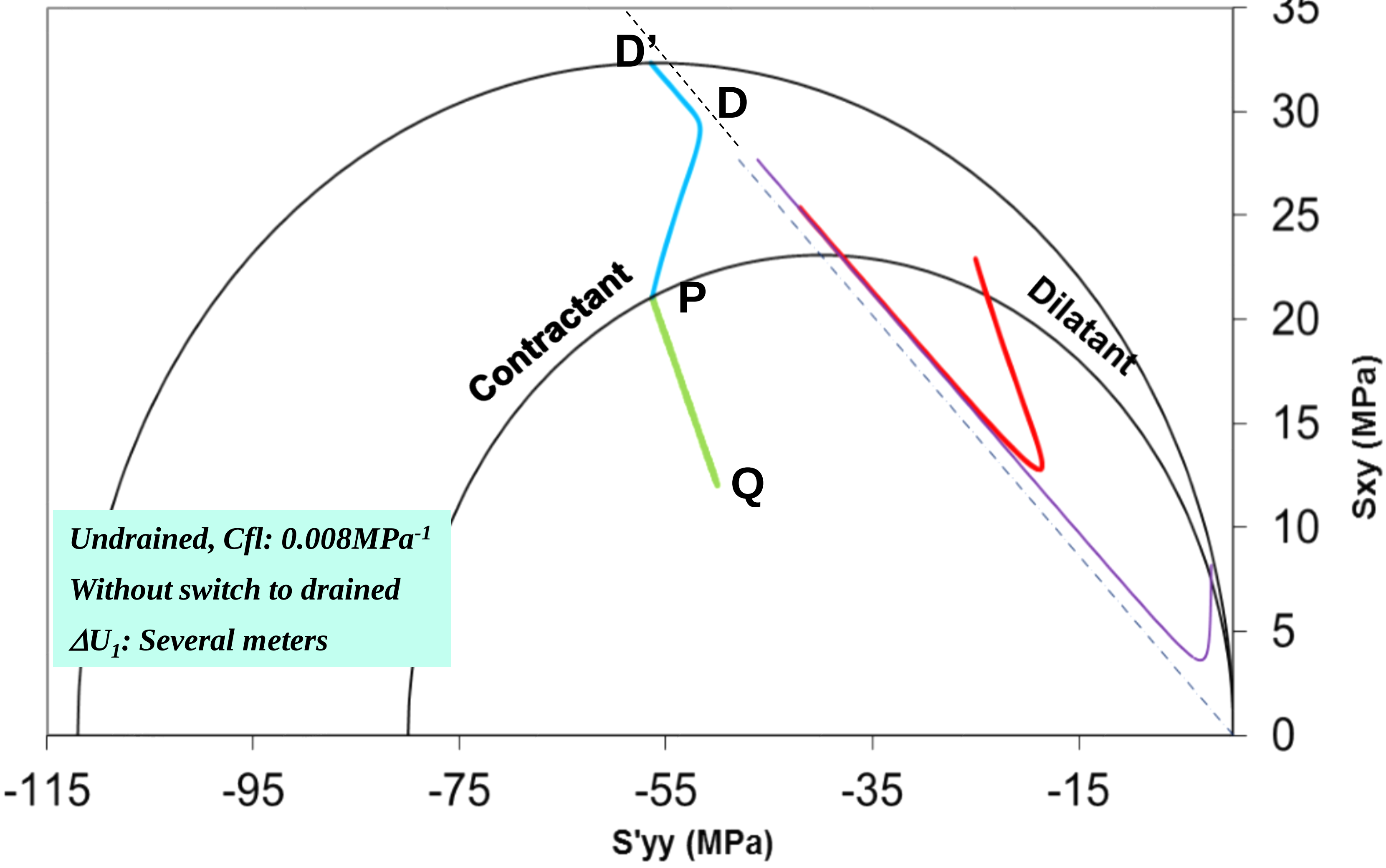
(Oceanic faults Géli et al., Nature 2016)



(e) Stress path QP leading to the contractant sector of the FC failure criterion:

No instability, stable plastic phase PD (SSE),

before reaching the Critical state line DD' **(geochemical processes not addressed)**



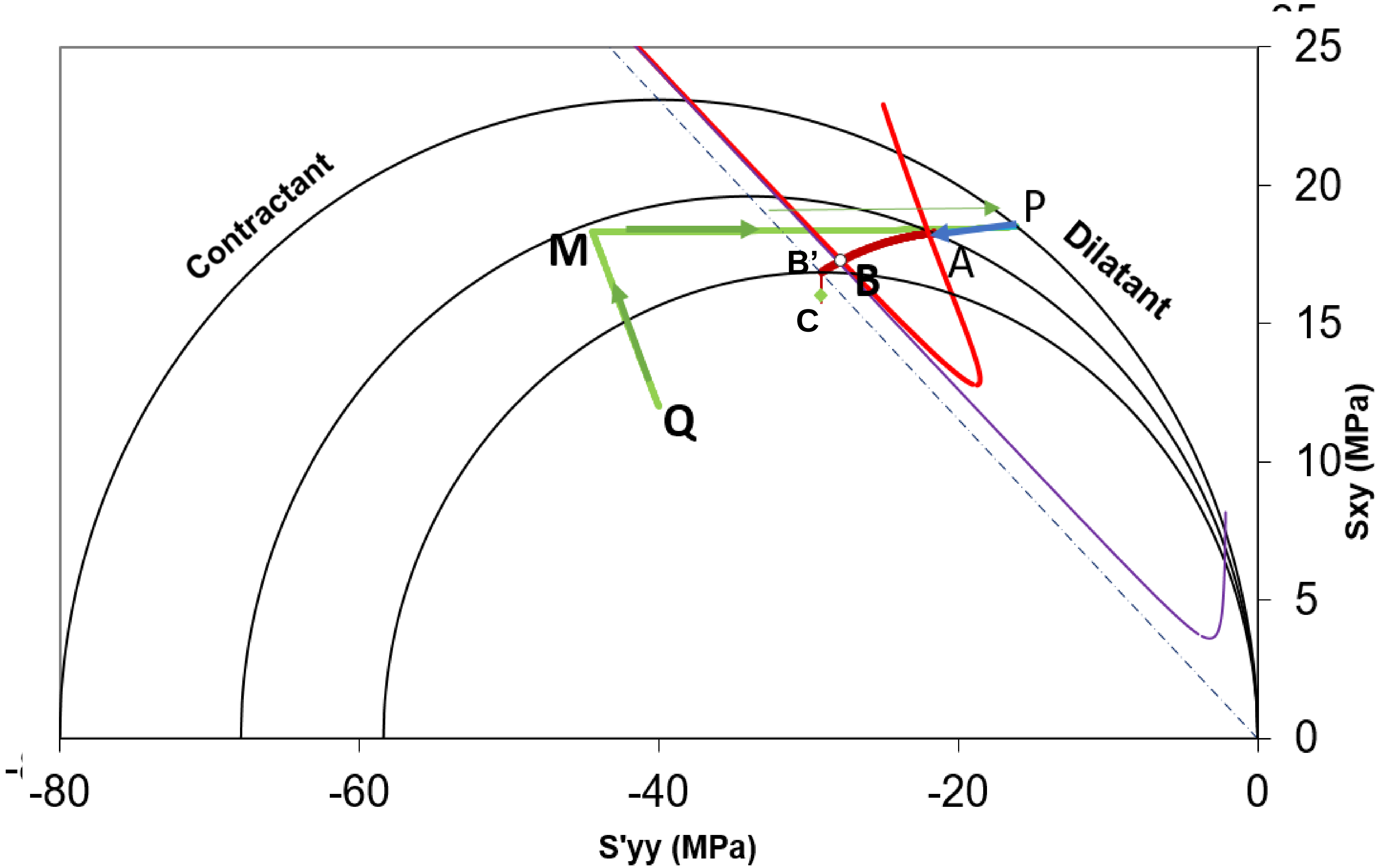
Undrained, Cfl: 0.008MPa^{-1}

Without switch to drained

ΔU_1: Several meters

(f) Same as (e) but with sudden switch to drained regime MP

Evolution (typical case): stable deformation PA (SSE), instability (AB,B',C,)



Conclusions (from the model)

- **Coupling between elastic pads and plastic interface, with the possibility of negative yield (rock crushing) makes appear**

  a zone of instable states of stresses in the Fault Core (σ',τ) plane

  (no need for rate dependent behaviour)

- **In case of undrained condition :**
  - **low Cfl (liquids, < 5 10^{-4}MPa^{-1}) → small zone of instability**

    → lesser risks of unstable evolution
  - **great Cfl (gas, phase change , > 10^{-3} MPa^{-1}) →**

  large zone of instability → higher risks of unstable evolution

Conclusions (Ctd)

- **For stress paths reaching the Fault Core failure criterion on the dilatant side:**
  - **Outside the unstable sector (on the failure criterion), the model shows:**
    - **for very low Cfl, a stable plastic deformation (SSE) without instability**
    - **for average Cfl, a stable plastic deformation followed by instability (EQ?)**
  - **Inside the unstable sector, *a sudden instability without precursory (SSE)***

Conclusions (Ctd)

- For states of stress on the contractant side of the failure criterion:
  - In undrained condition, a progressive stable plastic deformation (SSE) without risk of instability
  - In drained condition & link with an external source of over-pressure
    - sudden return to the dilatant part of the FC criterion
    - possibility of instability

Perspective - Practical aspects (as regards strike-slip outcropping for instance)

The model provides a framework for (and can be fed by):

- **geodetic data, providing farfield displacements values ($U_2(t)$, $V_2(t)$)**

  (and nearfield ($U_1(t)$, $V_1(t)$)) for model calibration)
- **geophysical data, providing geological fault core structure**
- **in situ stress measurements, giving the present state of stress**

  (at least order of magnitude)
- **in situ deformation (contractant, dilatant regime) of the fault core**
- **hydrogeological data, showing drained or undrained conditions**
- **geochemical data giving possible variation of the chemical content of fluids**

  (also indicating a switch from undrained to drained regime)
- **thermodynamical properties of fluids (possibility of fluid compressibility variation**

  due to depletion induced by dilatancy, case of some Oceanic faults L. Géli Nature)

Thank you for your attention

on behalf of the authors

Perspective - Modelling aspects

- **Bibliography shows that an important modelling work has been done, based upon the State & Rate constitutive law, with:**
  - **semi-analytical, FE,BE computation techniques,…**
  - **more realistic conditions than those considered here *(heterogenities, fault to fault interactions, …)***

- **Suggestion: revisit these models, by implementing and using the present poro-plastic interface constitutive law – Does it lead to a new vision of phenomena ?**
- **In particular, examine with the present interface constitutive law the « nucleation/propagation » aspects of EQ in heterogeneous context**
- **…**

Annexes (for discussion)

Interseismic (aseismic) period

- **For sake of simplicity, the model does not address the (possible) poroelastic behaviour of the fault core during this period) (part QP of the stress paths shown on various scenarii).**

- **Nevertheless, the role of fluids during this period must not be overlooked[1]:**

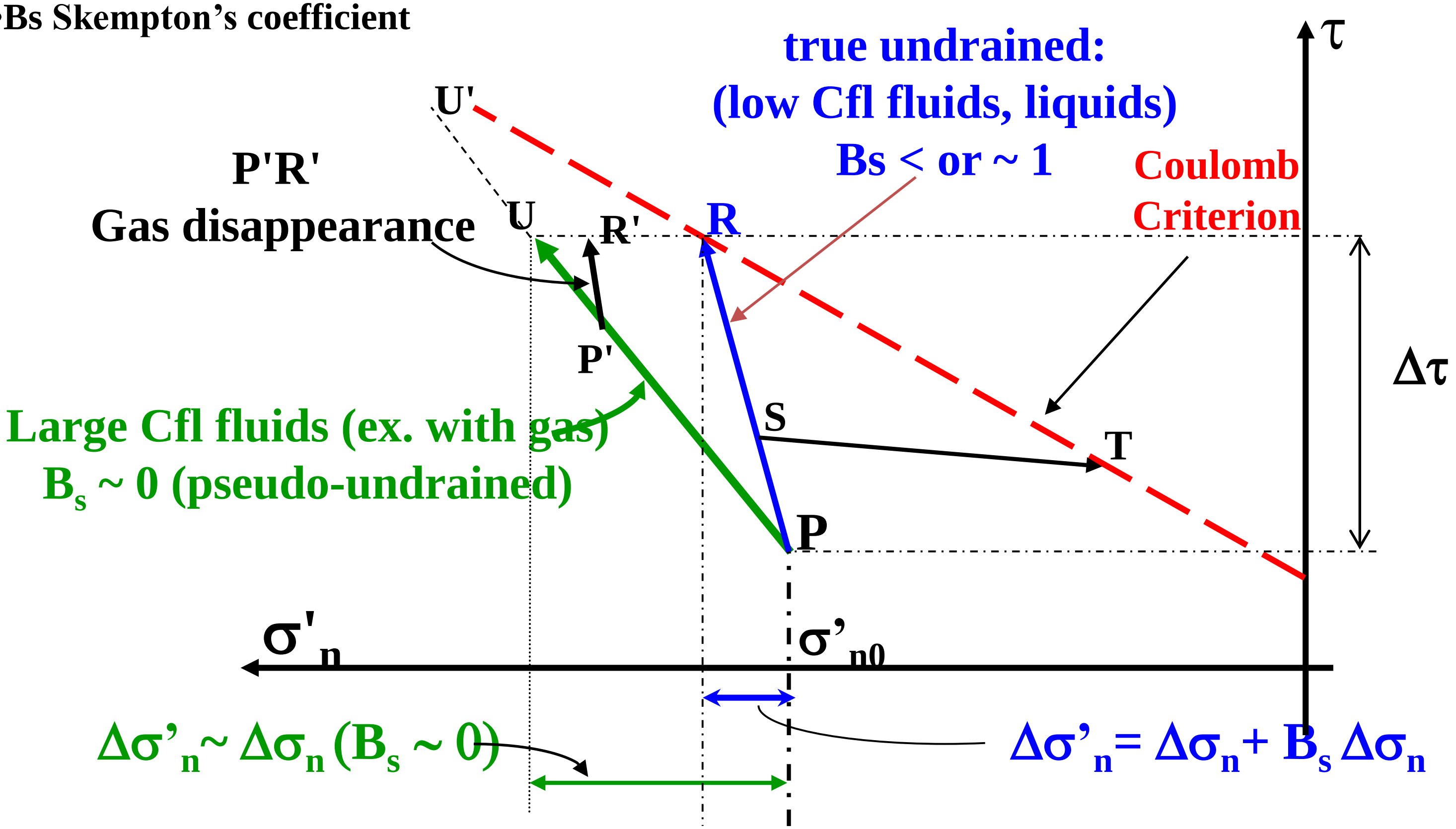
  if fluid compressibility increases (e.g. gas appearance), the same total stress increase (tectonic) induces a greater effective stress increase (Skempton's coefficient Bs tends to 0, see diapo herebelow)

- **This hypothesis was selected for evaluation of the stress path in the scenarii of stress leading to stability an/or instability**
- **(1) (see Diapos annexe, and Maury and al, ISRM Congress Beijin 2011 and Erice 2013)**

Preliminary: Stress paths on active faults, interseismic periods

(Comp. stress < 0, Cfl fluid compressibility))

- **PR: *(slow)* tectonic loading, low Cfl fluids (liquids without gas),**
- **PU (large Cfl fluids, with gas)**
- **P'R': gas disappearance**
- **ST: rapid linkage with external fluid overpressure**
- **Bs Skempton's coefficient**



Comments:

- **The model draws conclusions about in situ stress and fluid conditions leading to stability/instability) of a long-extended fault core panel,**

  (assumed homogeneous, and infinite in the x direction of the model)

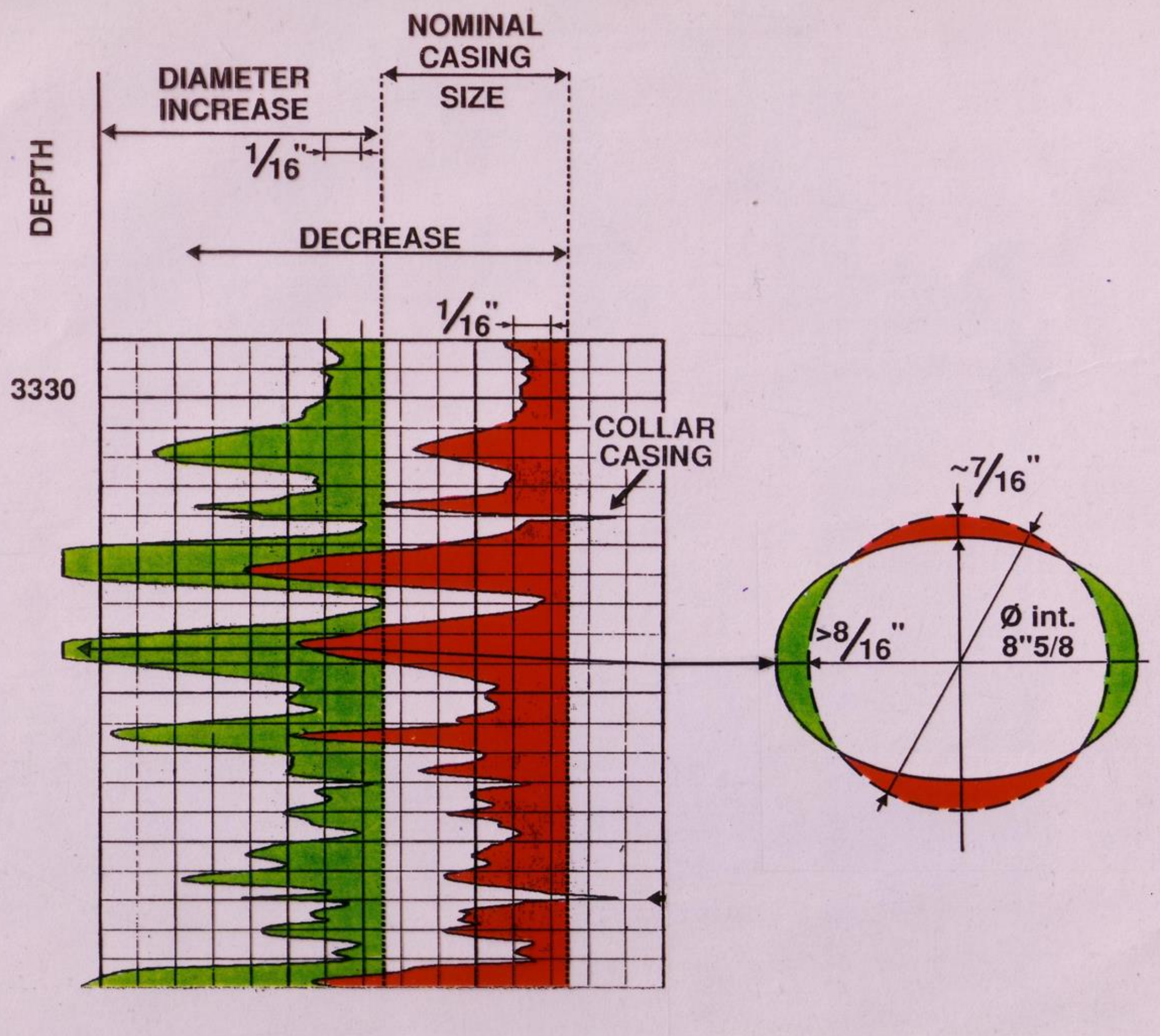
- **The model leads to a possibility of quasi-simultaneous instabilities occurring on large panels, relaying each ones, and resulting in very great extent of final global instability linked to heterogeneity in x direction of the fault core,**

  compared to more classical model of nucleation and instability propagation (see Bouchon et al. 2014), deduced from fracture dynamics theory, and linked to elastic properties of surrounding rocks

Observation of deformed casing by successive shear in a kink-band

Over 300m thickness caused by channeling of high pressure fluids

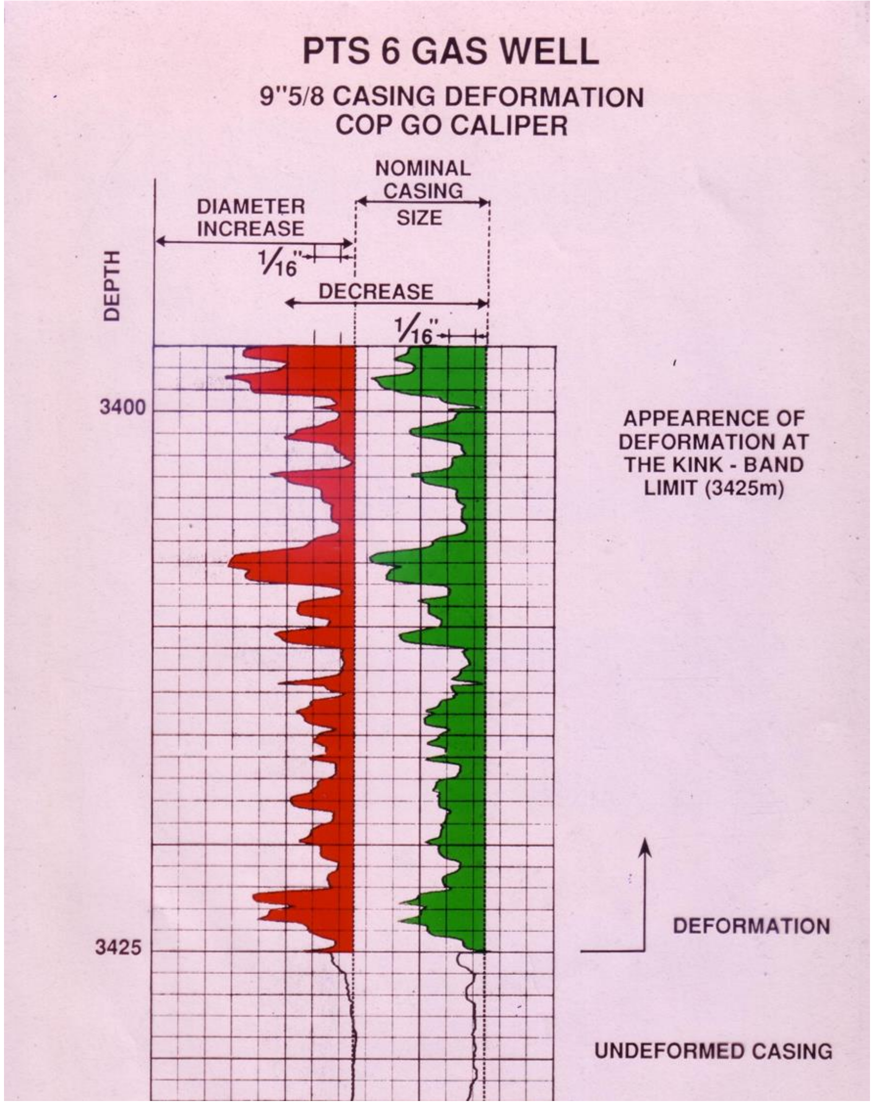
(Aquitaine, France) Maury V. and Zurdo C. SPE Drilling and Completion March 1996



PTS 6 GAS WELL - 9"5/8 CASING DEFORMATION
MULTIFINGER CALIPER

Observation of deformed casing by successive shear in a kink-band

Over 300m thickness (Aquitaine, France)



The shear deformation stops out of the kink-band

Main shock & (pseudo-) aftershocks by repressurization