Multiphysics couplings and instabilities II

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Engineering

More is less

Part I: Multiphysics and Plasticity

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Multiphysics - A new name to an old concept: physics

Momentum balance: $$\frac{\P s_{ij}}{\P x_j} = r \frac{\P v_i}{\P t}$$

Mass balance (species?): $$\frac{\P r^{(a)}}{\P t} + \frac{\P r^{(a)} v_k^{(a)}}{\P x_k} = j_a$$

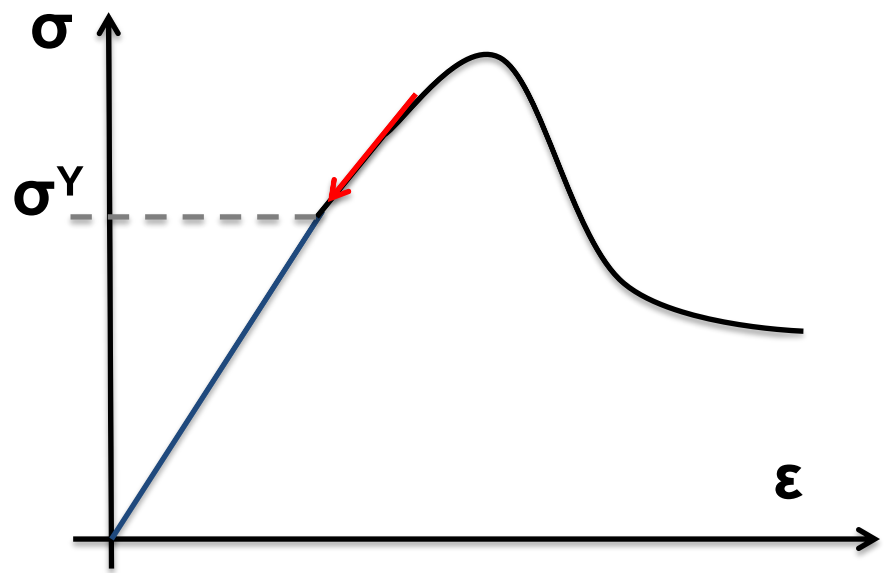
Energy balance: $$r C \frac{\partial T}{\partial t} + v_k^{(m)} \frac{\partial T}{\partial x_k} = k \frac{\partial^2 T}{\partial x_k^2} + \mathrm{F} + \mathrm{D} h_w \, r_w$$

2nd Law ThDyn: $$\Phi = \left(\sigma_{ij} - \sigma_{ij}^{Y}\right) \dot{\varepsilon}_{ij}^{p} - \Upsilon_a \dot{\xi}_a = \chi \bar{\sigma}_{ij} \dot{\varepsilon}_{ij}^{p} \geq 0$$

Plasticity Theory: Consistency vs Overstress

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{i}$$

$$\dot{\varepsilon}_{ij}^{i} = f\left(\frac{\sigma_{ij}}{\sigma_{ref}}\right)$$

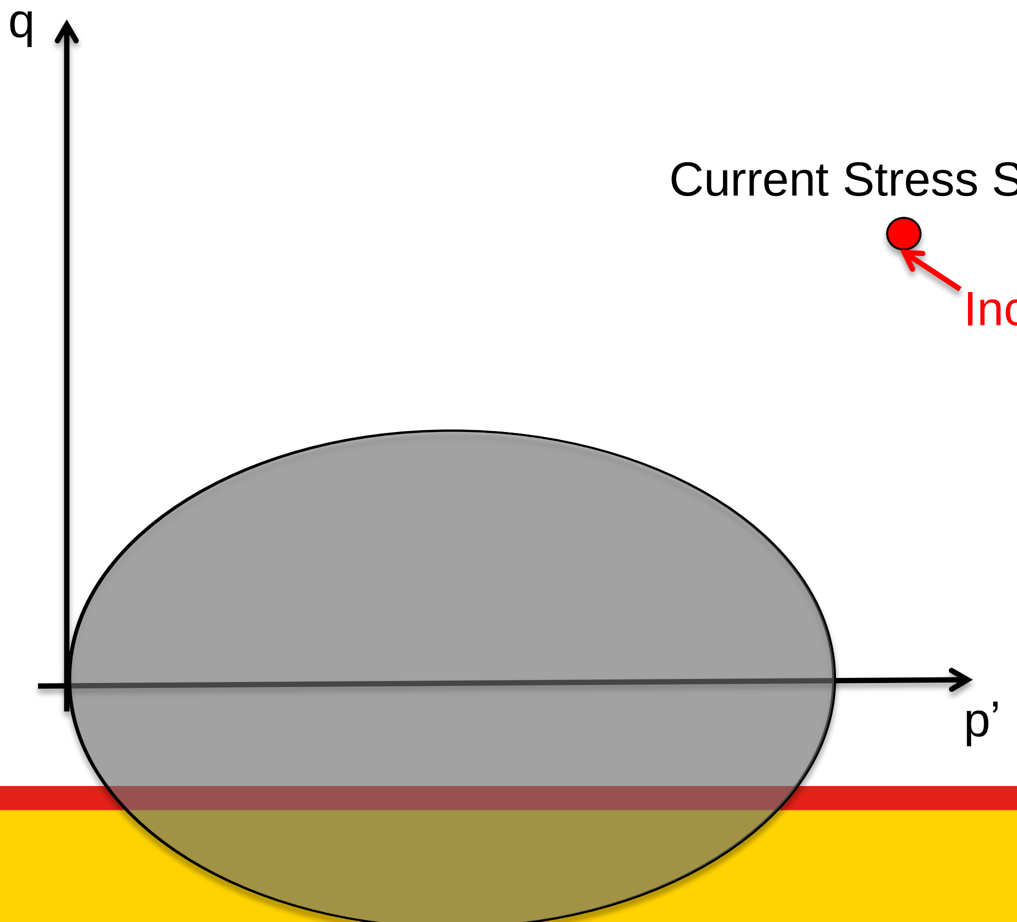


Even if the function f is not known, if it is sufficiently smooth we can expand it around the right limit of the yield surface in a Taylor series:

$$\dot{\varepsilon}_{ij}^{i} = f\left(\frac{\sigma_{ij}^{Y}}{\sigma_{ref}}\right) + \frac{\partial f}{\partial \sigma_{ij}^{Y}}\left\langle \frac{\sigma_{ij} - \sigma_{ij}^{Y}}{\sigma_{ref}} \right\rangle + \sum_{m\geq 2} \frac{\partial^{(m)} f}{\partial \sigma_{ij}^{Y,m}}\left\langle \frac{\sigma_{ij} - \sigma_{ij}^{Y}}{\sigma_{ref}} \right\rangle^{m}$$

Consistency Plasticity

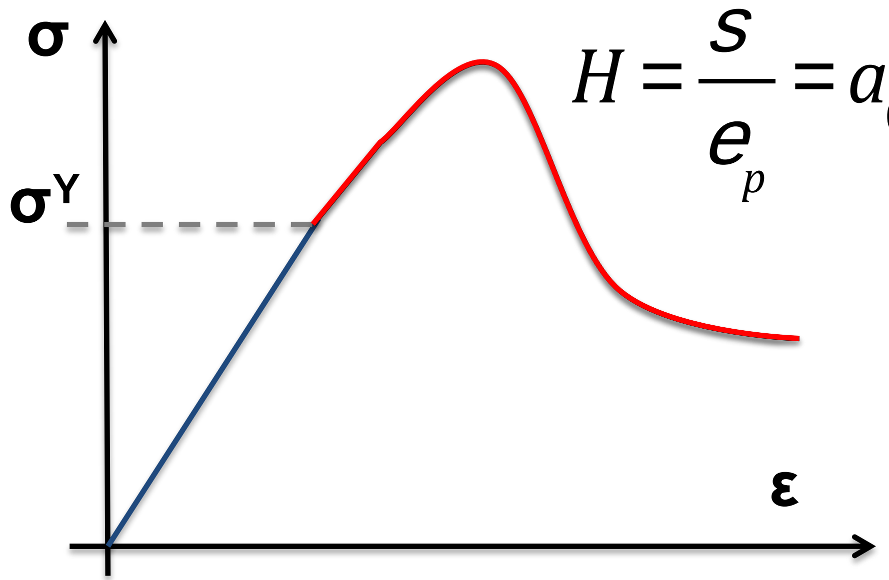
$$\dot{\varepsilon}_{ij}^{i} = \frac{\partial f}{\partial \sigma_{ij}^{Y}} \left\langle \frac{\sigma_{ij} - \sigma_{ij}^{Y}}{\sigma_{ref}} \right\rangle + \sum_{m \geq 2} \frac{\partial^{(m)} f}{\partial \sigma_{ij}^{Y,m}} \left\langle \frac{\sigma_{ij} - \sigma_{ij}^{Y}}{\sigma_{ref}} \right\rangle^{m}$$



$$\dot{\varepsilon}_{ij}^{i} = C_{ijkl}^{p} \dot{\sigma}_{kl}$$

Lack of predictive power - no need in engineering design

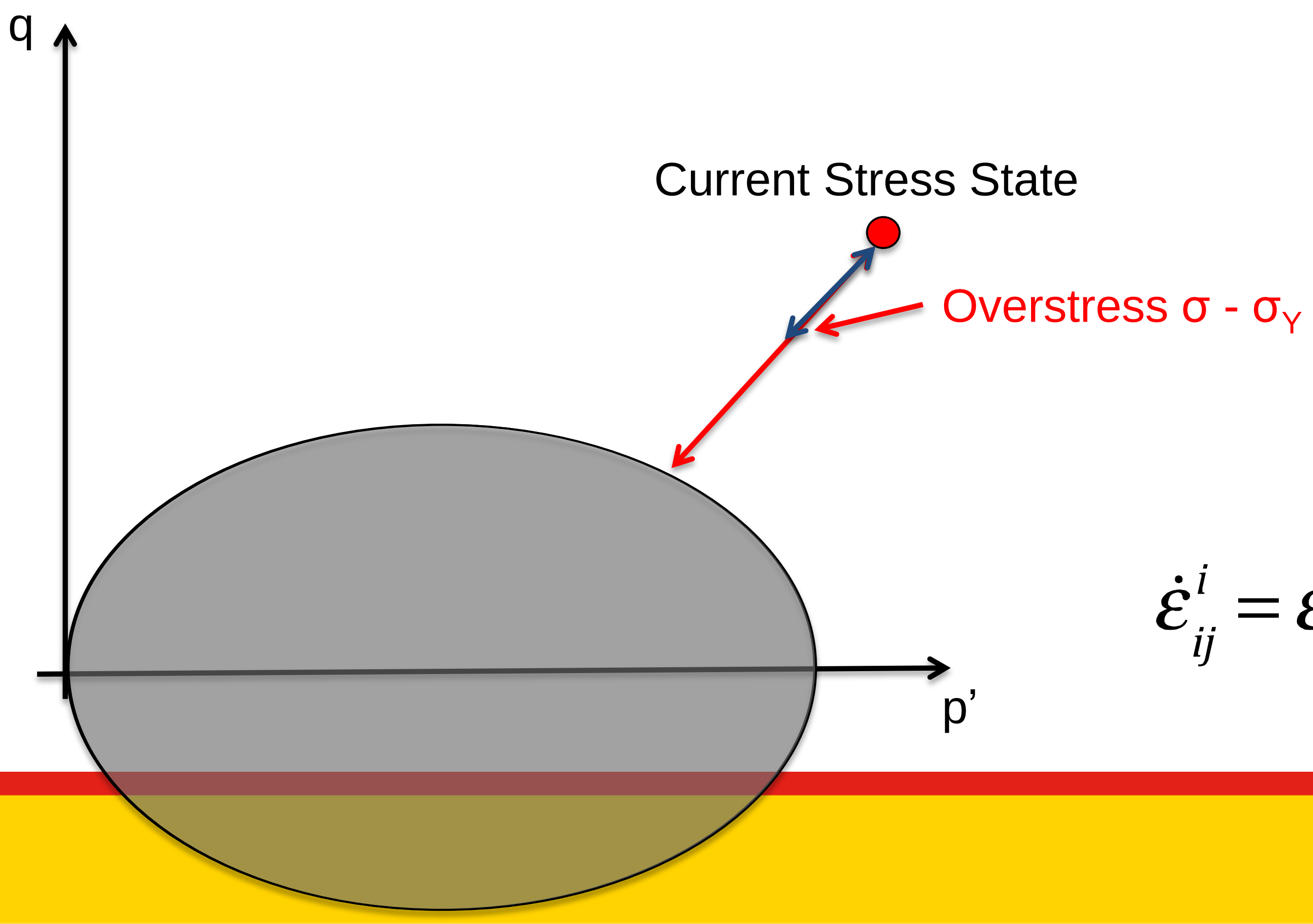
$$\dot{\varepsilon}_{ij}^{i} = C_{ijkl}^{p} \dot{\sigma}_{kl}$$



$$H = \frac{s}{e_p} = a_0 + a_1 e_p + a_2 e_p^2 + \ldots$$

Overstress Plasticity

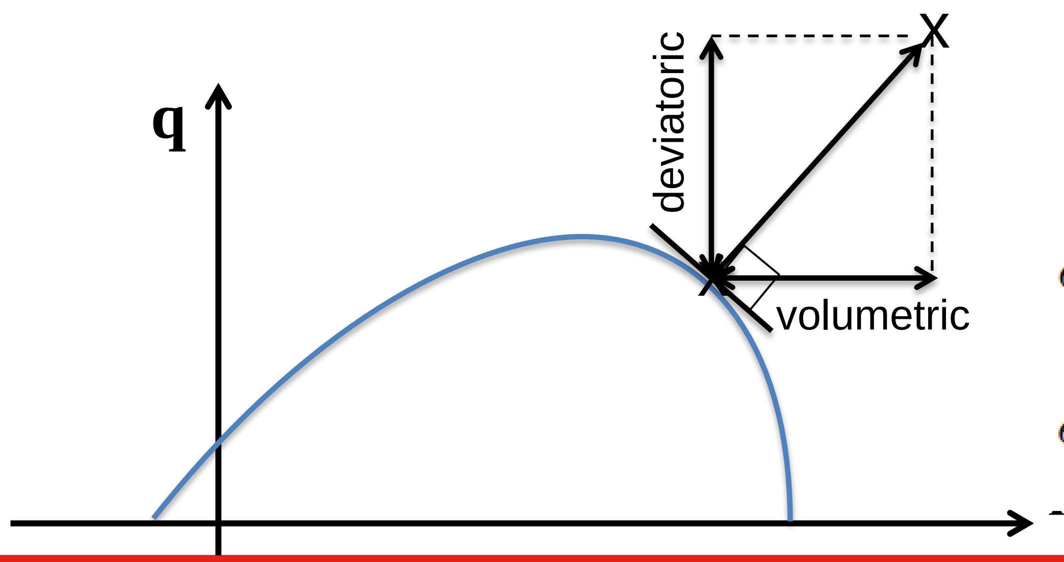
$$\dot{\varepsilon}_{ij}^{i} = \frac{\partial f}{\partial \sigma_{ij}^{Y}} \left\langle \frac{\sigma_{ij} - \sigma_{ij}^{Y}}{\sigma_{ref}} \right\rangle + \sum_{m \geq 2} \frac{\partial^{(m)} f}{\partial \sigma_{ij}^{Y,m}} \left\langle \frac{\sigma_{ij} - \sigma_{ij}^{Y}}{\sigma_{ref}} \right\rangle^{m}$$



$$\dot{\varepsilon}_{ij}^{i} = \dot{\varepsilon}_{0} \left\langle \frac{\sigma_{ij} - \sigma_{ij}^{Y}}{\sigma_{ref}} \right\rangle^{m}$$

Equations overstress plasticity: Towards a unified THMC approach

- Fluid-saturated rock
- Coaxial Elasto-visco-plasticity, deviatoric and volumetric components

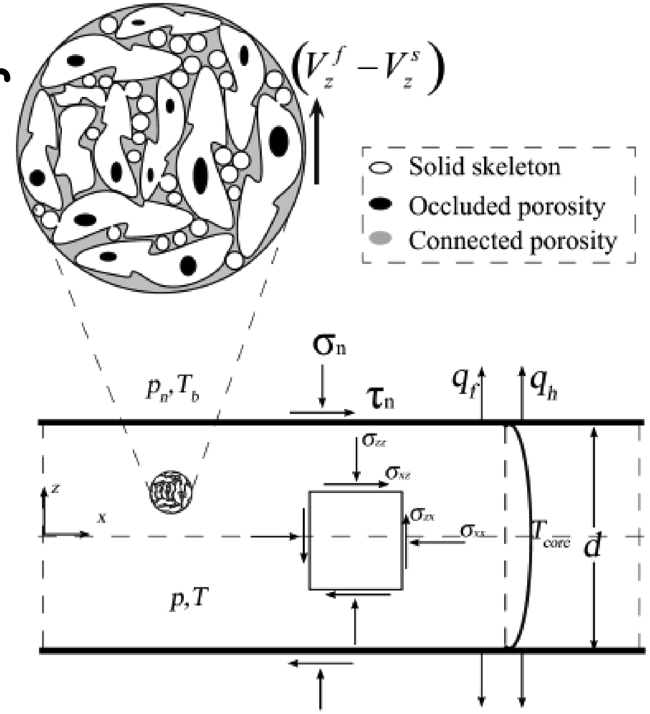


$$\dot{\epsilon}^i_{ij} = \dot{\lambda}\frac{\partial f}{\partial \sigma'_{ij}} \quad \dot{\lambda} = \sqrt{\dot{\epsilon}^{i\,2}_d + \dot{\epsilon}^{i\,2}_v}$$

$$\dot{\epsilon}^i_d = \dot{\epsilon}_0 \left\langle \frac{q - q_Y}{\sigma_{ref}} \right\rangle^m \exp\left(-\frac{Q^d_{mech}}{RT}\right)$$

$$\dot{\epsilon}^i_v = \dot{\epsilon}_0 \left\langle \frac{p' - p_Y}{\sigma_{ref}} \right\rangle^m \exp\left(-\frac{Q^V_{mech}}{RT}\right)$$

Towards a unified THMC appr



- Fluid-saturated rock
- Coaxial Elasto-visco-plasticity, deviatoric and volumetric components
- Mechanical (Shear) heating
- Endothermic fluid release reaction producing excess pore pressure

$$AB_{(solid)} \underset{r_R}{\overset{r_F}{\rightleftharpoons}} A_{(solid)} + B_{(\text{fluid})}$$

- Porosity and permeability linked with Kozeny-Carman law

$$k_\pi = k_{\pi 0} \frac{(1-\phi_0)^2}{\phi_0^3} \frac{\phi^3}{(1-\phi)^2}$$

$$f = f_0 + Df_{mech} + Df_{chem}$$

$$\Delta\phi_{\text{chem}} = A_\phi \frac{1-\phi_0}{1 + \frac{\rho_B}{\rho_A}\frac{M_A}{M_B}\frac{1}{s}},$$

$$s = \frac{\omega_{\text{rel}}}{1+\omega_{\text{rel}}}, \quad \text{and}$$

$$\omega_{rel} = \frac{\rho_{AB}}{\rho_A}\frac{M_A}{M_{AB}} K_c \exp\left(\frac{\Delta H}{RT}\right)$$

System of equations- Redback kernels

$$AB_{(solid)} \underset{r_R}{\overset{r_F}{\rightleftharpoons}} A_{(solid)} + B_{(\text{fluid})} \qquad r_{F,R} = k_{F,R}\, r_i\, e^{-\frac{Ar}{1+q}}$$

TimeDerivative | Redback MassConvection | Redback MassDiffusion | Redback ThermalPressurization | Redback Poromechanics | Redback ChemPressure

$$\frac{\partial P}{\partial t} + Pe_{mass}\, v.\nabla P - Pe_{temp}\, v.\nabla \theta - \nabla\left[\frac{1}{Le}\nabla P\right] - \bar{\Lambda}\frac{\partial \theta}{\partial t} + \frac{\dot{\varepsilon}_v^{pl}}{\beta^*} - \mu.r_F = 0$$

$$\frac{\partial \theta}{\partial t} + Pe_{thermal}\, v.\nabla \theta - \nabla^2\theta - \mathrm{X}.\tau.\dot{\varepsilon}_d^p - \mathrm{X}.\sigma.\dot{\varepsilon}_v^p + \left|\Delta H\right|.\mathrm{r}_F - \left|\Delta H\right|.r_R = 0$$

TimeDerivative | Redback ThermalConvection | Diffusion | Redback MechDissip | Redback ChemEndo | Redback ChemExo

Stress equilibrium

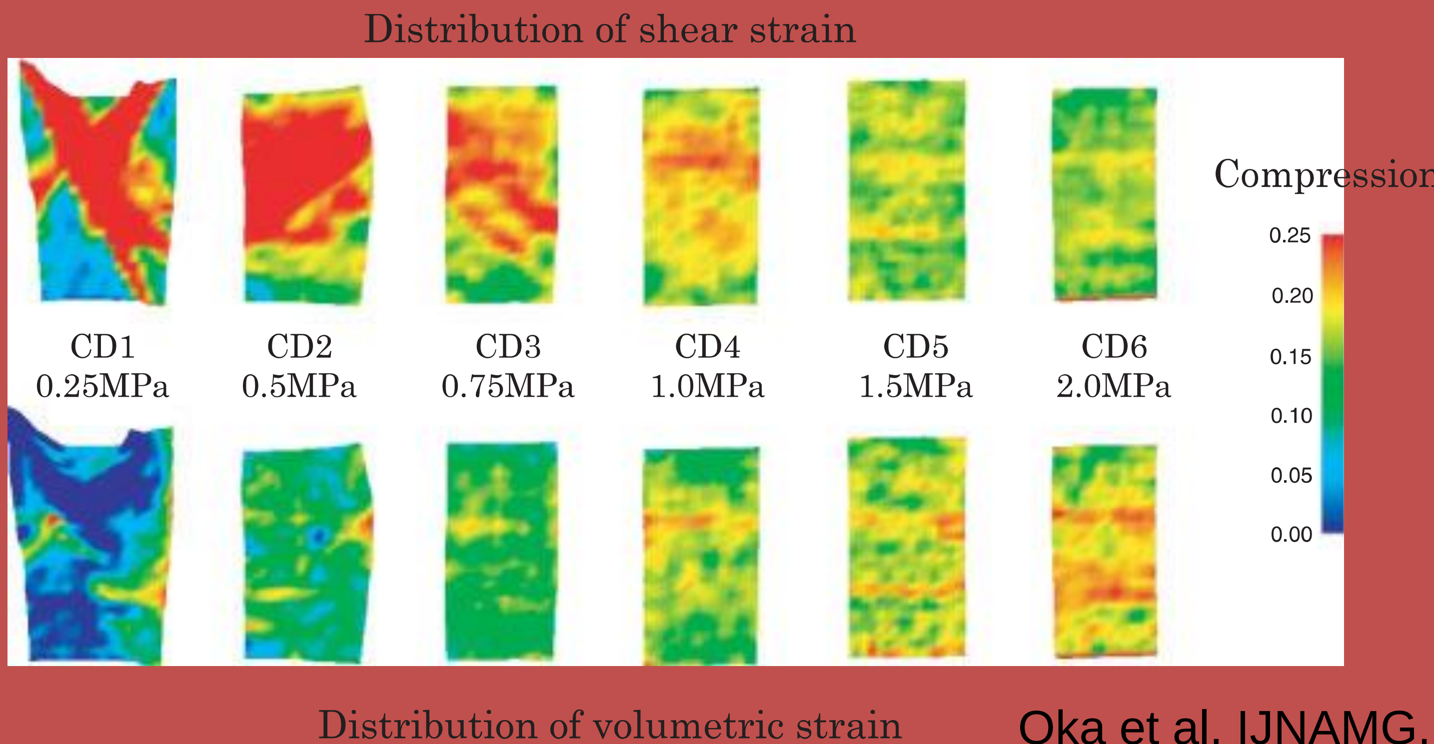
$$\frac{\partial(\sigma'_{ij} + P\delta_{ij})}{\partial x_i} = 0$$

RedbackMech Material

$$\dot{\varepsilon}_{ij} = C^{-1}_{ijkl}\dot{\sigma}_{kl} + \dot{\lambda}\frac{\partial f}{\partial \sigma_{ij}}$$

Calibrating the mechanics

Triaxial experiments in soft rocks



Oka et al, IJNAMG, 2011

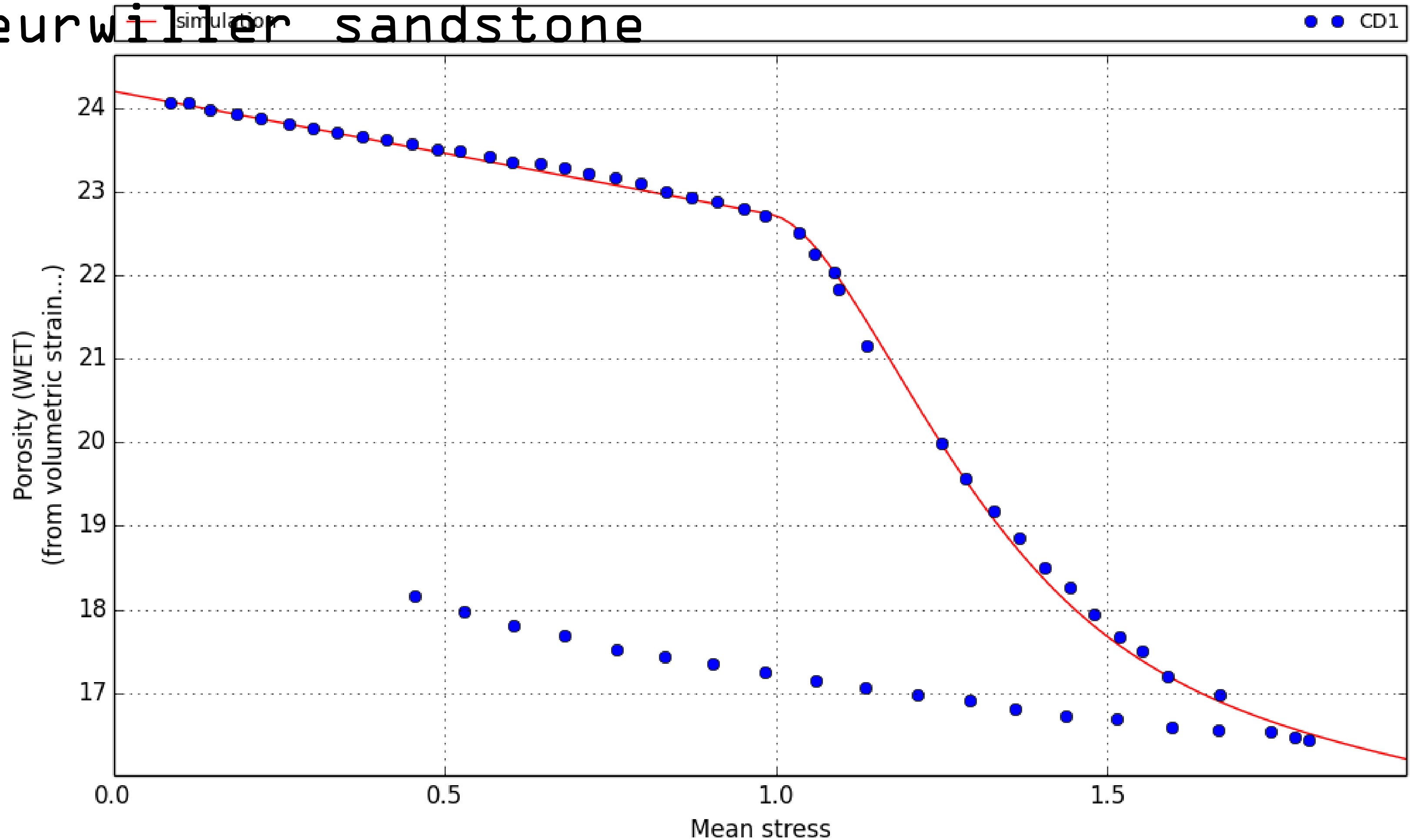
The goal is to constrain the hardening law:

$$Q_{mech} = E + p_f V_{act}$$

$$E = E_0 + DE$$

Diagenesis (pore collapse) in sandstone

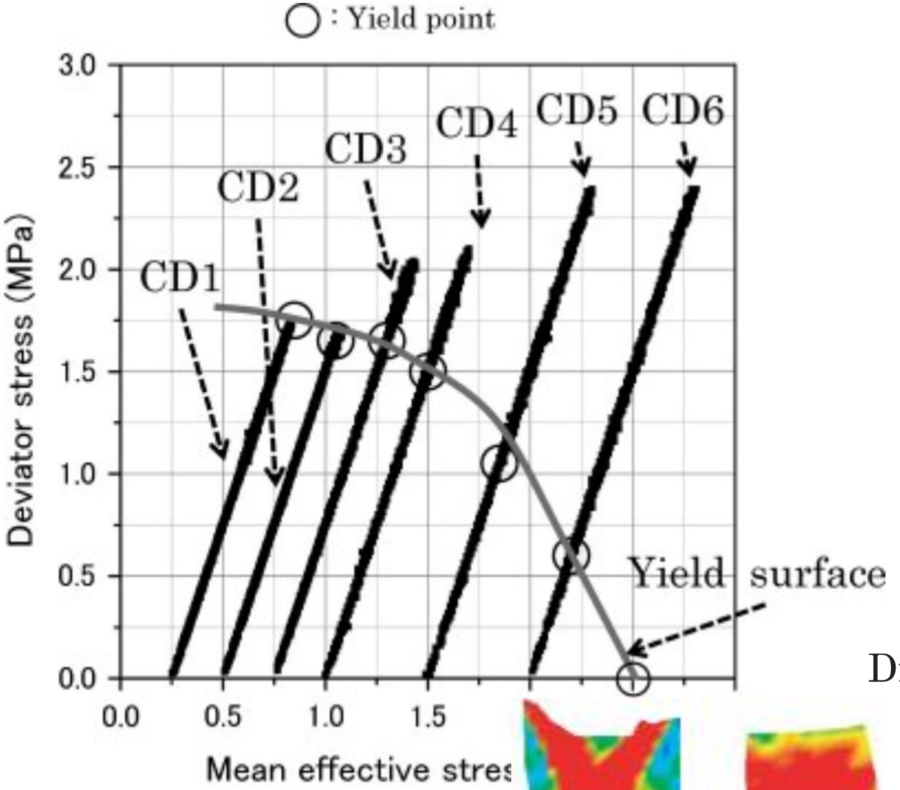
Isotropic consolidation of saturated Bleurwiller sandstone



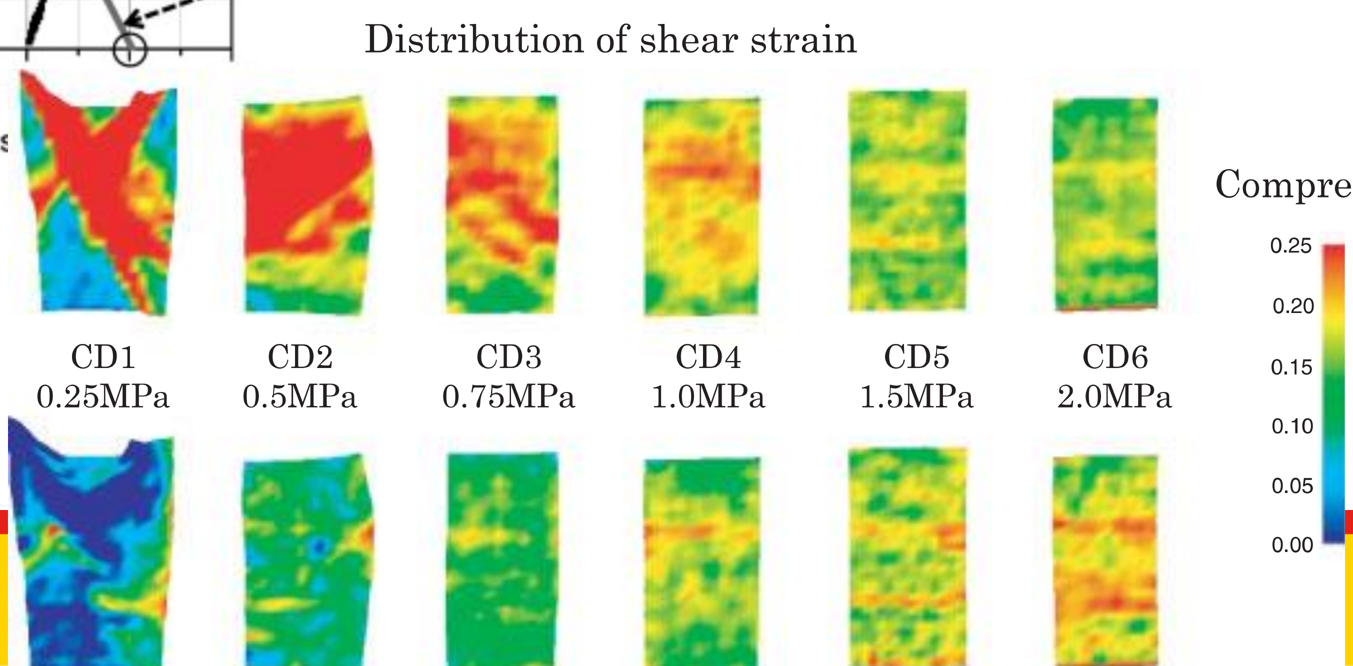
Fortin et al, JGR 2007

$$\Delta f^{\mathrm{pores}}_{\mathrm{nonint}} = p\frac{3(1-\nu_o)}{4E_o}\left\{\frac{10(1+\nu_o)}{7-5\nu_o}\mathrm{tr}(\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}) - \left[\frac{1+5\nu_o}{7-5\nu_o}+\frac{1}{3(1+\delta_s)}\right](\mathrm{tr}\,\boldsymbol{\sigma})^2\right\},$$

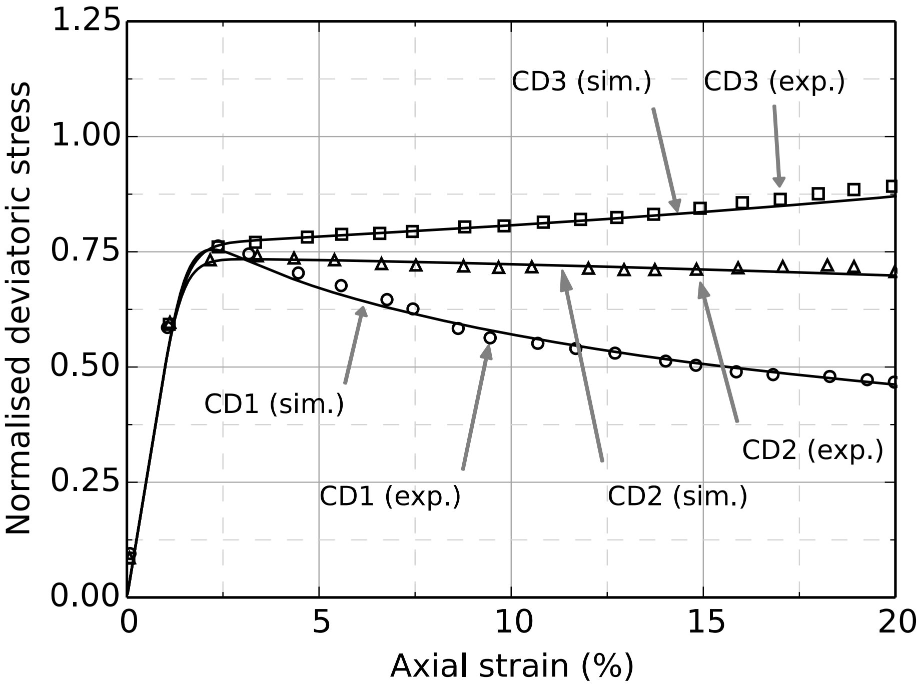
Drained consolidation of diatomaceous

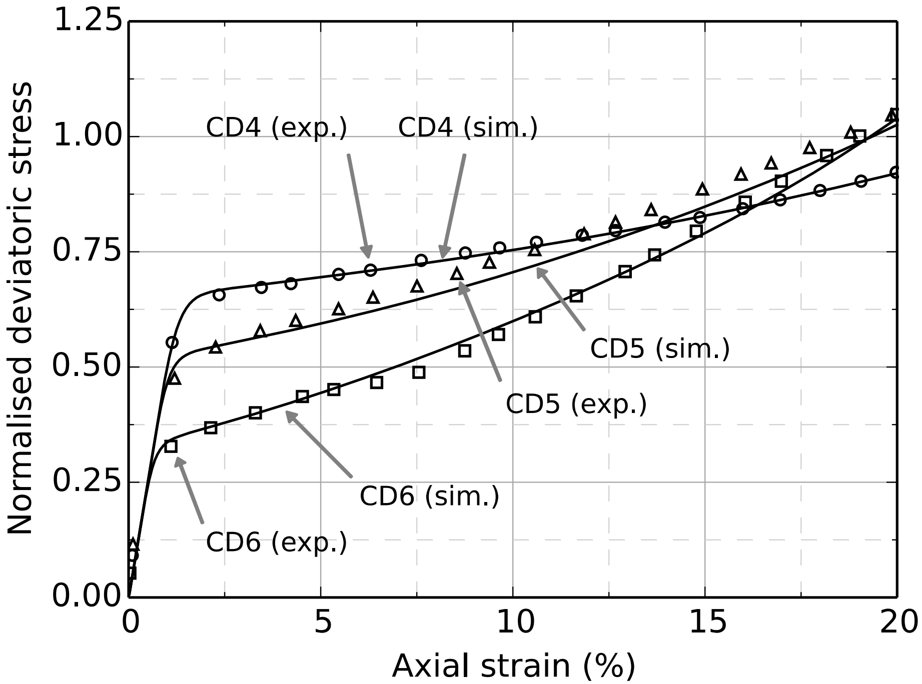


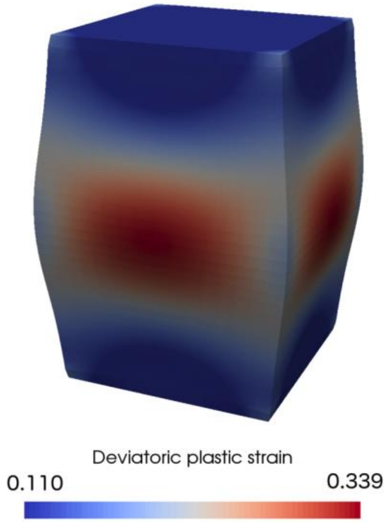
Oka et al, IJNAMG, 2011

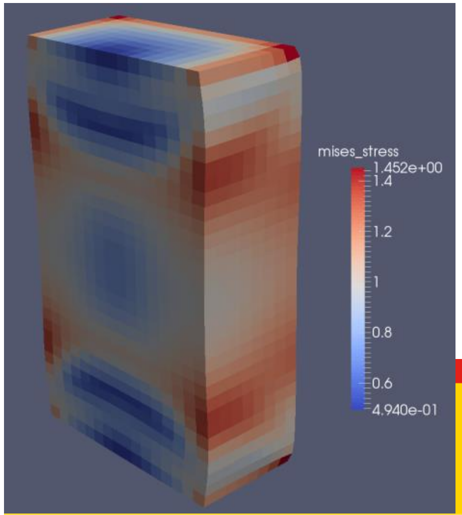


Matching the experiments

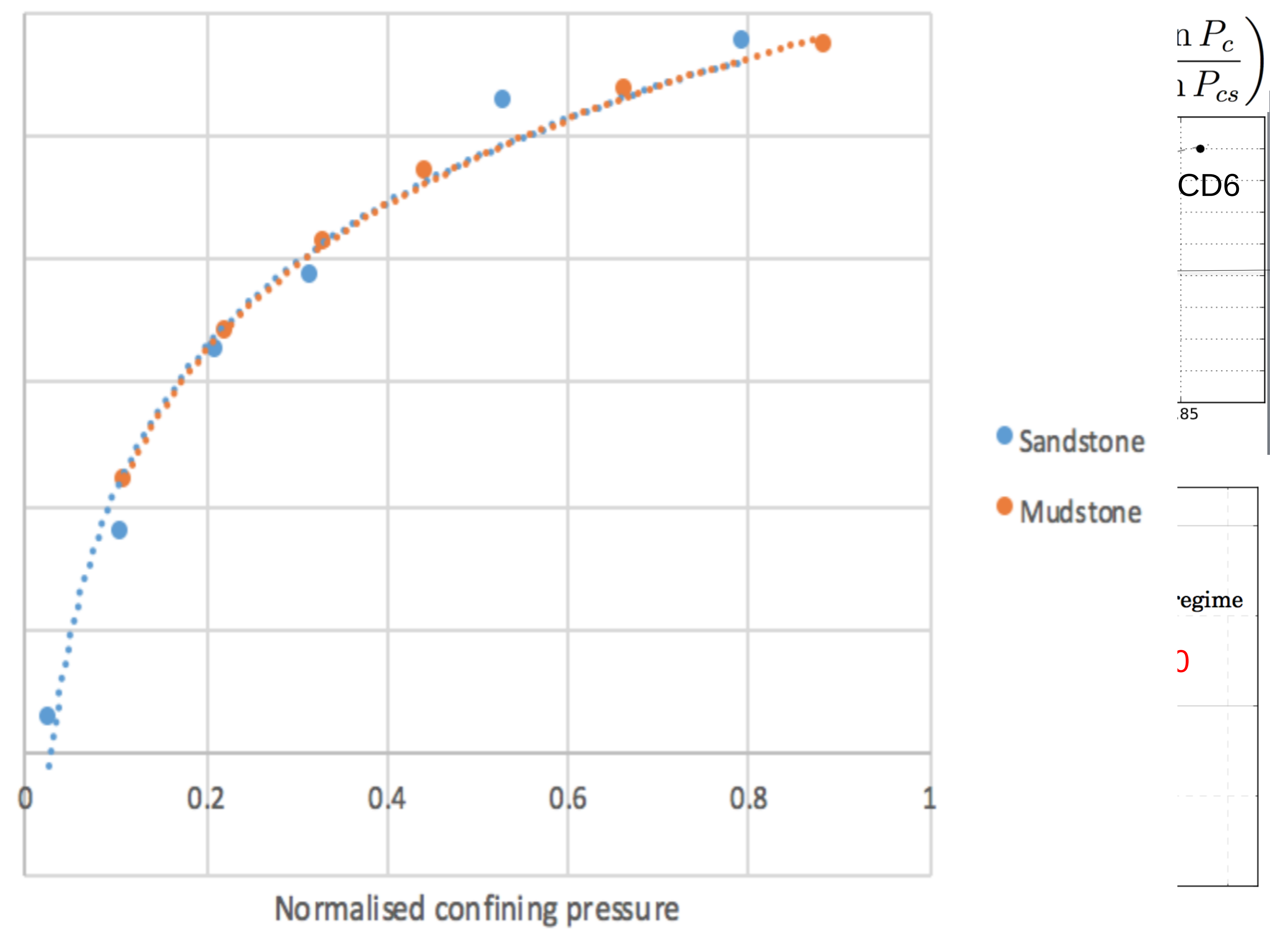








Poulet and Veveakis 2016 (COGE)


0
0.2
0.4
0.6
0.8
1
Normalised confining pressure
Sandstone
Mudstone
CD6
.85
regime

Part II: Bifurcation Analysis

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Equations and assumptions in multiphysics plasticity

Momentum balance: $$\frac{\P s_{ij}}{\P x_j} = r \frac{\P v_i}{\P t}$$

Mass balance (species): $$\frac{\P r^{(a)}}{\quad} \quad \frac{\quad}{\P x_k} = j_a$$

Energy balanc $$\frac{\quad T}{\partial t} + v_k^{(m)} \frac{\partial T}{\partial x_k} = k \frac{\partial^2 T}{\partial x_k^2} + F + Dh_w r_w$$

2nd : $$\Phi = \bar{\sigma}_{ij} \dot{\varepsilon}_{ij}^p - \mathrm{Y}_a \dot{\xi}_a = \chi \bar{\sigma}_{ij} \dot{\varepsilon}_{ij}^p \geq 0$$

Loss of ellipticity conditions?

Equations and assumptions in multiphysics plasticity

Momentum balance: $\frac{\P s_{ij}}{\P x_j} = r \frac{\P v_i}{\P t}$

Required, but not sufficient in these systems!!

Mass balance (species): $\frac{\P r^{(a)}}{\P t} + \frac{\P r^{(a)} v_k^{(a)}}{\P x_k} = j_a$

Energy balance: $r C \Box \frac{\partial T}{\partial t} + v_k^{(m)} \frac{\partial T}{\partial x_k} \Box = k \frac{\partial^2 T}{\partial x_k^2} + \mathrm{F} + \mathrm{D} h_w r_w$

2nd Law ThDyn: $\Phi = \chi \bar{\sigma}_{ij} \dot{\varepsilon}_{ij}^p \geq 0$

Key parameter for onset of bifurcation

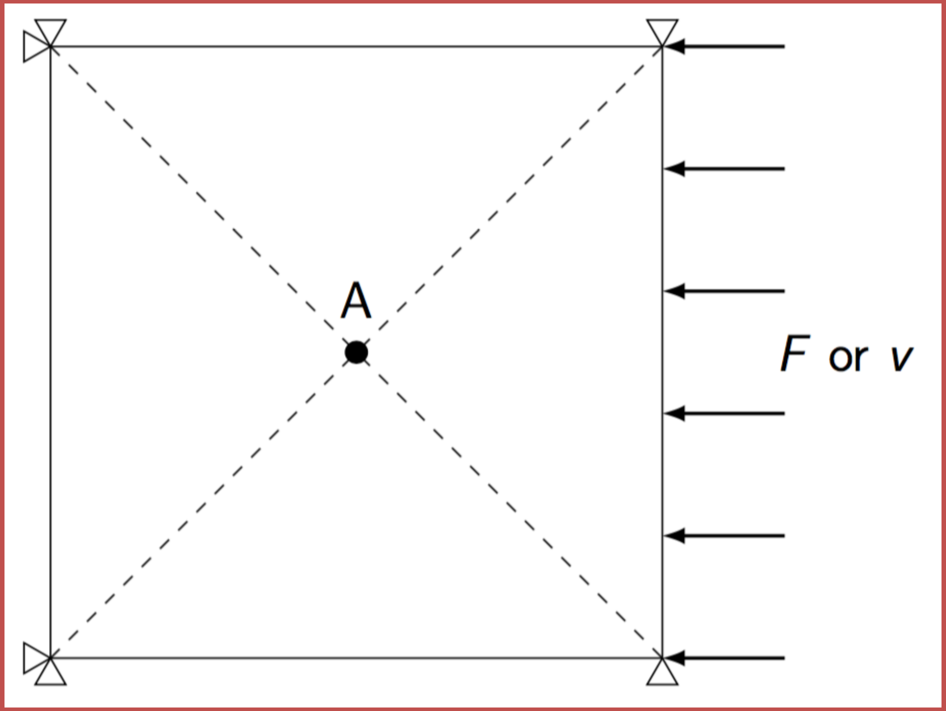
Bifurcation analysis

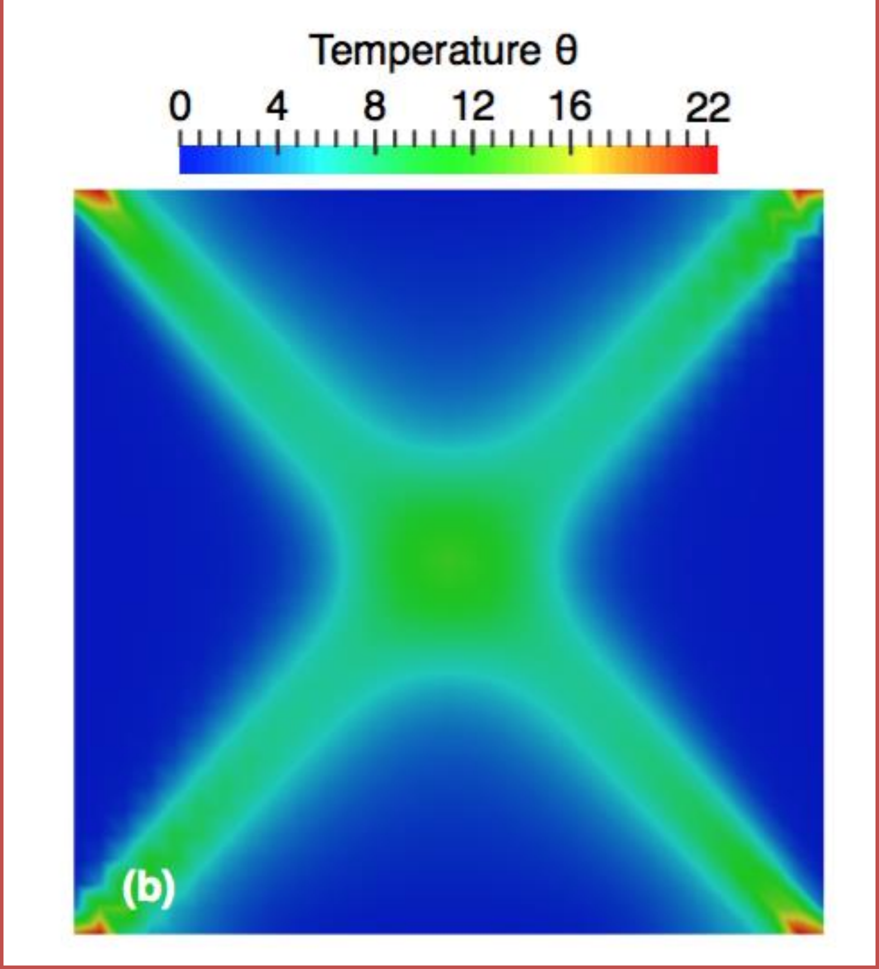
Bifurcation analysis aims on answering the following 3 questions:

1. What is the orientation of localized band(s)?
2. When does localization begin?
3. Where does localization begin?

Shear bands in perlite, Milos island Greece
Photo courtesy of I. Vardoulakis

Bifurcation in Thermo-mechanical systems





Paesold et al JoMMS 2016

Thermo-mechanics: Equations

Momentum balance:

$$r \frac{\P v_i}{\P t} = \frac{\P s_{ij}}{\P x_j}$$

Energy balance:

$$r C \frac{\P T}{\P t} = k \frac{\P^2 T}{\P x_k^2} + \mathrm{F}$$

$$\Phi = \chi \bar{\sigma}_{ij} \dot{\varepsilon}^i_{ij} = \chi \left(\bar{q} \dot{\varepsilon}^i_d + \bar{p}' \dot{\varepsilon}^i_v \right)$$

$$\dot{\epsilon}^i_d = \dot{\epsilon}_0 \left\langle \frac{q - q_Y}{\sigma_{ref}} \right\rangle^m \exp\left(-\frac{Q^d_{mech}}{RT} \right)$$

$$\dot{\epsilon}^i_v = \dot{\epsilon}_0 \left\langle \frac{p' - p_Y}{\sigma_{ref}} \right\rangle^m \exp\left(-\frac{Q^V_{mech}}{RT} \right)$$

Thermo-mechanics: Steady state analysis (fixed points)

Momentum balance: $$\frac{\P s_{ij}}{\P x_j} = 0$$

Energy balance: $$k\frac{\partial^2 T}{\partial x_k^2} + \chi\left(\left\langle \bar{p}' \right\rangle^m + \left\langle \bar{q} \right\rangle^m\right)\dot{\varepsilon}_0 e^{-\frac{Q_{mech}}{RT}} = 0$$

Normalising the equations is essential!!

$$s^* = \frac{s}{s_{ref}},\ x^* = \frac{x}{L_{ref}},\ q = \frac{T - T_{ref}}{T_{ref}}$$

Thermo-mechanics: Steady state analysis (fixed points)

Momentum balance:

$$\frac{\P s^{*}_{ij}}{\P x^{*}_{j}} = 0$$

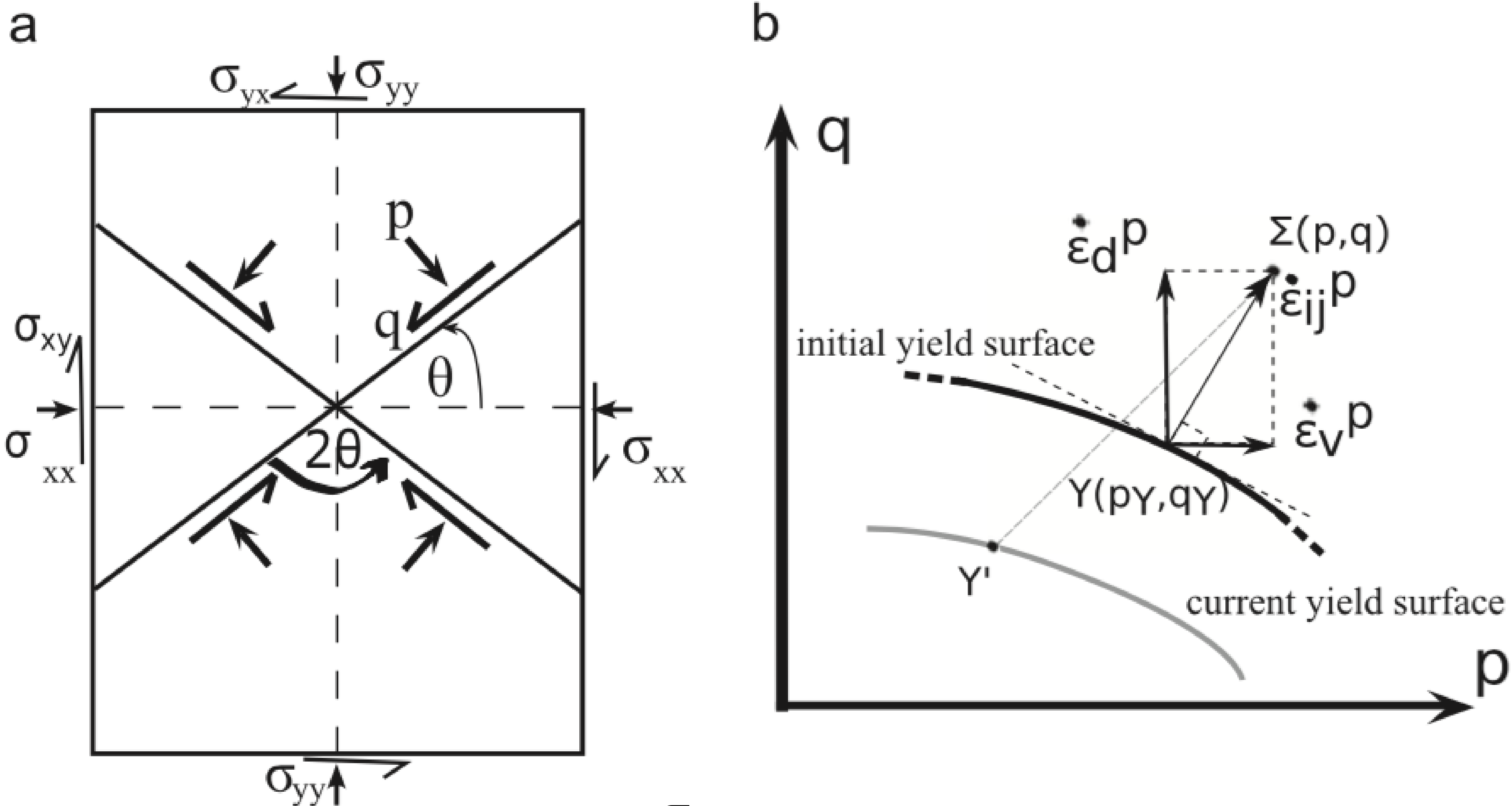
Energy balance:

$$\frac{\P^{2} q}{\P x^{*2}_{k}} + Gr\, e^{\frac{Ar\, q}{1+q}} = 0$$

$$Gr = \frac{\Phi_0 L^2_{ref}}{k T_{ref}} \quad , \quad \Phi_0 = \chi \left(\left\langle \bar{p}' \right\rangle^m + \left\langle \bar{q} \right\rangle^m \right) \dot{\varepsilon}_0 e^{-Ar}$$

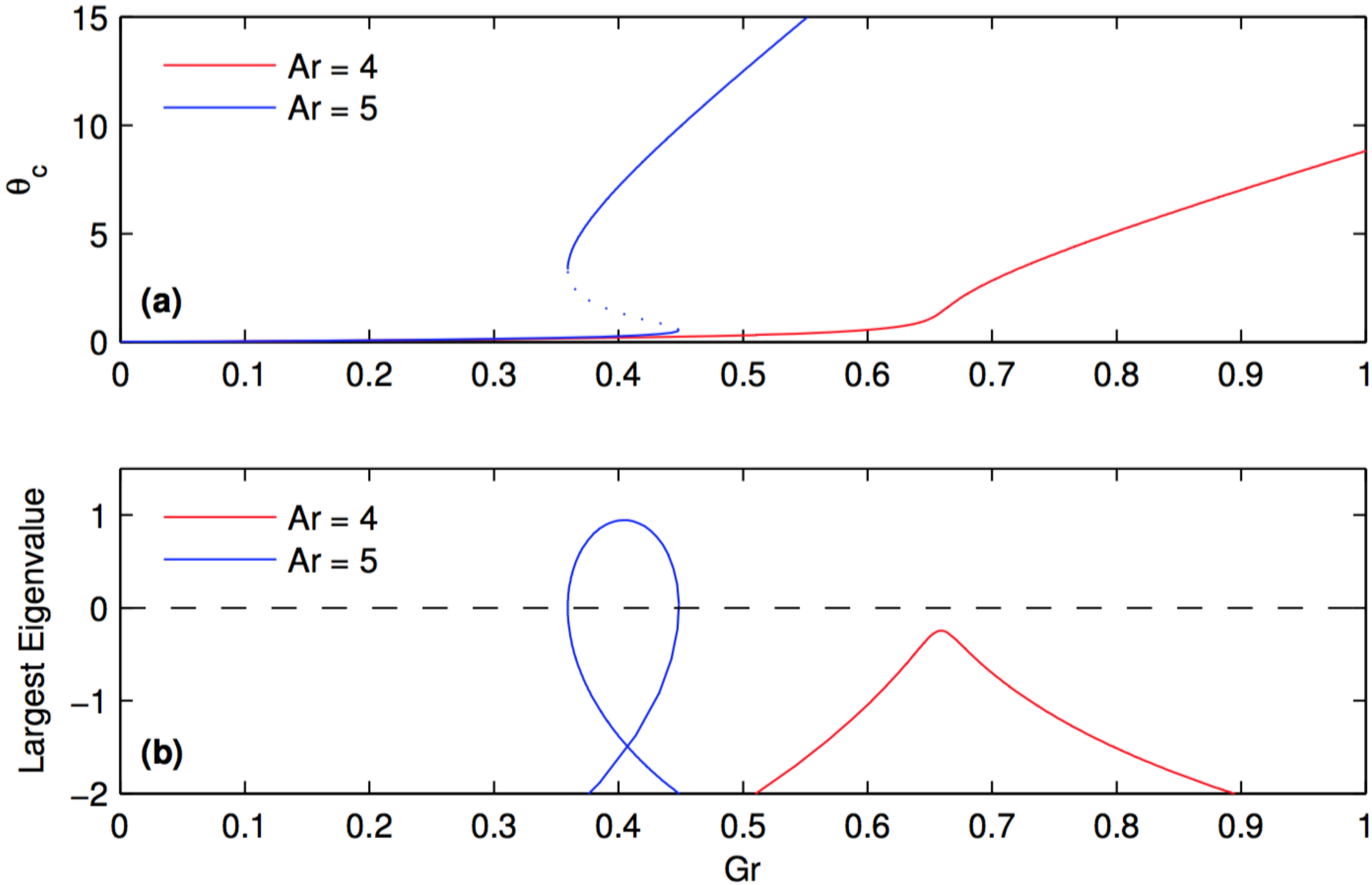
$$Ar = \frac{Q_{mech}}{R T_{ref}} \qquad \chi = 1 - \frac{\Upsilon_a \dot{\xi}_a}{\bar{\sigma}_{ij} \dot{\varepsilon}^p_{ij}} \; ; \; 0 \le \chi < 1$$

Orientation of the potential localisation patterns



$$\frac{\partial \sigma_{ij}}{\partial x_j} = 0$$

Thermo-mechanics: Bifurcation analysis



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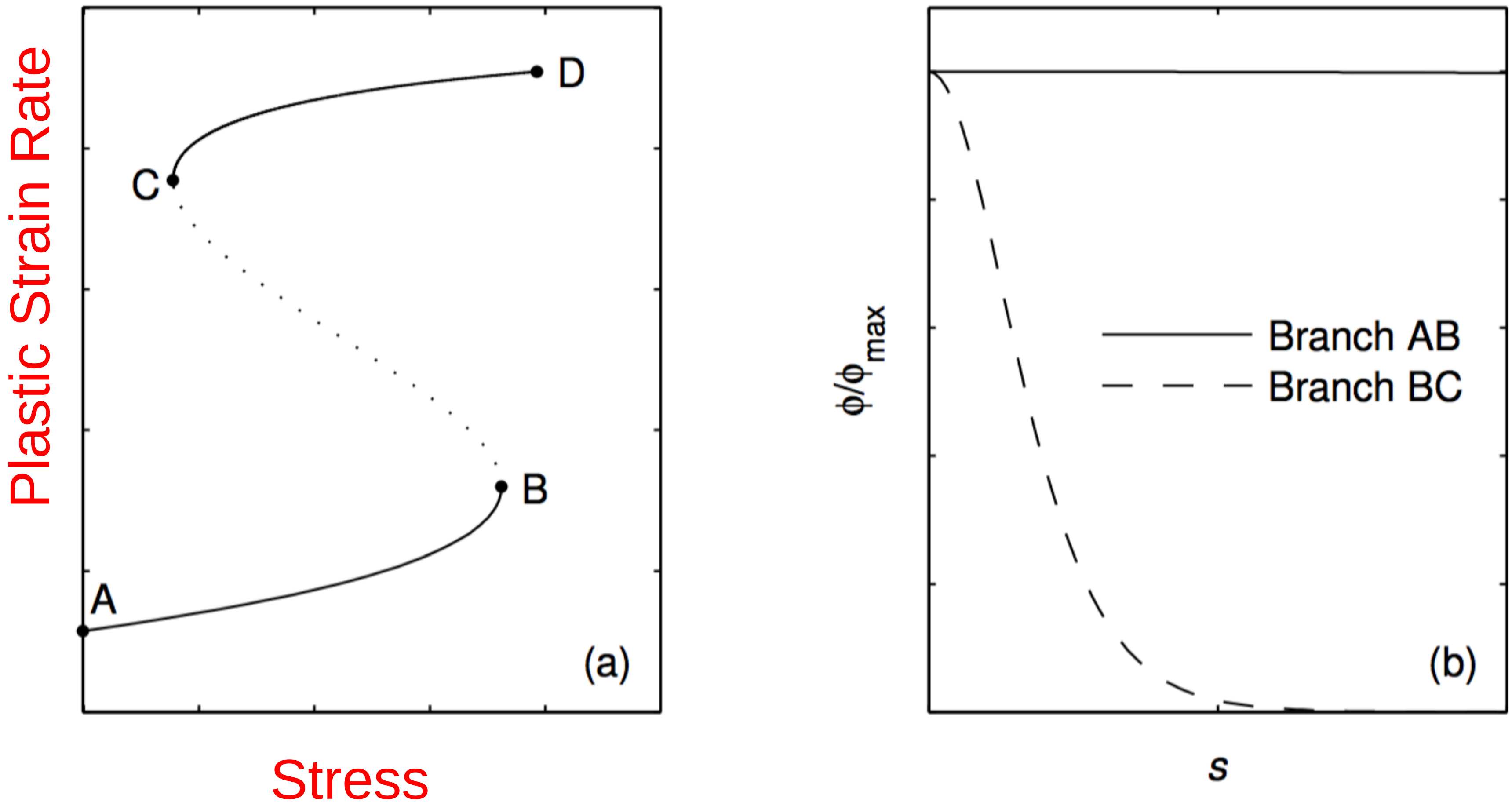
Thermo-mechanics: Bifurcation analysis



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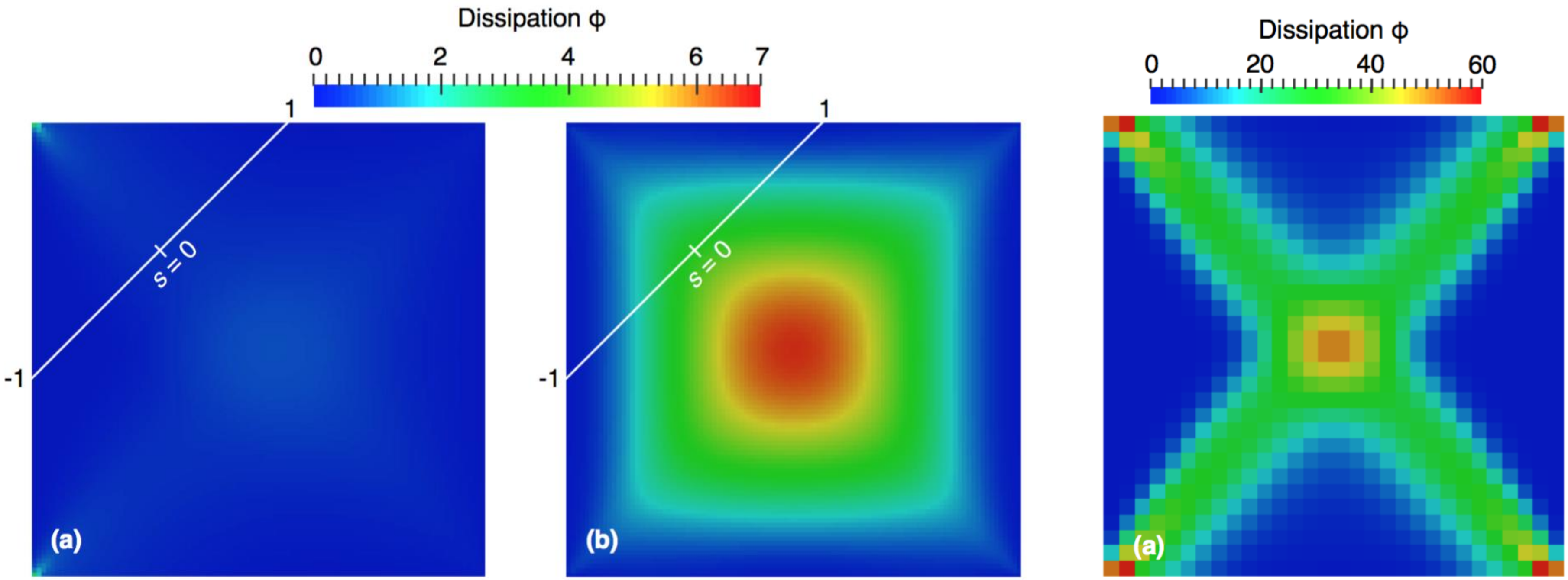
Spatial representation of localisation instability



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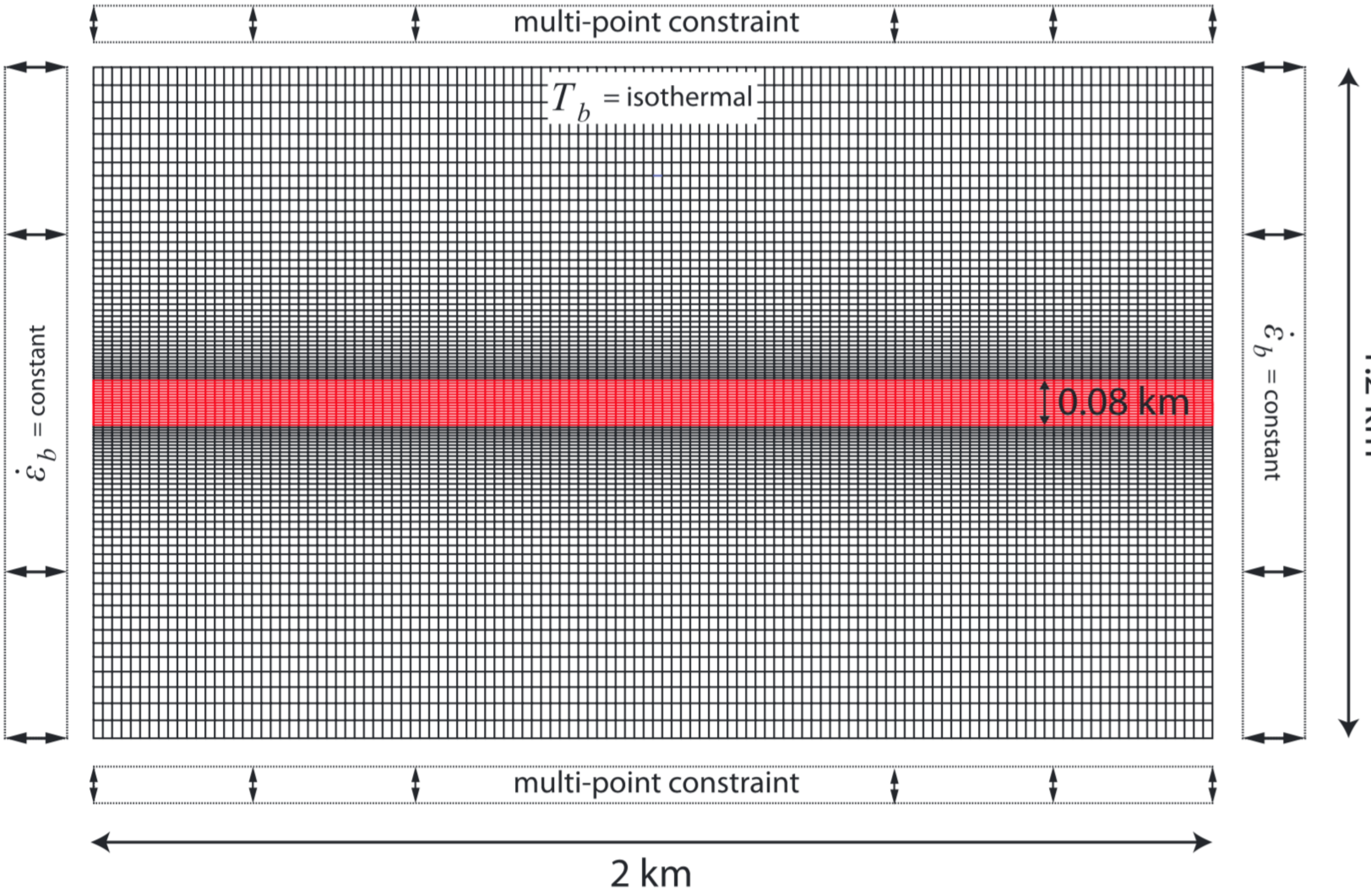
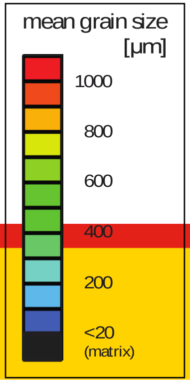
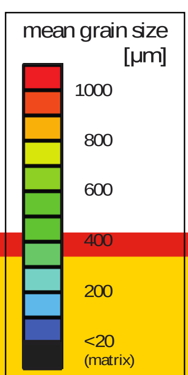
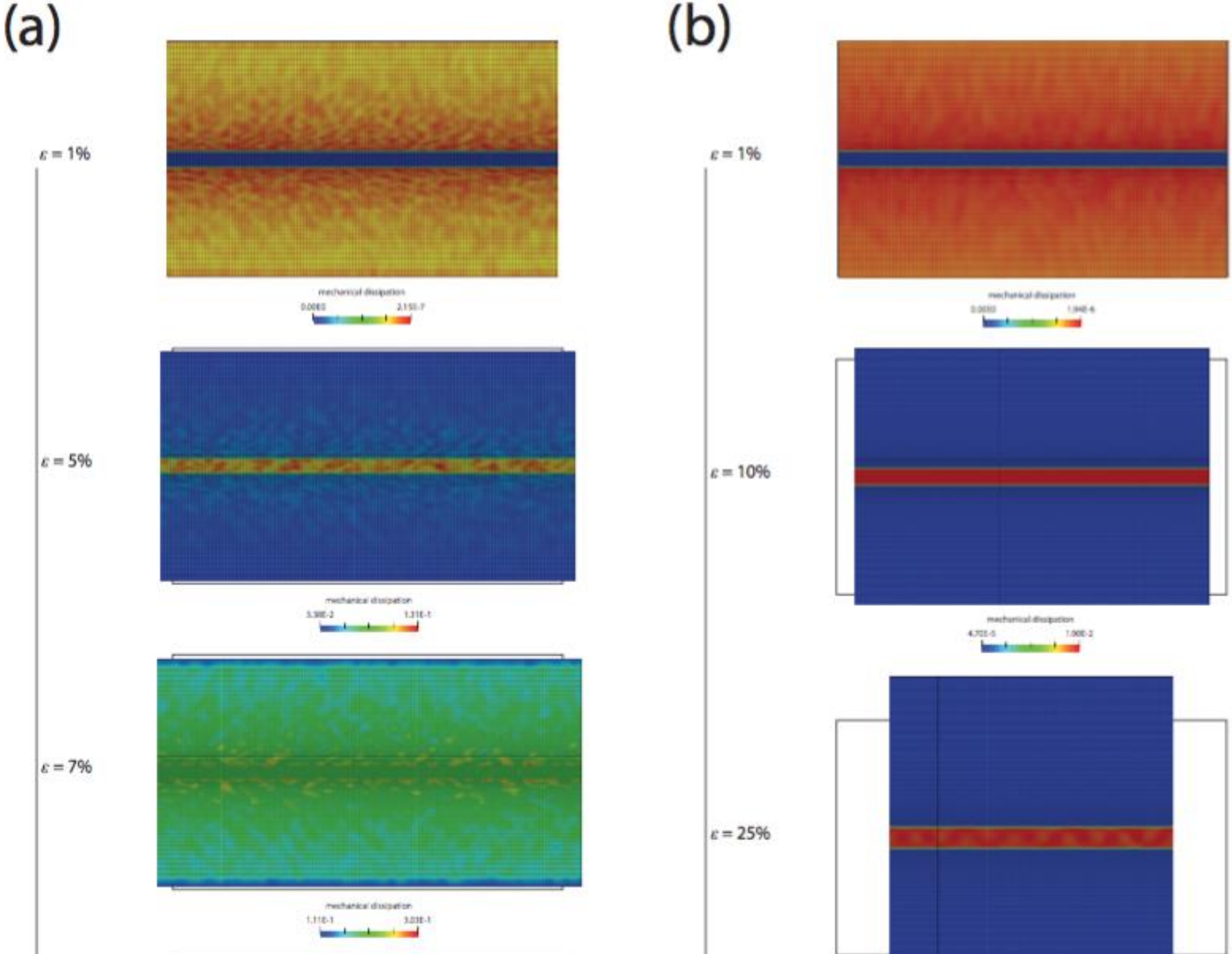


Peters et al 2016



mean grain size
[μm]
1000
800
600
400
200
<20
(matrix)

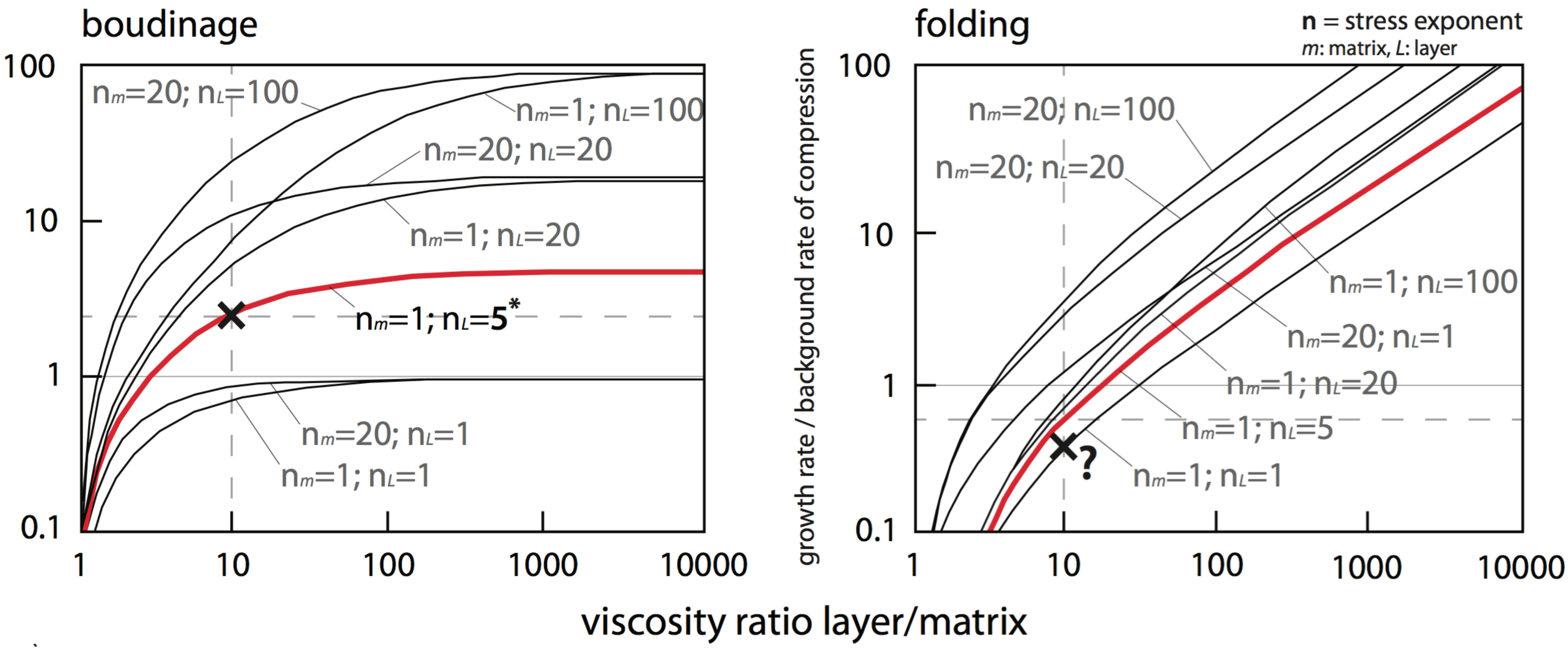

mean grain size
[µm]
1000
800
600
400
200
<20
(matrix)


(a)
(b)
ε = 1%
mechanical dissipation
ε = 5%
mechanical dissipation
ε = 7%
mechanical dissipation
ε = 1%
mechanical dissipation
ε = 10%
mechanical dissipation
ε = 25%

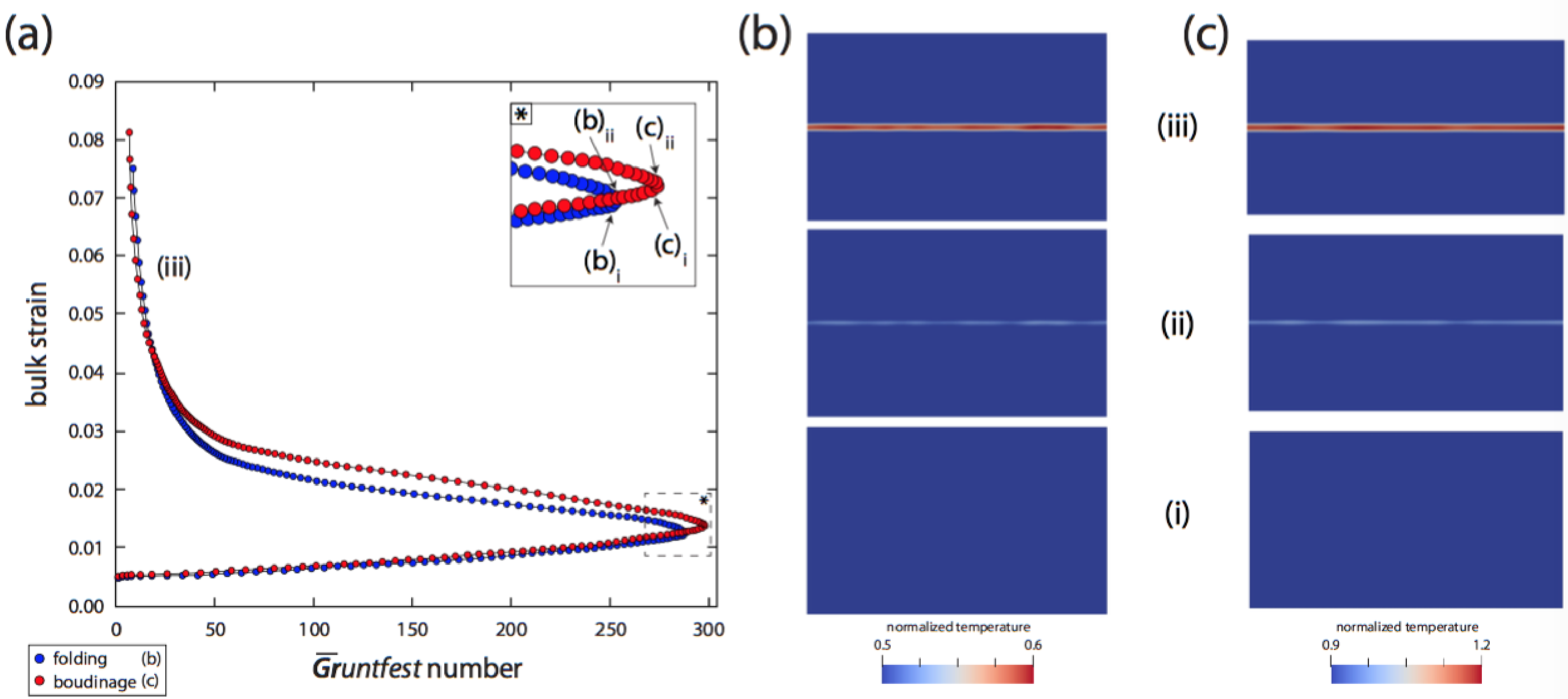
Classical approach - different material properties required

classical linear stability studies ... have some drawbacks!

e.g. Smith (1977): "solid mechanical" (plastic) materials



Folding and boudinage as the same energy attractor!



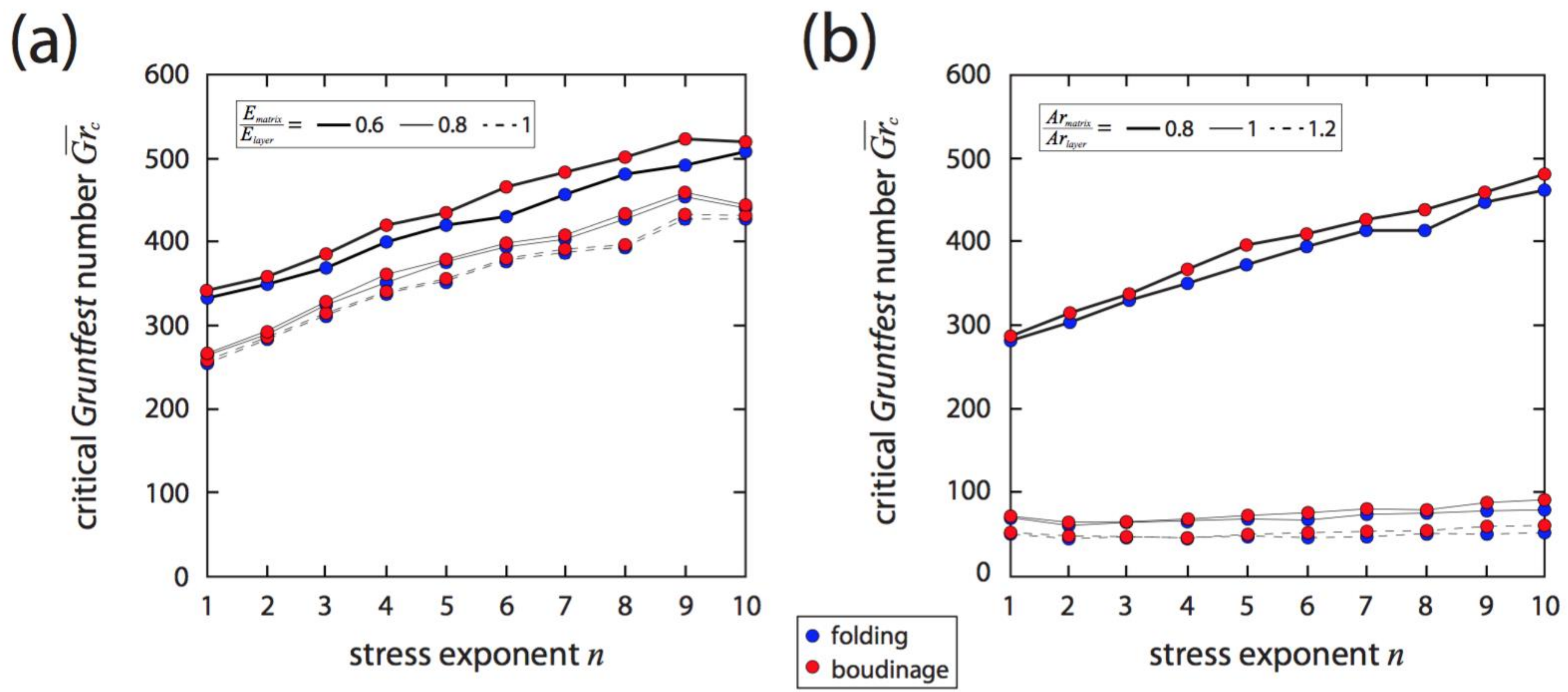
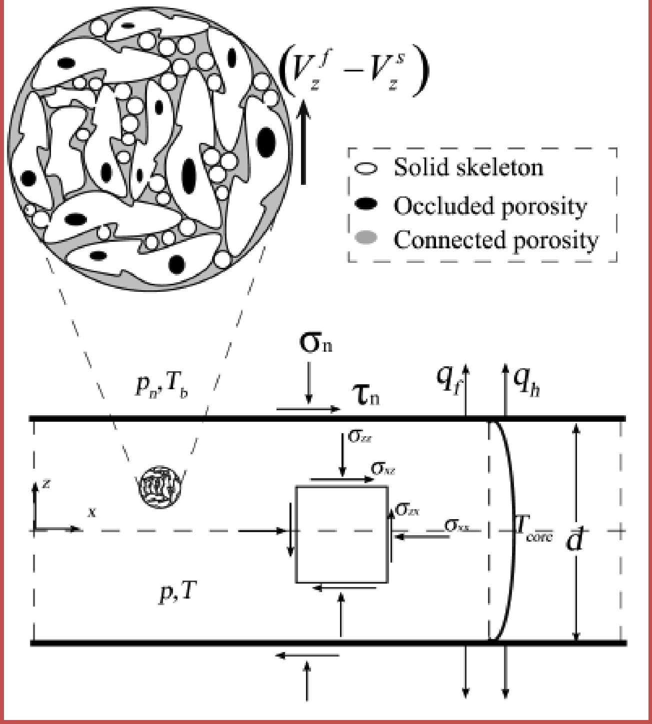


Figure 7. Parametric study of the influence of thermo-mechanical properties and the stress exponent n on the modified *Gruntfest* number $\overline{Gr}$. For all studies, the matrix obeys a linear rheology. **(a)** Evolution of $\overline{Gr}$ for changing ratios of *Young's* moduli E; constant $Ar = 8$. **(b)** Evolution of $\overline{Gr}$ for varying ratios of the *Arrhenius* number Ar; constant $E_{matrix}/E_{layer} = 0.8$. For (a) and (b) we find that $\overline{Gr}$ follows a folded instability curve. The value of $\overline{Gr}_c$ is almost identical for any non-linear rheology of the central layer. The energy bifurcation threshold is therefore a fixed value for any non-linear layer rheology. For thermo-mechanical parameters refer to Table 1a.

Bifurcation in THMC systems: A Homoclinic bifurcation



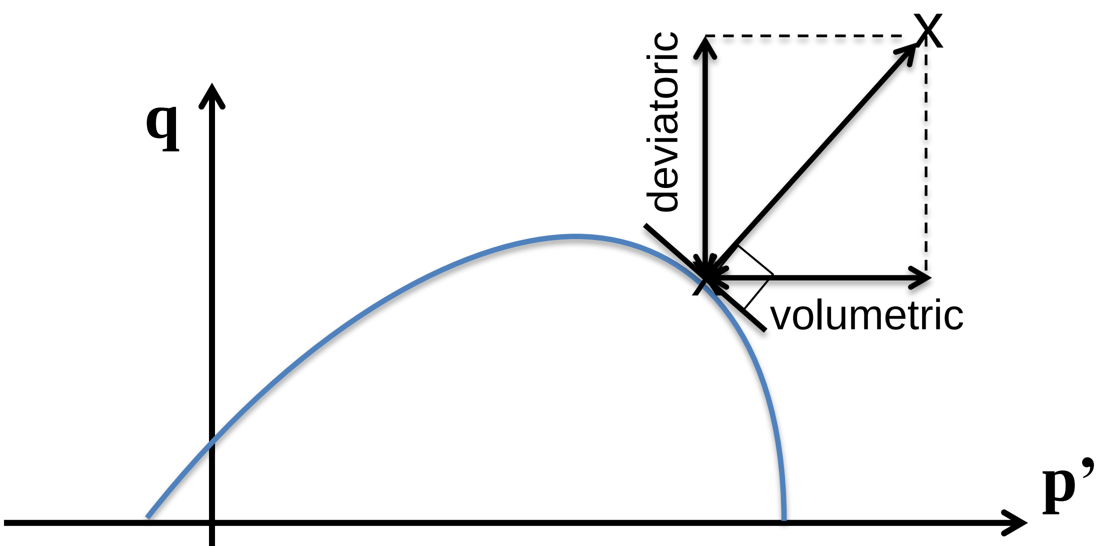
Remember the constitutive law

$$\dot{\varepsilon}^{p}_{ij} = \dot{\lambda}\frac{\partial f}{\partial \sigma'_{ij}}$$

$$\dot{\gamma}^{p} = \dot{\gamma}_{o}\left\langle \frac{q - q_{Y}}{\sigma_{ref}} \right\rangle^{m} \exp\left[-\frac{Q_{mech}}{RT}\right]$$

$$\dot{\lambda} = \sqrt{\dot{\gamma}^{p2} + \dot{\varepsilon}^{p2}}$$

$$\dot{\varepsilon}^{p} = \dot{\varepsilon}_{o}\left\langle \frac{p' - p'_{Y}}{\sigma_{ref}} \right\rangle^{m} \exp\left[-\frac{Q_{mech}}{RT}\right]$$

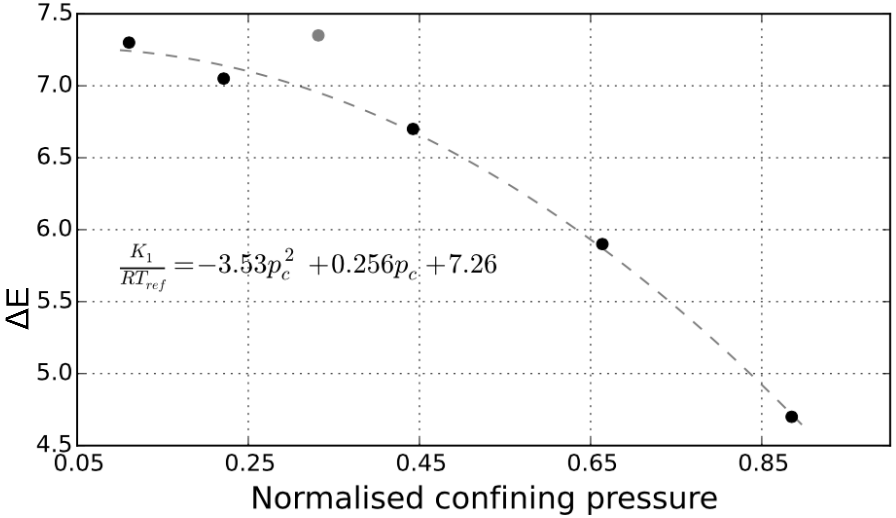


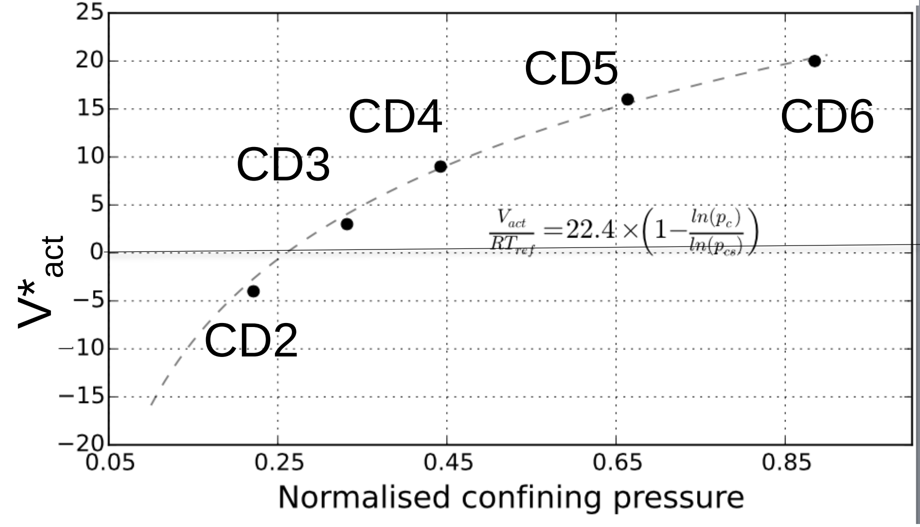
$$Q_{mech} = E + p_{f} V_{act}$$

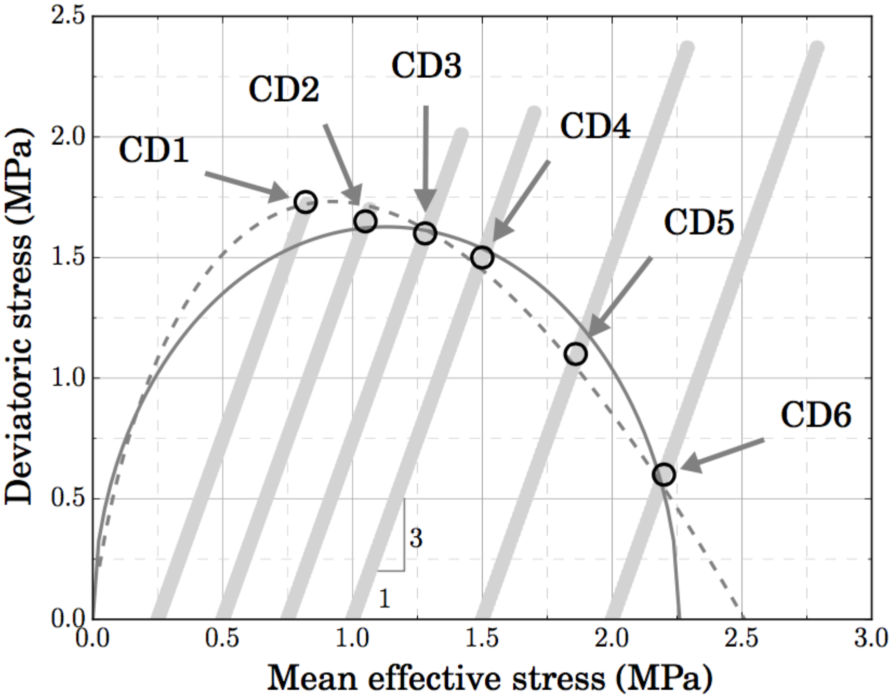
$$E = E_{0} + DE$$

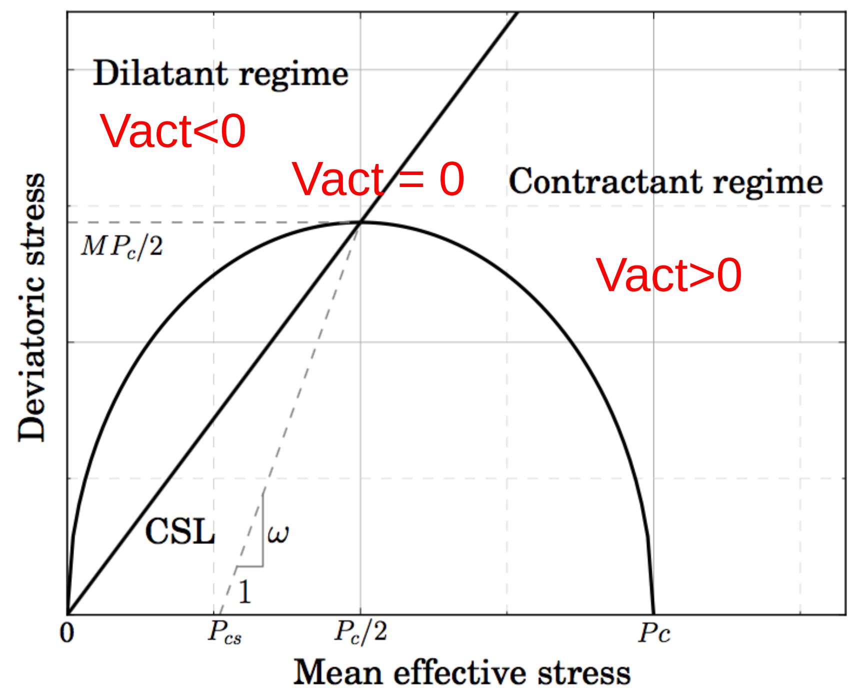
Retrieving information for tl

$$V_{act}^{(w)} = \frac{h_{act}^{(w)}}{\sigma_{ref}}\left(1 - \frac{\ln P_c}{\ln P_{cs}}\right)$$







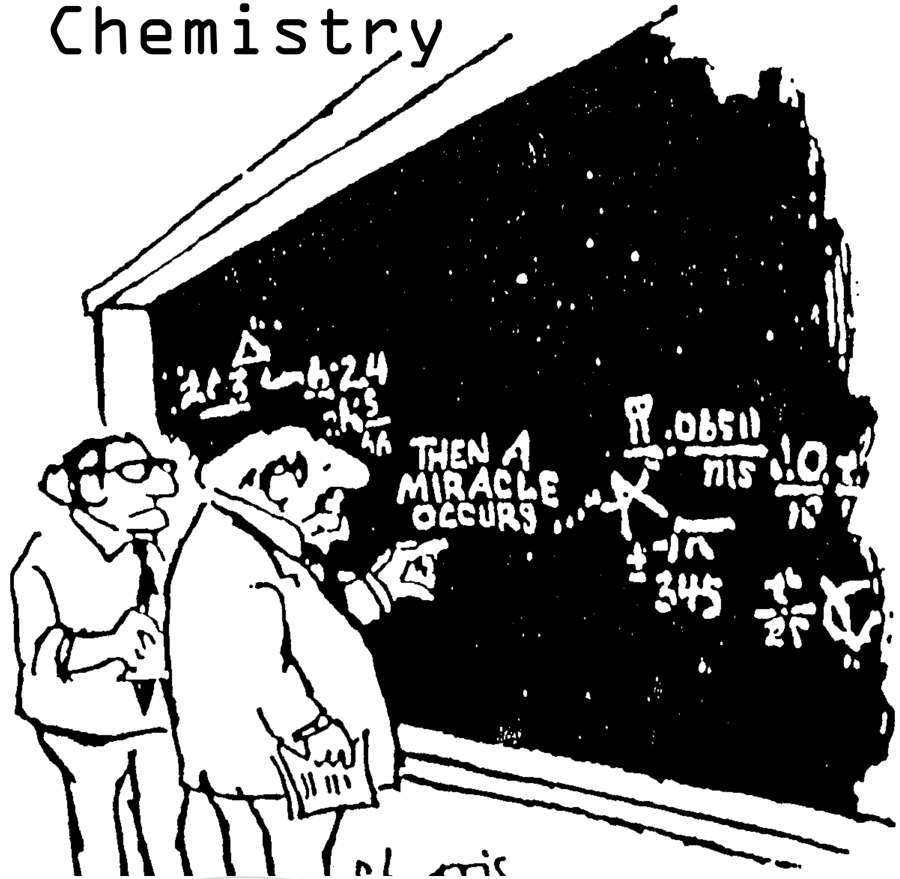


Modelling Physics + Chemistry of active faults

Part 1. Analytical Solution
-Multiple Steady States
-Asymptotic Solutions

Part 2. Transient Solutions
Spectral FE code SuCCoMBE

Part 3. Transition to Chaos



AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE
10.1002/2014JB011004

This is a companion paper to *Alevizos et al.* [2014], doi:10.1002/2013JB010070, and *Veveakis et al.* [2014].

Thermo-poro-mechanics of chemically active creeping faults: 3. The role of serpentinite in episodic tremor and slip sequences, and transition to chaos

T. Poulet[1], E. Veveakis[1,2], K. Regenauer-Lieb[1,3], and D. A. Yuen[4,5]

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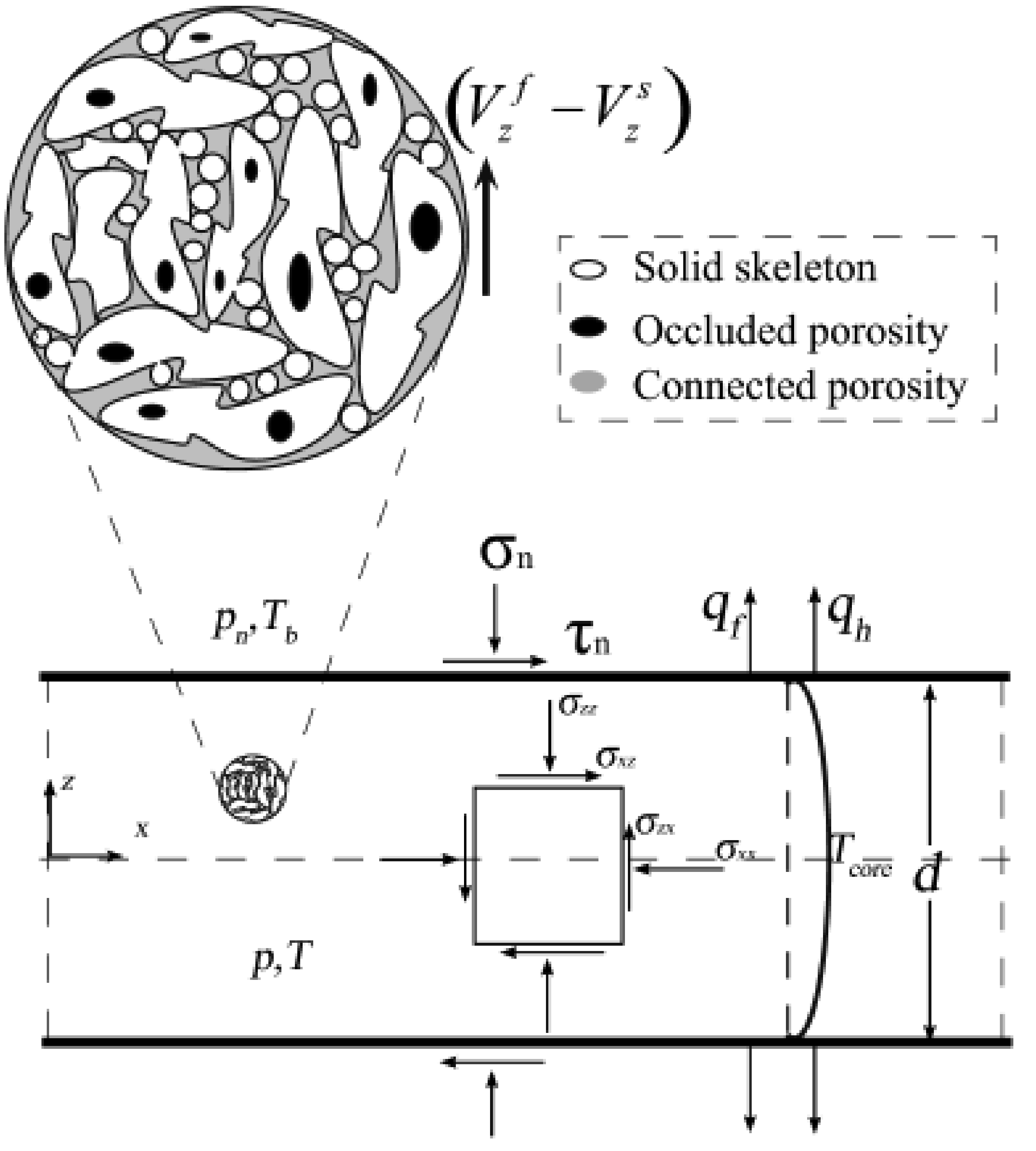
Ingredients of the model



Basic physical mechanisms

A. Creeping shear post-failure

B. Shear Heating in creeping chemical process zone

C. Chemical reaction/ decomposition of the skeleton (excess pore pressure and chemical softening/hardening)

D. Reverse chemical reaction

The mathematical system

- Normalised and reduced system of equations

$$t = t_d(t)\ ,\ \ s' = s'_n(t)$$

$$\frac{\partial DP}{\partial t} = \frac{\partial}{\partial z}\left(\frac{1}{Le}\frac{\partial DP}{\partial z}\right) + \frac{L}{m s'_n}\frac{\partial T}{\partial t} + (1-f)(1-s)m_r e^{\frac{Ar\,dT}{1+dT}}$$

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} + \left(Gr\, e^{-\frac{DP\,Vact}{1+dT}} e^{\frac{aAr}{1+dT}} - (1-f)(1-s)\, e^{\frac{Ar\,dT}{1+dT}}\right)$$

- Dimensionless Groups:

Lewis number

$$Le = \frac{\kappa_m \mu_f}{k_\pi \sigma'_n}, \quad \mu_r = \frac{(d/2)^2}{\kappa_m \sigma'_n}\frac{k_0}{\beta_f} e^{-Ar}, \quad Ar = \frac{E}{RT_c},$$

$$\delta = \frac{1}{mT_c}, \quad m = \frac{jk_m}{|\Delta H|(d/2)^2}\frac{e^{Ar}}{k_0 \rho_{AB}}, \quad Gr = \frac{\beta_T \tau_d \dot{\gamma}_0}{|\Delta H| k_0 \rho_{AB}}$$

Gruntfest number

The mathematical system

- Normalised and reduced system of equations

$$t = t_d(t)\ ,\ s' = s'_n(t)$$

$$\frac{\partial DP}{\partial t} = \frac{\partial}{\partial z}\left(\frac{1}{Le}\frac{\partial DP}{\partial z}\right) + \frac{L}{ms'_n}\frac{\partial T}{\partial t} + (1-f)(1-s)m_r e^{\frac{Ar\,dT}{1+dT}}$$

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} + \left(Gr\,e^{-\frac{DP\,Vact}{1+dT}}\,e^{\frac{aAr}{1+dT}} - (1-f)(1-s)\right)e^{\frac{Ar\,dT}{1+dT}}$$

- Dimensionless Groups:

Lewis number

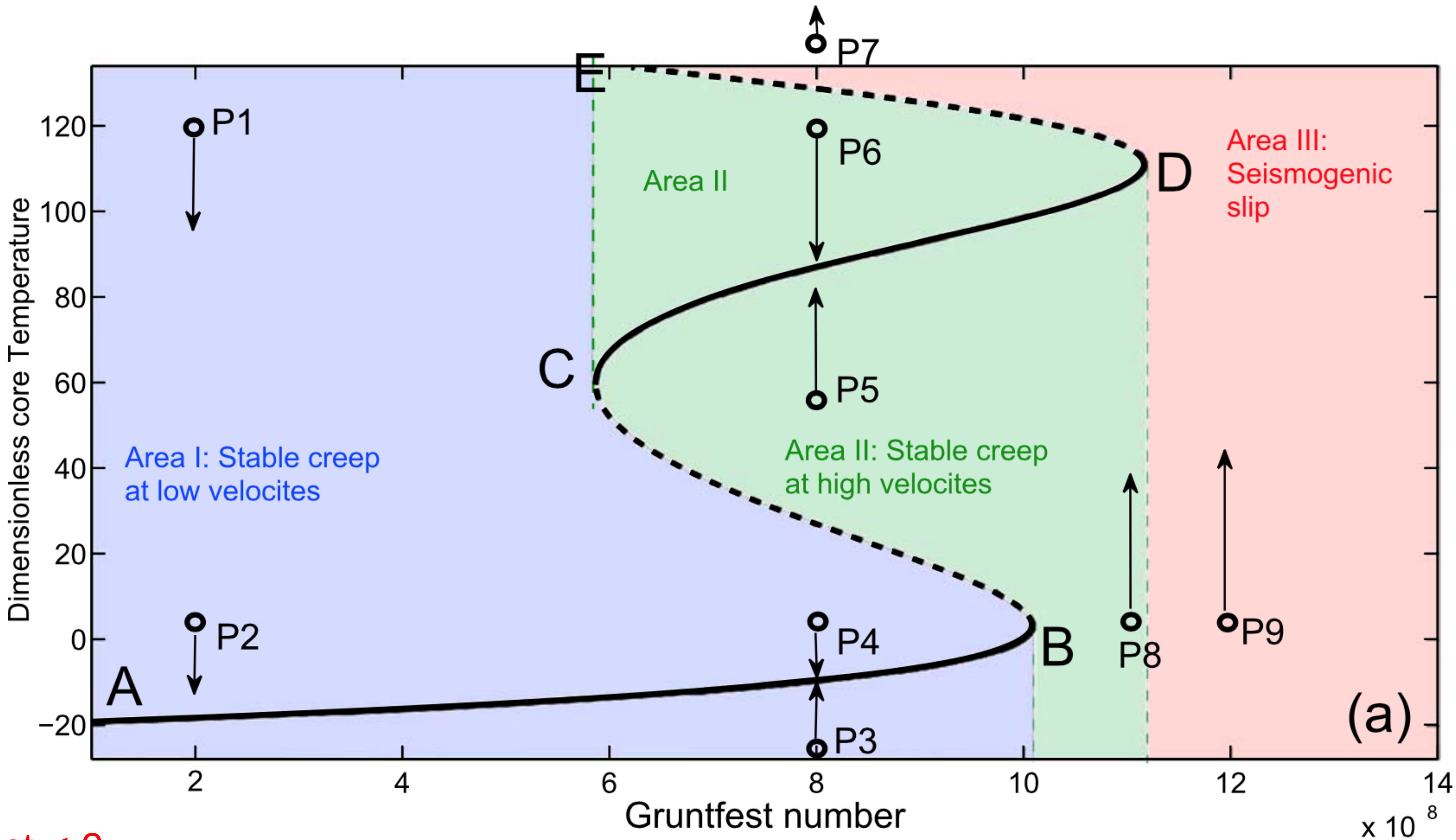
$$Le = \frac{\text{heat diffusion}}{\text{mass diffusion}}$$

$$Gr = \frac{\text{char. time scale heat production}}{\text{char. time scale energy transfer}}$$

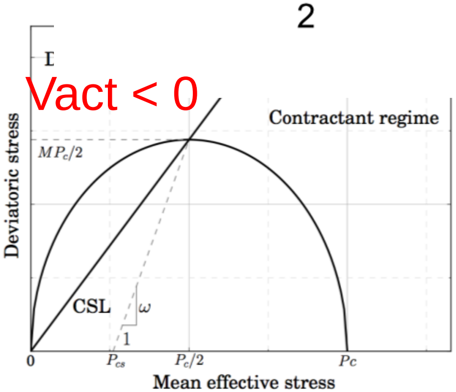
Gruntfest number

Vact < 0 : System's stability regimes

w



Vact < 0



$$Gr = \frac{\text{char. time scale heat production}}{\text{char. time scale energy transfer}}$$

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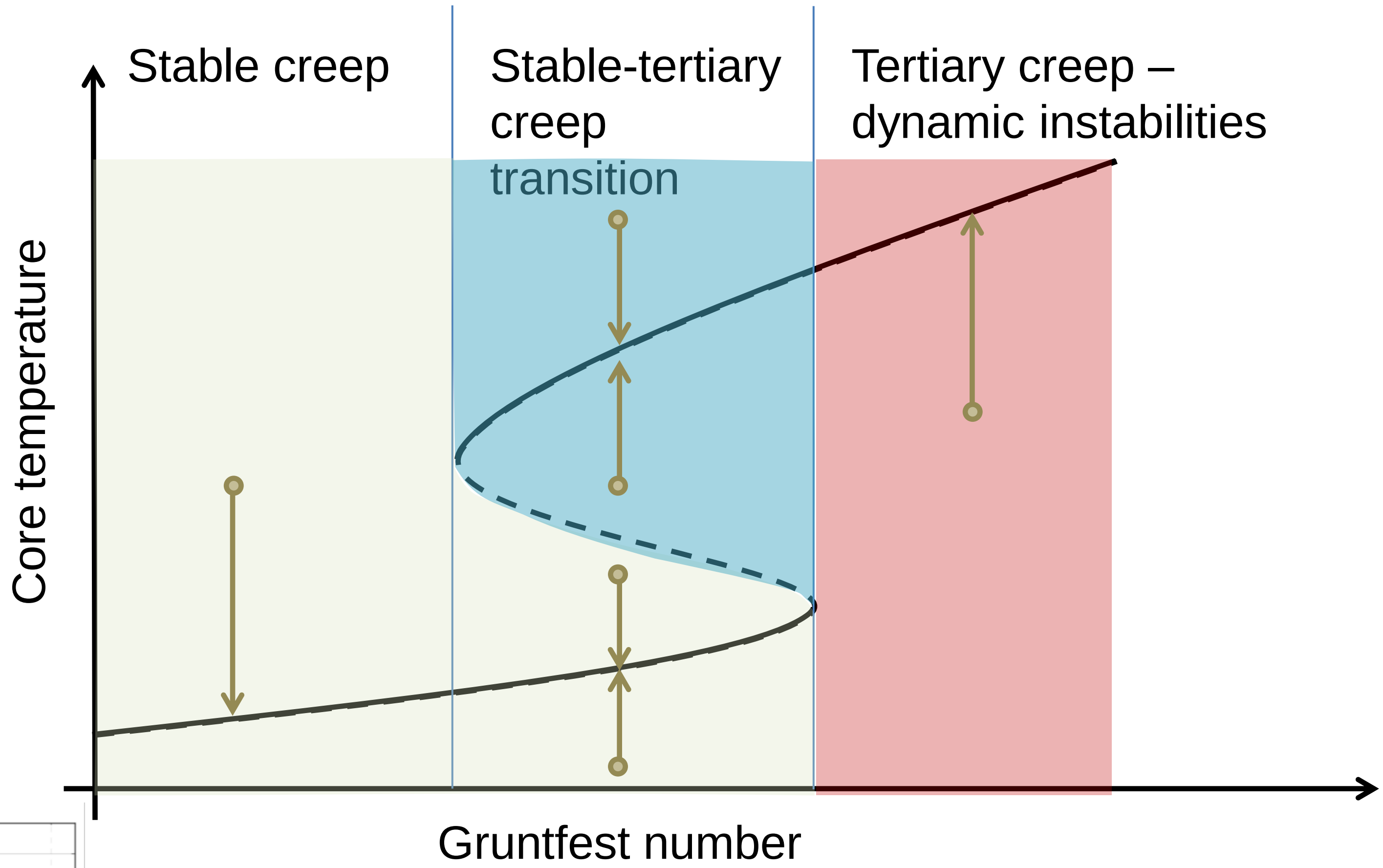
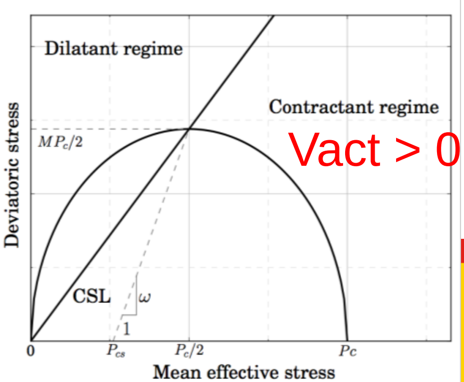
Vact > 0 : System's stability regimes w.r.t Gr

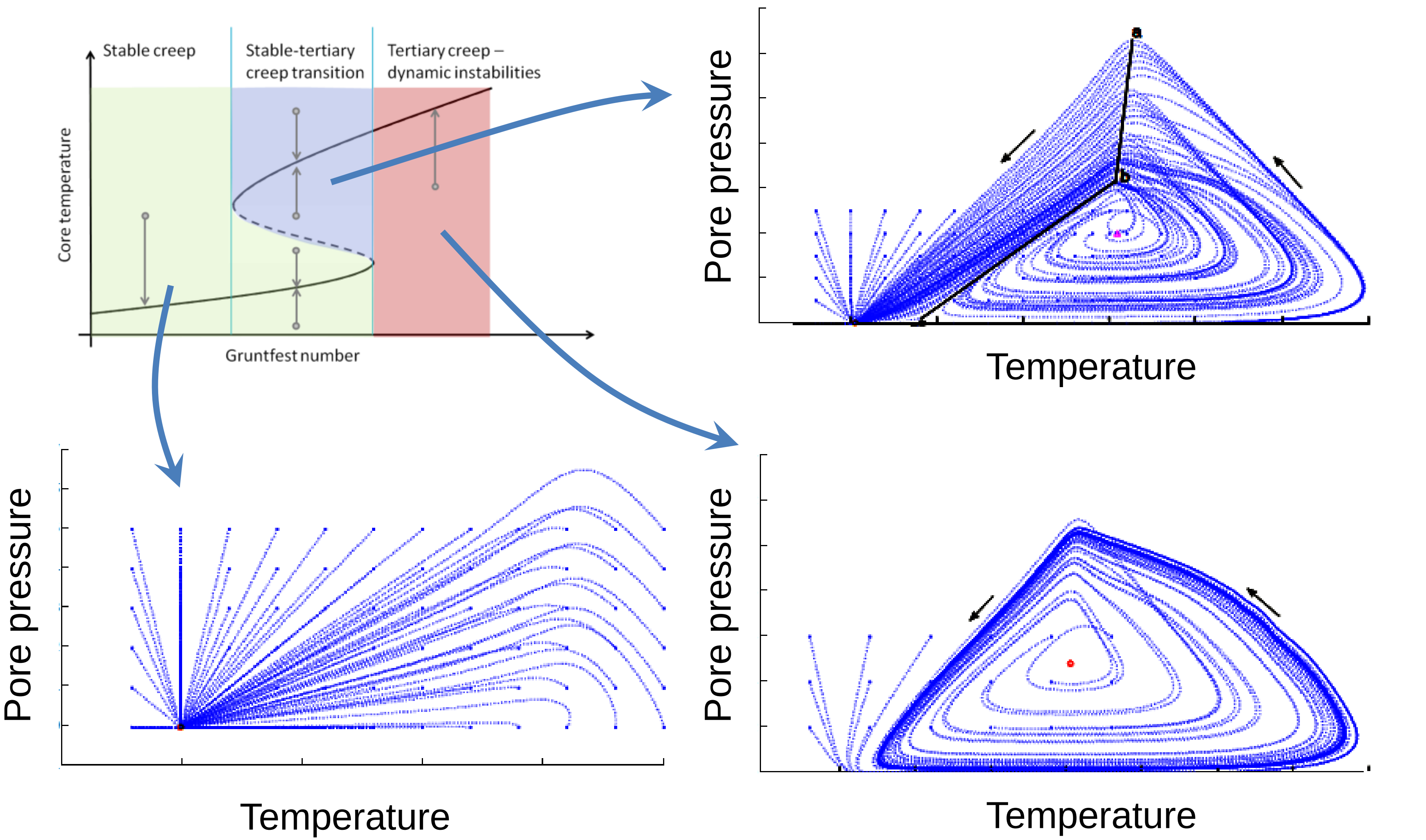


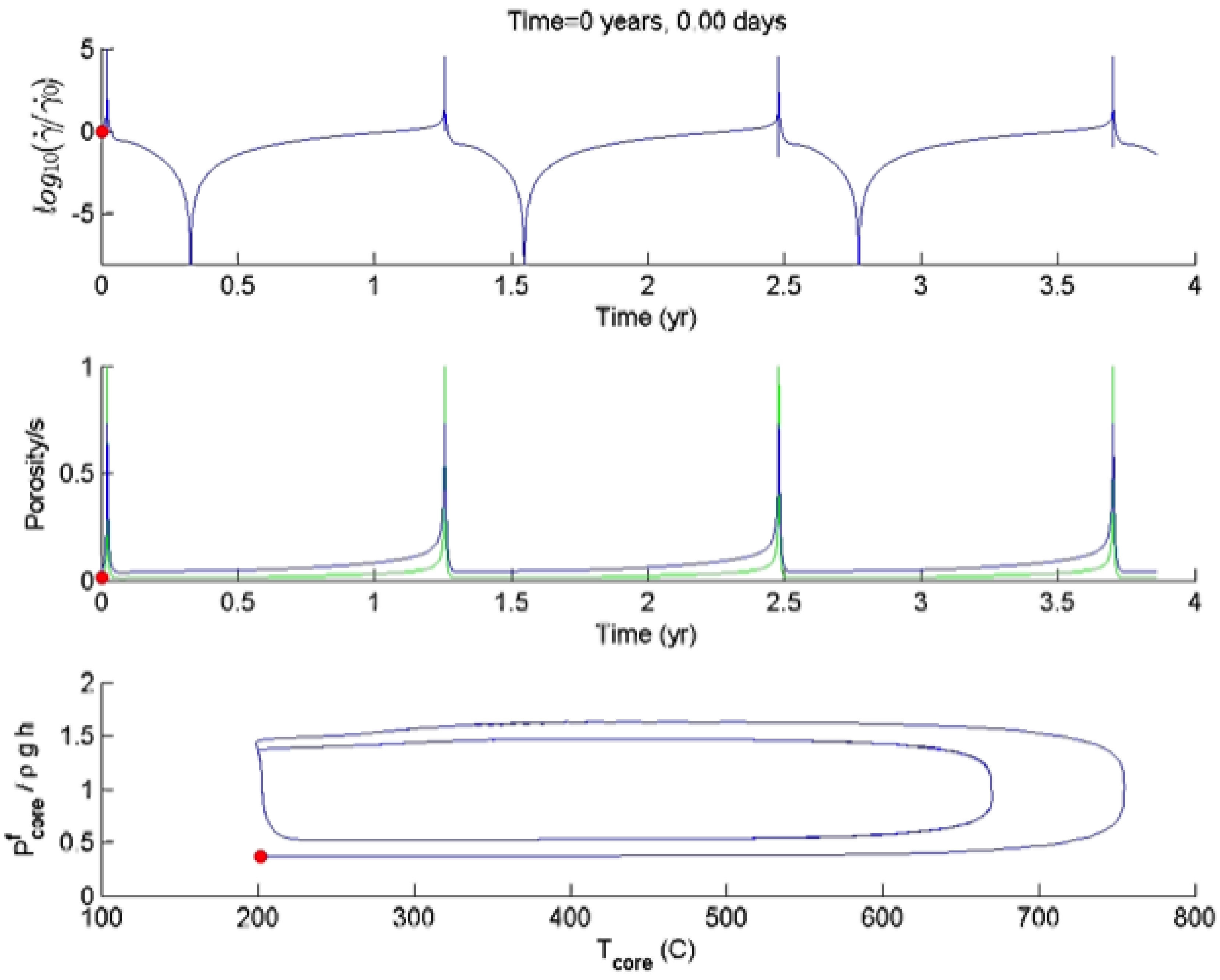


$$Gr = \frac{\text{char. time scale heat production}}{\text{char. time scale energy transfer}}$$

Phase diagrams

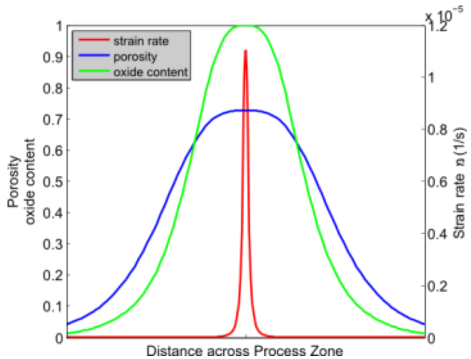
Natural localised instability

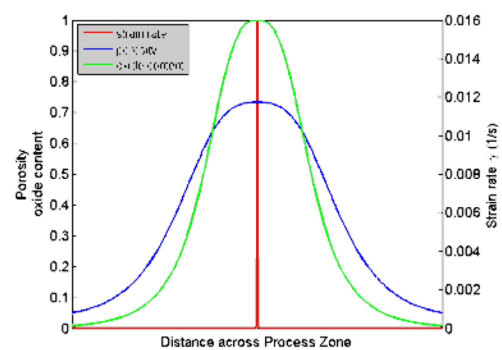



Time=0 years, 0.00 days
$log_{10}(\dot{\gamma}/\dot{\gamma}_0)$
5
0
-5
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (yr)
Porosity/s
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (yr)
$P^f_{core} / \rho g h$
2
1.5
1
0.5
0
100
200
300
400
500
600
700
800
T_{core} (C)

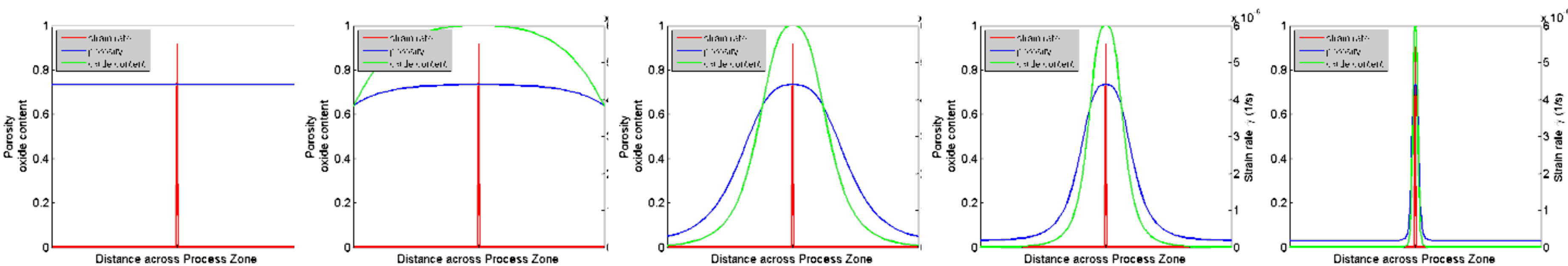
Spatial distributions

- Directly observable in the field
- Mechanical localisation: activation energy





- Chemical localisation: enthalpy of the reaction



Part III: Applications

Fault Mechanics

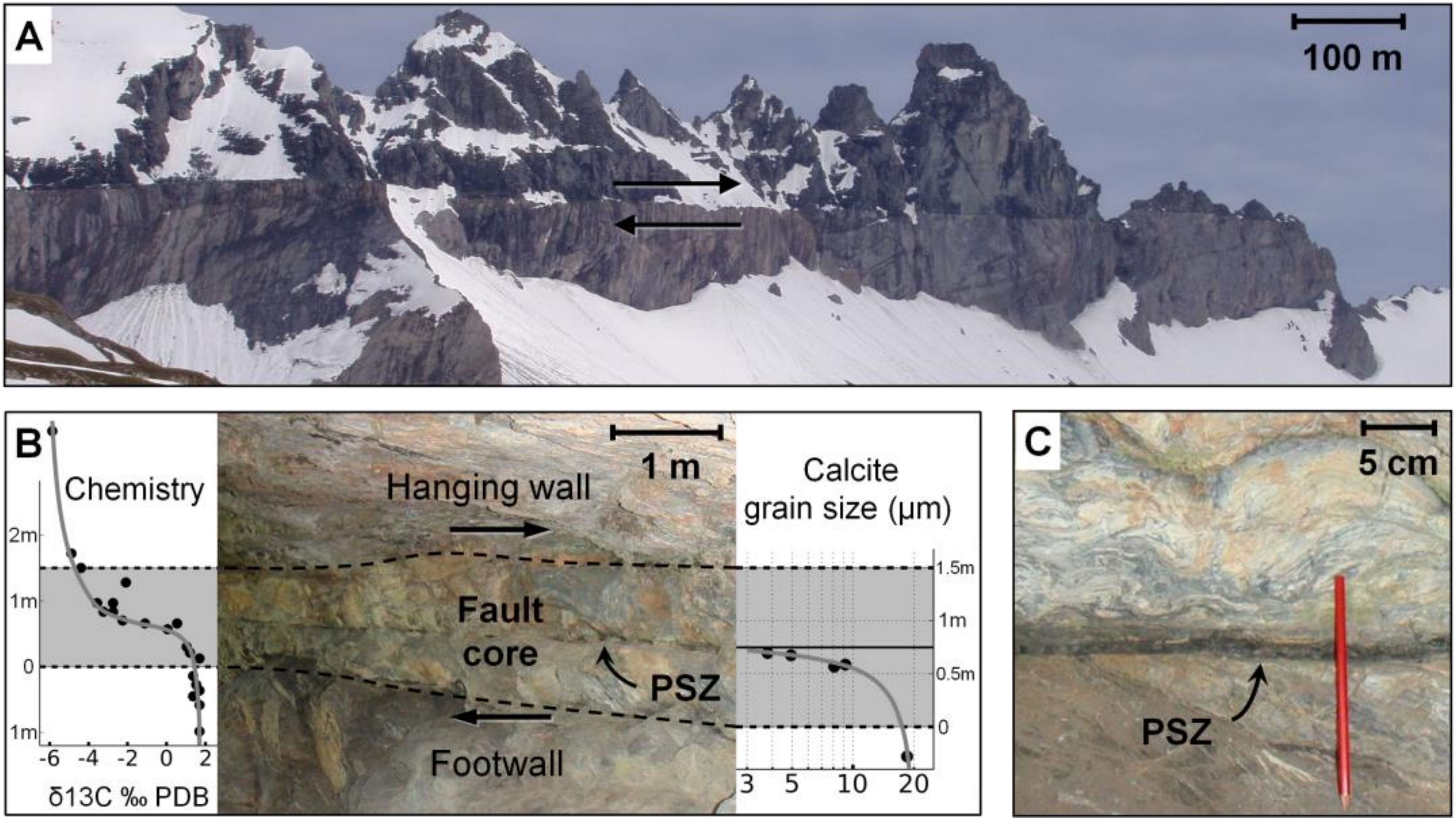
Never Stand Still

Engineering

The Glarus Thrust

A carbonate decomposition example

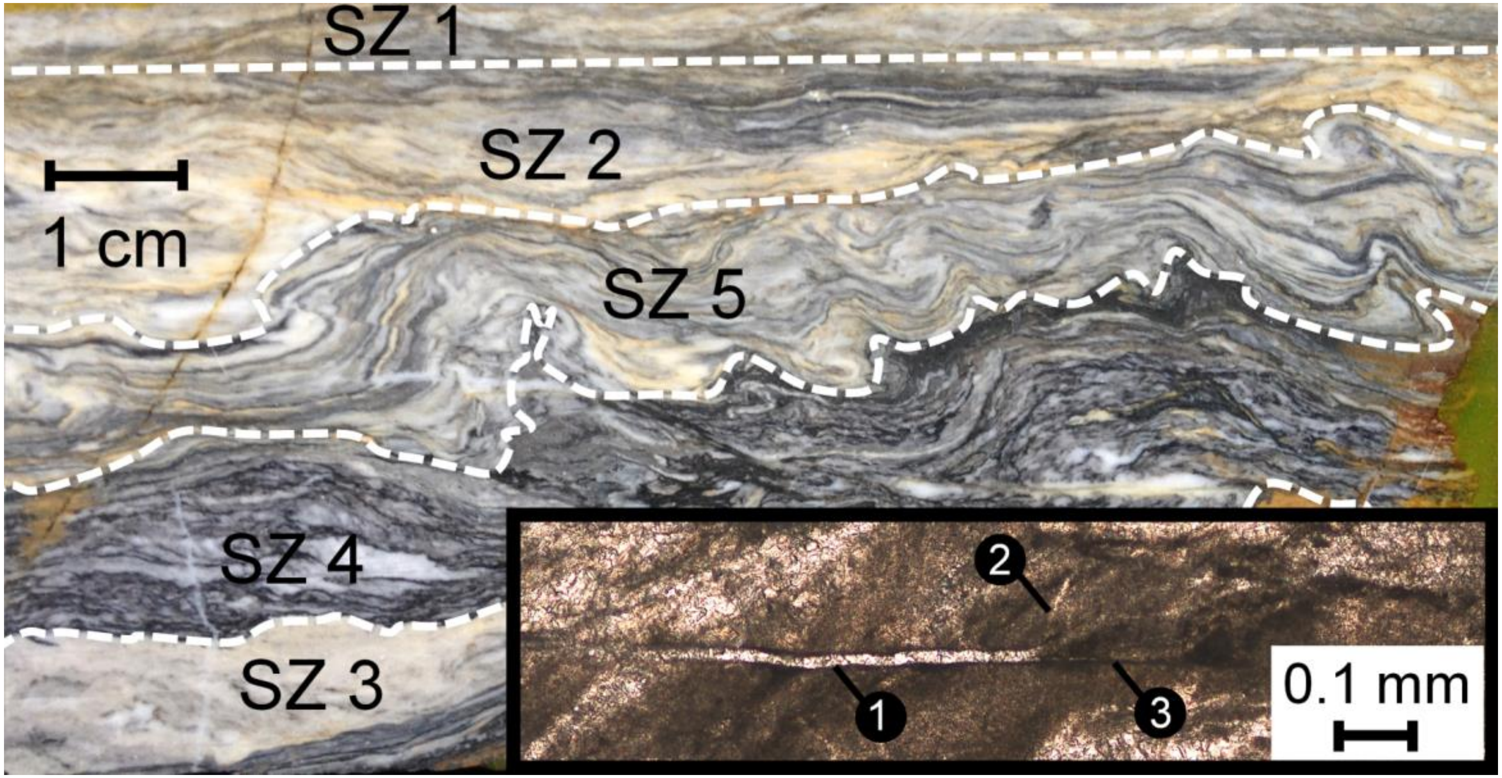

The Glarus Thrust, Switzerland



The Glarus thrust - cyclicity

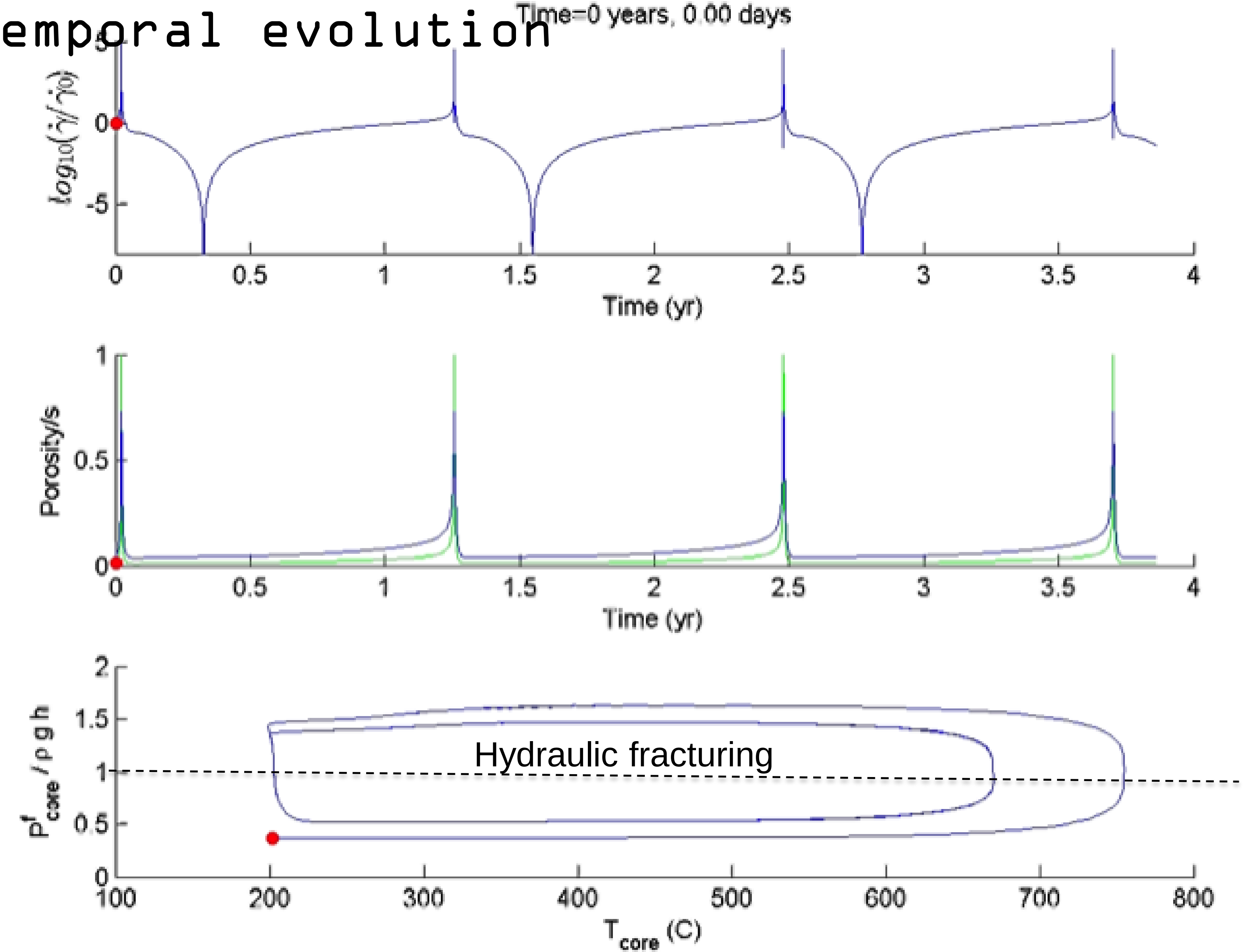
Hanging wall

Lochsite Tectonite

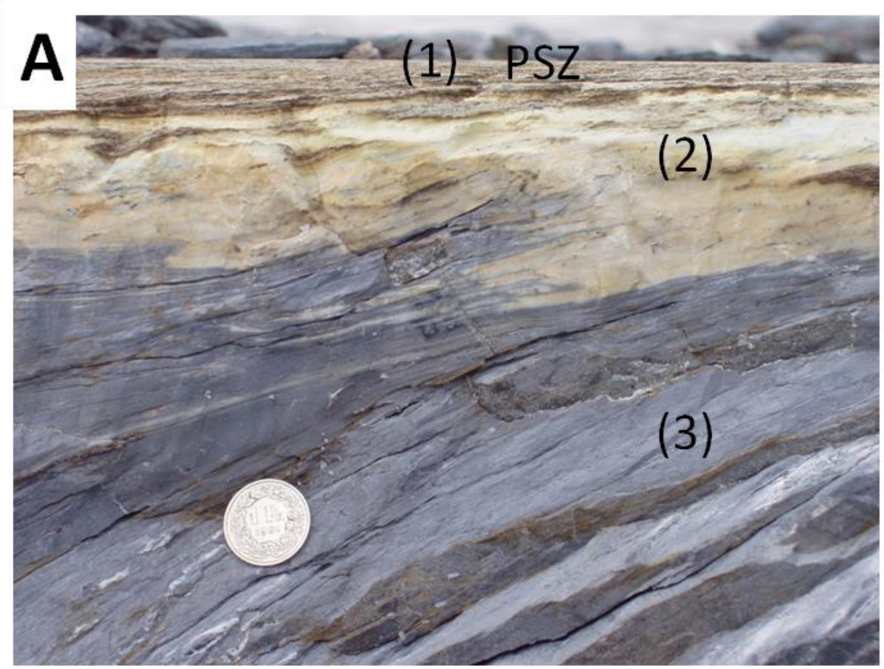


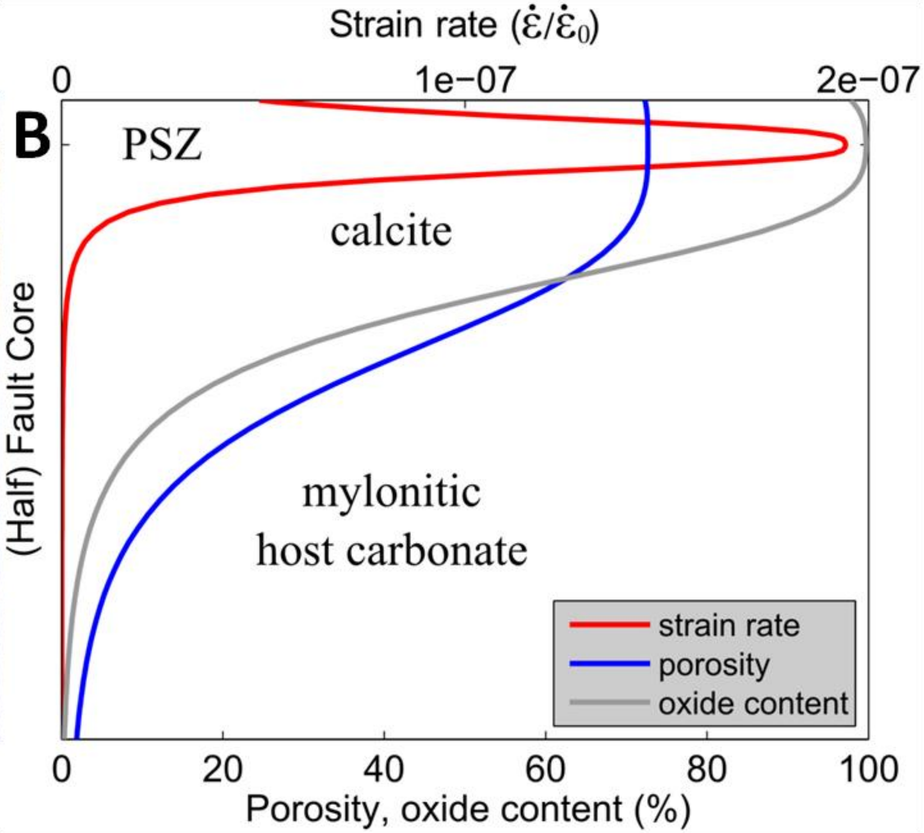
Footwall

Temporal evolution



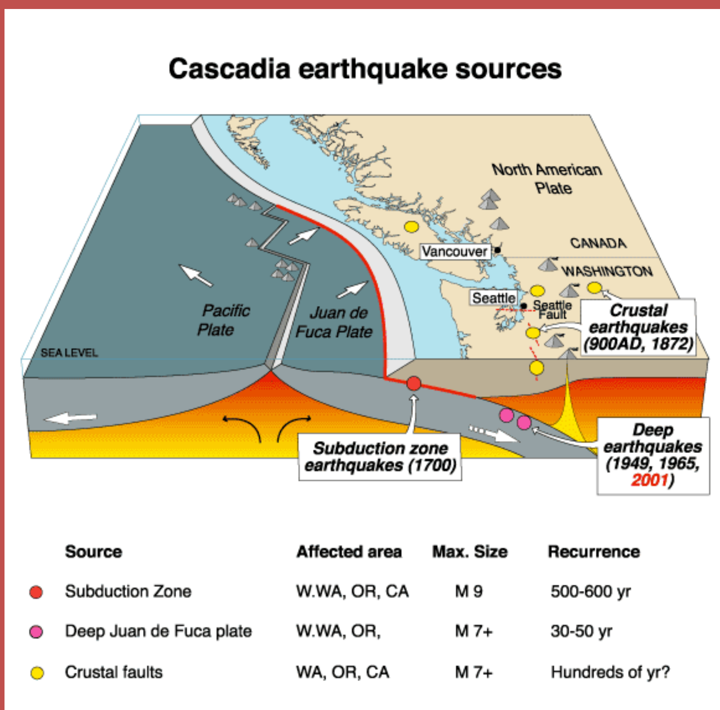
A Glarus pattern

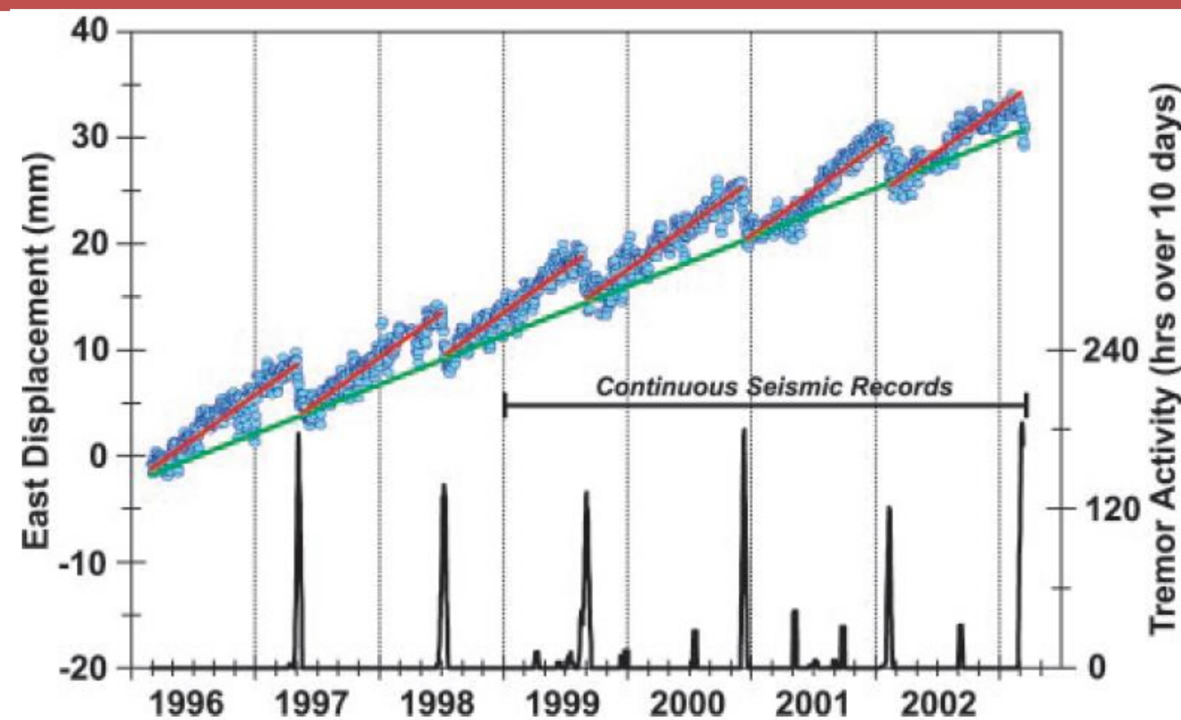




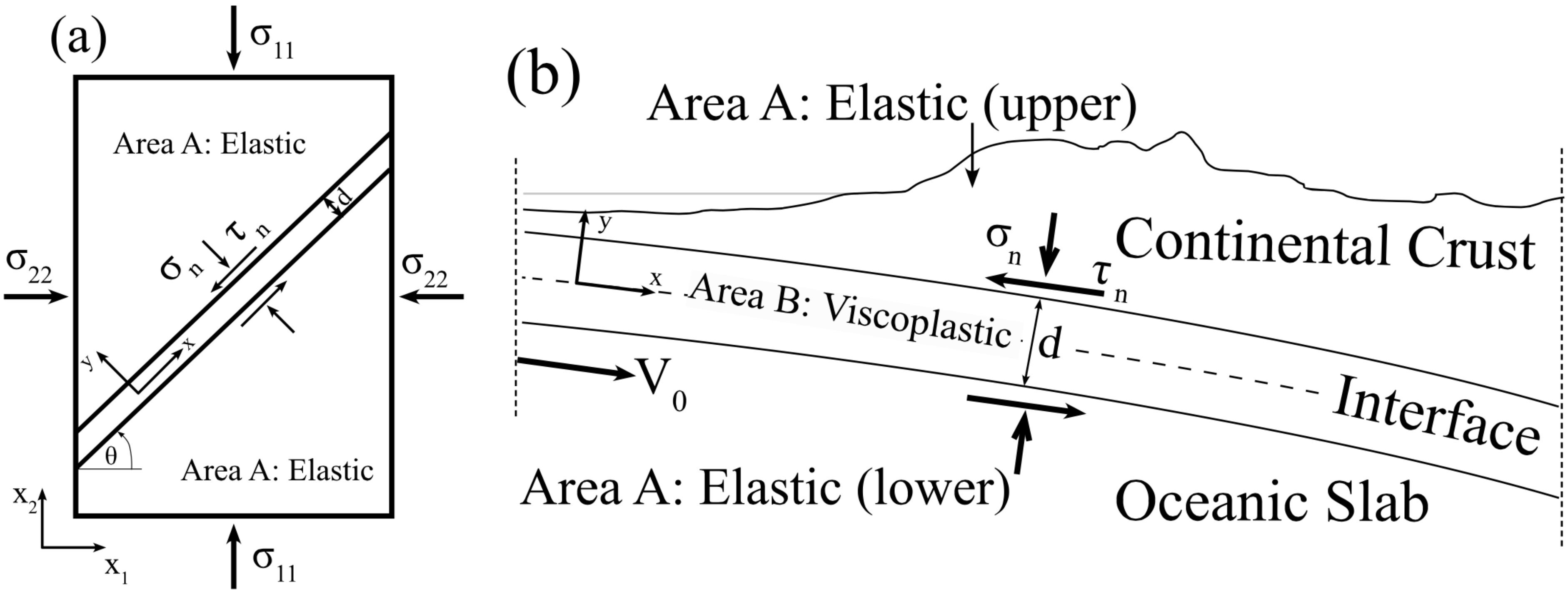
- Calcite as a cause (inverting activation enthalpy from thickness)
- Source of fluid explained (*in-situ* carbonate decomposition)

Subduction zones
Large scale modelling



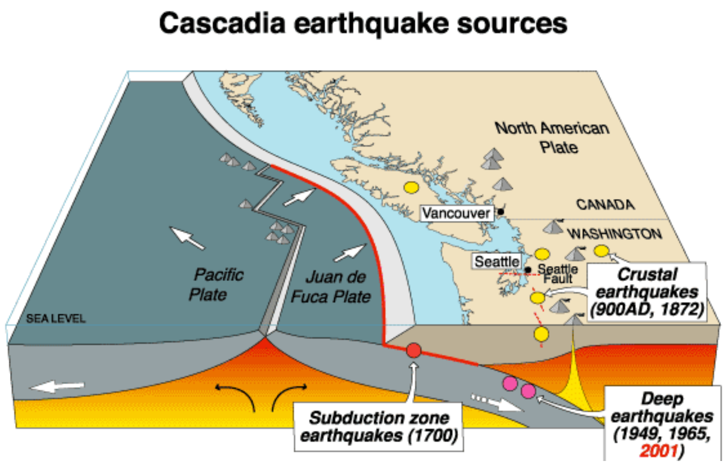


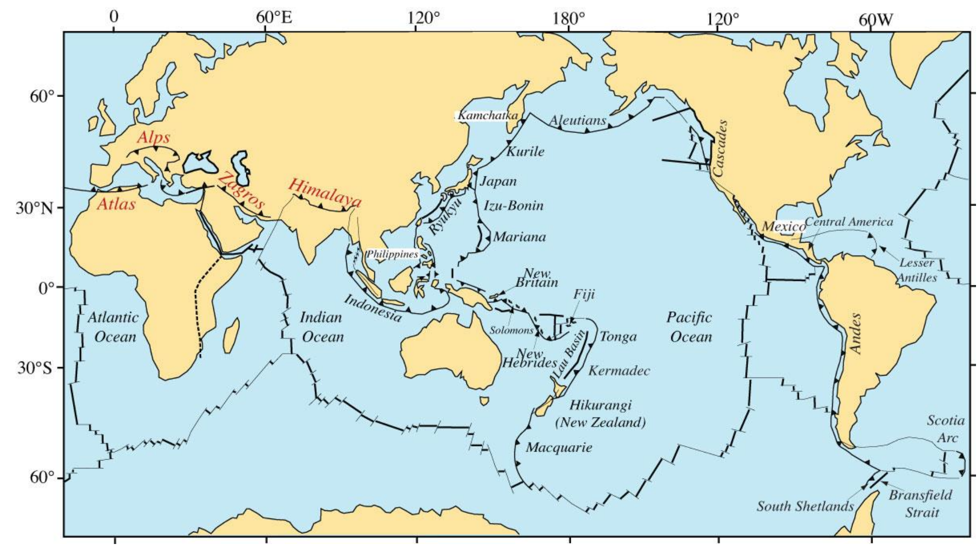
Modelling Subduction zones: Serpentinite dehydration oscillator

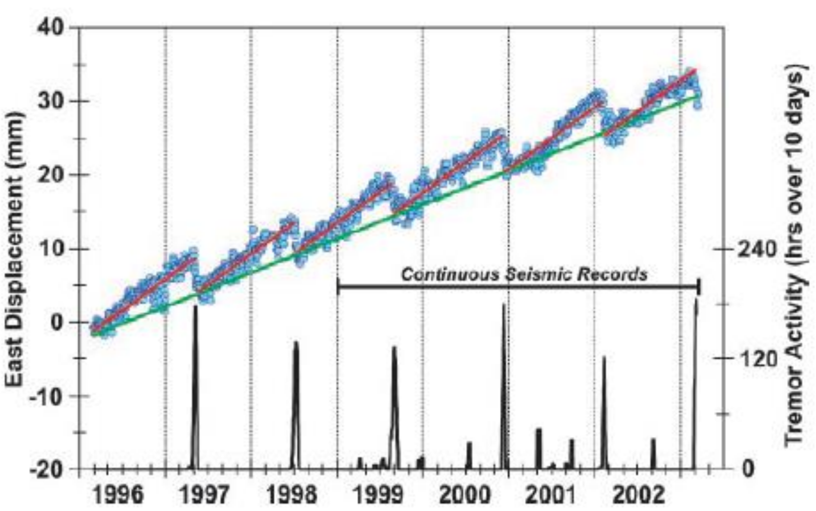


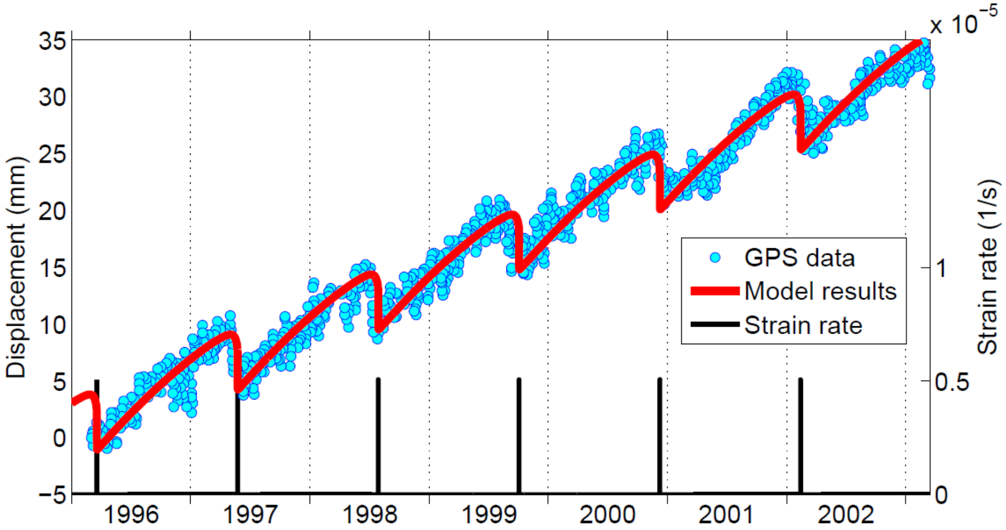
The problem: we require stress continuity at the shear band interface, because of the definition of the shear band as zone of velocity gradient discontinuities. So which BCs do we use?

Modelling subduction zones









Rogers & Dragert, Science (2003)

Alevizos et al, JGR (2014)

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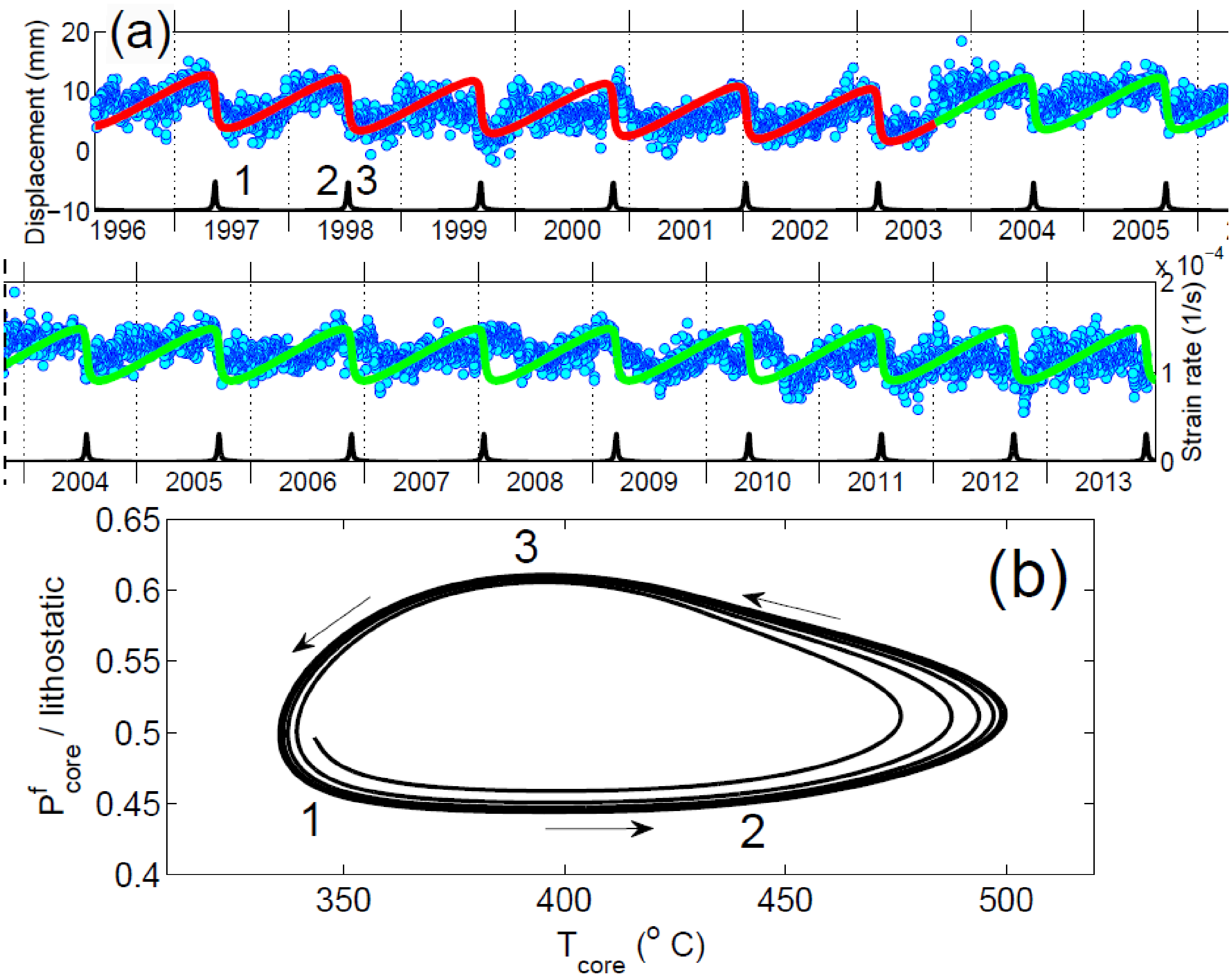
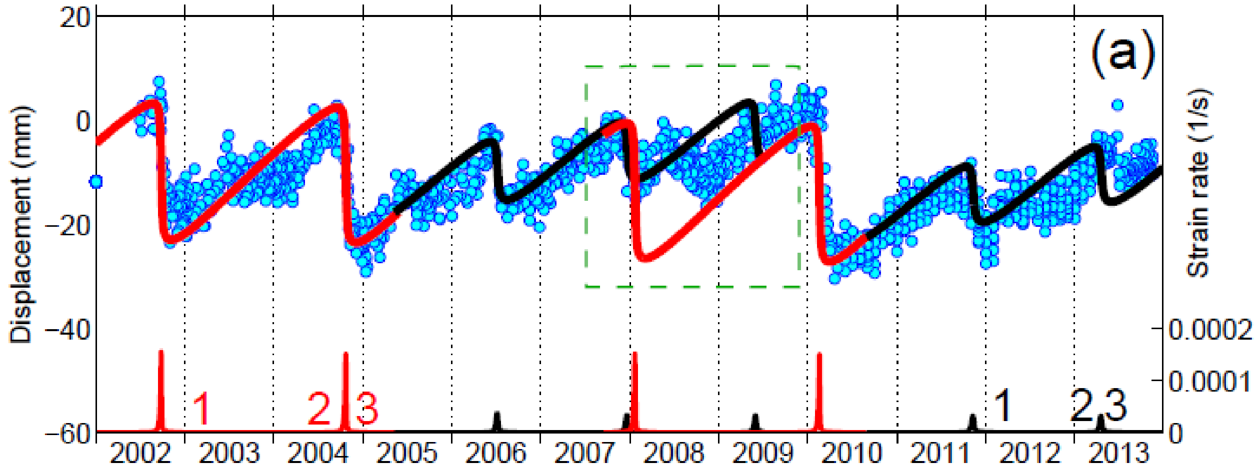
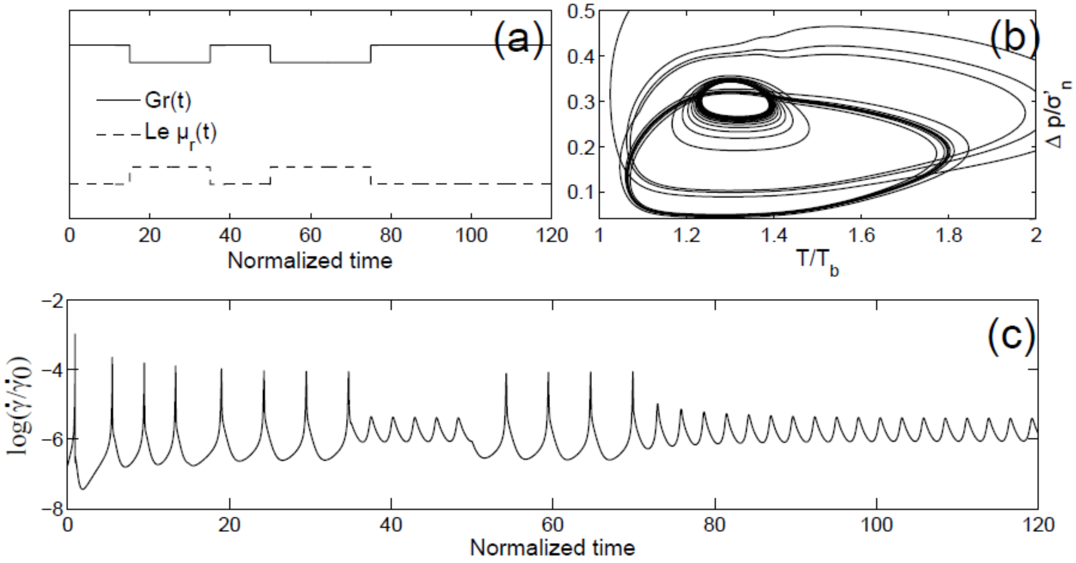
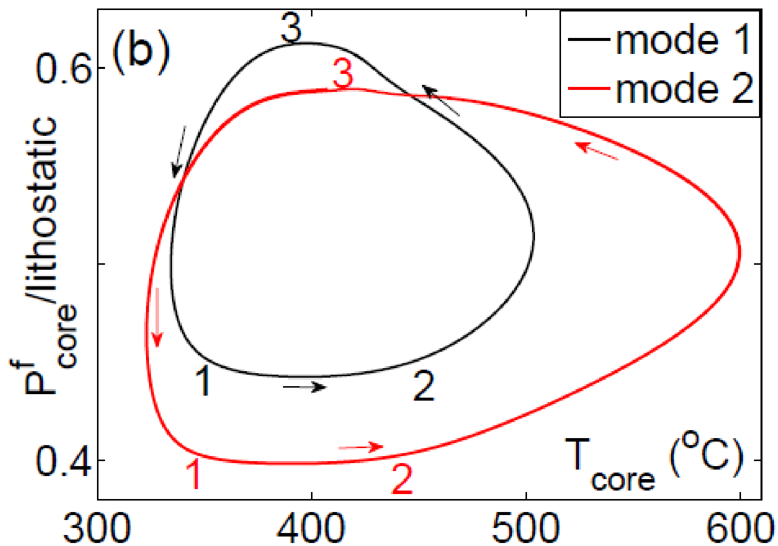
Oscillator cycles, Earth's heartbeats



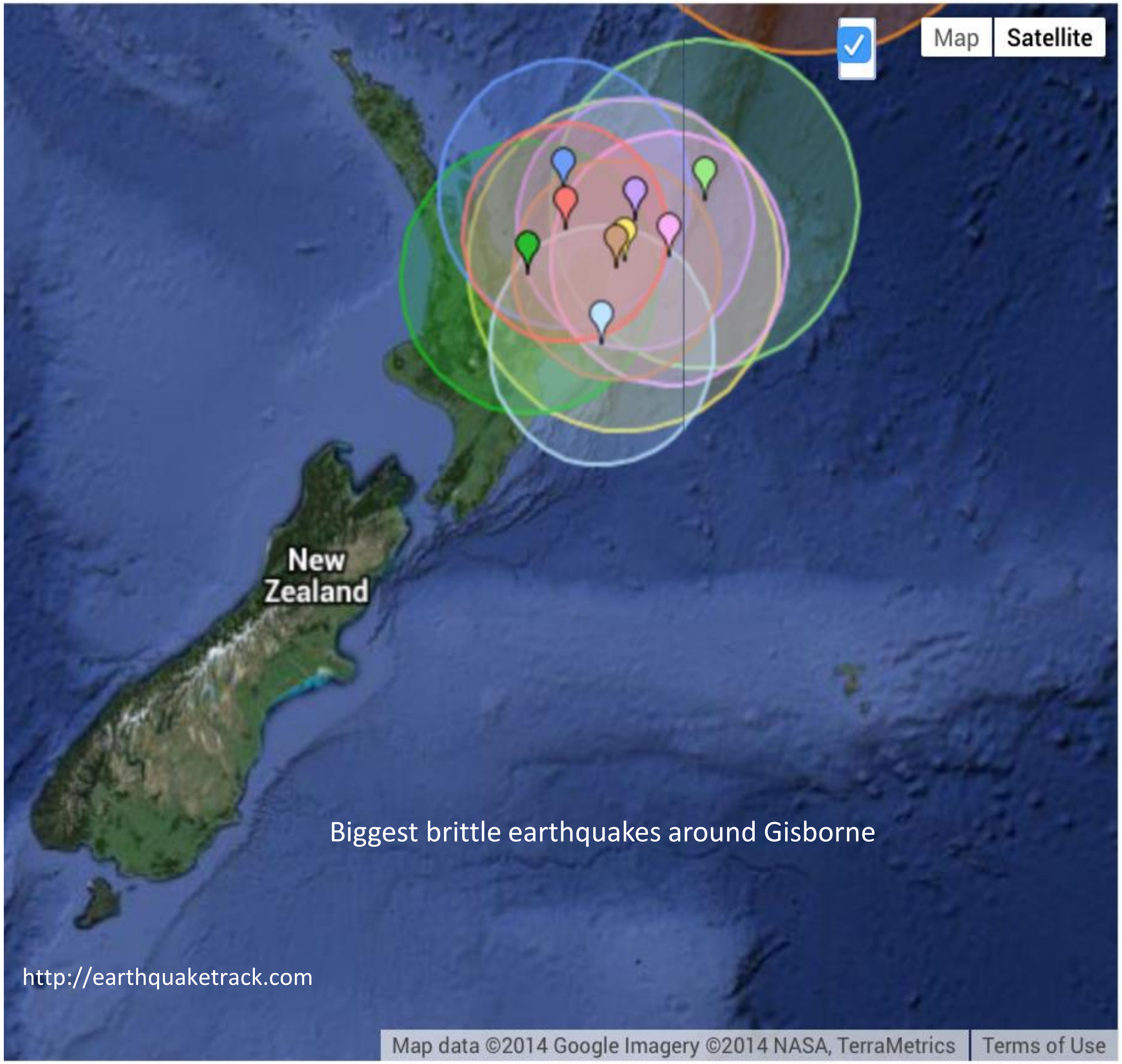
Chaotic signals - Gisborne (New Zealand)







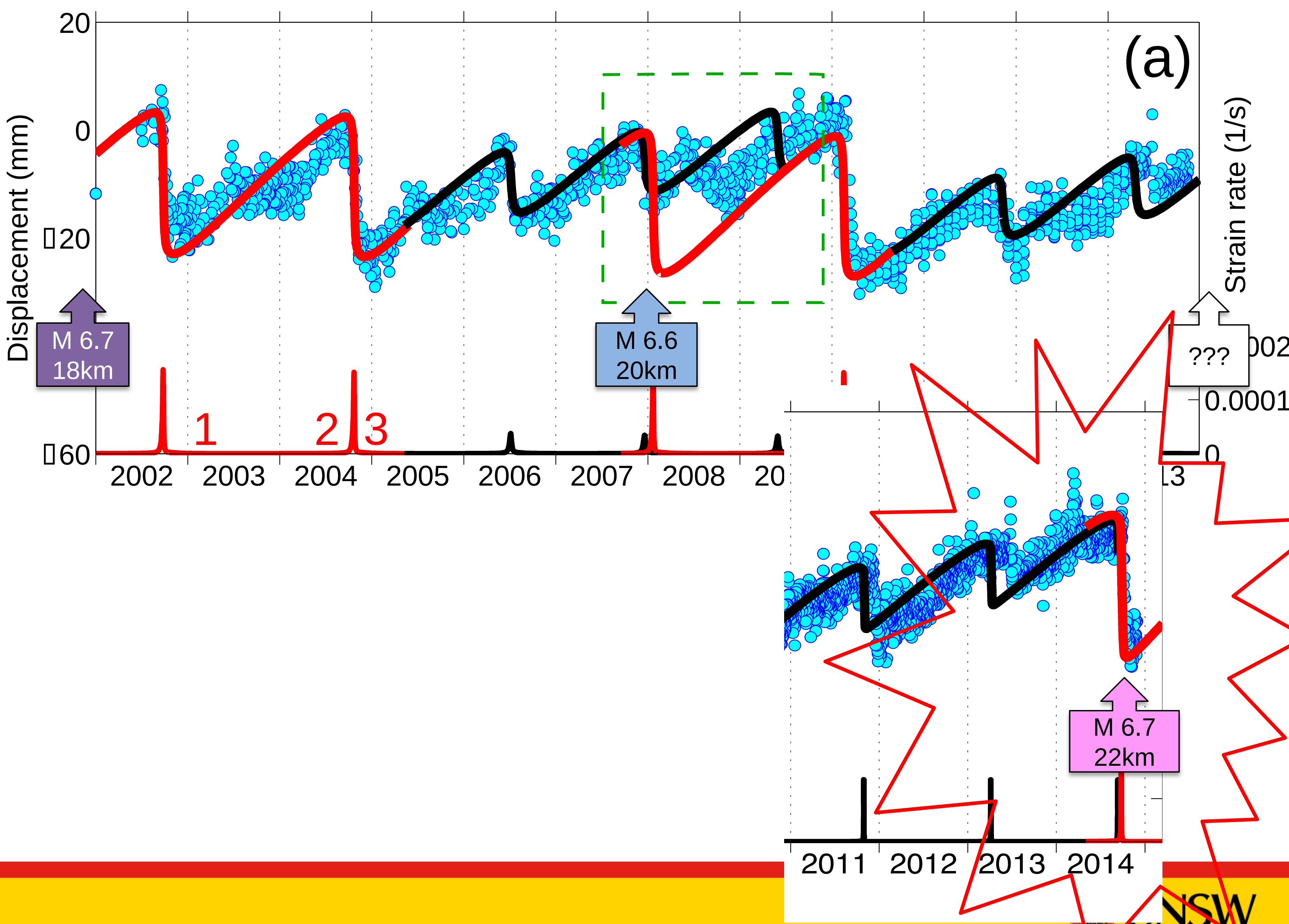
Can we predict brittle earthquakes? (NO,



Biggest brittle earthquakes around Gisborne

http://earthquaketrack.com

37 years ago 7.7 magnitude, 33 km depth	Whangarei, Auckland, New Zealand
20 years ago 7.1 magnitude, 21 km depth	Gisborne, Gisborne, New Zealand
13 years ago 7.1 magnitude, 33 km depth	Gisborne, Gisborne, New Zealand
28 years ago 6.8 magnitude, 19 km depth	Whakatane, Auckland, New Zealand
30 years ago 6.8 magnitude, 39 km depth	Whakatane, Auckland, New Zealand
13 years ago 6.7 magnitude, 18 km depth	Gisborne, Gisborne, New Zealand
24 days ago 6.7 magnitude, 22 km depth	Gisborne, Gisborne, New Zealand
7 years ago 6.6 magnitude, 20 km depth	Gisborne, Gisborne, New Zealand
20 years ago 6.5 magnitude, 28 km depth	Gisborne, Gisborne, New Zealand
20 years ago 6.5 magnitude, 33 km depth	Whakatane, Auckland, New Zealand



(a)
Displacement (mm)
Strain rate (1/s)
M 6.7
18km
M 6.6
20km
???
M 6.7
22km
1
2
3
2002
2003
2004
2005
2006
2007
2008
2011
2012
2013
2014

Matching observations

- **I**ntern. **O**cean **D**iscovery **P**rogram
- Japan Trench Fast Drilling Project

Nature news, Dec 2013:

"The localization of deformation onto a limited thickness (~5 meters) of pelagic clay is the defining characteristic of the shallow earthquake fault" (Chester et al / Science 2013). **"That's just weird"** says Emily Brodsky (UC Santa Cruz)

Table 3. Material Parameters Inverted From the ETS Sequences, After Fitting the GPS Data[a]

Parameter	Units	ALBH	GISB 1	GISB 2
$\dot{\gamma}_0$	s^{-1}	200	230	230
d	m	6.4	6.4	6.4
$\bar{\sigma}'_n$	MPa	49	**49**	**74**
$\beta_T \bar{\tau}_n$	MPa	0.3	**0.26**	**0.20**
k_F	s^{-1}	10^8	10^8	10^8
Q_F	kJ/mol	114	114	114
k_R	s^{-1}	10^{-2}	10^{-2}	10^{-2}
ΔH	kJ/mol	80	80	80
Q_R	kJ/mol	34	34	34

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE

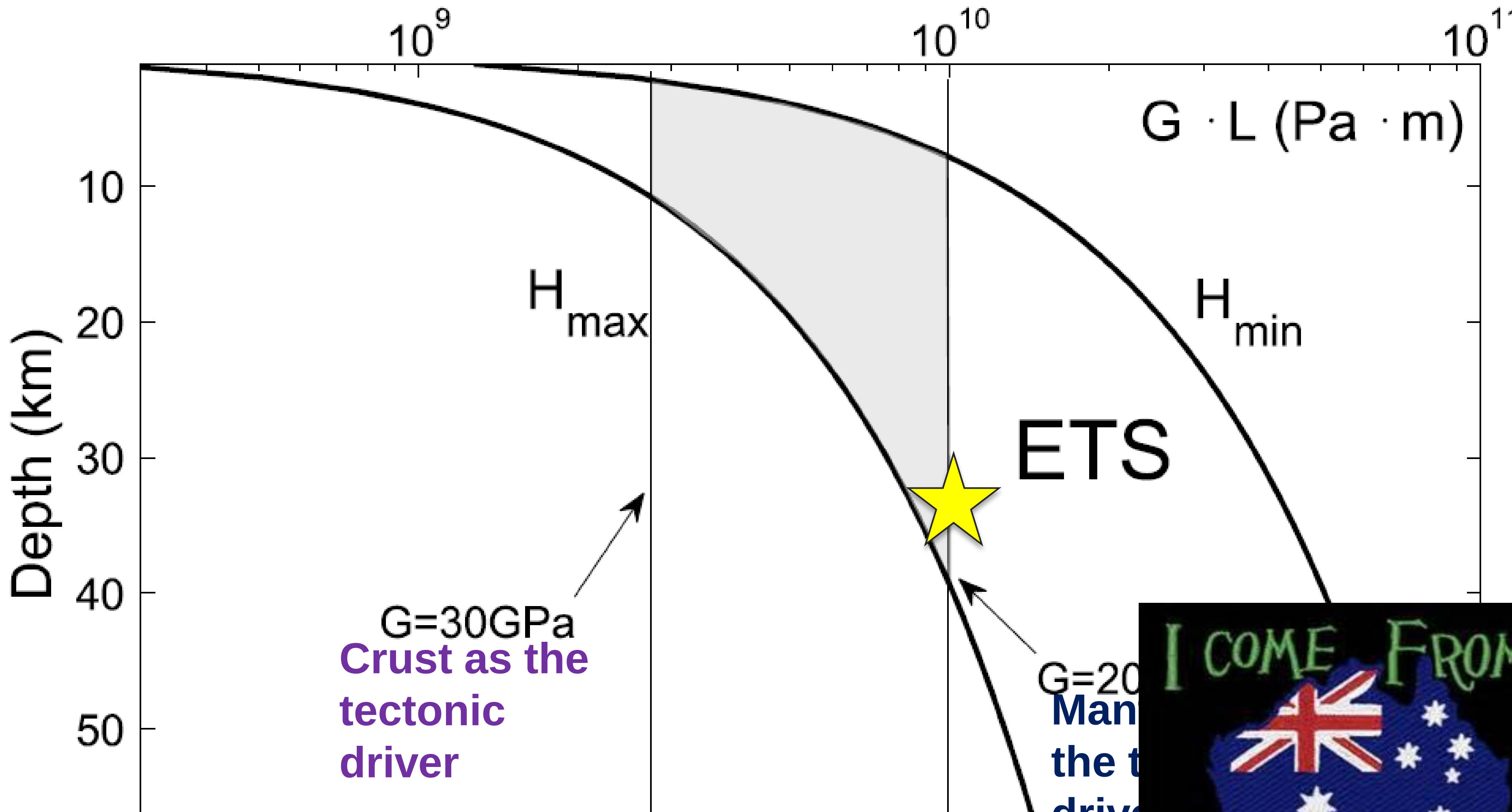
10.1002/2014JB011004

This is a companion paper to *Alevizos et al.* [2014], doi:10.1002/2013JB010070,

Thermo-poro-mechanics of chemically active creeping faults: 3. The role of serpentinite in episodic tremor and slip sequences, and transition to chaos

T. Poulet[1], E. Veveakis[1,2], K. Regenauer-Lieb[1,3], and D. A. Yuen[4,5]

ETS location and tectonic driver: Cascadia



TECTONICS DOWN-UNDER!

More is less

Thank you!

http://github.com/pou036/redback.git

Some of our work on the topic

- Veveakis E, Alevizos S., T. Poulet, 2016. Episodic tremor and slip (ETS) as a chaotic multiphysics spring, *Phys. Earth and Planetary Interiors, in press*
- Alevizos S., T. Poulet, E. Veveakis and K. Regenauer-Lieb, 2016. Analysis of dynamics in multiphysics modelling of active faults, *Mathematics, 4, 57, doi: 10.3390/math4040057*
- Poulet T., M. Paesold and E. Veveakis, 2016. Multiphysics modelling for fault mechanics using REDBACK: A parallel open–source simulator for tightly coupled problems, *Rock Mechanics and Rock Engineering, in press (available online), doi: 10.1007/s00603-016-0927-y*
- Peters M., M. Herwegh, M. K. Paesold, T. Poulet, K. Regenauer-Lieb and E. Veveakis, 2016. Boudinage and folding as the same energy attractor of ductile deformation, *J. Geophys. Res., 121, 3996–4013, doi: 10.1002/ 2016JB012801*
- Paesold M., A. Bassom, K. Regenauer-Lieb and E. Veveakis, 2016. Conditions for the localization of plastic deformation in temperature sensitive visco-plastic materials, *J. Mech. Mat. Structures, 11 (2), 113-136, doi: 10.2140/jomms.2016.11.113*
- Poulet T. and E. Veveakis, 2016. A viscoplastic approach for pore collapse in saturated soft rocks using REDBACK: an open-source parallel simulator for Rock mEchanics with Dissipative feedBACKs, *Computers and Geotechnics*, *74, 211-221, doi:10.1016/j.compgeo.2015.12.015*
- Veveakis E. and K. Regenauer-Lieb, 2015. Review of extremum postulates. *Current Opinion in Chemical Engineering, 7, 40-46, doi: 10.1016/j.coche.2014.10.006*
- Veveakis E. and K. Regenauer-Lieb, 2015. Cnoidal waves in solids. *J. Mech. Phys. Solids,* 78, 231– 248*, doi: 10.1016/j.jmps.2015.02.010.*
- Peters M., E. Veveakis, T. Poulet, A. Karrech, M. Herwegh and K. Regenauer-Lieb, 2015. Boudinage as a material instability of elasto-visco-plastic rocks. *J. Struct. Geology, Vol. 78, 86–102, doi:10.1016/j.jsg.2015.06.005*
- Alevizos S., Poulet T. and Veveakis, E., 2014. Thermo-poro-mechanics of chemically active faults. 1: Theory and steady-state considerations, *J. Geophys. Res. Vol 119 (6), 4558-4582, doi: 10.1002/2013JB010070,*
- Veveakis E., Poulet T. and Alevizos S, 2014. Thermo-poro-mechanics of chemically active faults. 2: Transient Considerations, *J. Geophys. Res. Vol 119 (6), 4583-4605 doi: 10.1002/2013JB010071.*
- Poulet T., Veveakis E., K. Regenauer-Lieb, D.A. Yuen, 2014. Thermo-Poro-Mechanics of chemically active creeping faults. 3: The role of Serpentinite in Episodic Tremor and Slip sequences, and transition to chaos, *J. Geophys. Res. Vol 119 (6), 4606-4625, doi: 10.1002/ 2014JB011004.*
- Veveakis E. and K. Regenauer-Lieb, 2014. The Fluid Dynamics of Solid Mechanical Shear Zones, *Pure Appl. Geophys., Vol 171 (11), pp 3159-3174, doi: 10.1007/s00024-014-0835-6.*
- Poulet T, E. Veveakis, M. Herwegh, T. Buckingham and K. Regenauer-Lieb, 2014. Modeling episodic fluid-release events in the ductile carbonates of the Glarus thrust, *Geophys. Res. Lett.,41(20), 7121- 7128, doi: 10.1002/2014GL061715*
- Veveakis E., Alevizos S. and Vardoulakis I., 2010. Chemical Reaction Capping of Thermal Instabilities During Shear of Frictional Faults, *J. Mech. Phys. Solids*, 58, 1175-1194, doi: *10.1016/j.jmps.2010.06.010*.
- Alevizos S., Gerolymatou E. and Veveakis E., 2010. Thermoporomechanics of landslides: A review of the Vaiont slide. *Eur. J. Env. Civ. Eng.* 14 (8-9), 1185-1198, doi: *10.3166/EJECE.14.1185-1198*.
- Veveakis, E., I. Vardoulakis, and G. Di Toro, 2007, Thermoporomechanics of creeping landslides: The 1963 Vaiont slide, northern Italy, *J. Geophys. Res*., 112, F03026, doi: *10.1029/2006JF000702*

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Key references for further reading

- Chen, H., A. S. Douglas, and R. Malek-Madani (1989), An asymptotic stability condition for inhomogeneous simple shear, *Q. Appl. Math.*, *47*, 247–262.
- Colletini, C., C. Viti, T. Tesei, and S. Mollo (2013), Thermal decomposition along natural carbonate faults duing earthquakes, *Geology*, *41*, 927–930, doi:10.1130/G34421.1.
- Coussy, O. (Ed.) (2004), *Poromechanics*, John Wiley & Sons, Chichester, U. K.
- Dieterich, J. (1972), Time-dependent friction in rocks, *J. Geophys. Res.*, *377*, 3690–3697.
- Dieterich, J. (1978), Time-dependent friction and the mechanics of stick-slip, *Pure Appl. Geophys.*, *116*, 790–806.
- Fialko, Y., and Y. Khazan (2005), Fusion by earthquake fault friction: Stick or slip?, *J. Geophys. Res.*, *110*, B12407, doi:10.1029/2005JB003869.
- Fowler, A. (Ed.) (1997), *Mathematical Models in the Applied Sciences*, 2nd ed., Cambridge Univ. Press, Cambridge, U. K.
- Gruntfest, I. (1963), Thermal feedback in liquid flow: Plane shear at constant stress, *Trans. Soc. Rheol.*, *7*, 195–207.
- Hilairet, N., B. Reynard, Y. Wang, I. Daniel, S. Merkel, N. Nishiyama, and S. Petigirard (2007), High-pressure creep of serpentine, interseismic deformation, and initiation of subduction, *Science*, *318*, 1910–1912.
- Hueckel, T., and G. Baldi (1990), Thermoplastic behavior of saturated clays: An experimental constitutive study, *J. Geotech. Eng.*, *116*(12),
- 1778–1796.
- Hueckel, T., and R. Pellegrini (2002), Reactive plasticity for clays: Application to a natural analog of long-term geomechanical effects of nuclear waste disposal, *Eng. Geol.*, *64*, 195–215.
- Kanamori, H., and E. Brodsky (2004), Physics of earthquakes, *Rep. Prog. Phys.*, *67*(8), 1429–1496.
- Karato, S. (Ed.) (2008), *Deformation of Earth Materials*, pp. 347–349, Cambridge Univ. Press, Cambrige, U. K.
- Law, C. (Ed.) (2006), *Combustion Physics*, Cambridge Univ. Press, Cambridge, U. K.
- Perzyna, P. (1966), Fundamental problems in viscoplasticity, *Adv. Appl. Mech.*, *9*, 243–377.
- Regenauer-Lieb, K., D. Yuen, and F. Fusseis (2009), Landslides, ice quakes, earthquakes: A thermodynamic approach to surface
- instabilities, *Pure Appl. Geophys.*, *166*(10-11), 1885–1908.
- Rice, J., N. Lapusta, and K. Ranjith (2001), Rate and state dependent friction and the stability of sliding between elastically deformable
- solids, *J. Mech. Phys. Solids*, *49*, 1865–1898.
- Rice, J. R. (2006), Heating and weakening of faults during earthquake slip, *J. Geophys. Res.*, *111*, B05311, doi:10.1029/2005JB004006.
- Rosakis, P., A. Rosakis, G. Ravichandran, and J. Hodowany (2000), A thermodynamic internal variable model for the partition of plastic
- work into heat and stored energy in metals, *J. Mech. Phys. Solids*, *48*, 581–607.
- Rowe, C., A. Fagereng, J. Miller, and B. Mapani (2012), Signature of coseismic decarbonation in dolomitic fault rocks of the Naukluft
- Thrust, Namimbia, *Earth Planet. Sci. Lett.*, *333-334*, 200–210.
- Ruina, A. (1983), Slip instability and state variable friction laws, *J. Geophys. Res.*, *88*(B12), 10,359–10,370, doi:10.1029/JB088iB12p10359.
- Scholz, C. (1998), Earthquakes and friction laws, *Nature*, *391*, 37–42.
- Sulem, J., and V. Famin (2009), Thermal decomposition of carbonates in fault zones: Slip-weakening and temperature-limiting effects., *J. Geophys. Res.*, *114*, B03309, doi:10.1029/2008JB006004.
- Sulem, J., P. Lazar, and I. Vardoulakis (2007), Thermo-poro-mechanical properties of clayey gouge and application to rapid fault shearing, *Int. J. Num. Anal. Meth. Geomechan.*, *31*(3), 523–540.
- Taylor, G., and H. Quinney (1934), The latent energy remaining in a metal after cold working, *Proc. R. Soc. Ser. A.*, *143*, 307–326.
- Truesdell, C., and R. Toupin (1960), The classical field theories. Encyclopedia of physics, III/1, in *Principles of Classical Mechanics and Field*
- *Theory/Prinzipien der Klassischen Mechanik und Feldtheorie*, edited by S. Flügge, pp. 226–793, Handbuch der Physik (Encyclopedia of Physics). III/1, Springer-Verlag, New York.
- Tse, S., and J. Rice (1986), Crustal earthquake instability in relation to the depth variation of frictional slip properties, *J. Geophys. Res.*, *91*(B9), 9452–9472.
- Vardoulakis, I. (2002a), Steady shear and thermal run-away in clayey gouges, *Int. J. Solids Struct.*, *39*, 3831–3844.
- Vardoulakis, I. (2002b), Dynamic thermo-poro-mechanical analysis of catastrophic landslides, *Geotechnique*, *52*, 157–171.
- Vardoulakis, I., and J. Sulem (Eds.) (1995), *Bifurcation Analysis in Geomechanics*, Blankie Acc. and Professional., Bishopbriggs, Glasgow.
- Wibberley, C., and T. Shimamoto (2005), Earthquake slip weakening and asperities explained by thermal pressurization, *Nature*, *426*(4), 68[illegible]–6[illegible]2.
- Yuen, D., M. Saari, and G. Schubert (1986), Explosive growth of shear-heating instabilities in the down-slope creep of ice sheets, *J. Glaciol.*, *32*(11[illegible]), 814–32[illegible].

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