(Carbonate) Fault Reactivation as a THMC instability

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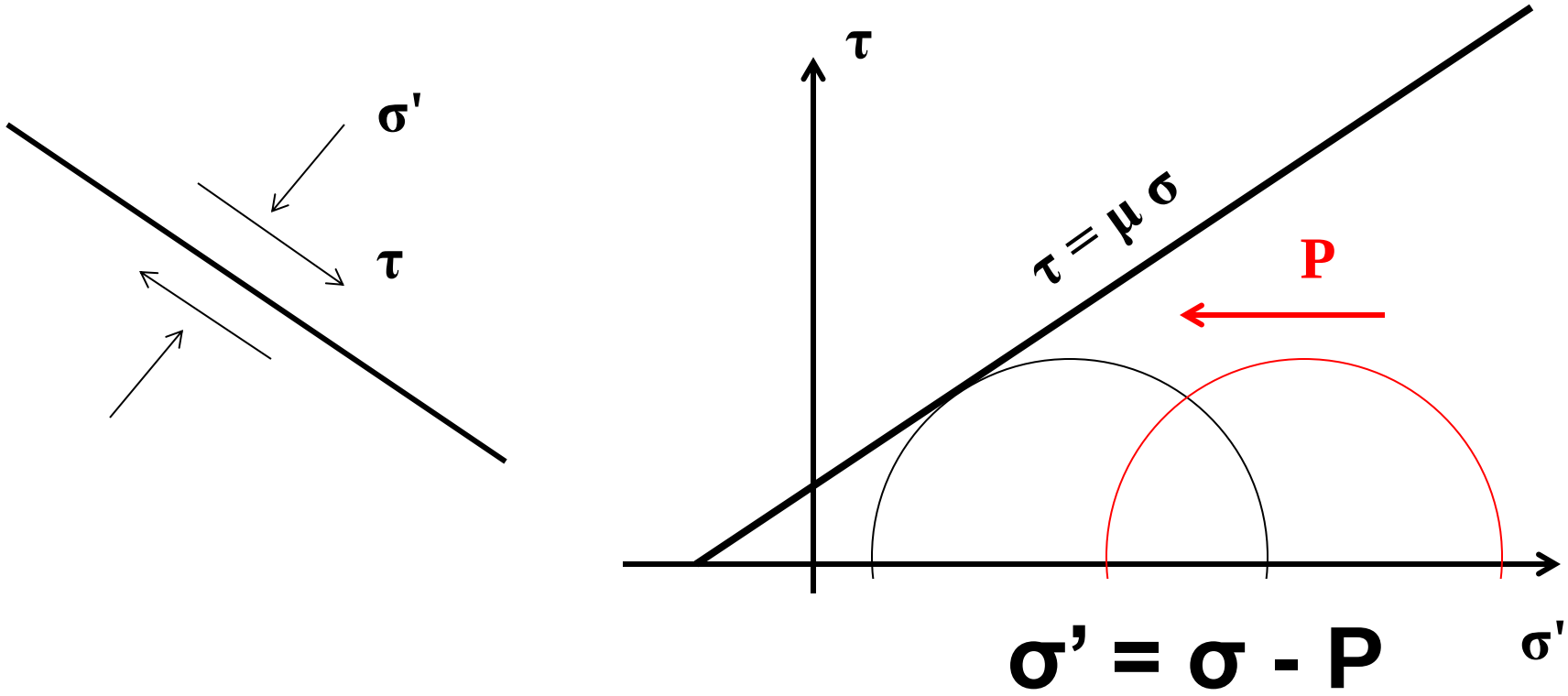
GEOPROC

Fault Reactivation – Classical Definitions

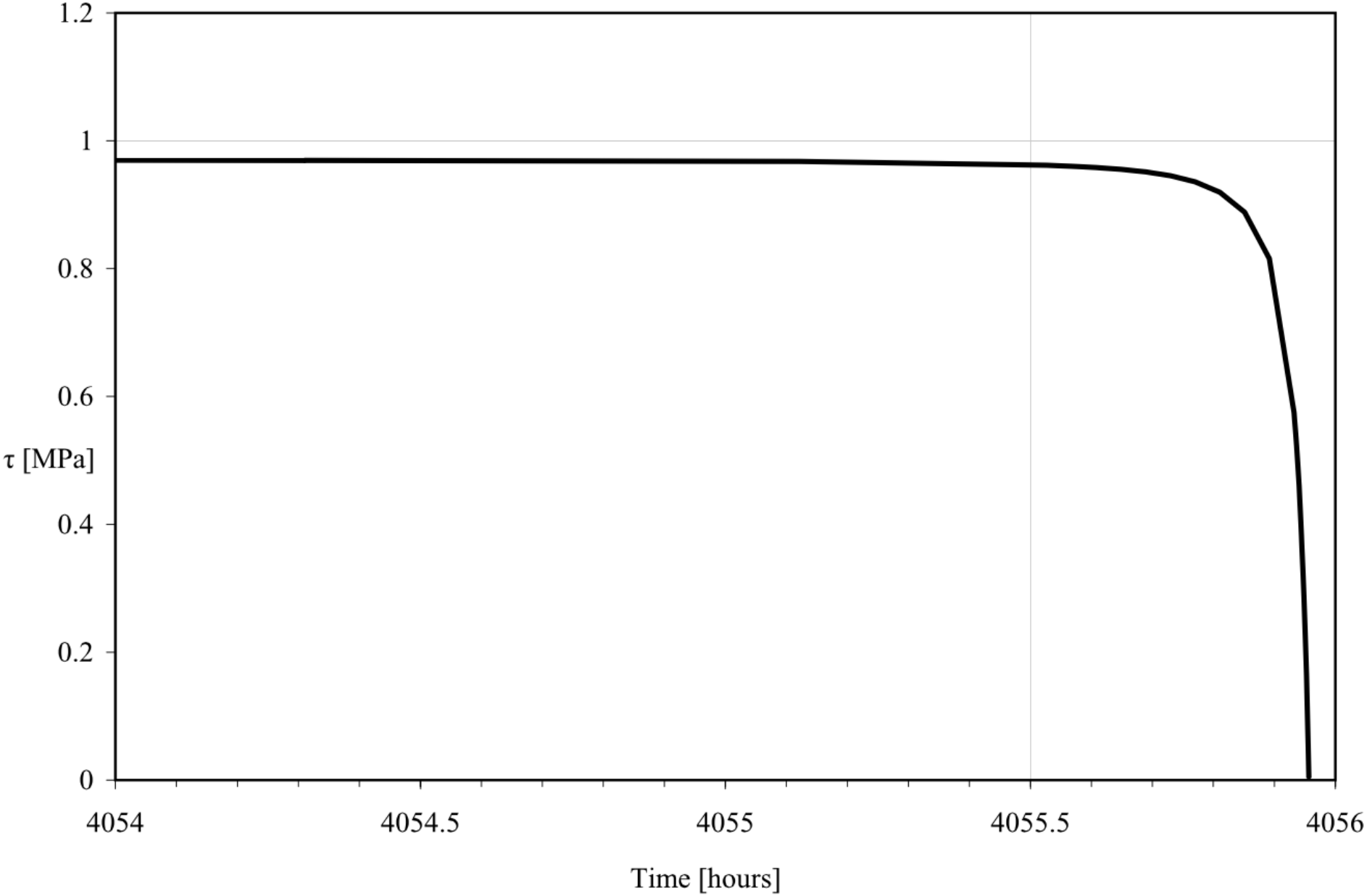


$$\sigma' = \sigma - P$$

Very well known conclusions:

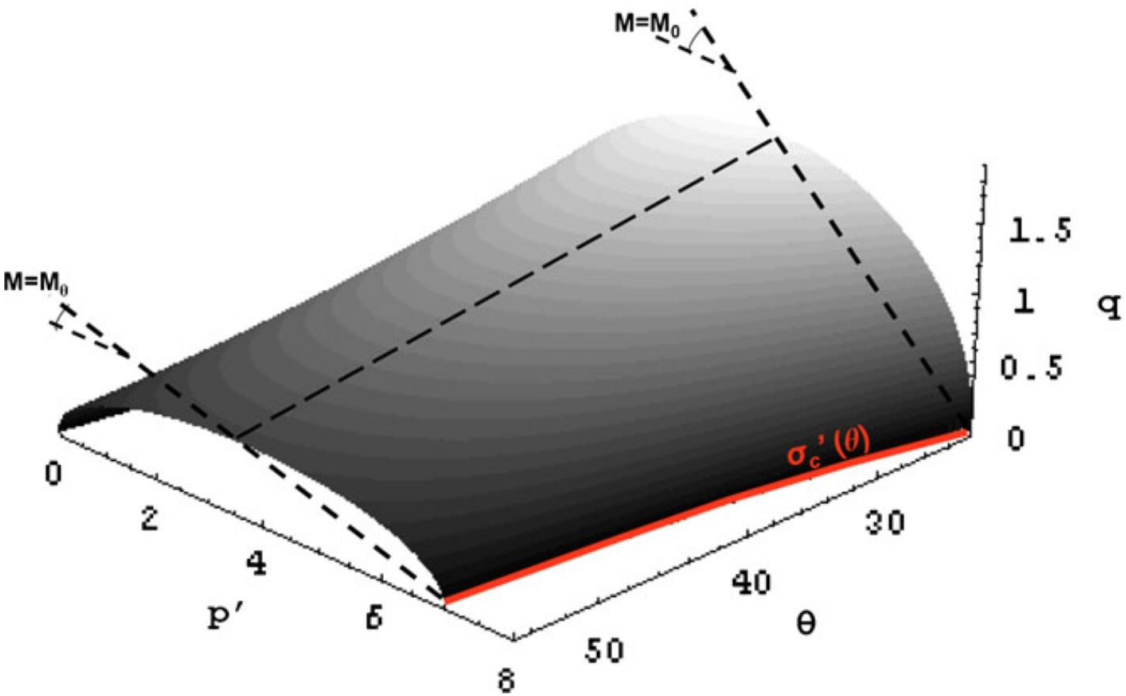
1. If the effective stresses are constant, pore-fluid pressure drives the process
2. In the absence of pore fluid variations, the friction coefficient drives the instability

Example that emphasizes the need for more info

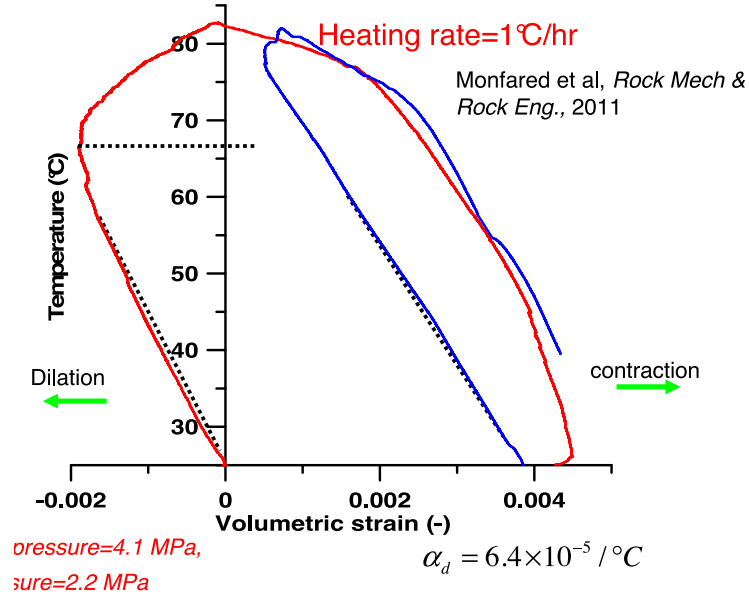


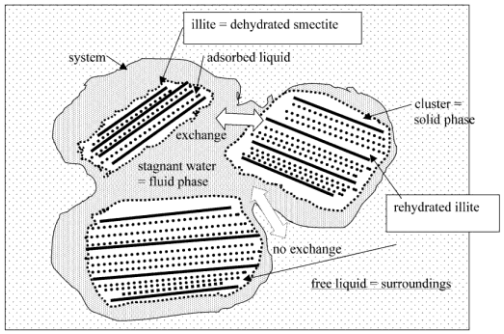
Clay thermal properties: Rheology and Dehydration

Cecinato et al., 2011, IJNAMG



Drained heating test on Opalinus clay





The solution was found in… combustion physics!

Energy+Entropy balance laws:

$$\frac{\partial \theta}{\partial t} = \kappa_m \frac{\partial^2 \theta}{\partial z^2} + \frac{1}{j(\rho C)_m} D_{loc}$$

Local Dissipation, deviatoric component only:

$$D_{loc} = \sigma_{xz} D_{xz} + \sigma_{zx} D_{zx} \approx \tau_d \frac{\partial v}{\partial z} = \tau_d \dot{\gamma}$$

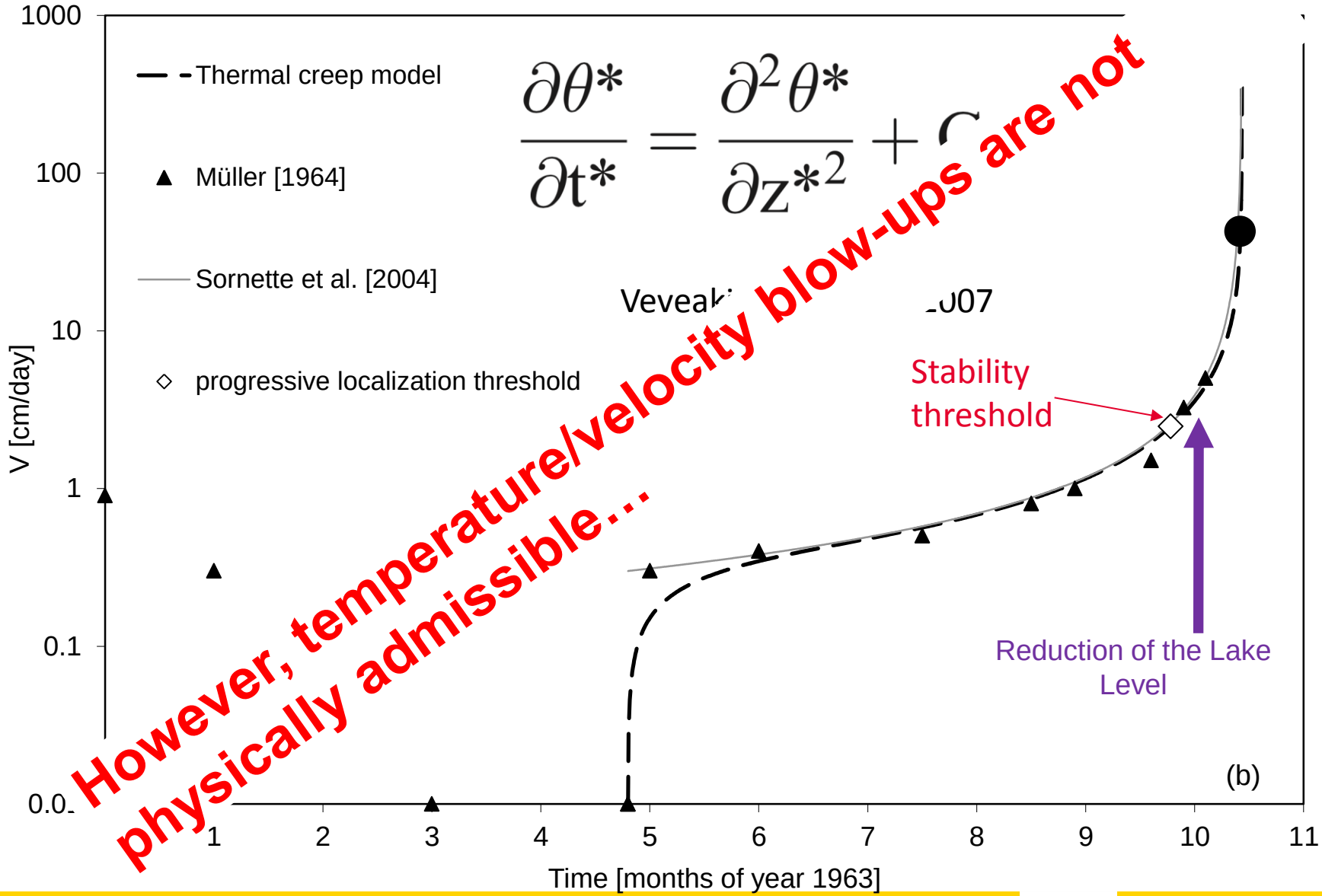
Overstress plasticity – deviatoric component

$$\dot{\gamma} = \dot{\gamma}_0 \left(1 - \frac{\Delta p}{\sigma'_n}\right)^{-1/N} e^{-\frac{xE_F}{NRT}}$$

Frank-Kamenetskii (low temperature) approximation:

$$\dot{\gamma} = \dot{\gamma}_0 e^{m(\theta - \theta_1)}$$

Reproducing Vaiont's history with Frank-Kamenetskii's equation



$$\frac{\partial \theta^*}{\partial t^*} = \frac{\partial^2 \theta^*}{\partial z^{*2}} + C$$

However, temperature/velocity blow-ups are not physically admissible…

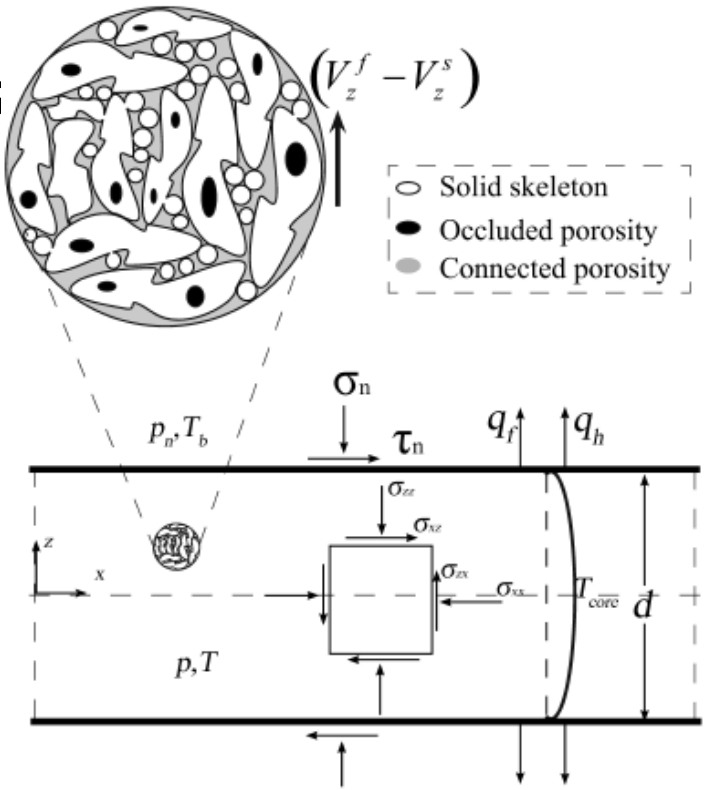
Adding information – and complexity…

<u>Goal:</u> understand the **driving** physics

<u>Tool:</u> **T**hermo-**H**ydro-**M**echanical-**C**hemical model

- Creeping shear-band (constant normal stress) in the post failure regime.
- Shear heating
- Fluid-saturated fault rock
- Carbonate decomposition reaction that decomposes calcite and produces excess pore pressure

$$CaCO_{3\,(solid)} \rightleftharpoons CaO_{(solid)} + CO_{2\,(fluid)}$$



Alevizos, Poulet & Veveakis
JGR 2014

A bit more detail on the Chemical Damage model

$$\varphi = \varphi_0 + \Delta\varphi_{chem} = \frac{V_B}{V}, \quad s = \frac{V_A}{V_{AB} + V_A}$$

$$\omega_1 = -\frac{\rho_1}{M_{AB}} k_0 \exp(-E/RT)$$

$$\omega_2 = \frac{\rho_2}{M_A} k_2 \exp(-E_b/RT)$$

$$\omega_3 = \Delta\varphi_{chem} \frac{\rho_B}{M_B} k_f \exp(-E_b/RT)$$

$$s = \frac{j_{rel}}{1 + j_{rel}}$$

$$\Delta\varphi_{chem} = A_f \frac{1-\varphi_0}{1 + \frac{\rho_B}{\rho_A}\frac{M_A}{M_B}\frac{k_f}{k_2}\frac{1}{s}}$$

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

$$K_c = k_0/k_2, \quad \Delta E = E - E_b$$

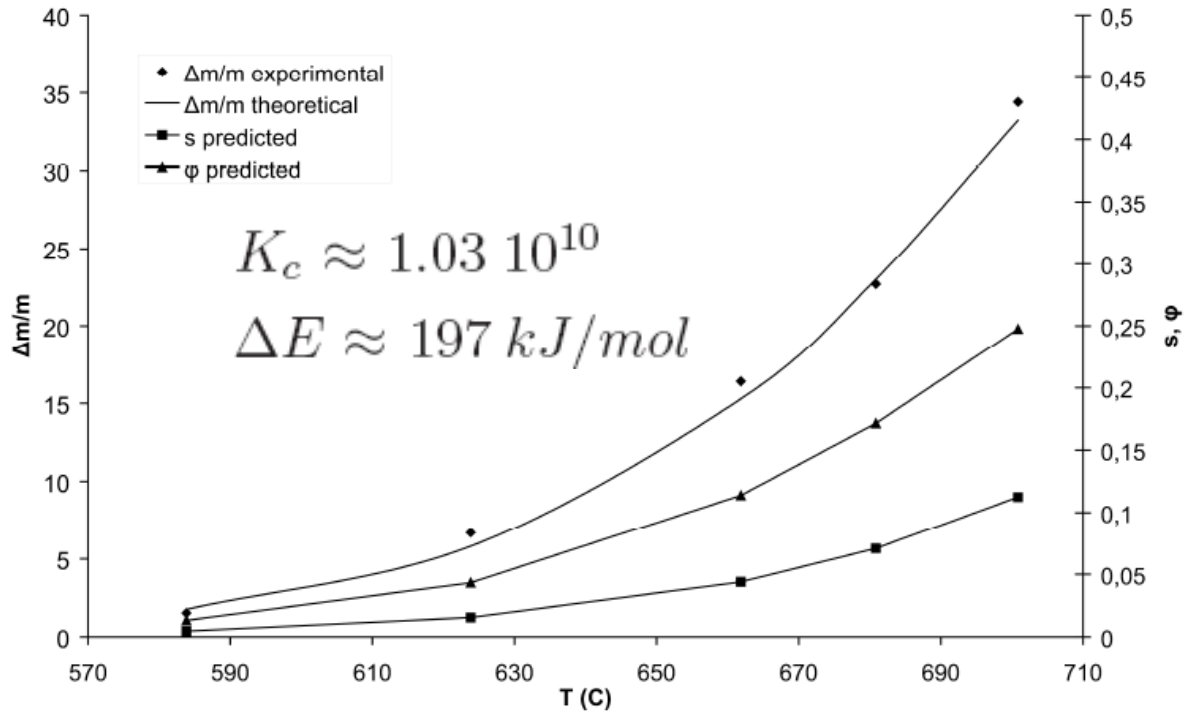


Figure 14: Fitting of the experimental data of [31], for the reaction of calcite decomposition at low pressures ($8\ mbar$)

$$\frac{\Delta m}{m} = \frac{m_{init} - m_{fin}}{m_{init}} = 1 - \frac{\rho_{CaCO_3} V_{fin}}{\rho_{CaCO_3} V_{init}} = 1 - (1-\phi)(1-s)$$

The mathematical system

Normalised and reduced system of equations

$$\frac{\partial \Delta P}{\partial t} = \frac{\partial}{\partial z}\left[\frac{1}{Le}\frac{\partial \Delta P}{\partial z}\right] + \frac{\Lambda}{m\sigma'_n}\frac{\partial T}{\partial t} + (1-\phi)(1-s)\mu_r\, e^{\frac{Ar\delta T}{1+\delta T}}$$

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} + \left[Gr\left(1-\Delta P\right)^N e^{\frac{aAr}{1+\delta T}} - (1-\phi)(1-s)\right] e^{\frac{Ar\delta T}{1+\delta T}}$$

Dimensionless Groups:

Lewis number

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

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

Gruntfest number

The mathematical system

Normalised and reduced system of equations

$$\frac{\partial \Delta P}{\partial t} = \frac{\partial}{\partial z}\left[\frac{1}{Le}\frac{\partial \Delta P}{\partial z}\right] + \frac{\Lambda}{m\sigma'_n}\frac{\partial T}{\partial t} + (1-\phi)(1-s)\mu_r\, e^{\frac{Ar\delta T}{1+\delta T}}$$

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} + \left[Gr\left(1-\Delta P\right)^N e^{\frac{aAr}{1+\delta T}} - (1-\phi)(1-s)\right] e^{\frac{Ar\delta T}{1+\delta T}}$$

Dimensionless Groups:

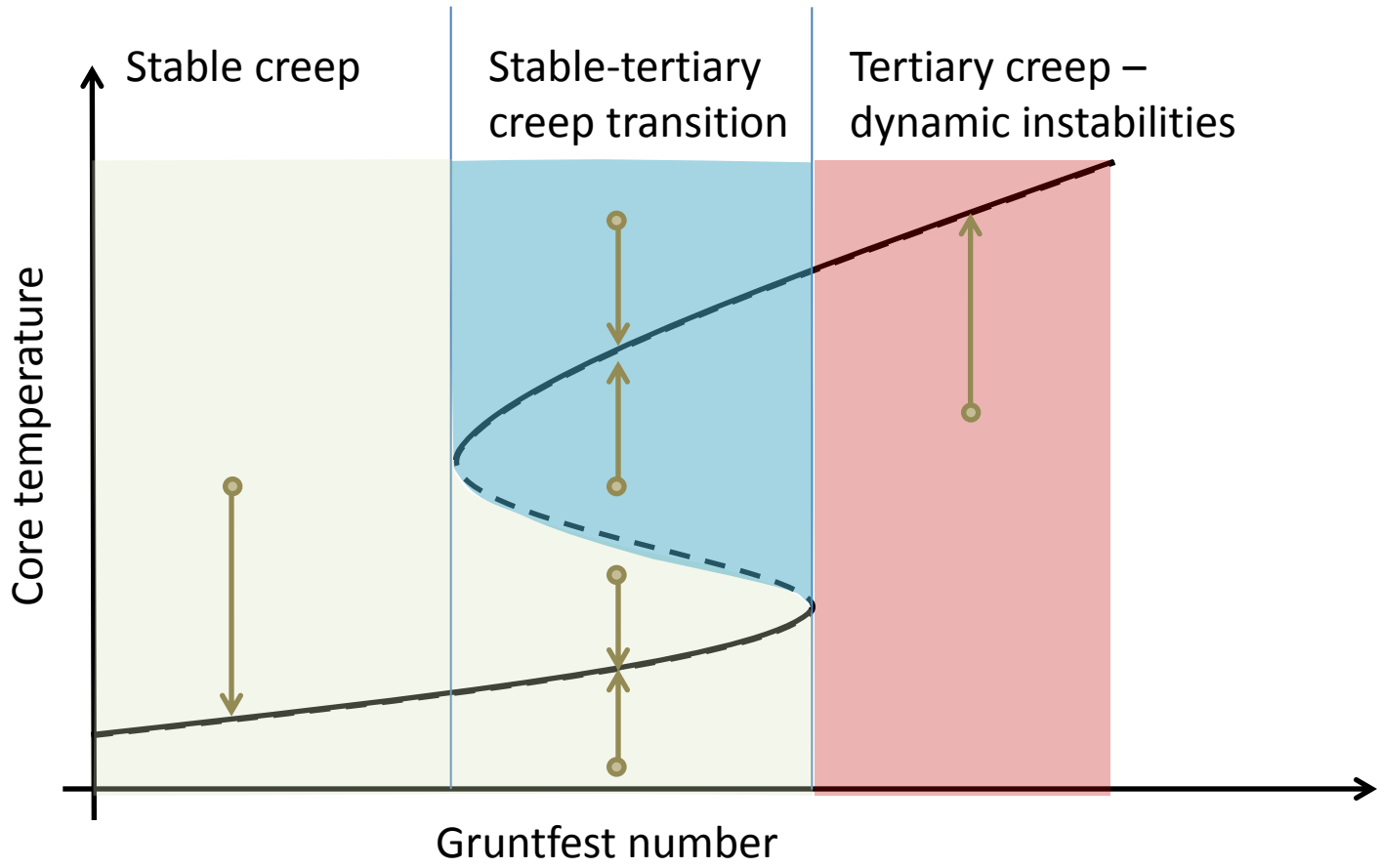
Lewis number

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

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

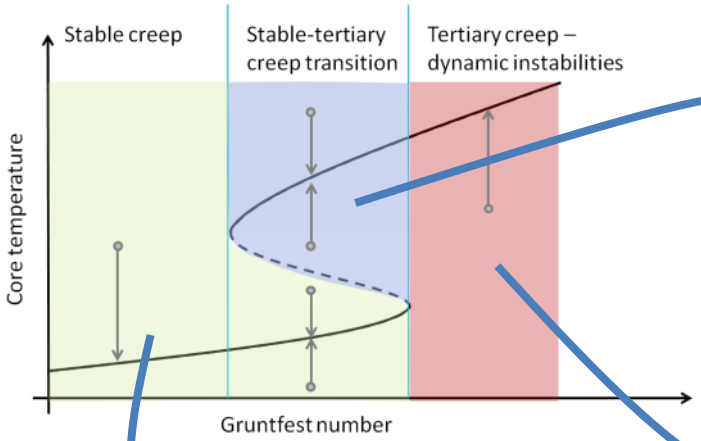
Gruntfest number

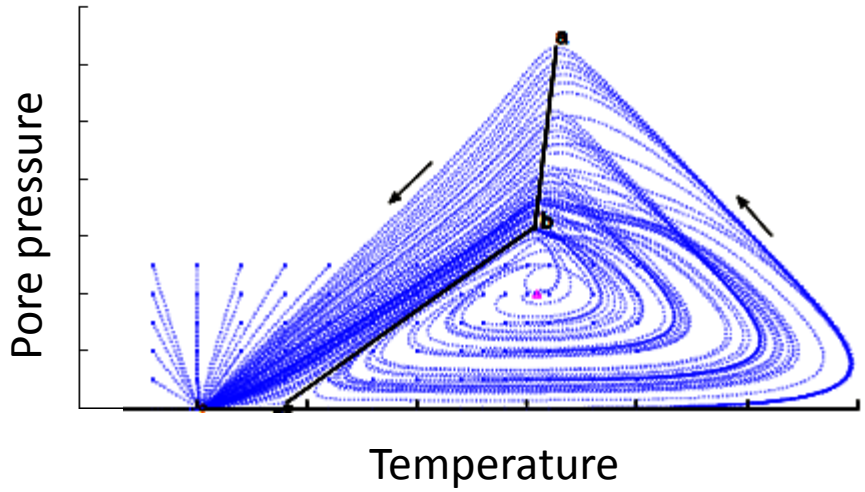
System's stability regimes w.r.t Gr

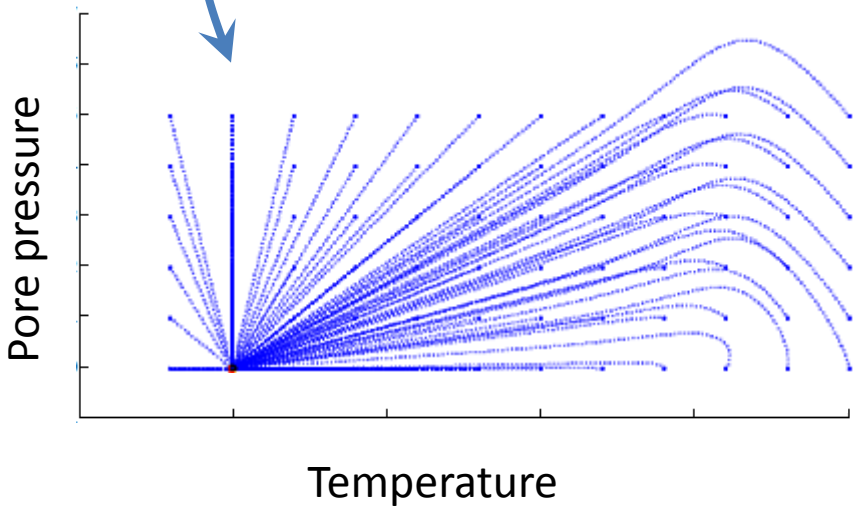


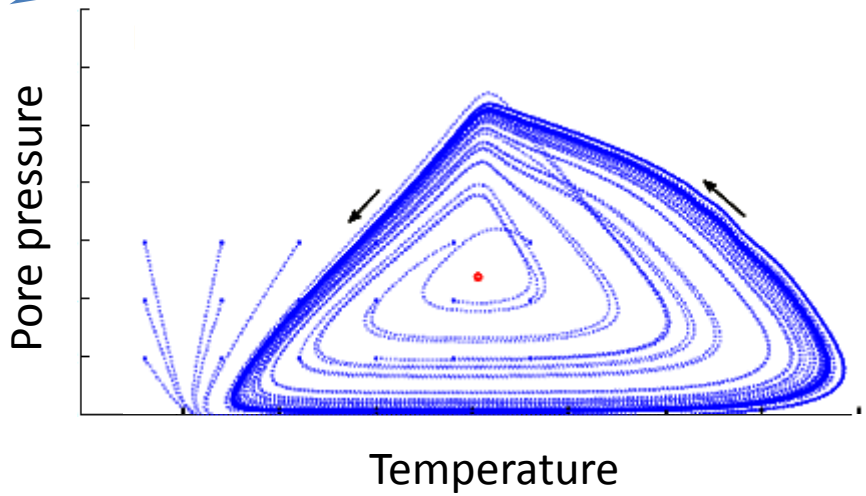
Phase diagrams

Natural localised instability

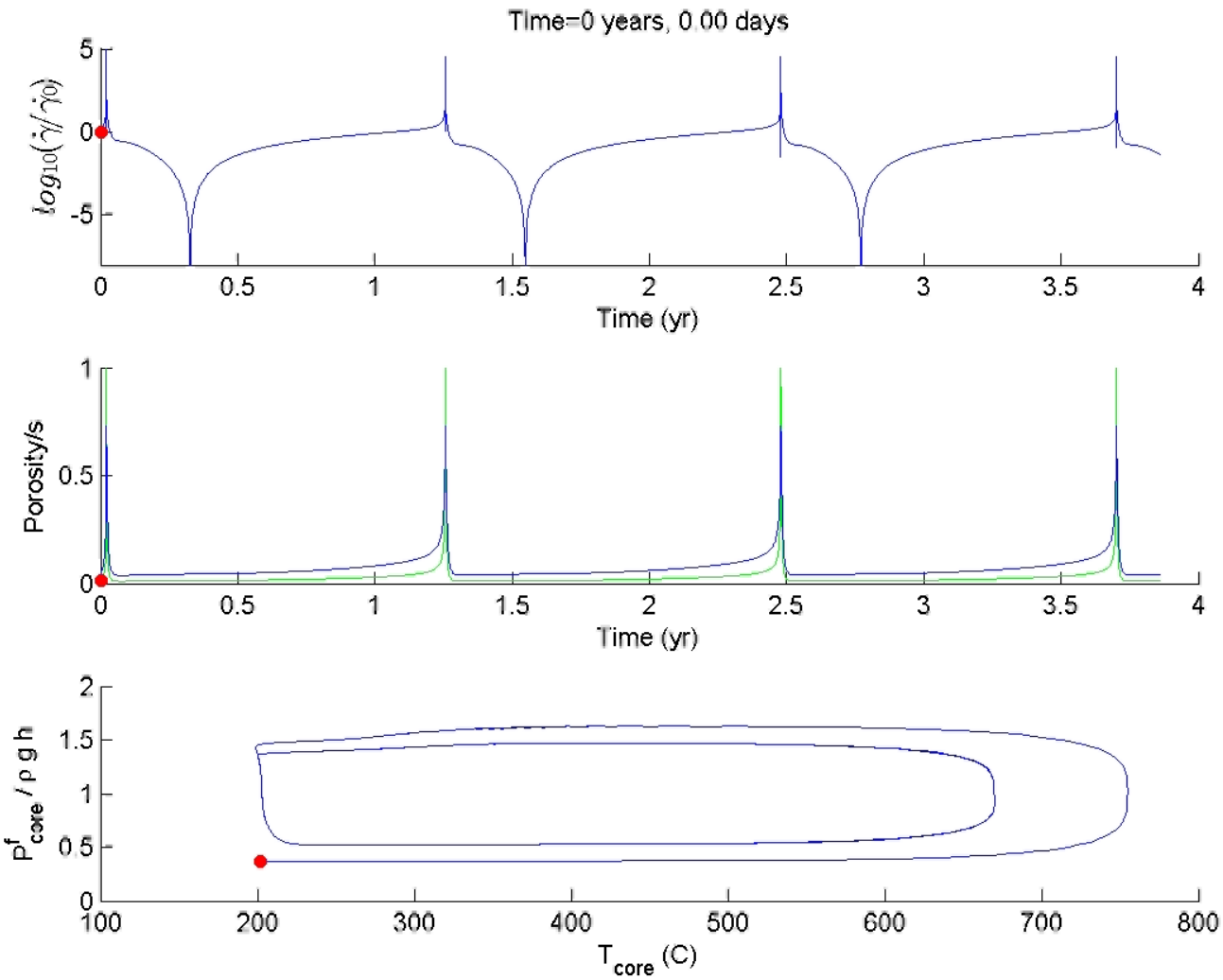








A multi-physics/scale oscillator

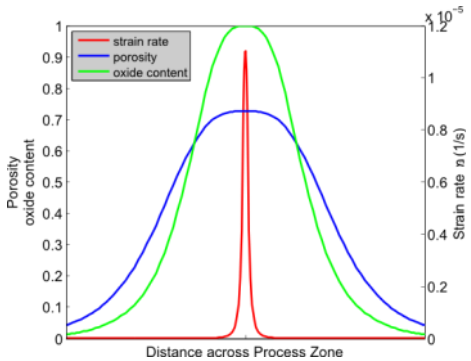


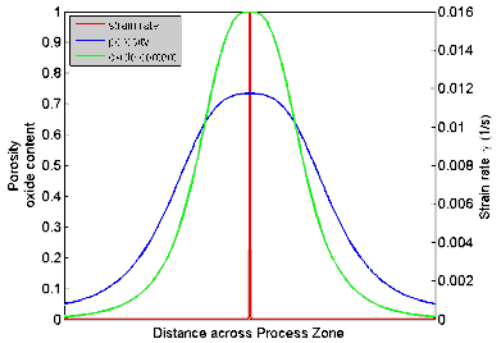
Localization patterns

- Alevizos, Poulet & Veveakis, JGR Part 12014
- Veveakis, Poulet & Alevizos, JGR Part 2, 2014

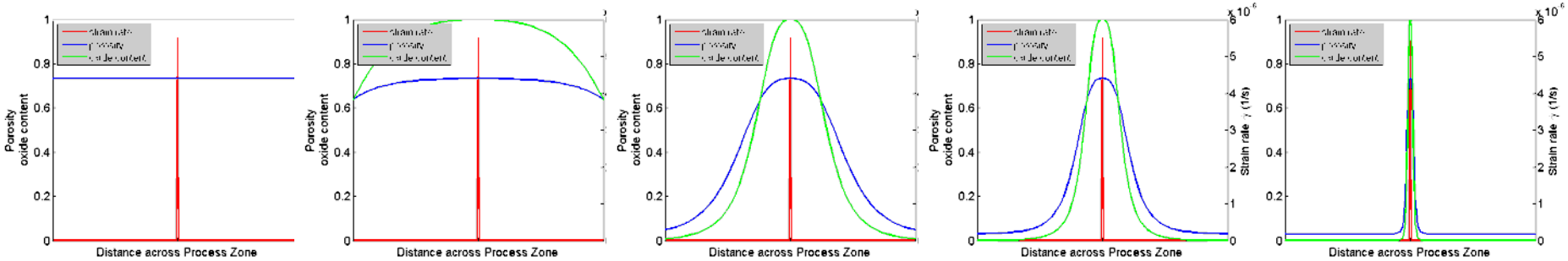
Parameter sensitivity analysis?

Mechanical localisation: activation energy

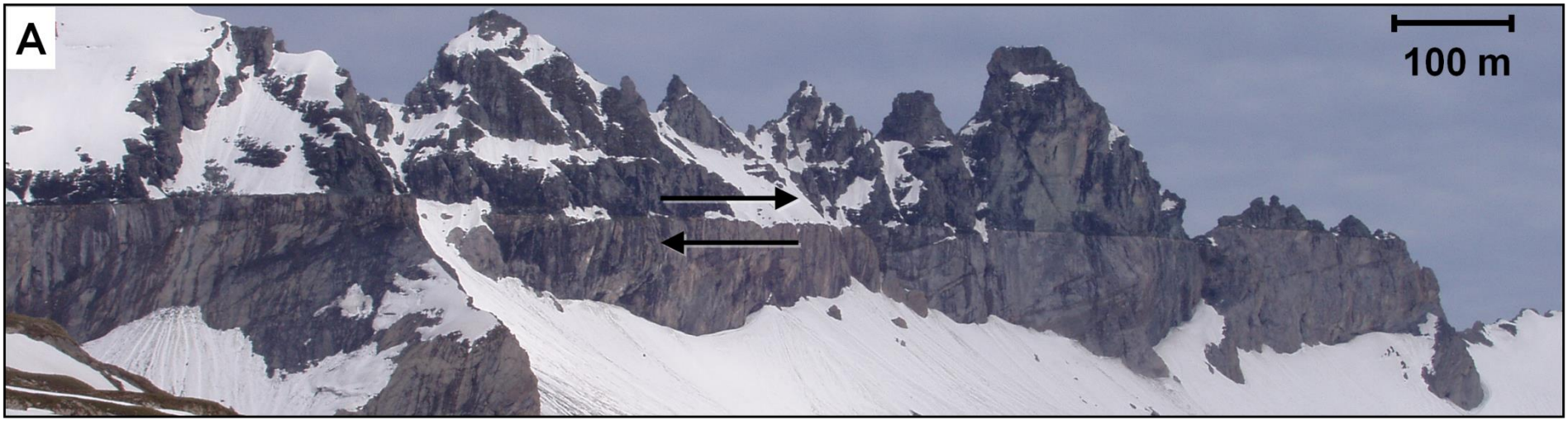


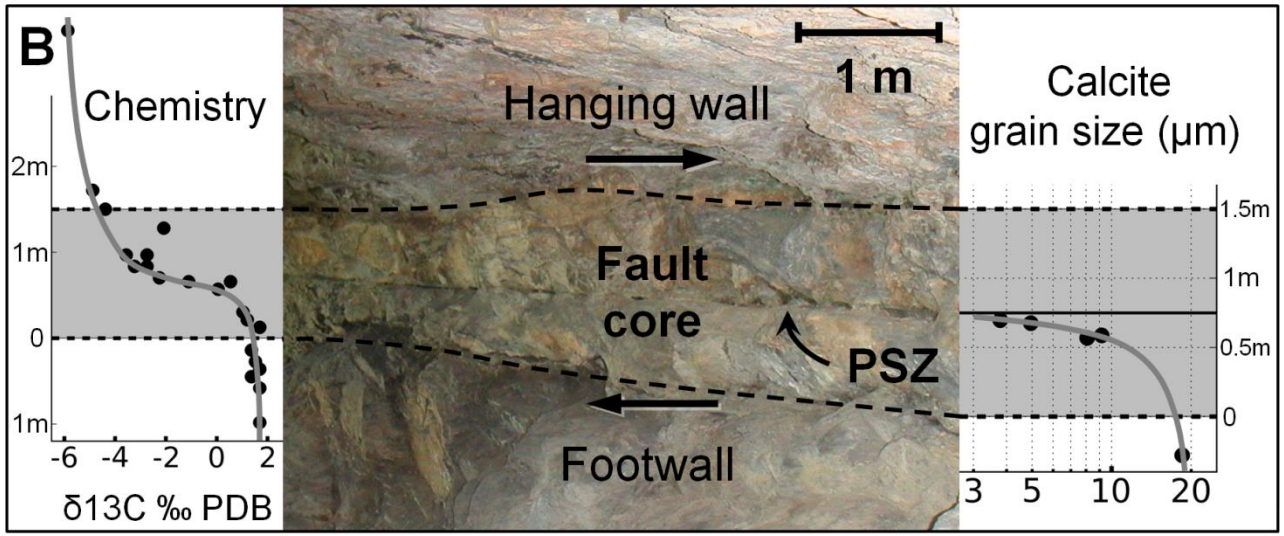


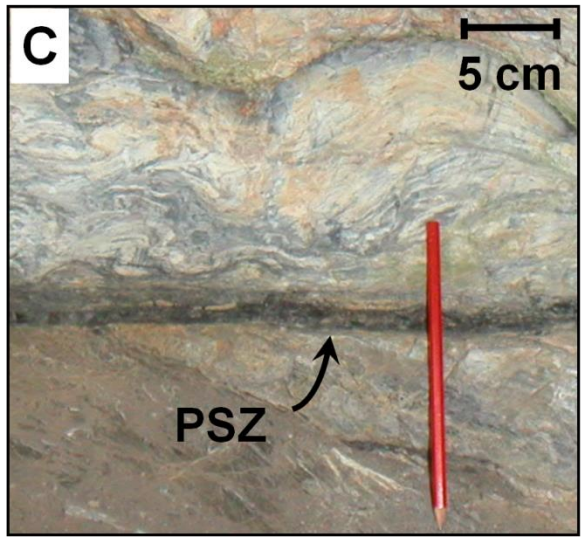
Chemical localisation: enthalpy of the reaction



The Glarus Thrust, Switzerland





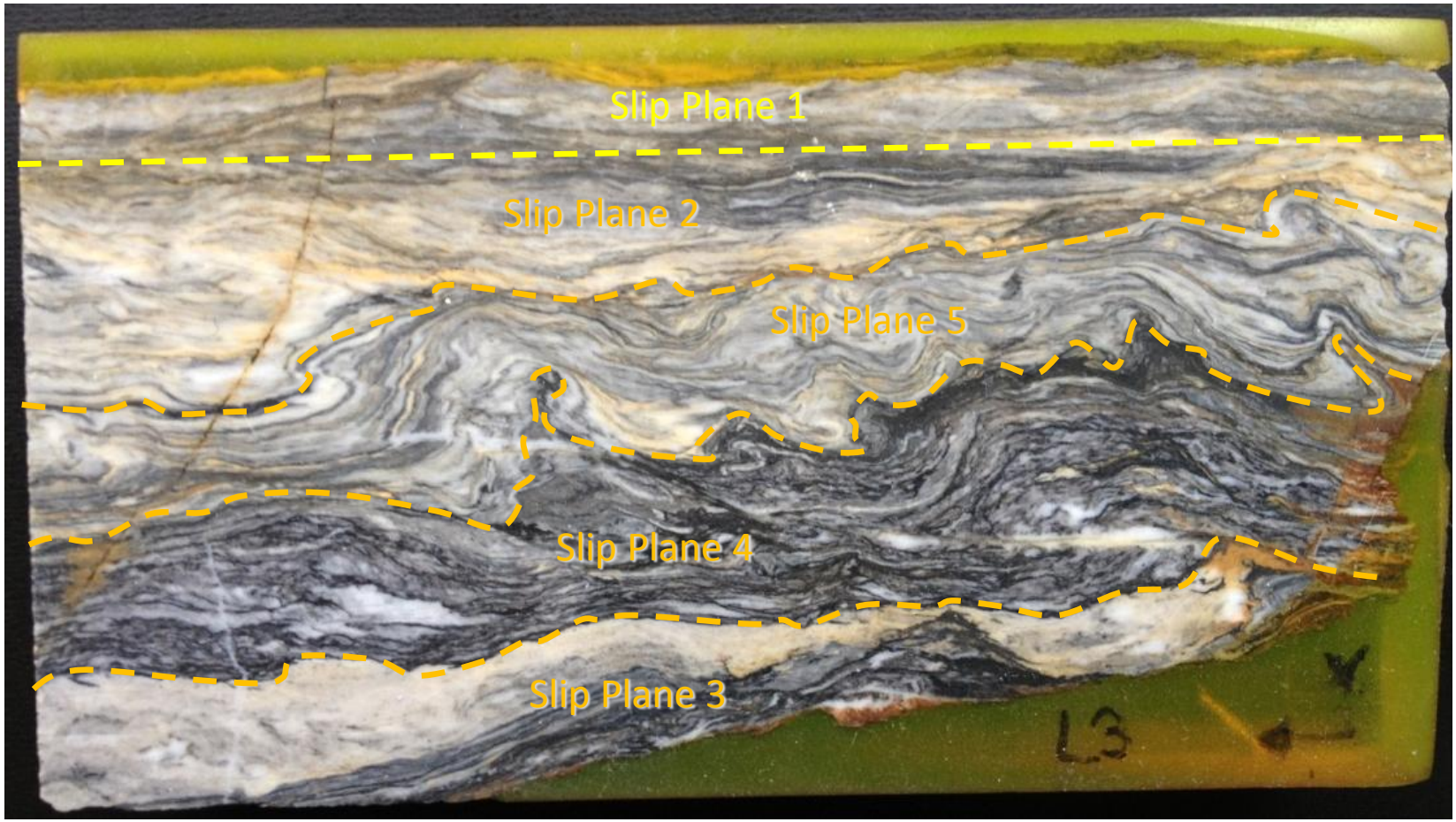


Cyclicity

1 cm

Hanging wall

Lochsite Tectonite

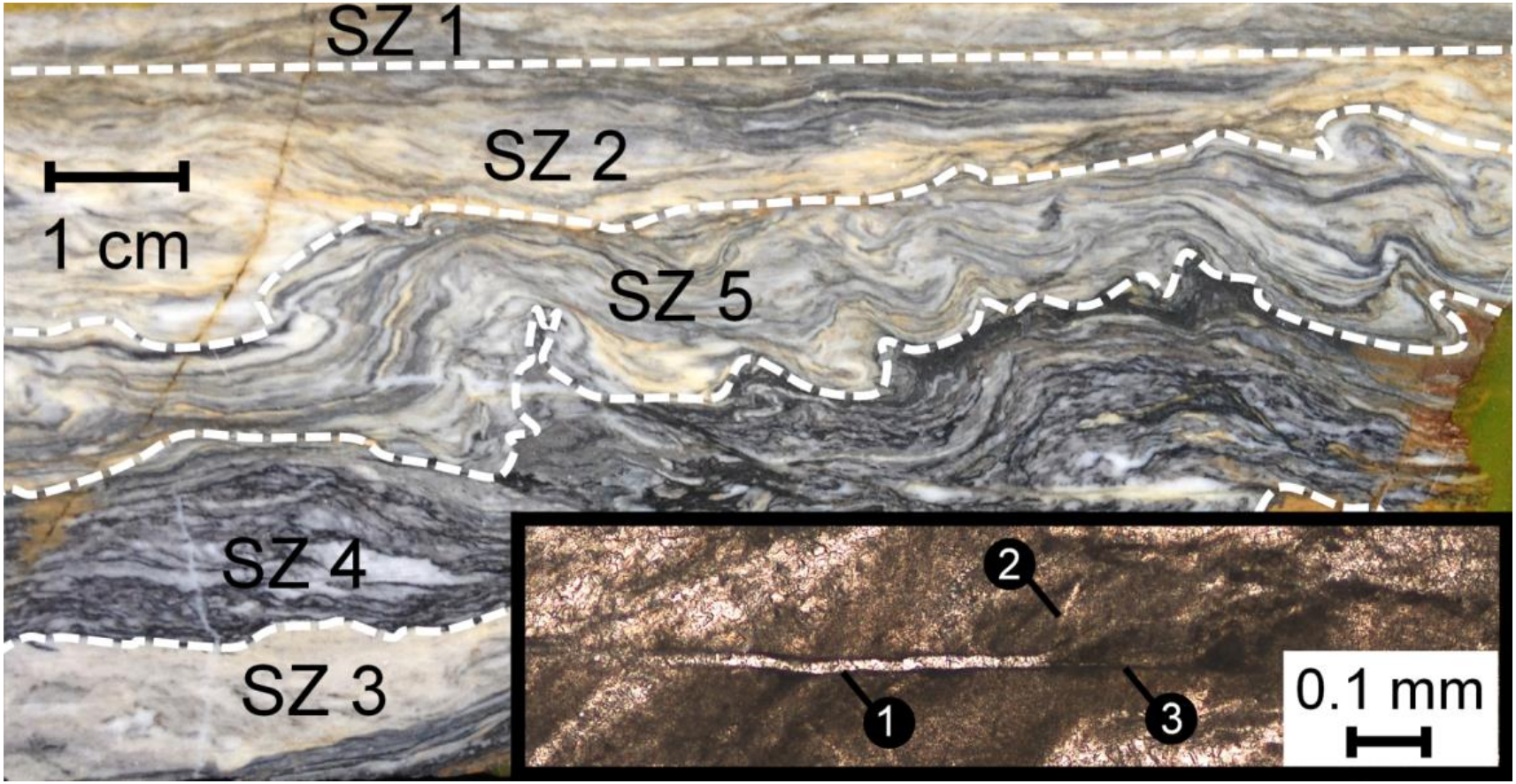


Footwall

Cyclicity

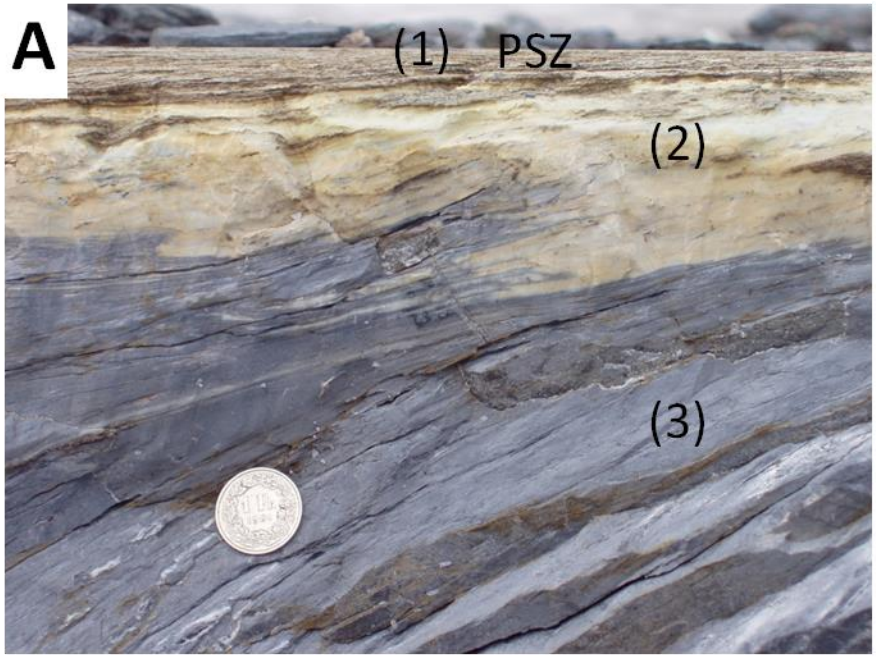
Hanging wall

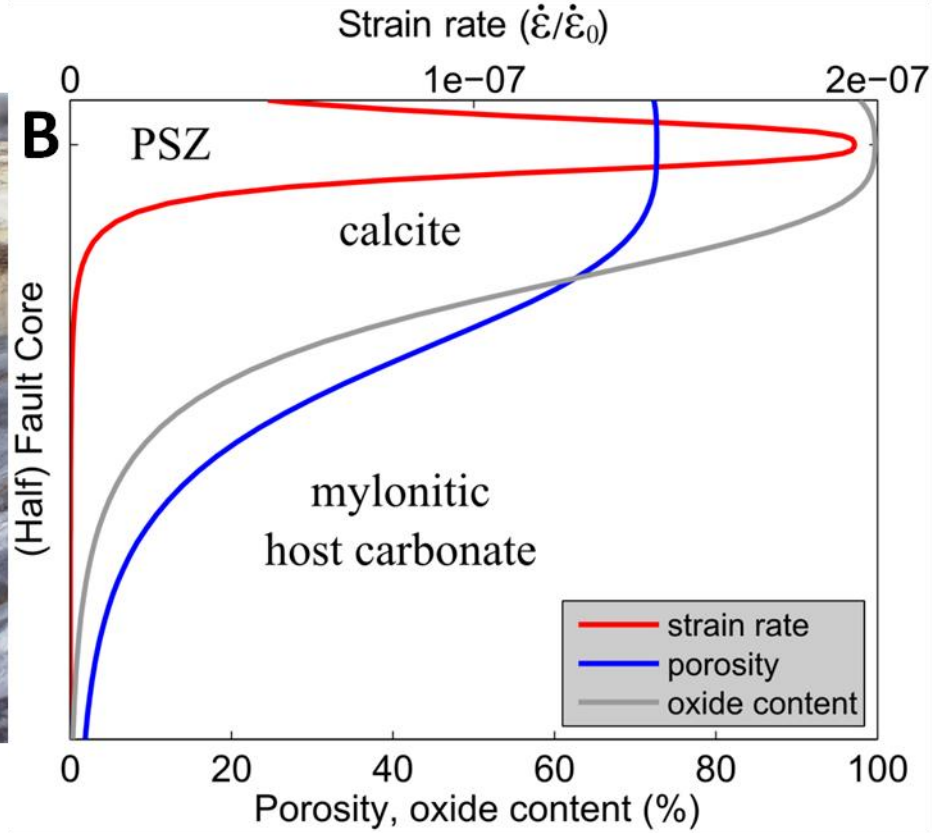
Lochsite Tectonite



Footwall

A Glarus pattern

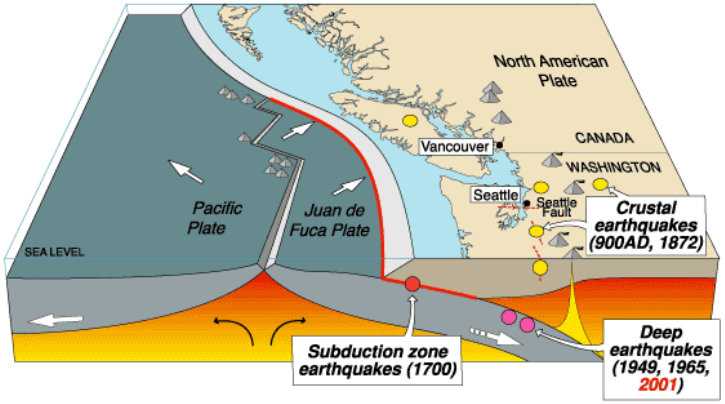




- Calcite as a cause
- Source of fluid explained!

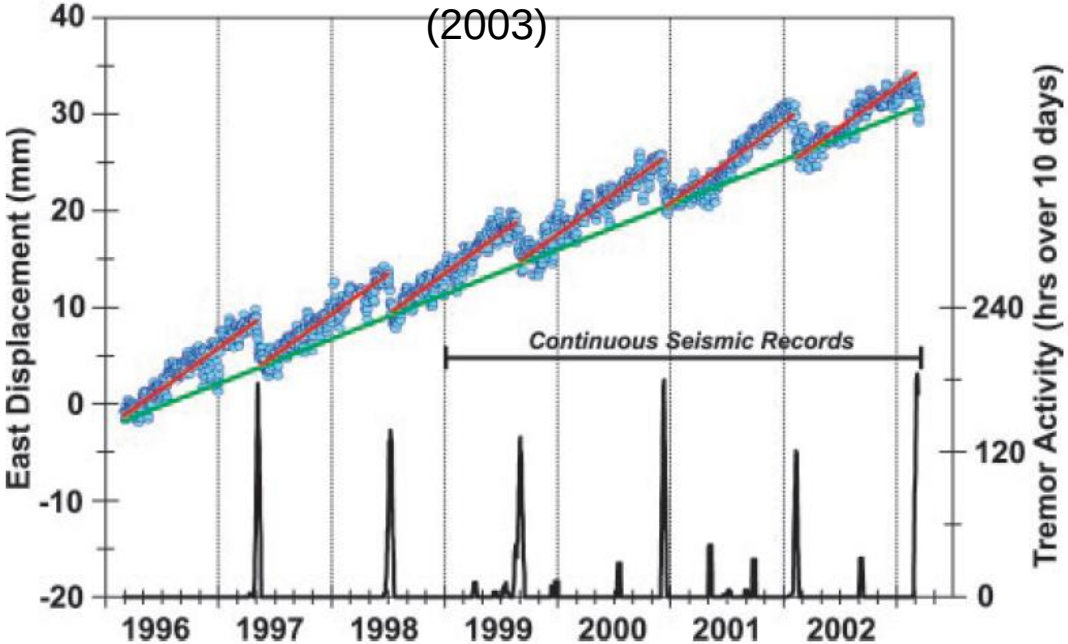
Episodic Tremor and Slip (ETS)

Cascadia earthquake sources

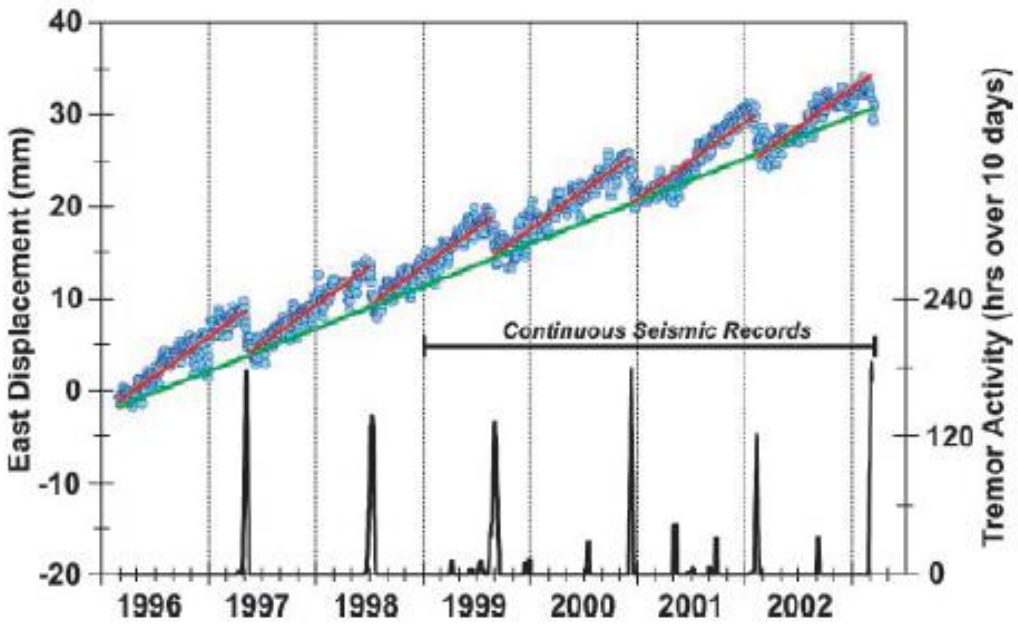


	Source	Affected area	Max. Size	Recurrence
●	Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
●	Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
●	Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?

Rogers and Dragert / Science (2003)



Cascadia: serpentinite oscillator

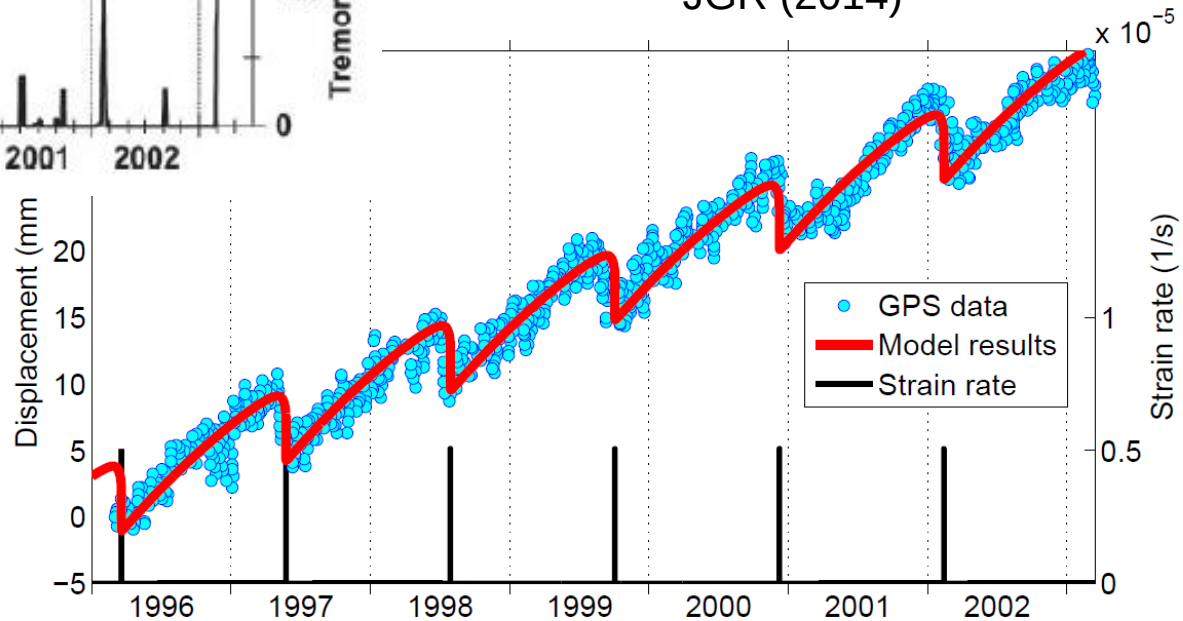


Observations

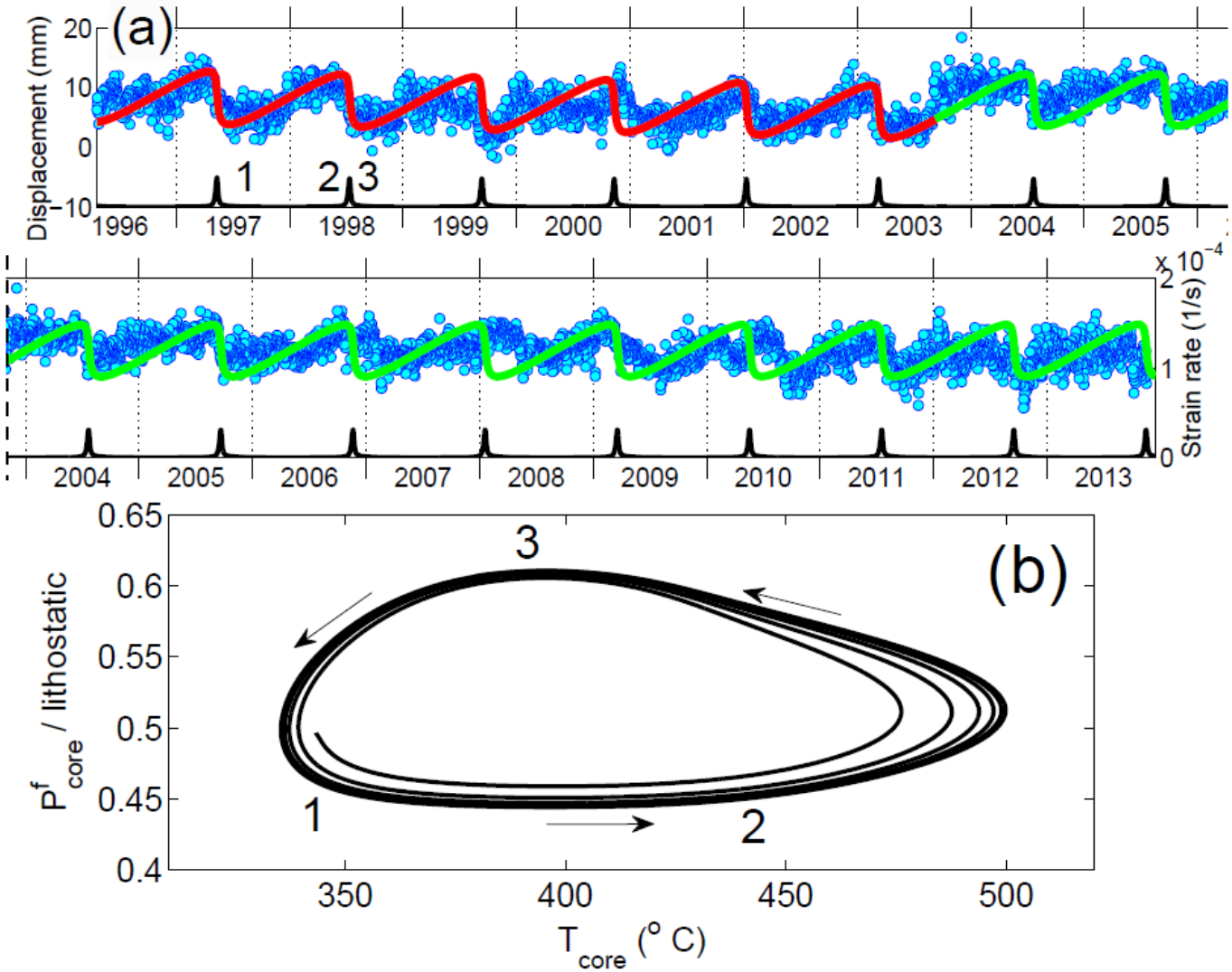
Rogers & Dragert
Science (2003)

Numerical results

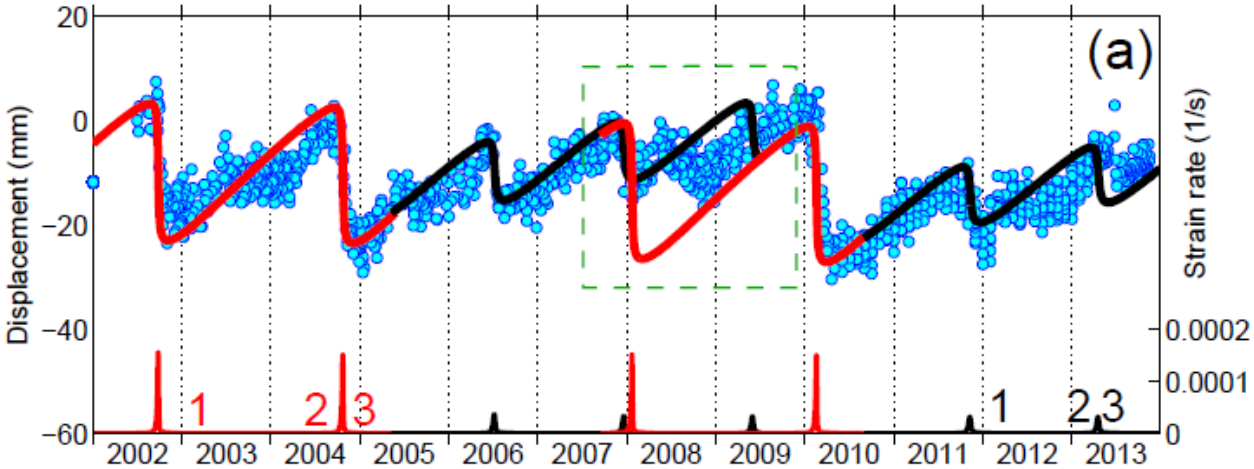
Alevizos, Poulet &
Veveakis
JGR (2014)

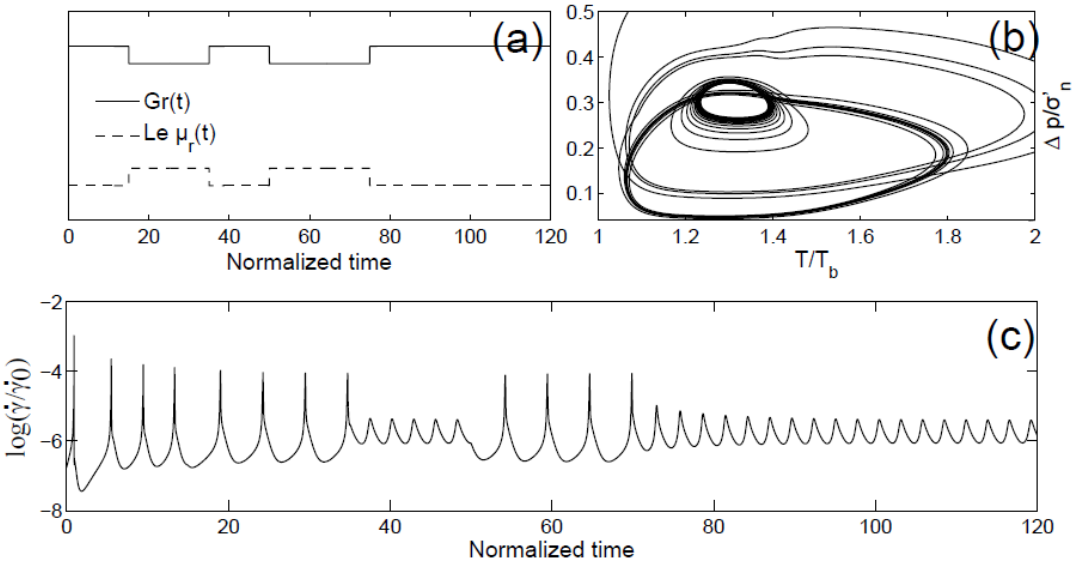


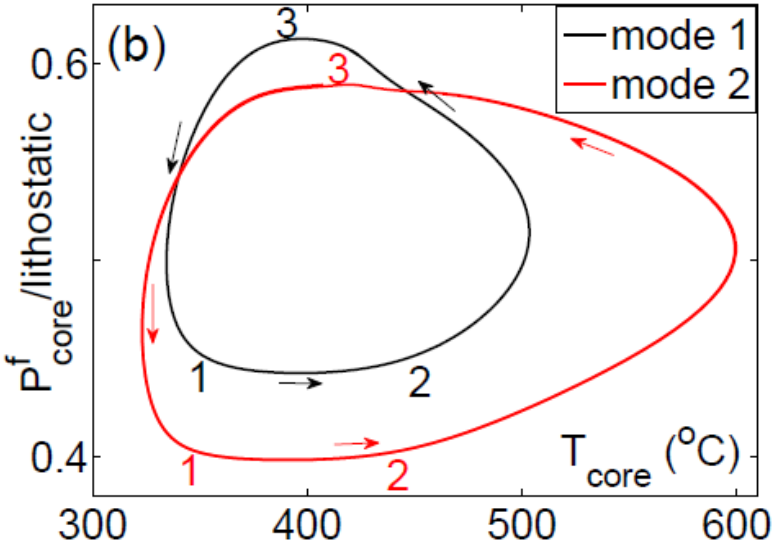
Oscillator cycles, Earth's heartbeats



Chaotic signals – Gisborne (New Zealand)







Summary and conclusions

1. Fault reactivation is a difficult problem
2. The classical theories provide a phenomelogical mechanism, but it is not always descriptive
3. The addition of physics provides a global theory for the response of a fault in any setting
4. What is the role of the volumetric component of dissipation, that we neglected here? (see KRL's presentation later on the day)
5. Can we use these models in supercomputers? (See Thomas Poulet's presentation in a while)