# Multi-physics Multi-scale Modelling in Geomechanics

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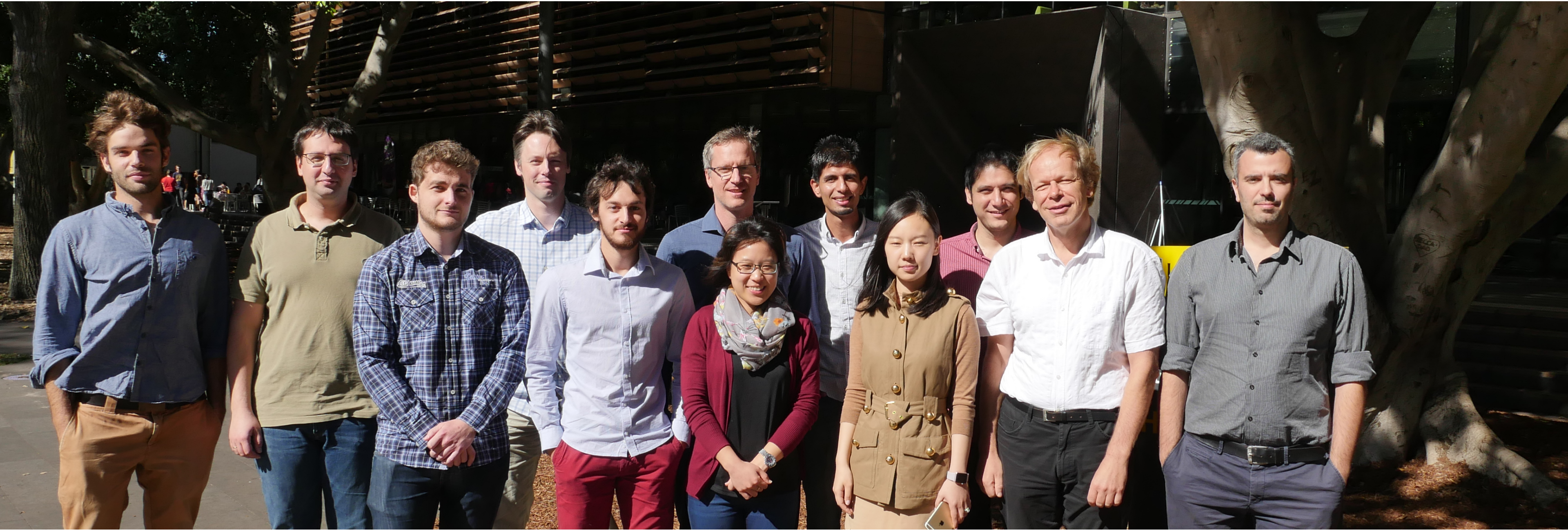
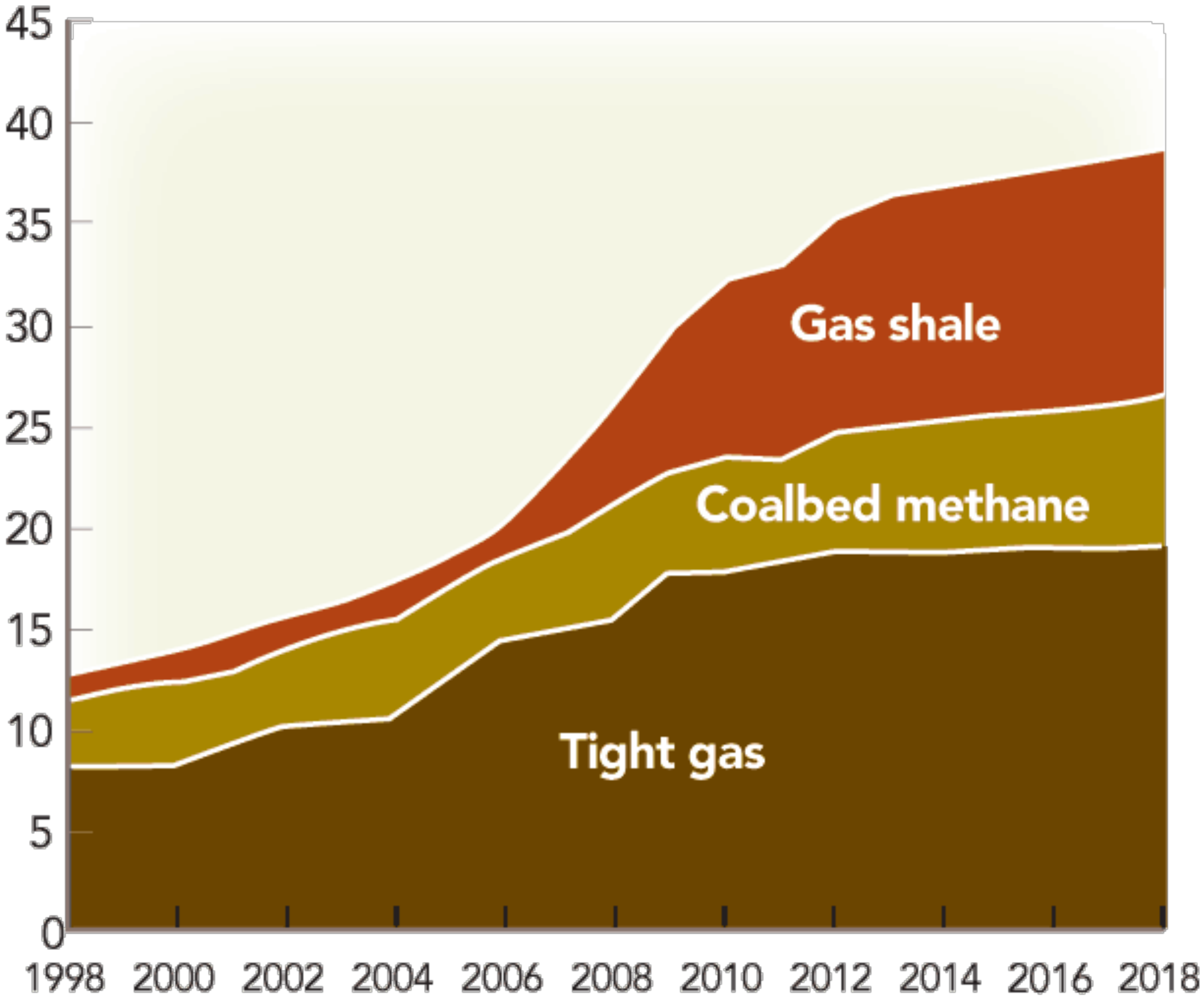
Never Stand Still

School of Petroleum Engineering

## Unconventional Geomechanics Group (UGG)



# First Question: Why Multi-physics?



Source: US DOE 2008

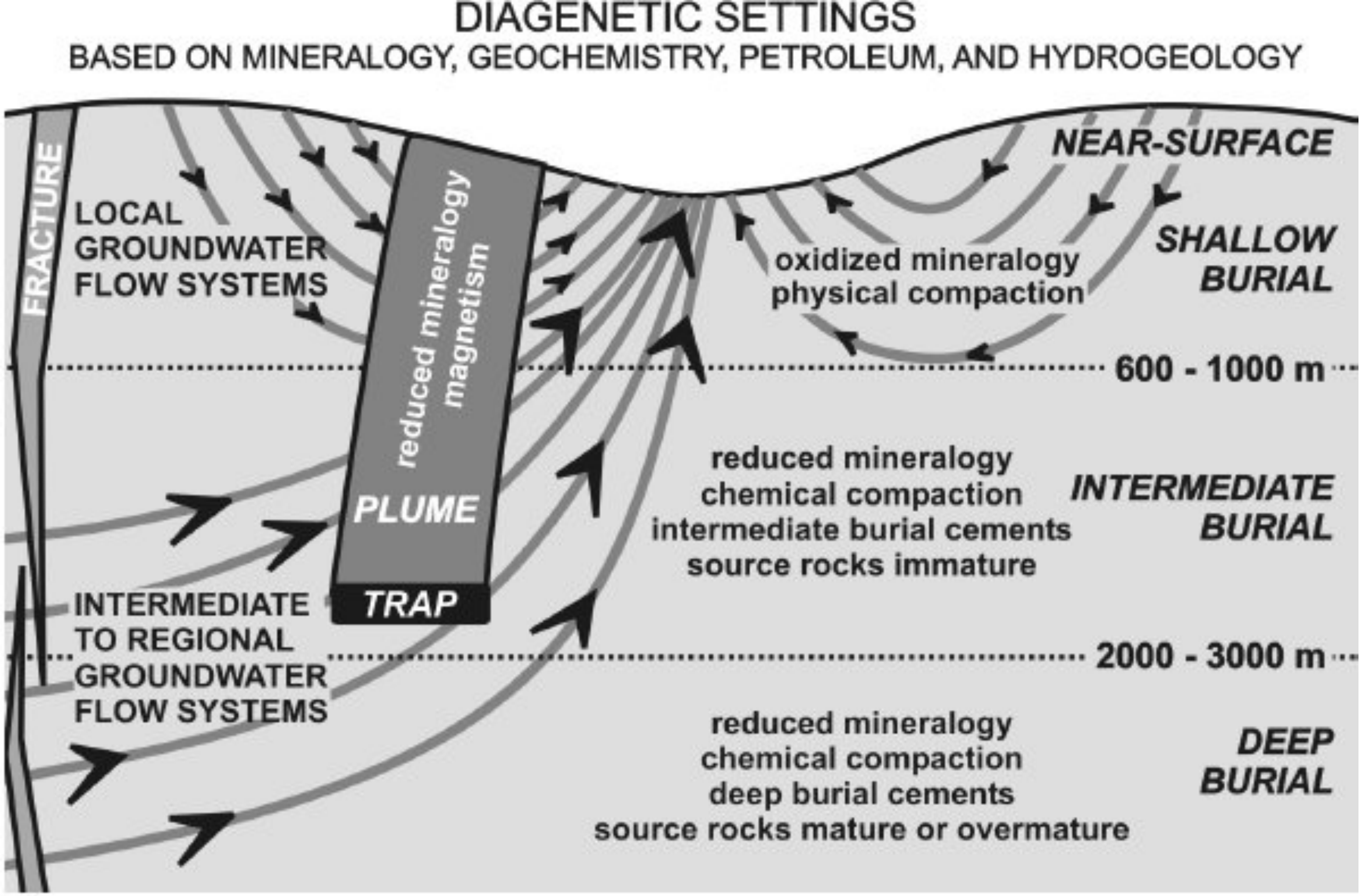
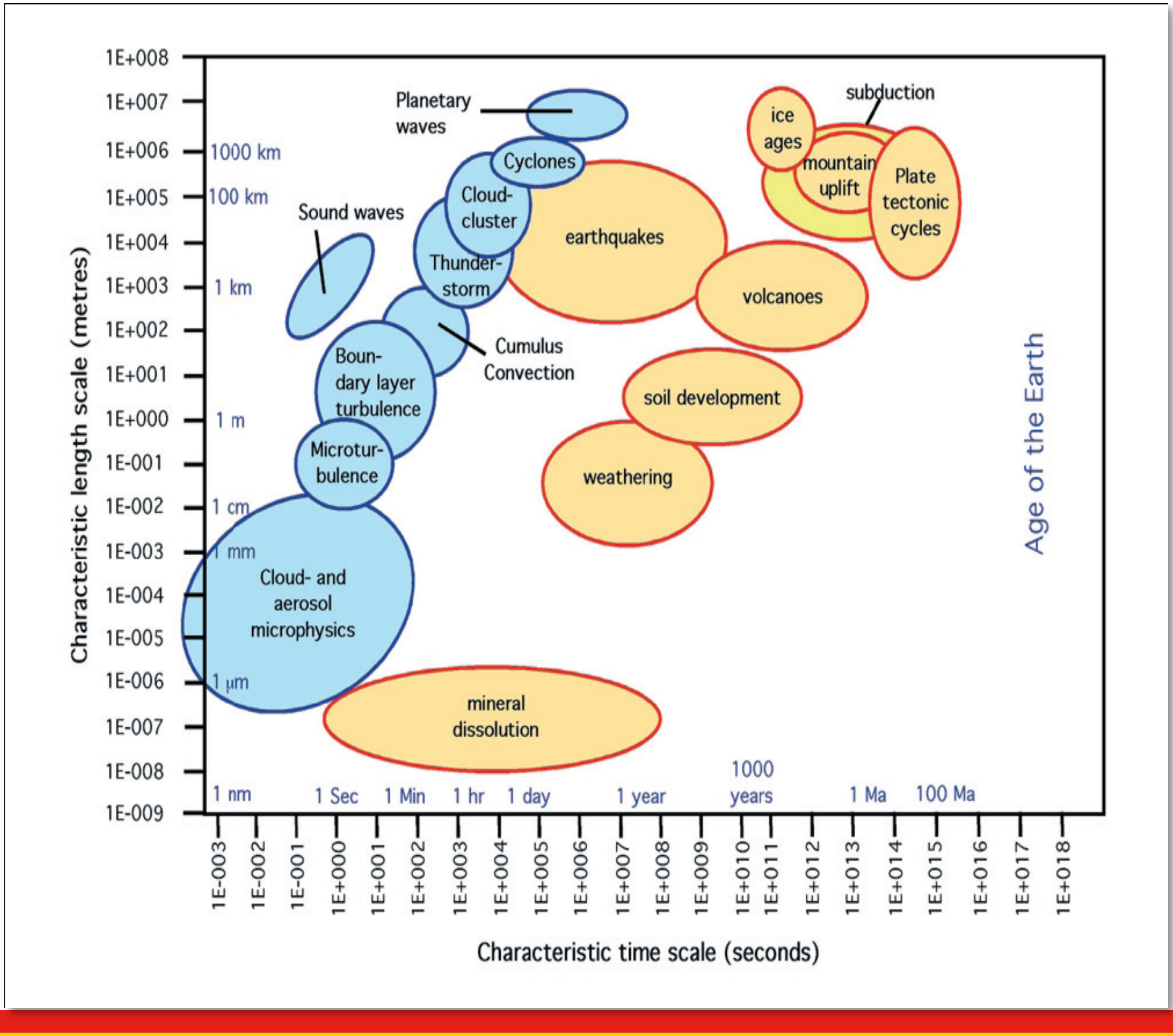
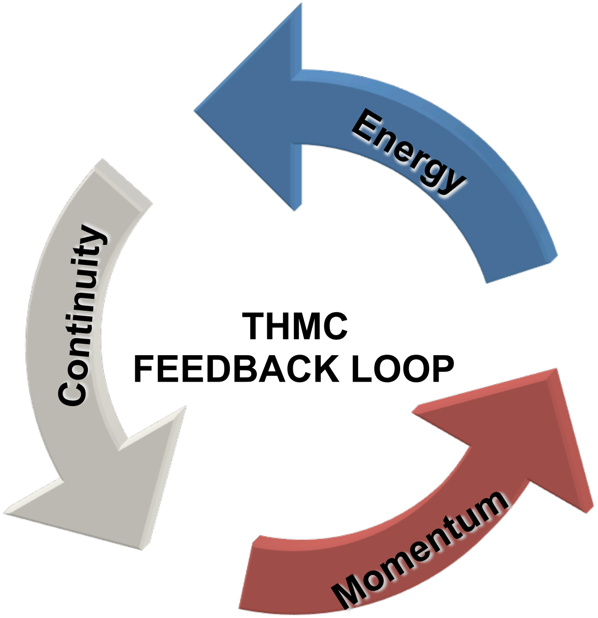


**Figure 2.** Classification of diagenetic settings on the basis of mineralogy, petroleum, hydrogeochemistry, and hydrogeology. For illustrative simplicity, the geologic section is assumed to be isotropic and homogeneous, with idealized groundwater flow lines. The hydrocarbon-contaminated plume is slightly deflected by the local and regional groundwater flow systems. The depth limits separating the burial diagenetic settings are approximate and based on geologic phenomena that are easily recognizable. Near-surface settings may be meteoric, brackish, marine, or hypersaline. Adapted from Machel (1999).

# Second Question: Why Multi-scale?

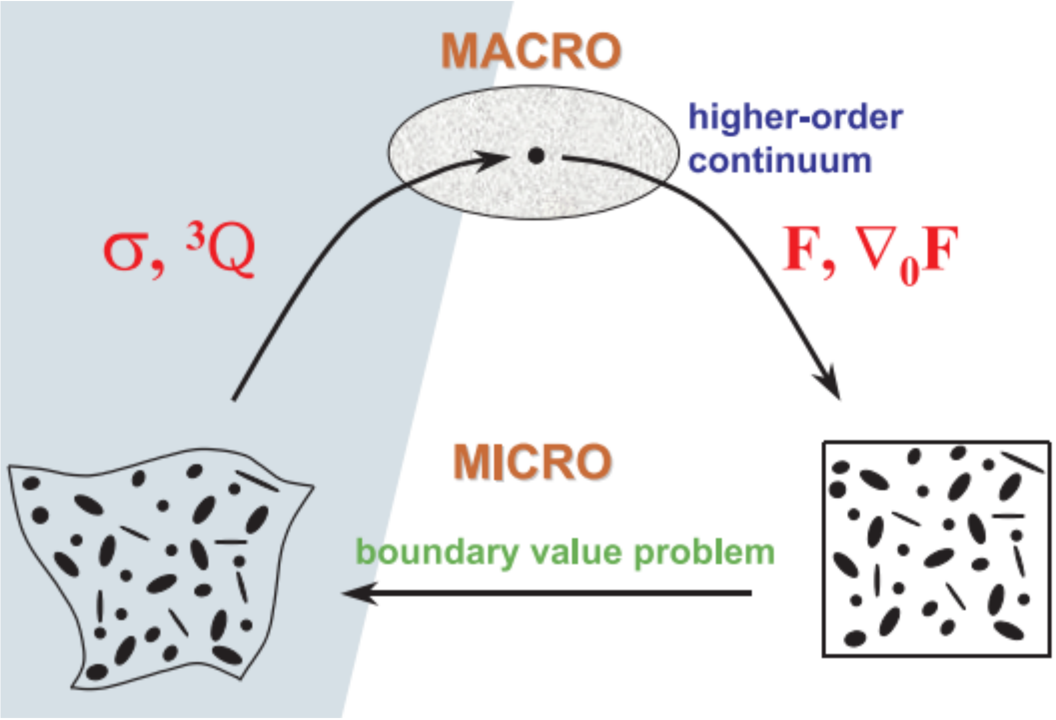




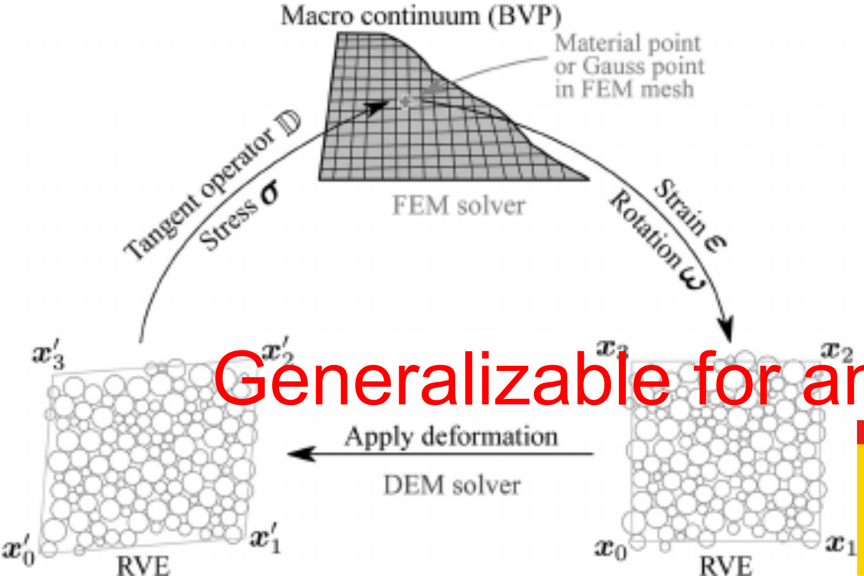
**THMC FEEDBACK LOOP**

ICME framework, Horstemeyer 2009

# Current Paradigm: computational homogenisation/upscalling



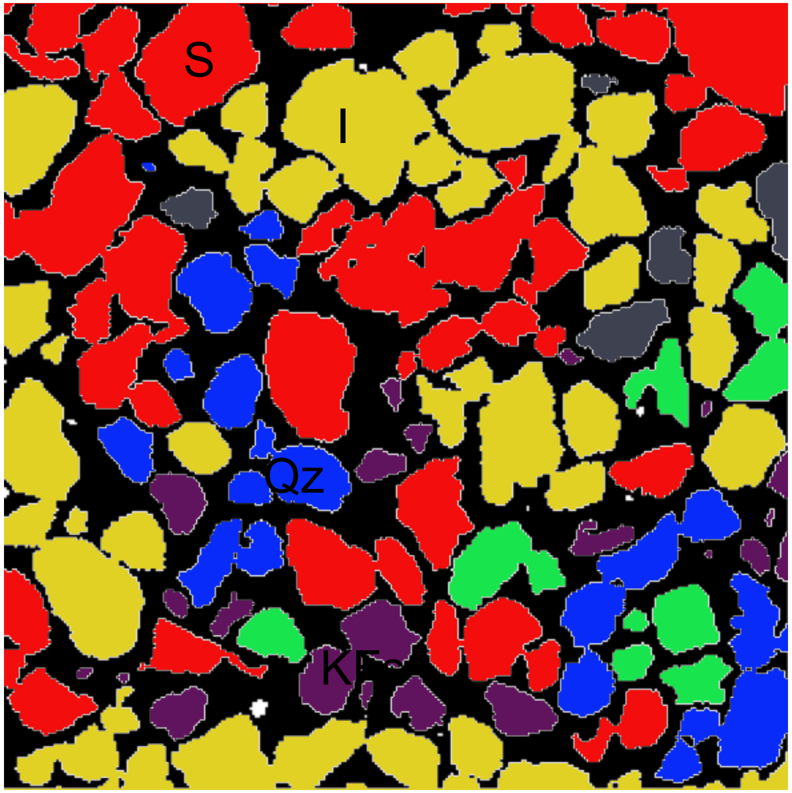
Zhao and Guo, 2011



Dulikravich, G. S., & Tanaka, M. (2000). Inverse Problems in Engineering Mechanics II. Elsevier.

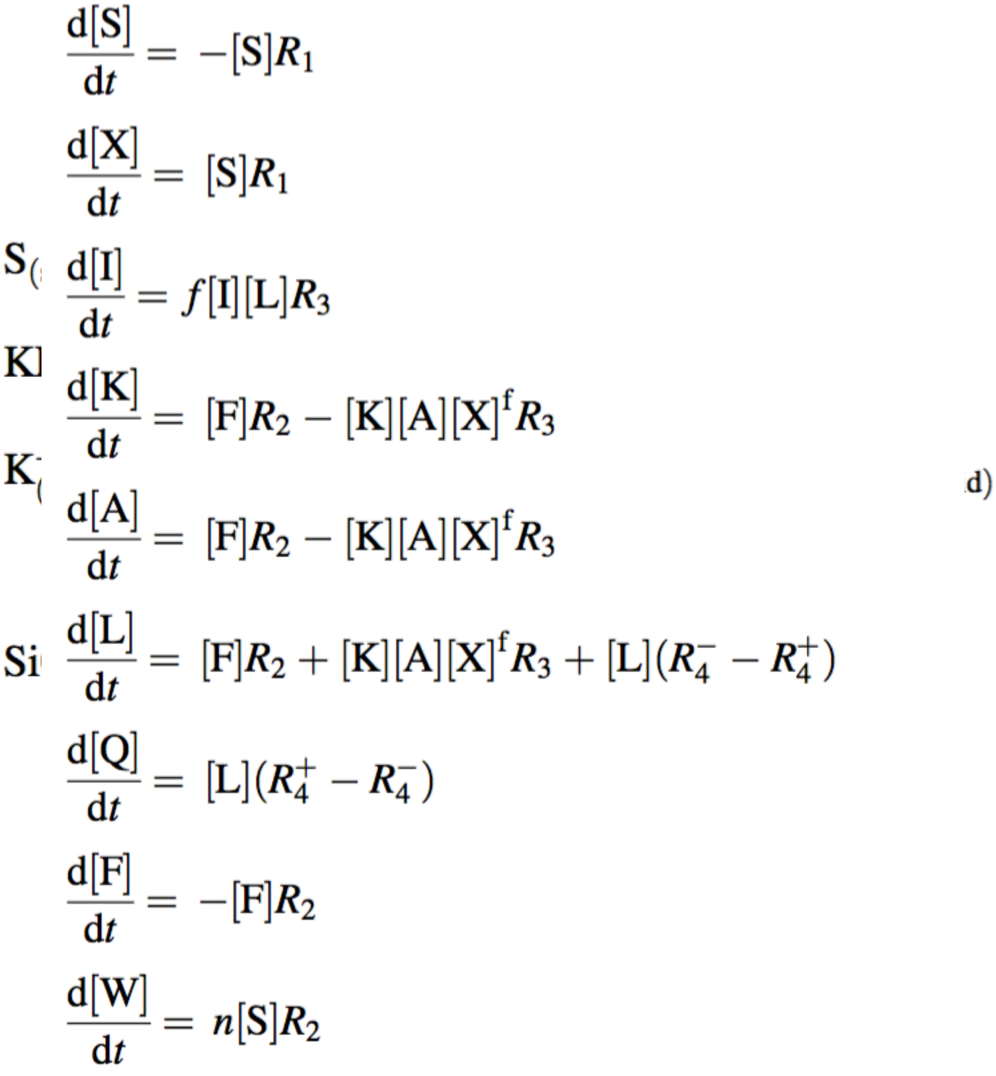
Generalizable for any thermodynamic flux/force

# How does it work?



Stack of CT-scan images
Chemical composition

# Chemical system reduction (chemical homogenisation)



$$\frac{\mathrm{d}[\mathrm{S}]}{\mathrm{d}t} = -[\mathrm{S}]R_1$$

$$\frac{\mathrm{d}[\mathrm{X}]}{\mathrm{d}t} = [\mathrm{S}]R_1$$

$$\frac{\mathrm{d}[\mathrm{I}]}{\mathrm{d}t} = f[\mathrm{I}][\mathrm{L}]R_3$$

$$\frac{\mathrm{d}[\mathrm{K}]}{\mathrm{d}t} = [\mathrm{F}]R_2 - [\mathrm{K}][\mathrm{A}][\mathrm{X}]^{\mathrm{f}}R_3$$

$$\frac{\mathrm{d}[\mathrm{A}]}{\mathrm{d}t} = [\mathrm{F}]R_2 - [\mathrm{K}][\mathrm{A}][\mathrm{X}]^{\mathrm{f}}R_3$$

$$\frac{\mathrm{d}[\mathrm{L}]}{\mathrm{d}t} = [\mathrm{F}]R_2 + [\mathrm{K}][\mathrm{A}][\mathrm{X}]^{\mathrm{f}}R_3 + [\mathrm{L}](R_4^- - R_4^+)$$

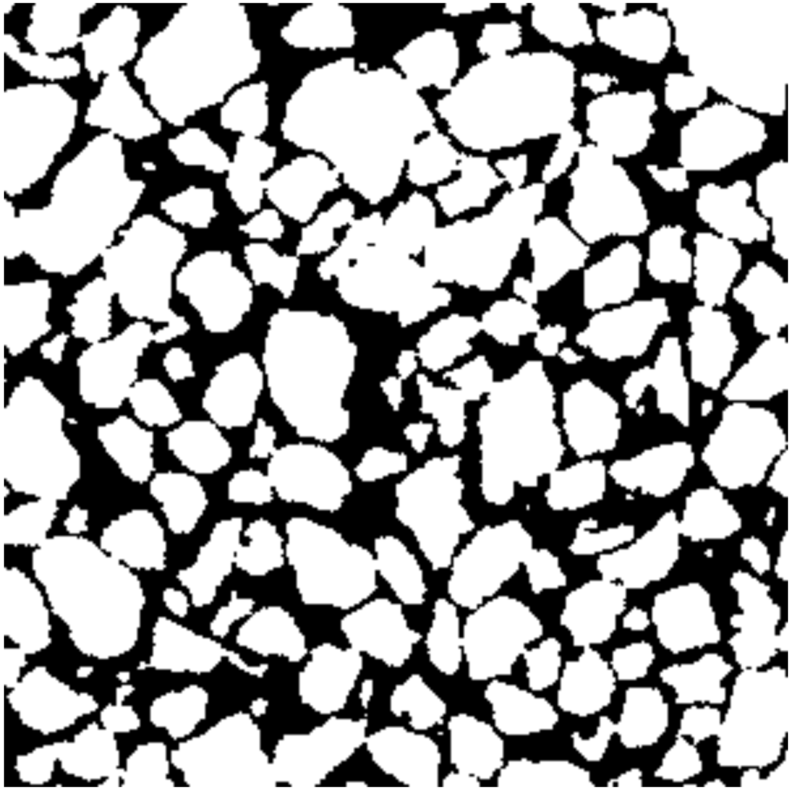
$$\frac{\mathrm{d}[\mathrm{Q}]}{\mathrm{d}t} = [\mathrm{L}](R_4^+ - R_4^-)$$

$$\frac{\mathrm{d}[\mathrm{F}]}{\mathrm{d}t} = -[\mathrm{F}]R_2$$

$$\frac{\mathrm{d}[\mathrm{W}]}{\mathrm{d}t} = n[\mathrm{S}]R_2$$

Alevizos et al. RMRE 2016
See also the poster by Sotiris Alevizos

# How does it work?



Stack of CT-scan images
Chemical composition

# Chemical system reduction (chemical homogenisation)

Invariant manifold selection. E.g. steady state approximation for the intermediate species:

$$\frac{d[X]}{dt} = \frac{d[A]}{dt} = \frac{d[L]}{dt} = 0$$

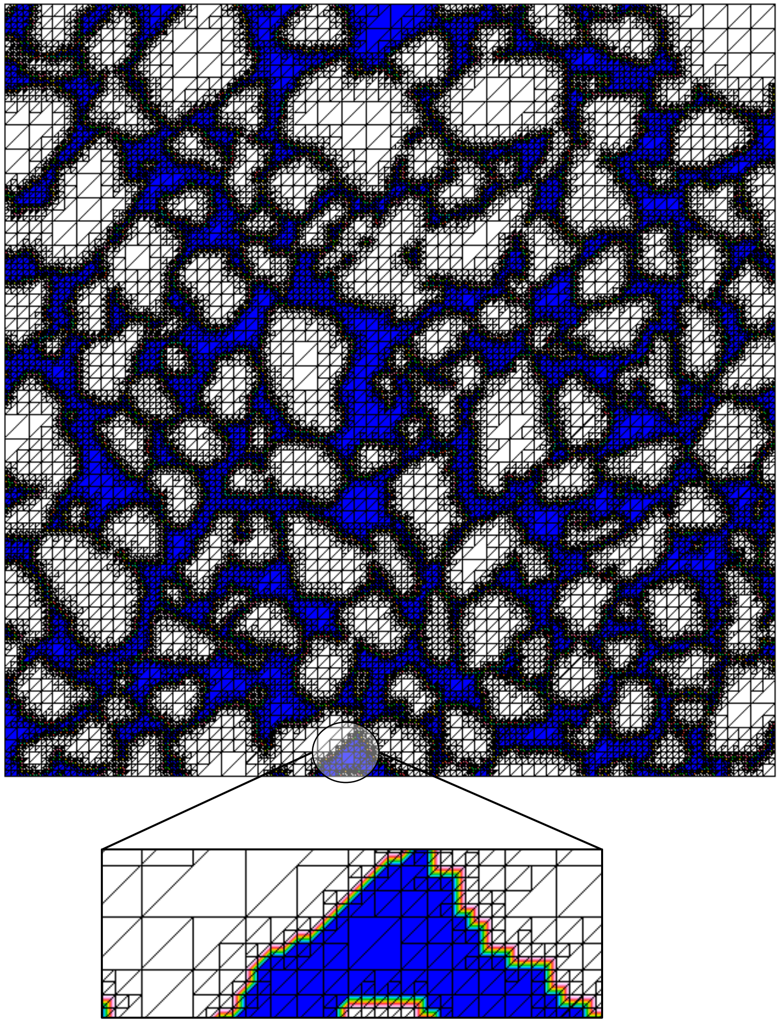
$$AB_{(\text{solid})} \underset{r^-}{\overset{r^+}{\rightleftharpoons}} A_{(\text{solid})} + B_{(\text{fluid})}$$

$$r^+ = C_{AB} k^+(T) = [S][F] R_1 R_2$$

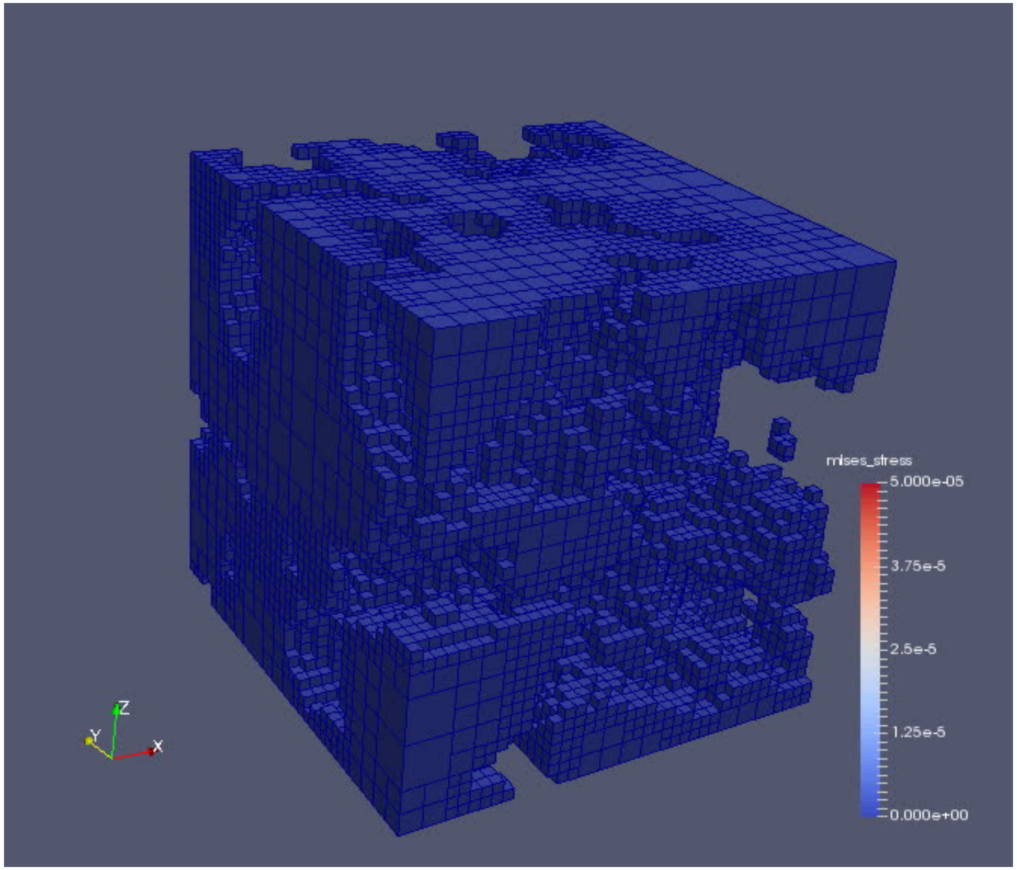
$$r^- = C_A C_B k^-(T) = 2nf[I][S][F]^2 \frac{R_2^3 R_3}{(R_4^+ - R_4^-)}$$

Alevizos et al. RMRE 2016
See also the poster by Sotiris Alevizos

# How does it work?



## Navier-Stokes fluid flow (hydraulic homogenisation)



See also the poster by Martin Lesueur

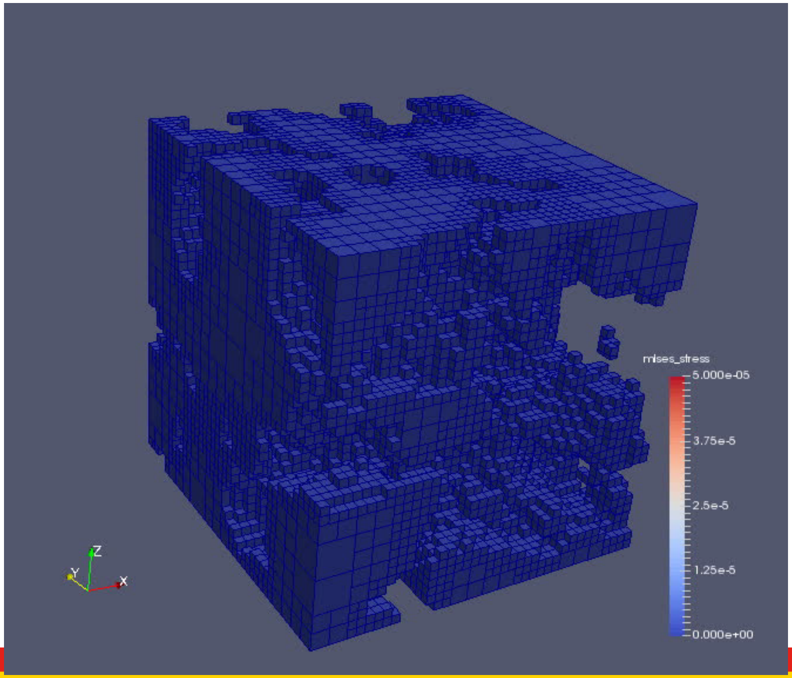
# How does it work?

Laboratory scale
THMC

Forces

Fluxes (disp)

CT-scan scale



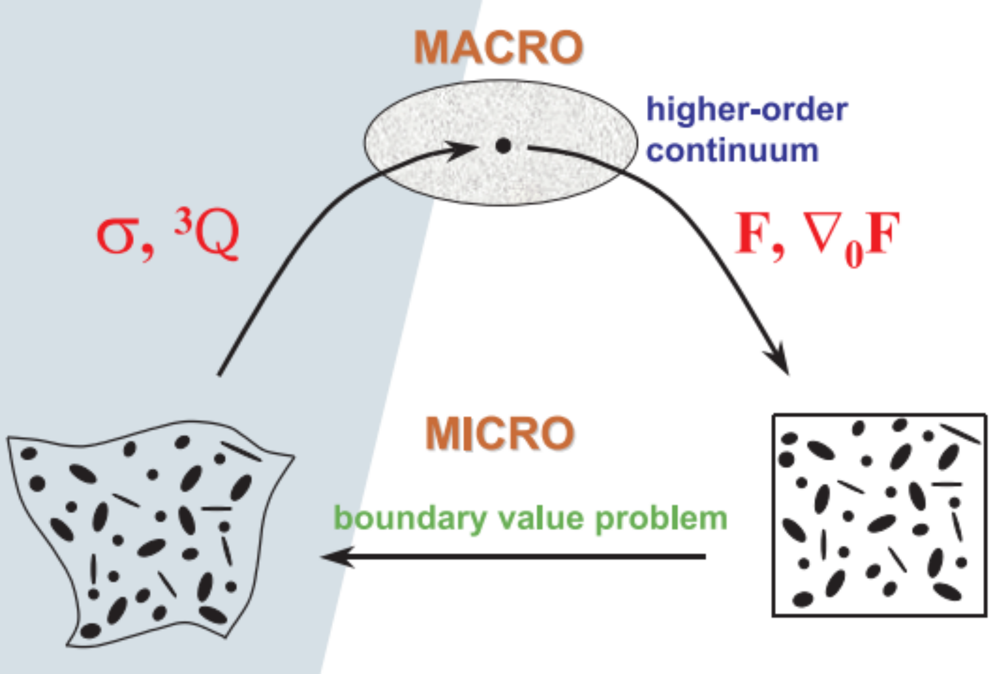
Navier-Stokes eqs
Linear elasto-plasticity

Fluxes (disp)

Forces

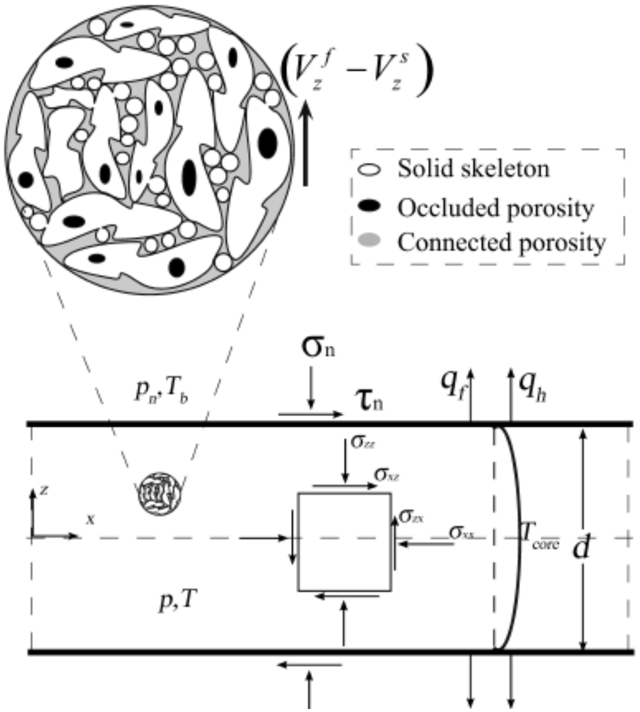
# How do we scale up from lab scale to geodynamics?

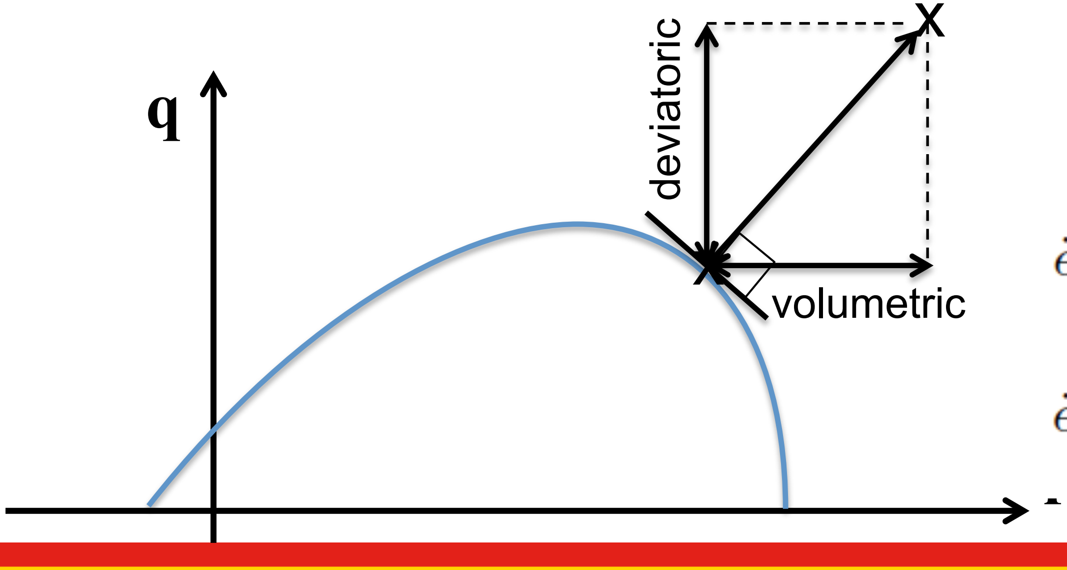
- THMC systems obey MaxEP, MinEP or something else? Does the choice of BCs make any difference?
- Current paradigm in computational homogenisation follows the MaxEP path
- Is MaxEP representative for THMC systems? How do we deal with the cascade of length/time scales of localisation?



# The multiphysics (THMC) approach

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





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

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

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

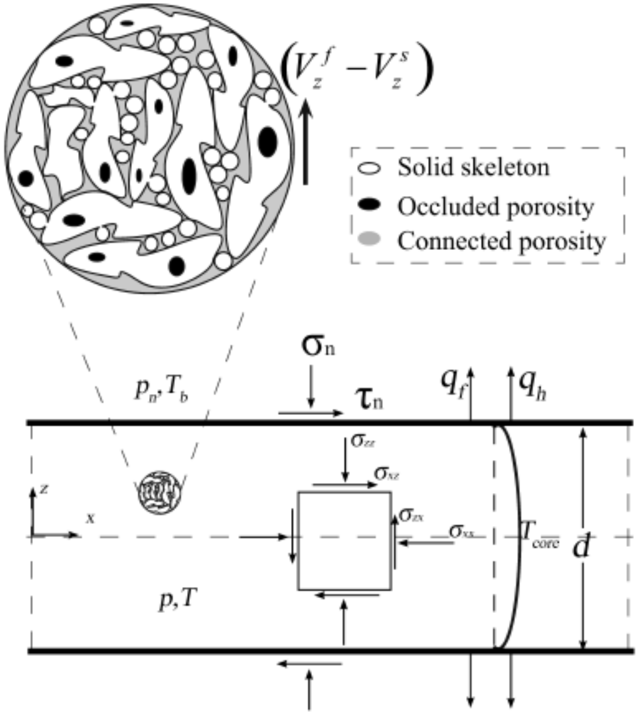
# Towards a unified THMC approach

- 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

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

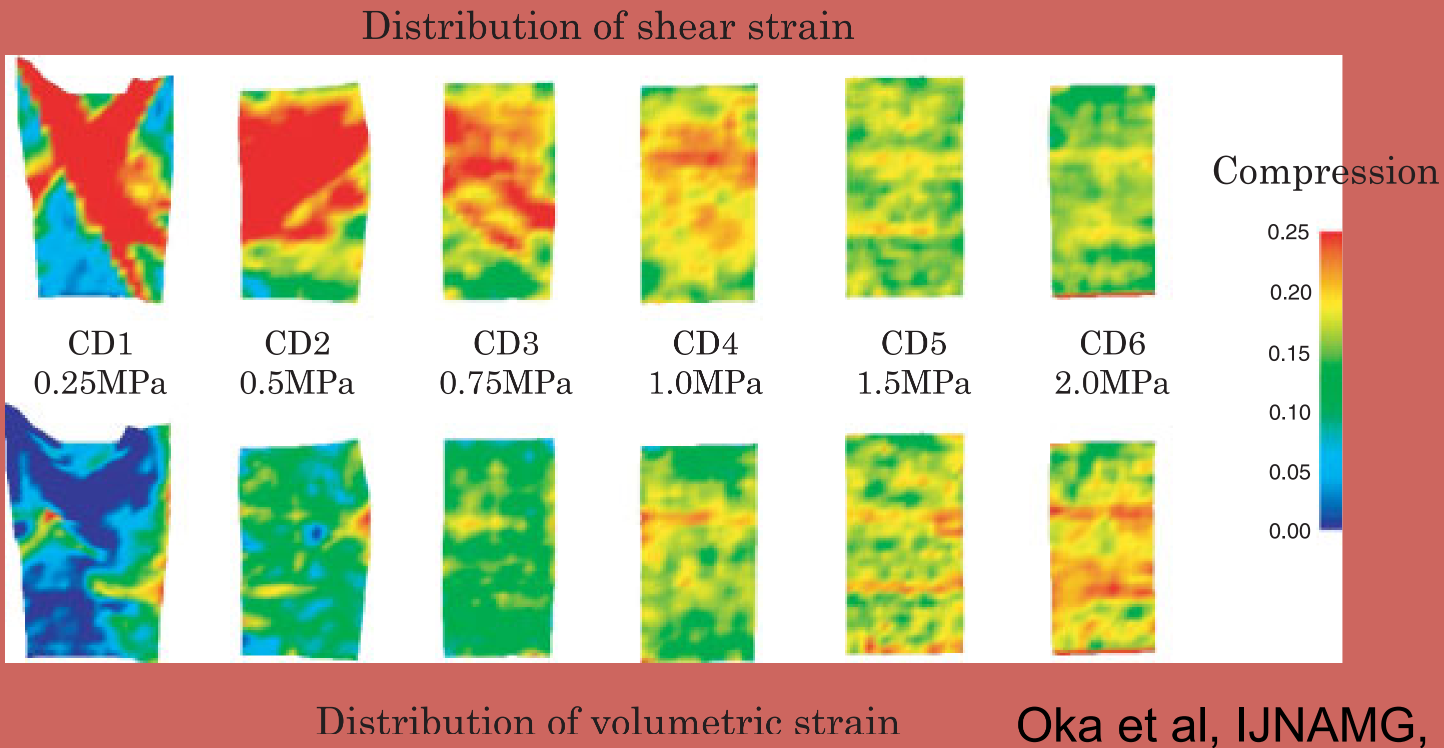


$$\phi = \phi_0 + \Delta\phi_{mech} + \Delta\phi_{chem}$$

$$\boxed{\begin{aligned} \Delta\phi_{\text{chem}} &= A_\phi \frac{1-\phi_0}{1+\frac{\rho_B}{\rho_A}\frac{M_A}{M_B}\frac{1}{s}}, \\ s &= \frac{\omega_{\text{rel}}}{1+\omega_{\text{rel}}}, \quad \text{and} \\ \omega_{rel} &= \frac{\rho_{AB}}{\rho_A}\frac{M_A}{M_{AB}} K_c \exp\left(\frac{\Delta H}{RT}\right) \end{aligned}}$$

# Do we need chemistry?

## Triaxial experiments (THM) in soft rocks



Oka et al, IJNAMG, 2011

The goal is to constrain the hardening law:

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

$$E = E_0 + \Delta \text{E}$$

# a (T)HM system for pore collapse

$$0 = \partial_j \sigma'_{ij} - \partial_i \Delta p_f + b_i,$$

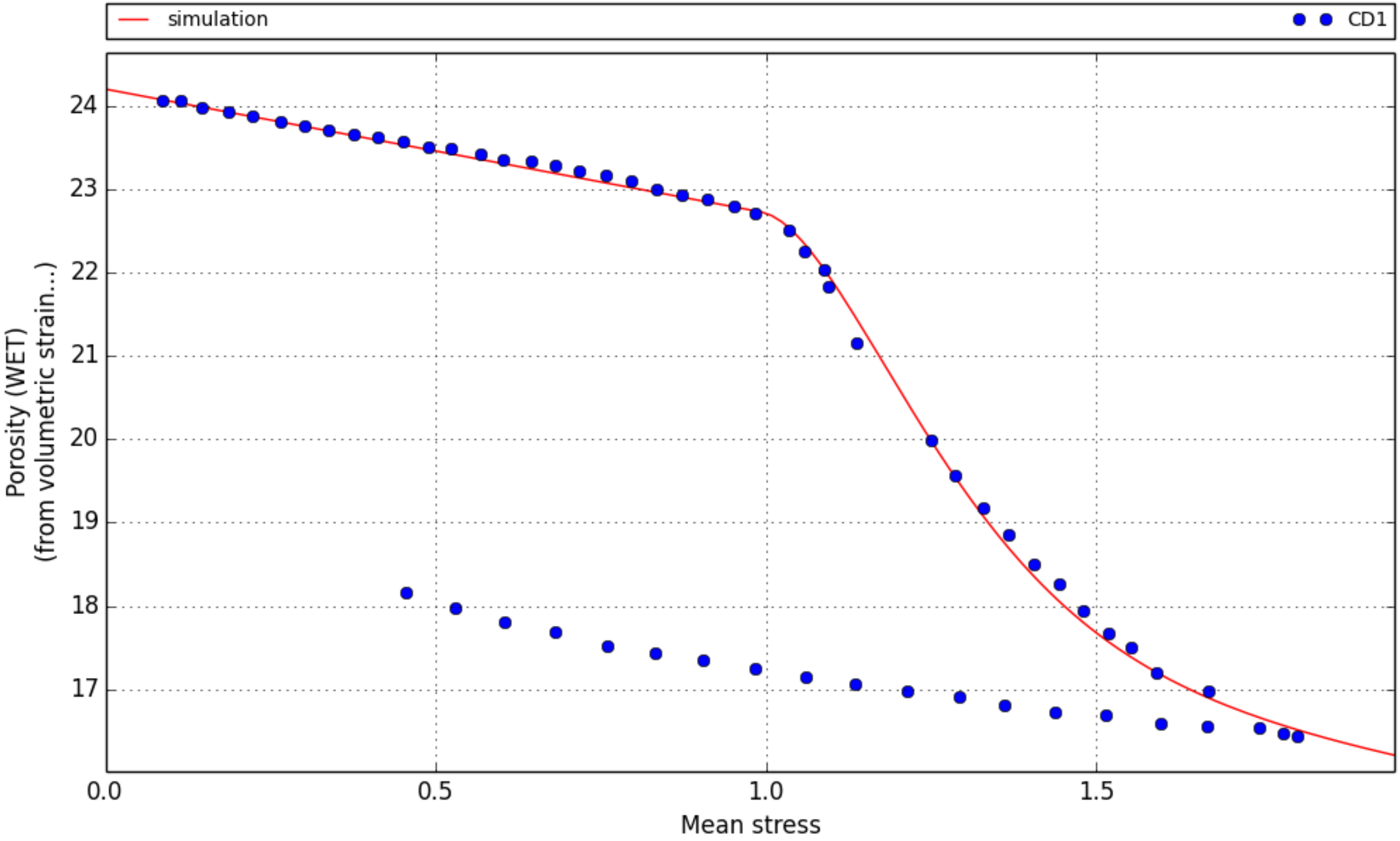
$$0 = \partial_t \Delta p_f - \partial_i \left[ \frac{1}{Le} \partial_i \Delta p_f \right] - \Lambda \partial_t T + \frac{\dot{\epsilon}_V}{\bar{\beta}},$$

$$\boxed{0 = \partial_t T - \partial^2_{ii} T - Gr\, \sigma_{ij} \dot{\epsilon}^{pl}_{ij}.}$$

The energy and entropy balance laws are solved explicitly to determine the global attractor of the system

# Diagenesis (pore collapse) in sandstone

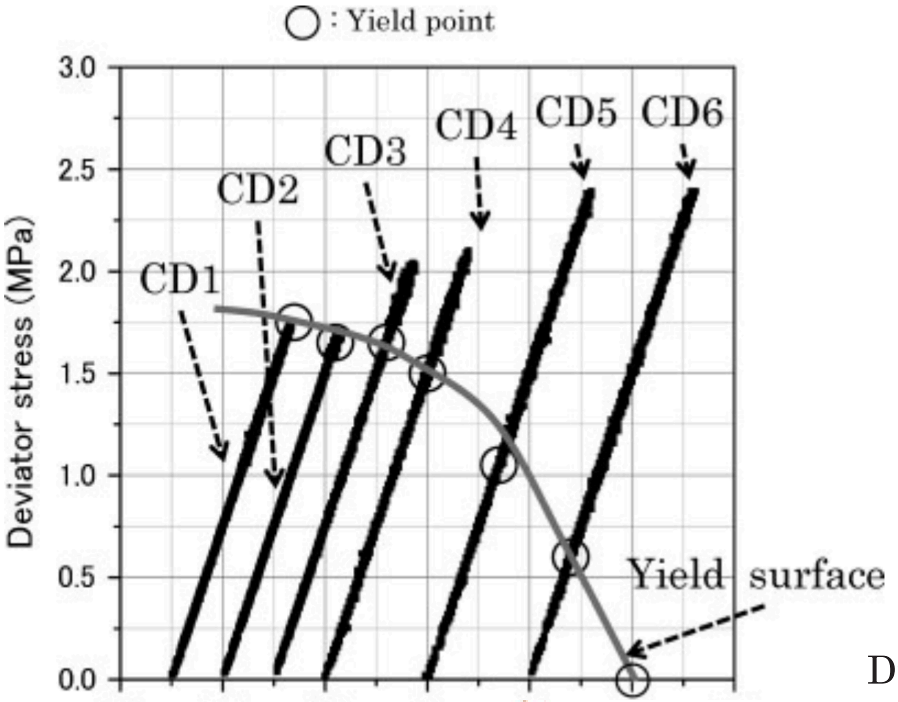
## Isotropic consolidation of saturated Bleurwiller sandstone



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

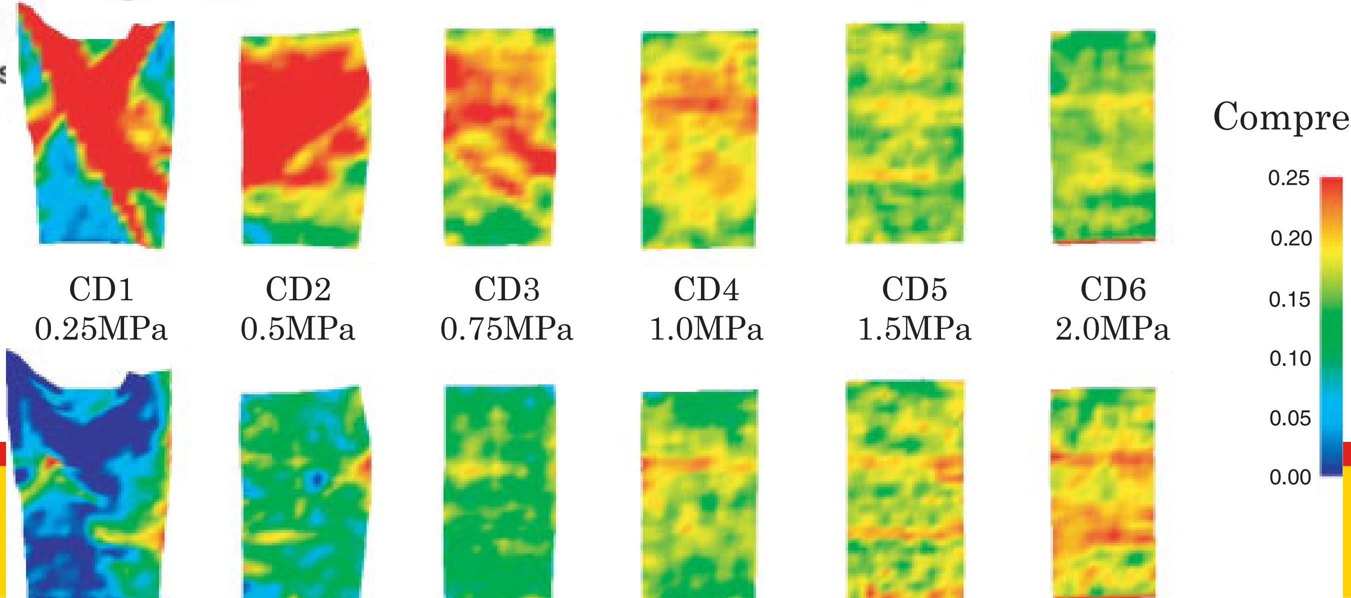
Fortin et al, JGR 2007

# Drained consolidation of diatomaceous mudstone

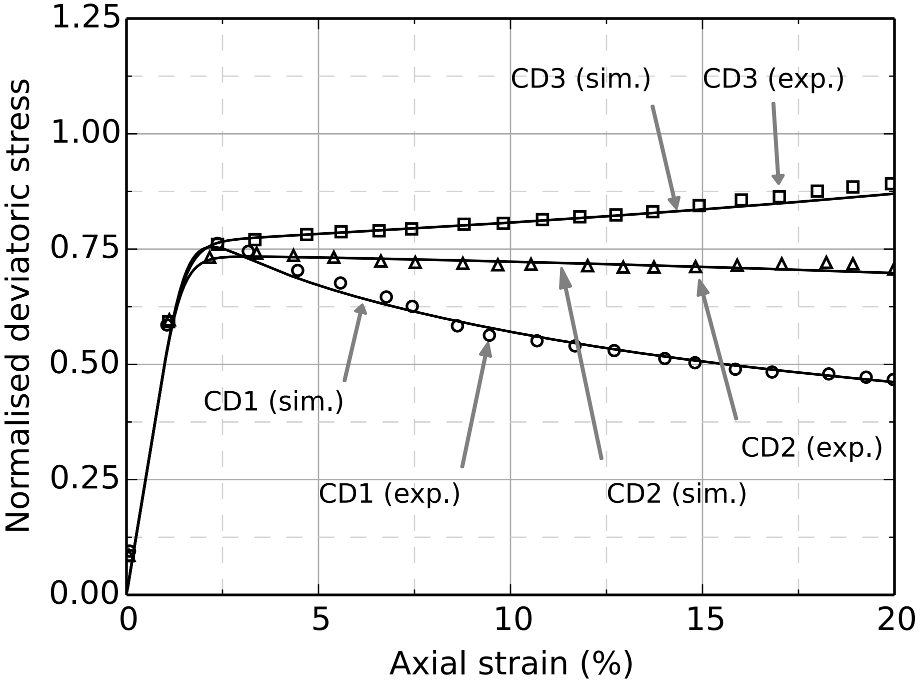


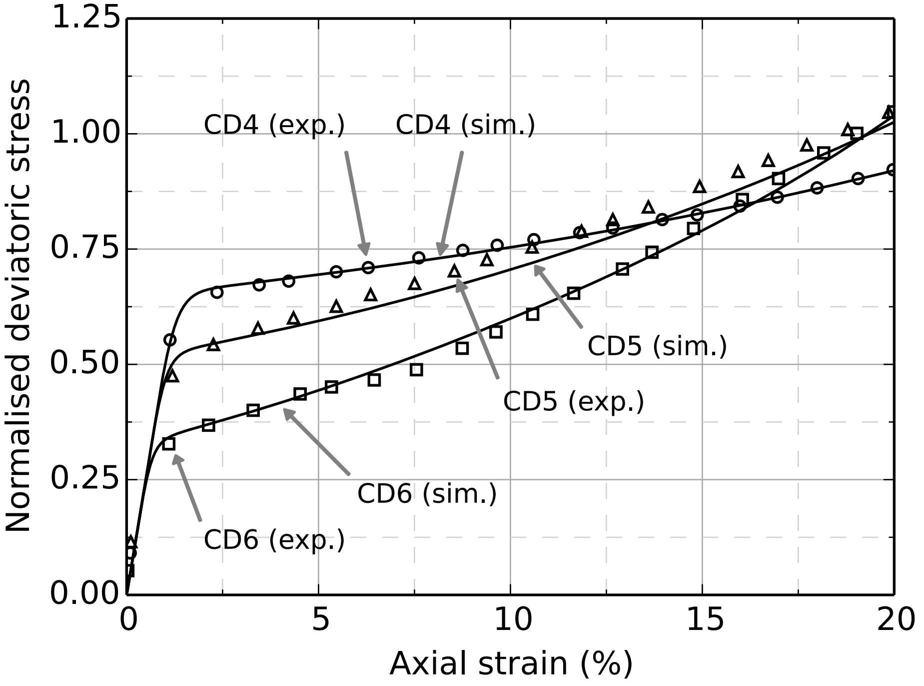
Oka et al, IJNAMG, 2011

Distribution of shear strain

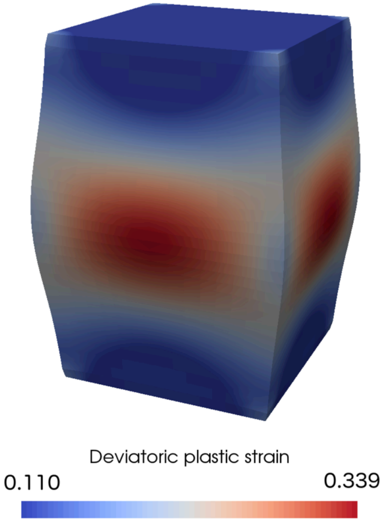


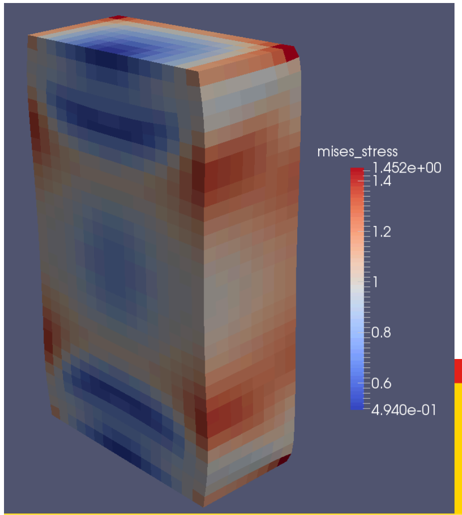
# Matching the experiments





See also poster by Mustafa Sari for more materials (sandstone, carbonates…)

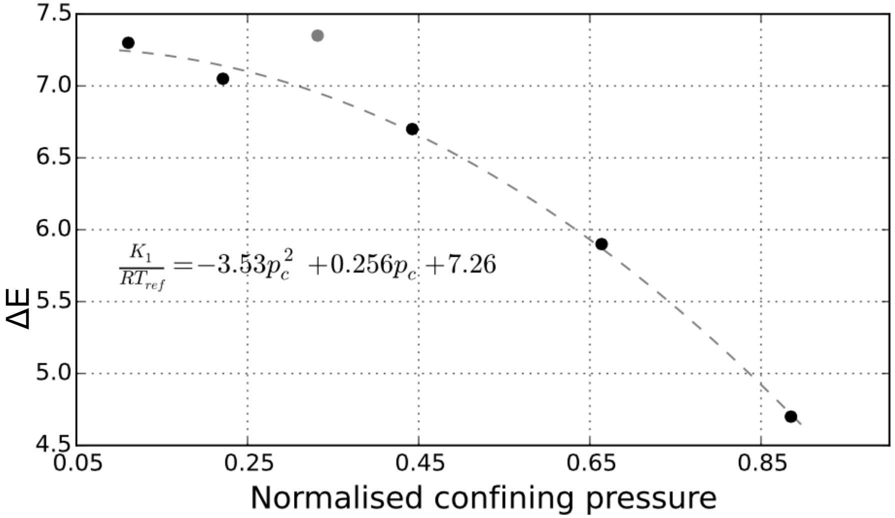


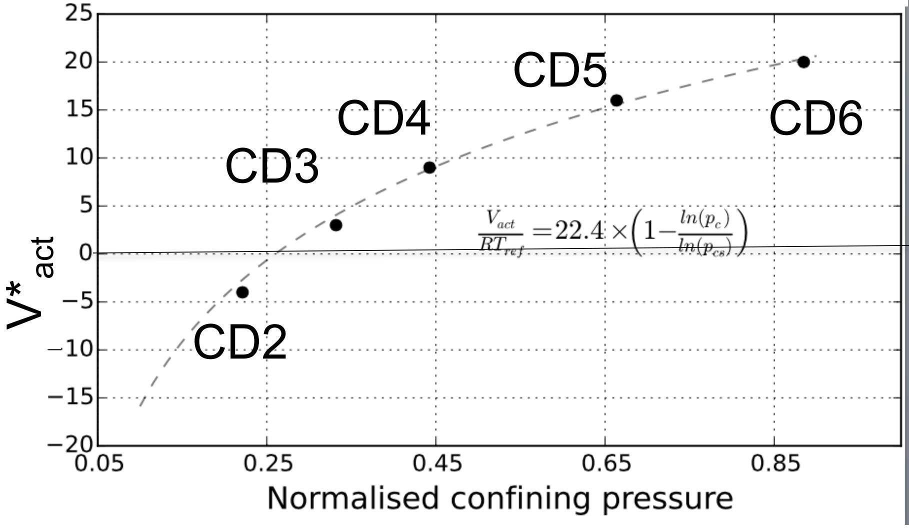


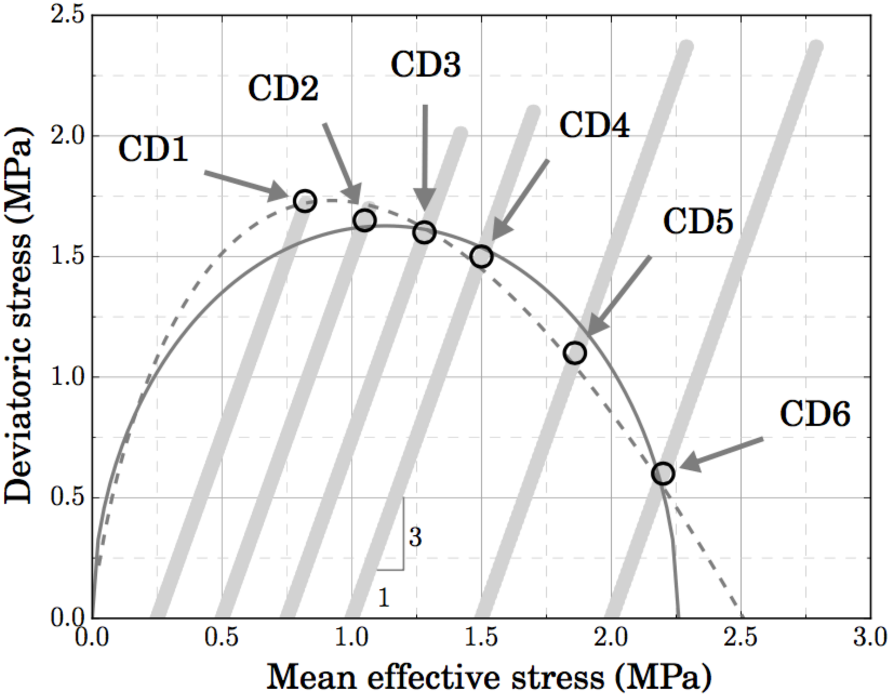
Poulet and Veveakis COGE 2016

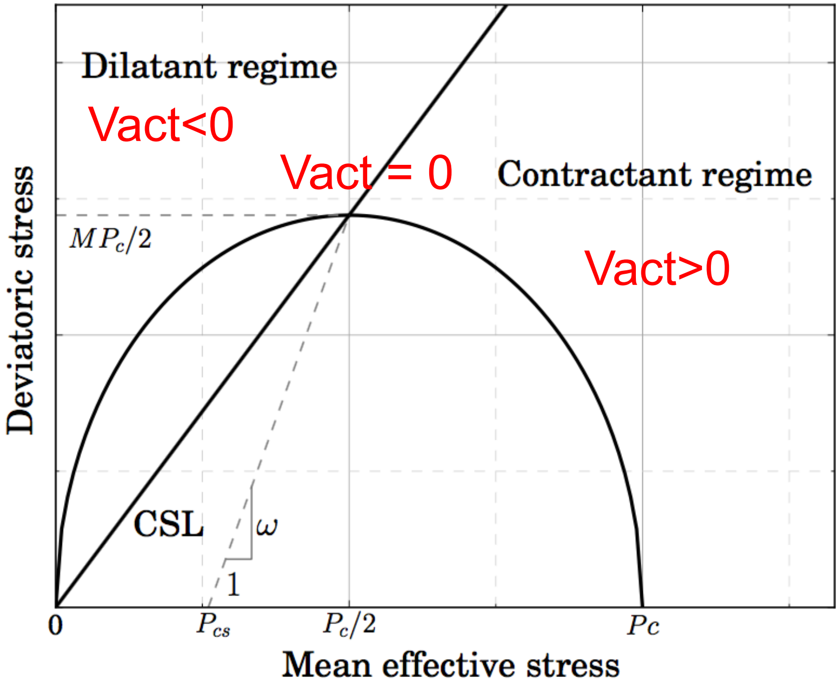
# Retrieving information for the rheology

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



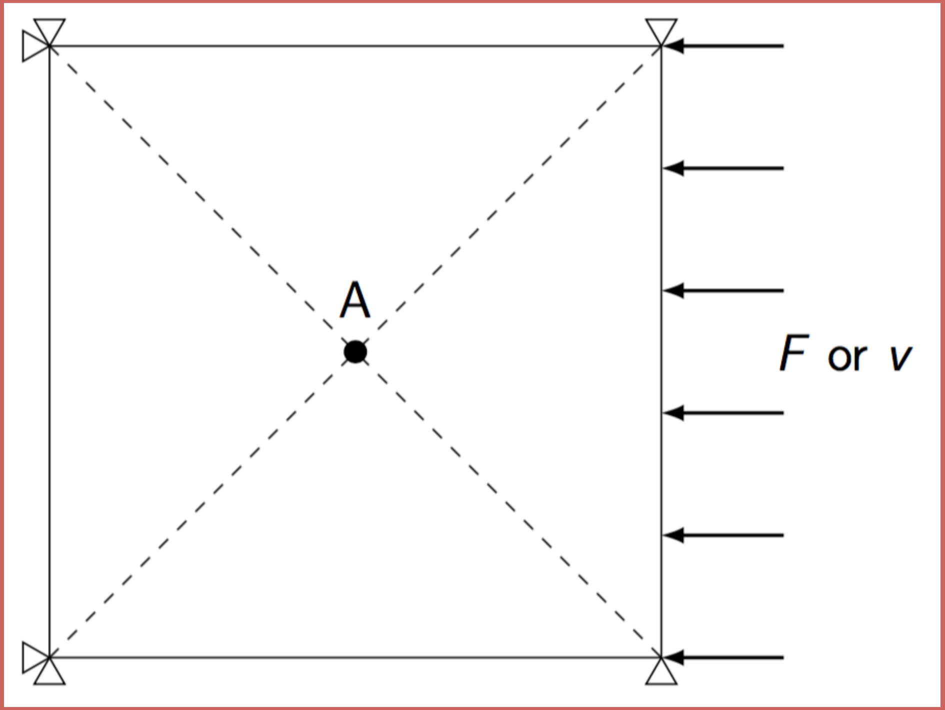


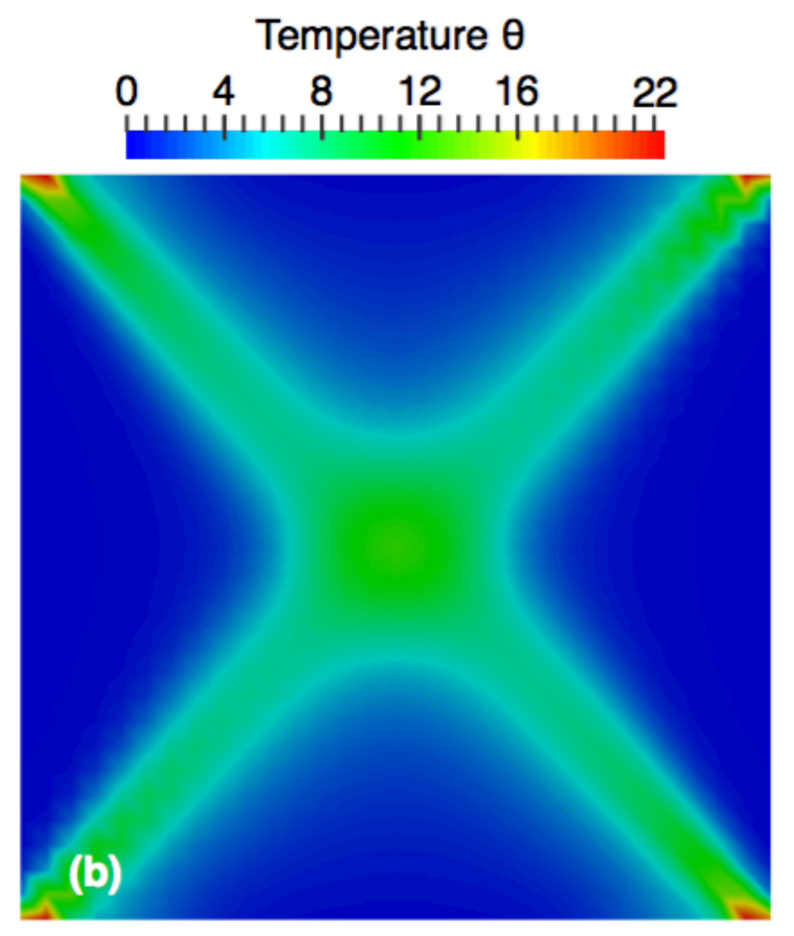




# MaxEP or MinEP

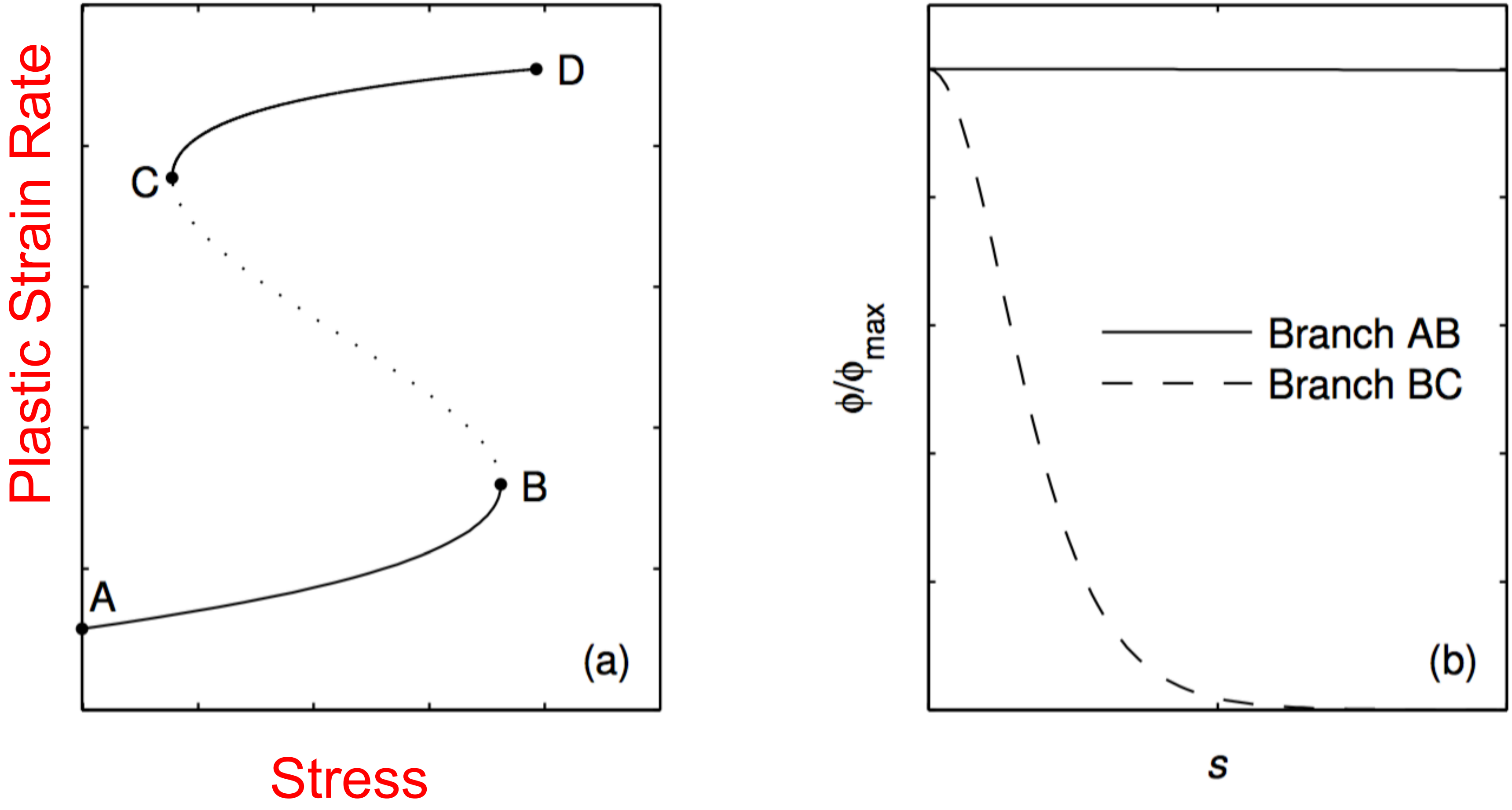
## Where do THM systems self-organise?





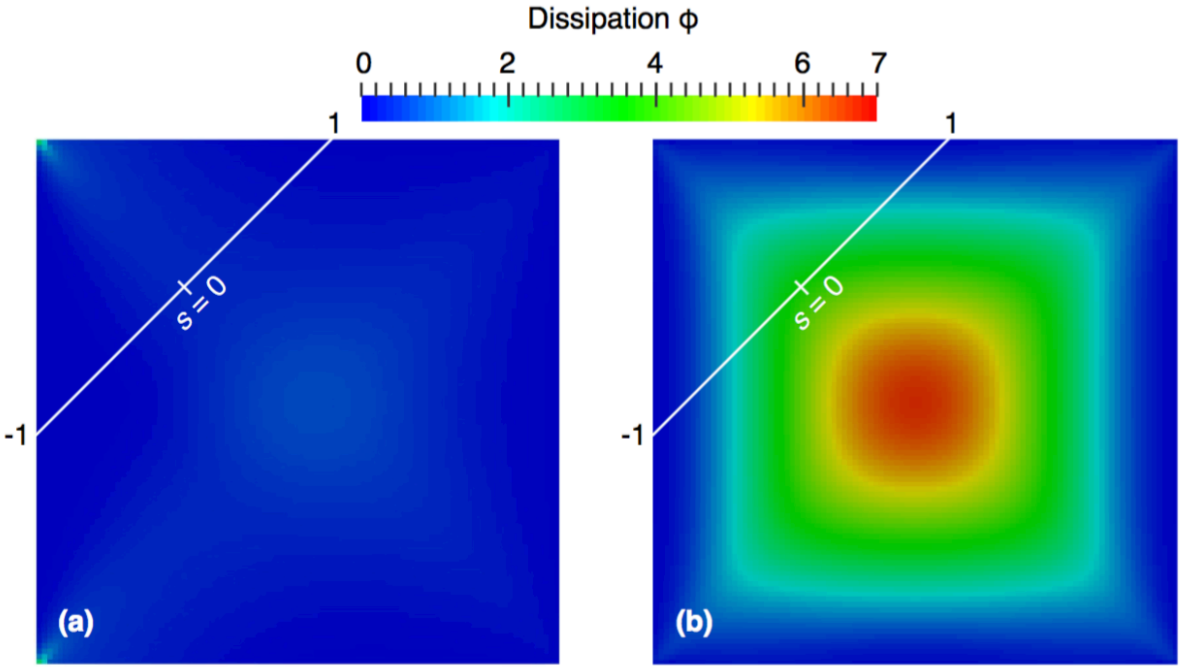
Paesold et al JoMMS 2016

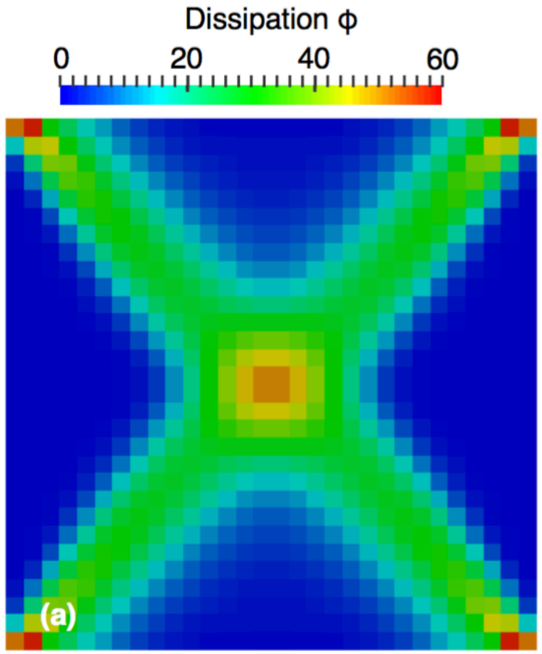
# T(H)M systems self-organise at MaxEP



Paesold et al JoMMS 2016

# T(H)M systems self-organise at MaxEP

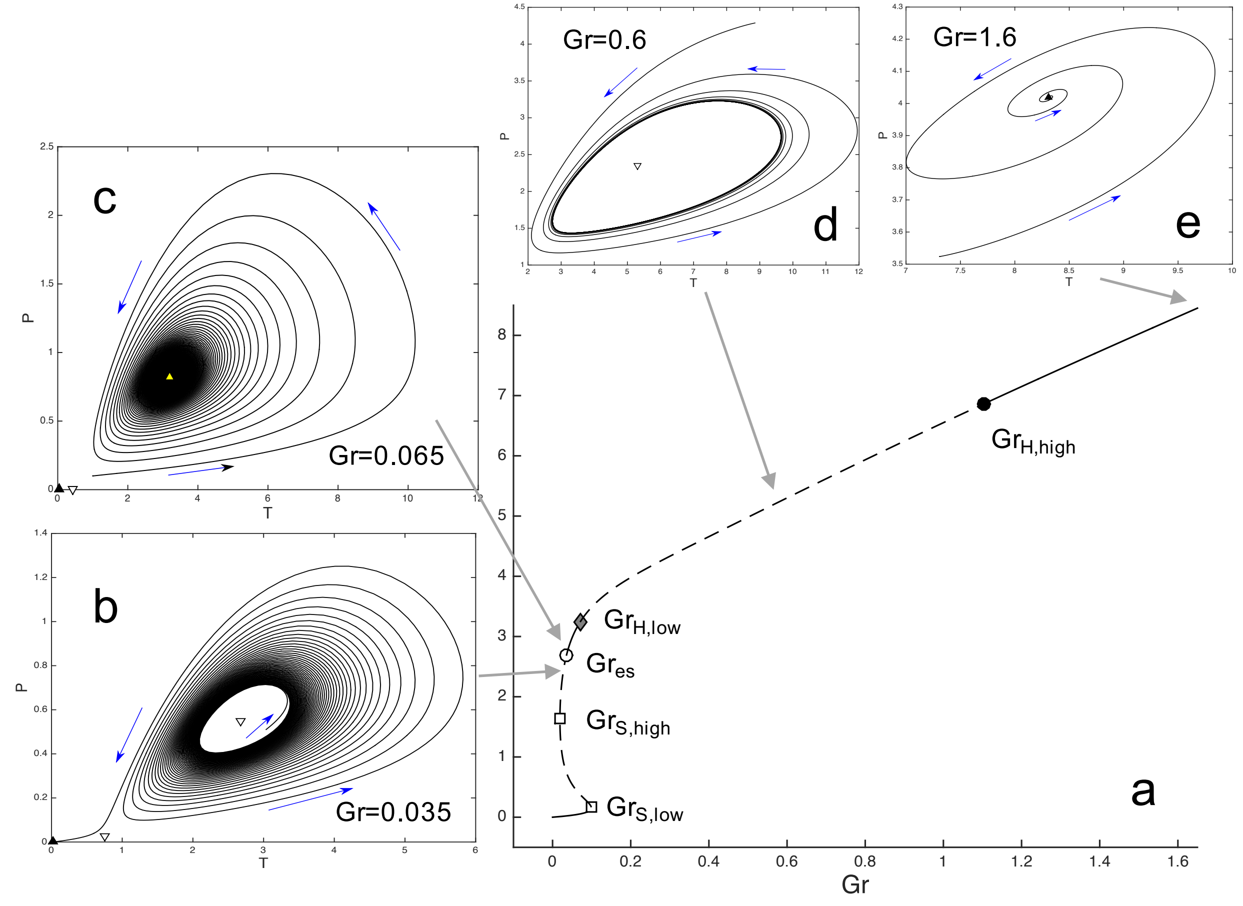




Paesold et al JoMMS 2016

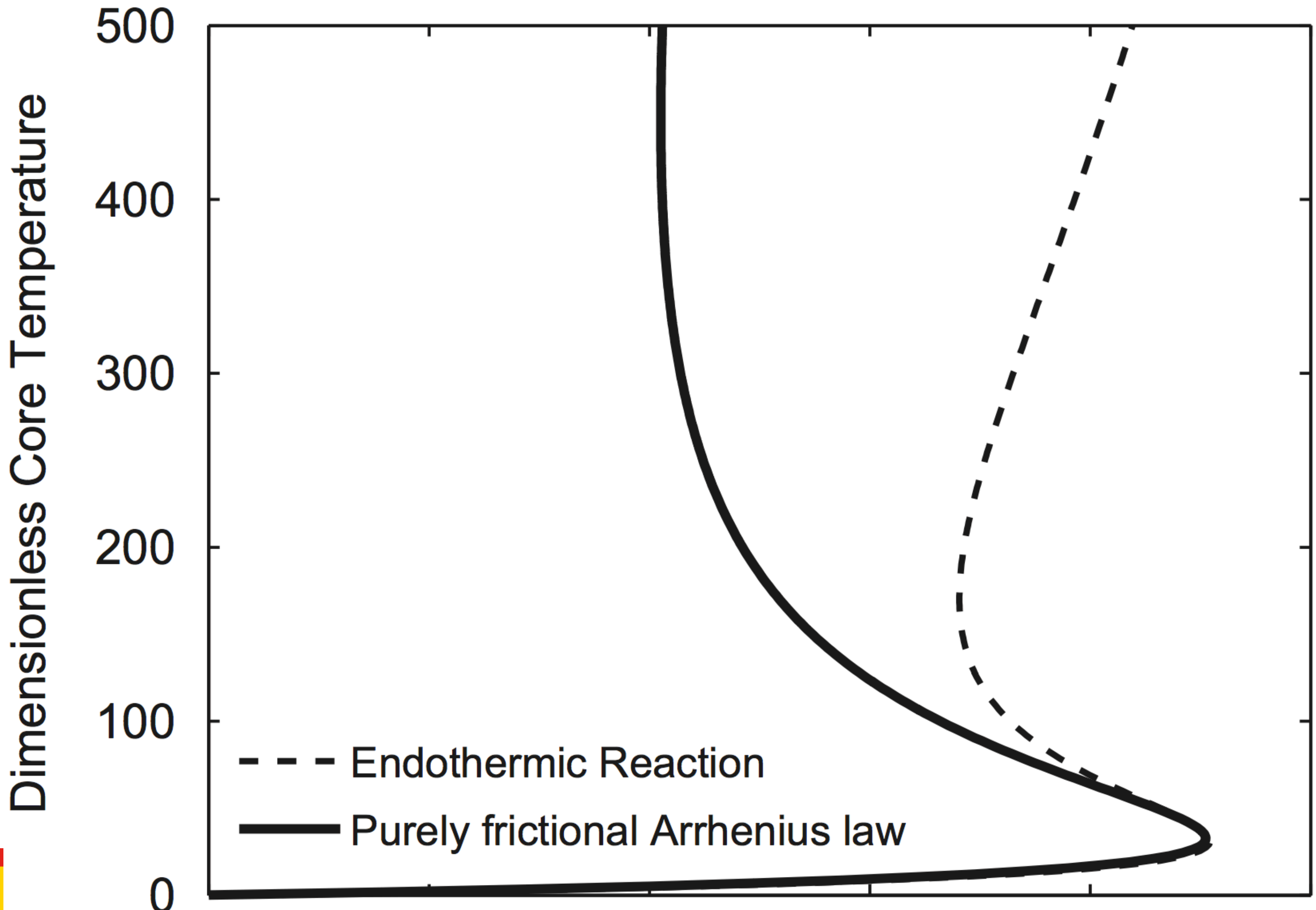
# So…

# Where do THMC systems self-organise?



Alevizos et al, Mathematics 2016

# What changes when chemistry is included?



Veveakis et al, JMPS 2010

# System of equations

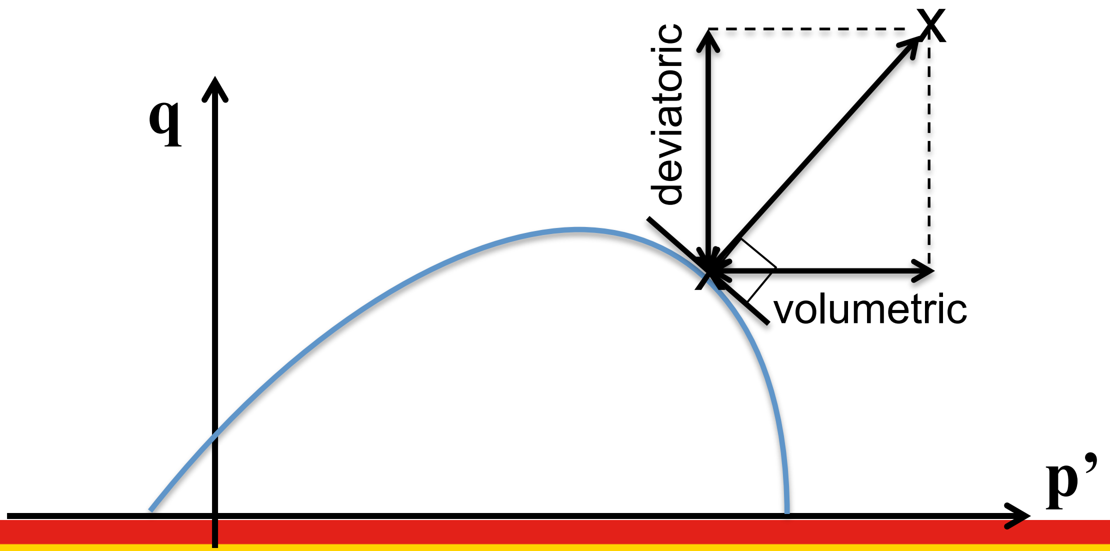
$$AB_{(solid)} \underset{r_R}{\overset{r_F}{\rightleftharpoons}} A_{(solid)} + B_{\text{(fluid)}} \qquad r_{F,R} = k_{F,R}\rho_i\, \mathrm{e}^{-\frac{Ar}{1+\theta}}$$

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

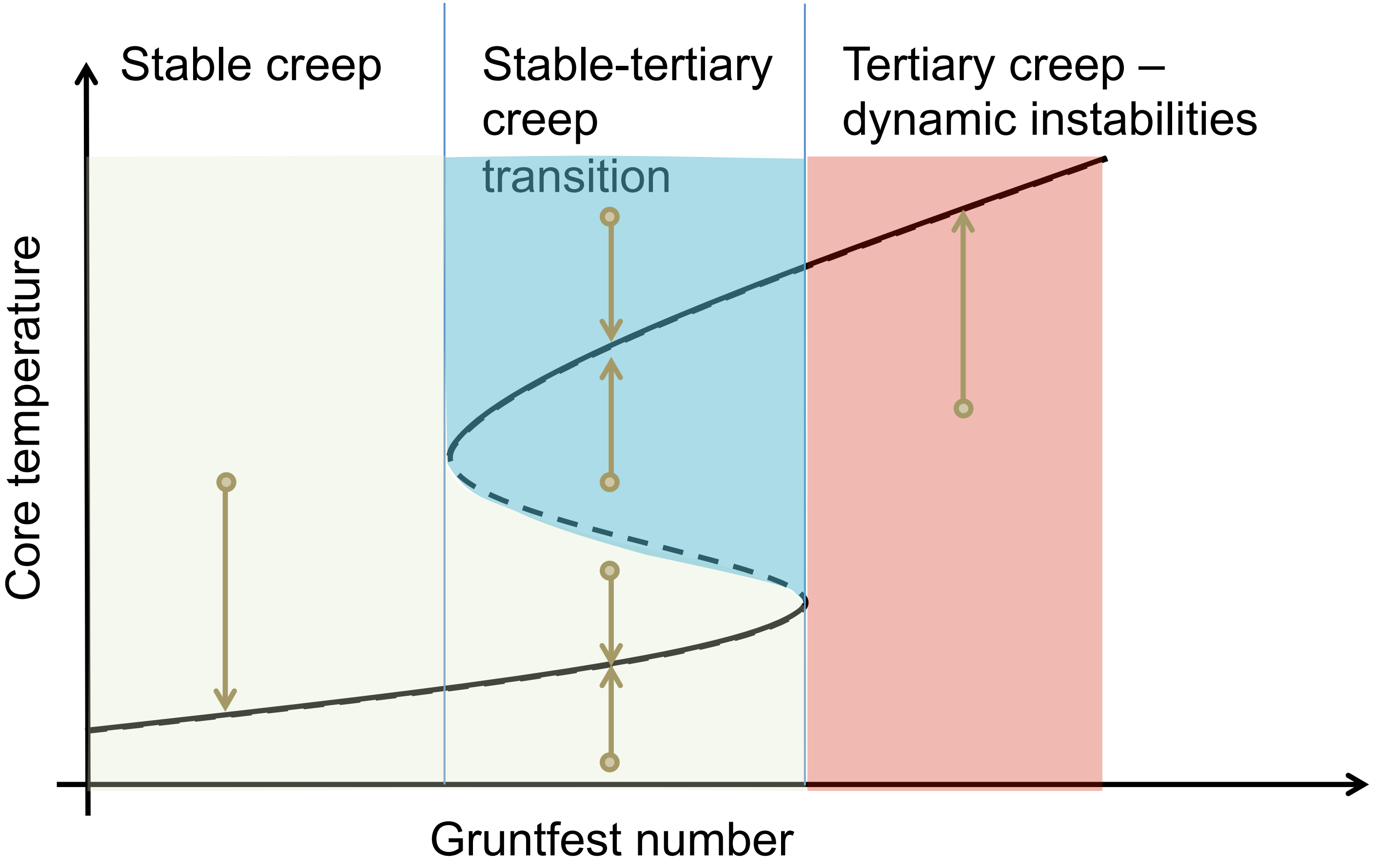
$$\frac{\partial\theta}{\partial t} + Pe_{thermal}\, v.\nabla\theta - \nabla^2\theta - \mathrm{X}.\tau.\dot{\varepsilon}_d^p - \mathrm{X}.\sigma.\dot{\varepsilon}_v^p + \left|\Delta H\right|.\mathrm{r}_F - \left|\Delta H\right|.r_R = 0$$

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

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



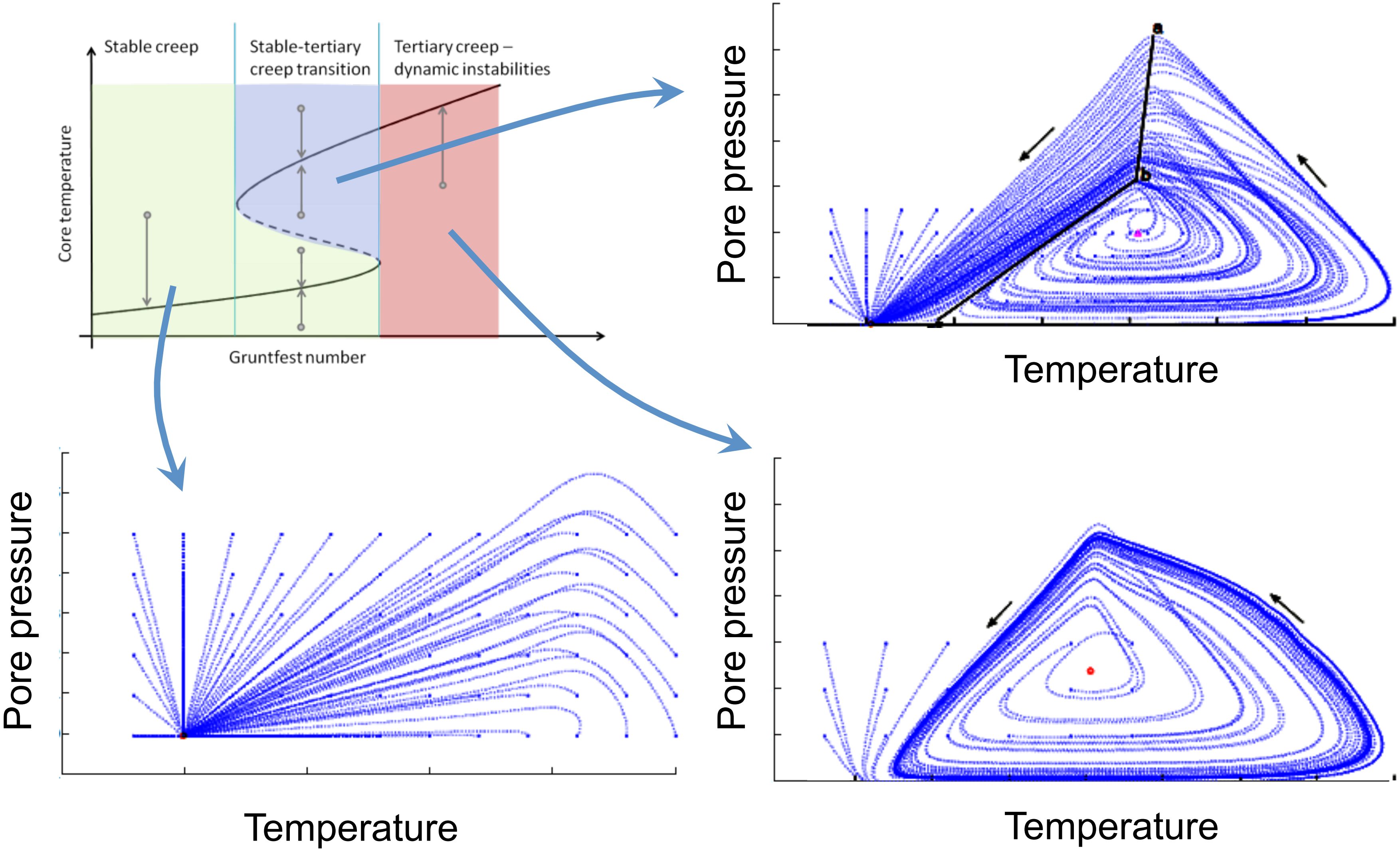
# System's stability regimes



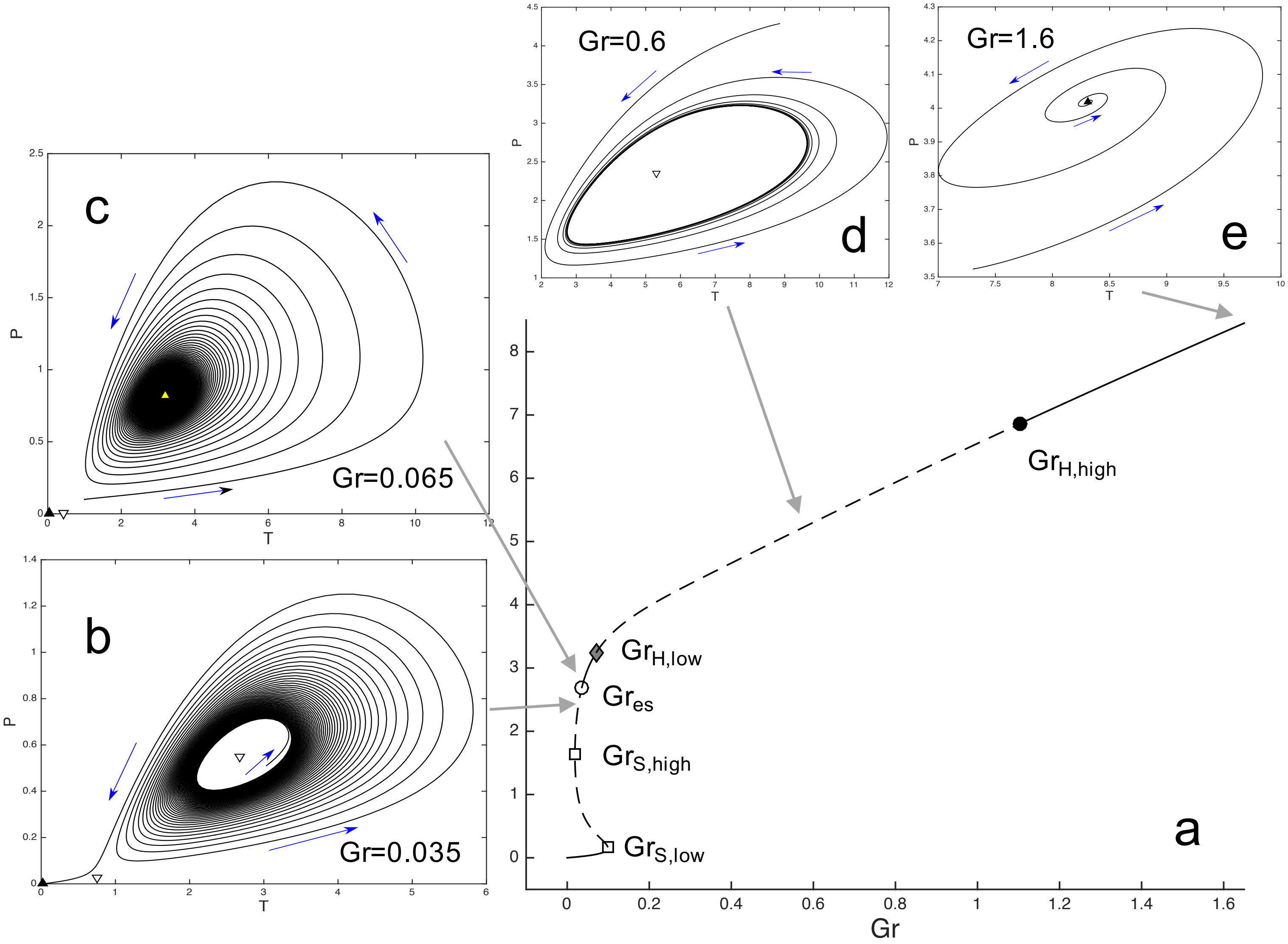
$$Gr = \frac{\text{char. time scale heat production}}{\text{char. time scale energy transfer}}$$

# Phase diagrams

Natural localised instability

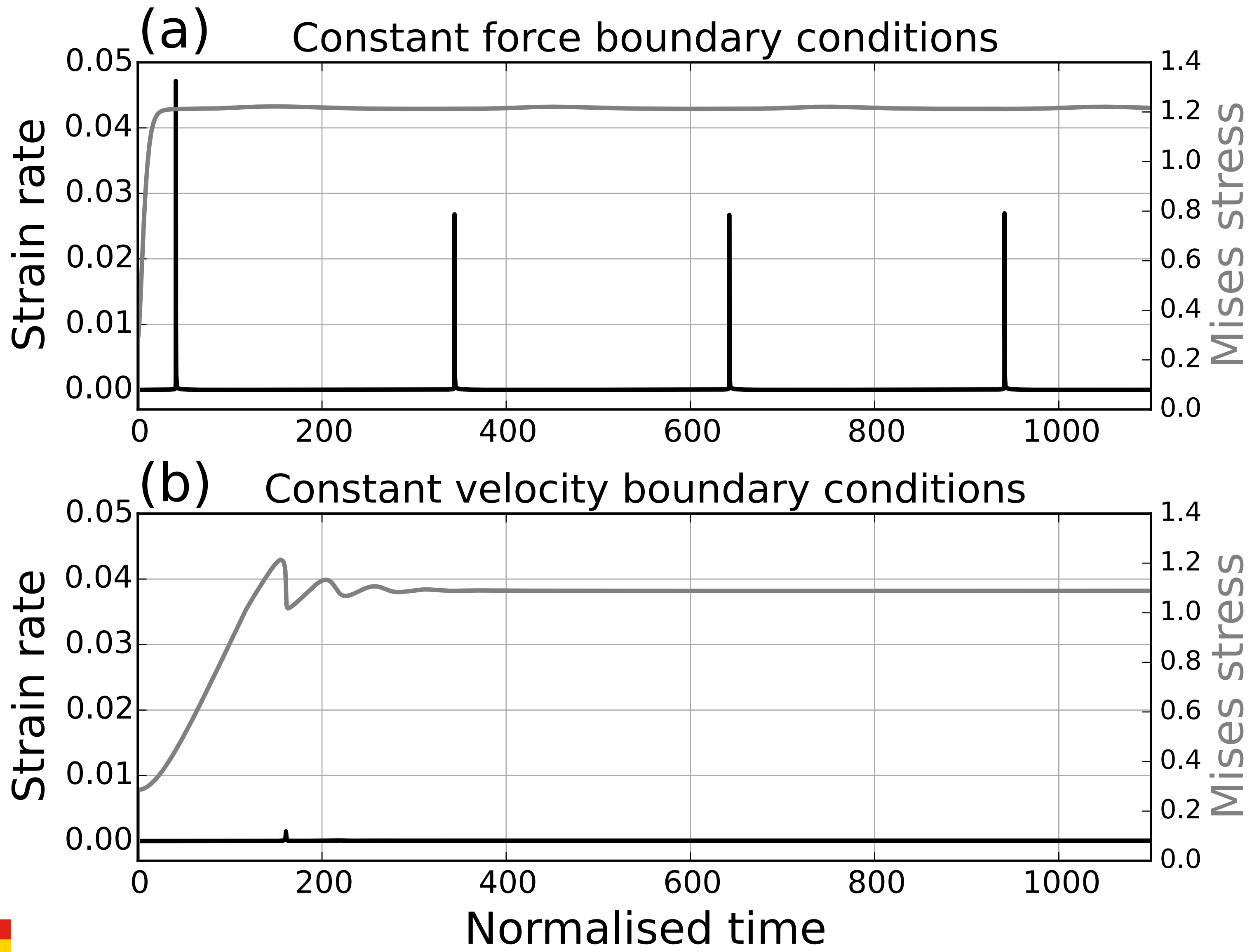


# THMC systems self-organise around MinEP

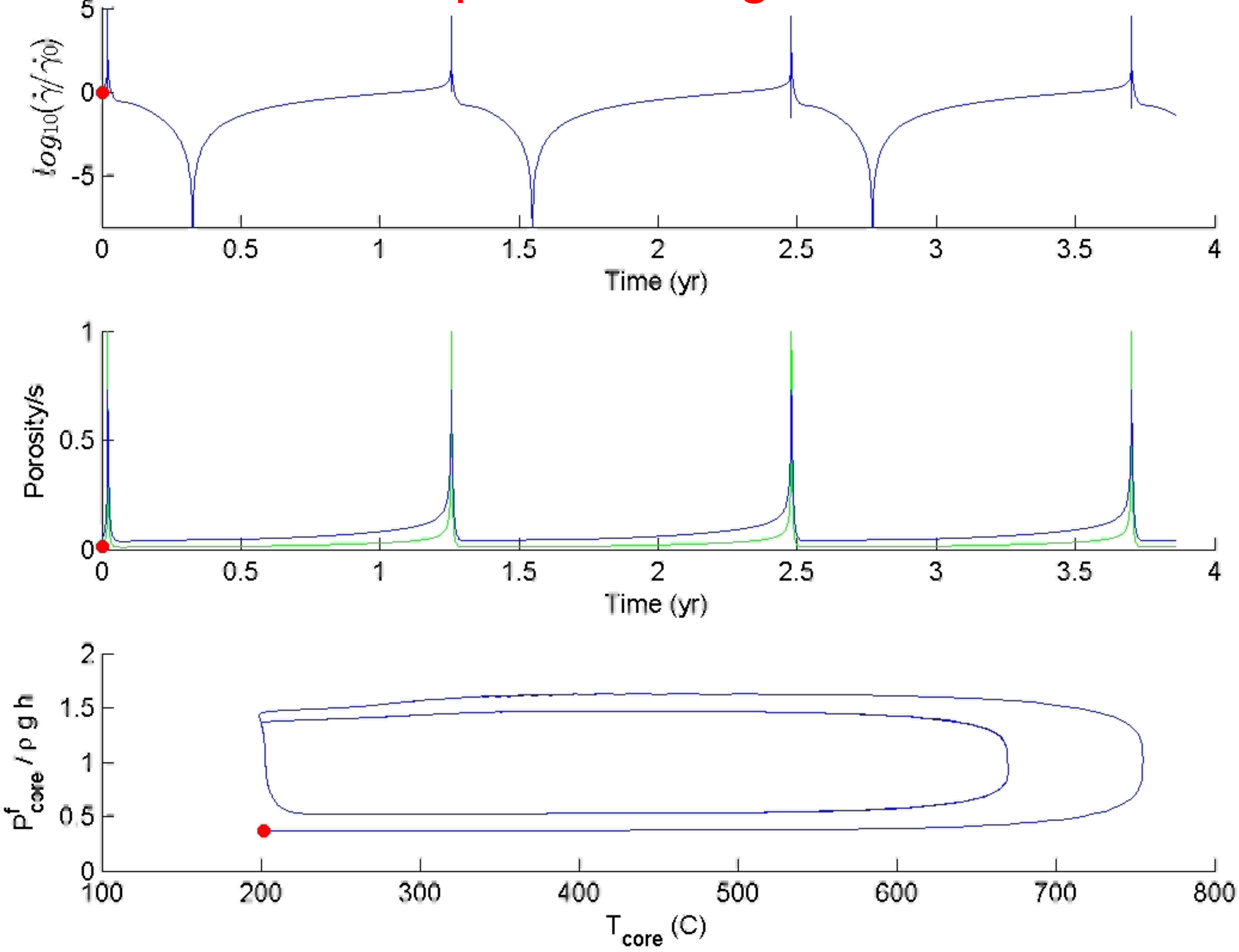


Alevizos et al, Mathematics 2016

# How do we upscale from here? Constant force vs flux BCs

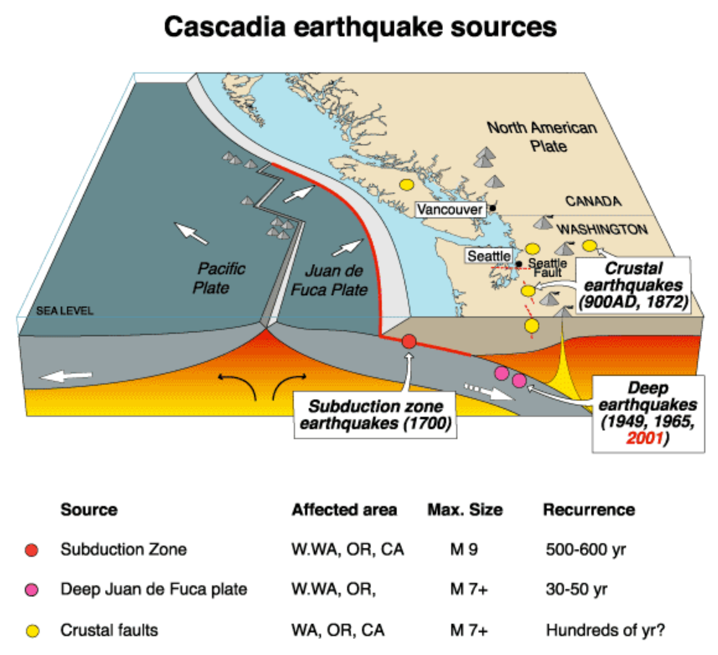


# Multiple time/length-scales



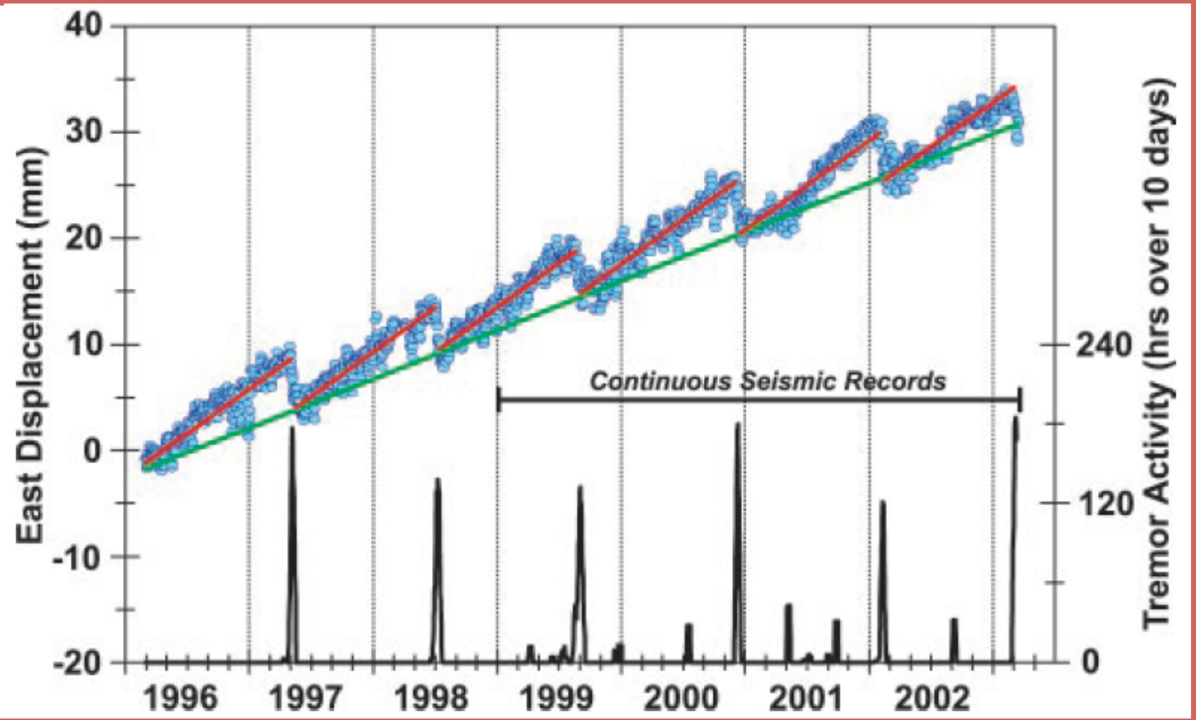
# Exrtapolation to large scales?

# Large scale modelling

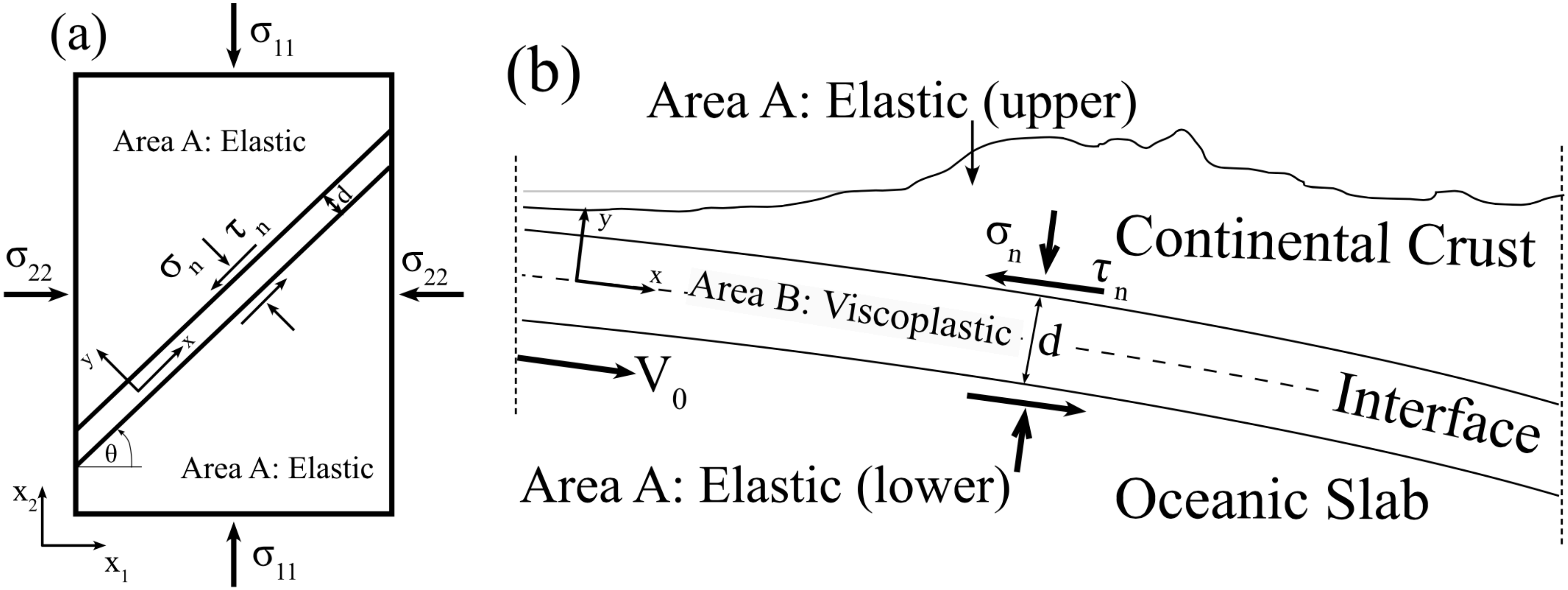


**Cascadia earthquake sources**

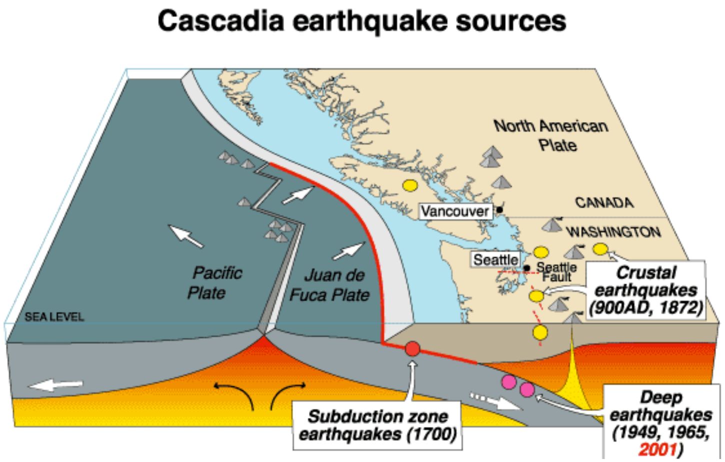
| | Source | Affected area | Max. Size | Recurrence |
|---|---|---|---|---|
| ● | Subduction Zone | W.WA, OR, CA | M 9 | 500-600 yr |
| ● | Deep Juan de Fuca plate | W.WA, OR, | M 7+ | 30-50 yr |
| ● | Crustal faults | WA, OR, CA | M 7+ | Hundreds of yr? |

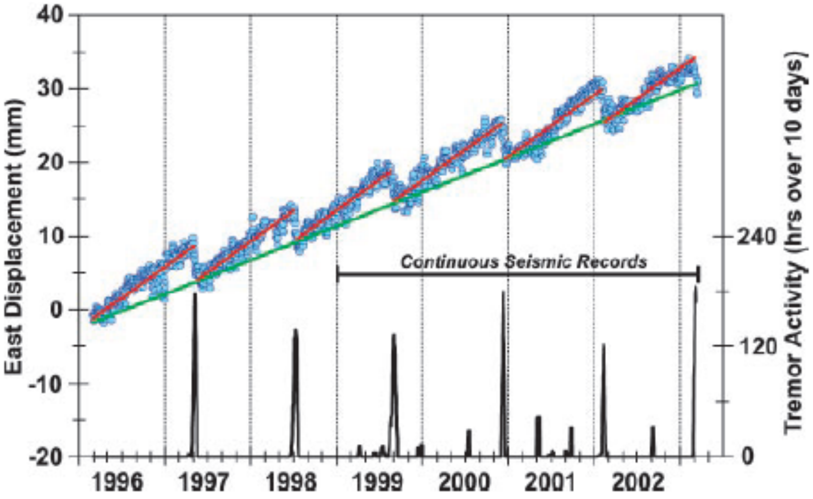


# Modelling Subduction zones: Serpentinite dehydration oscillator

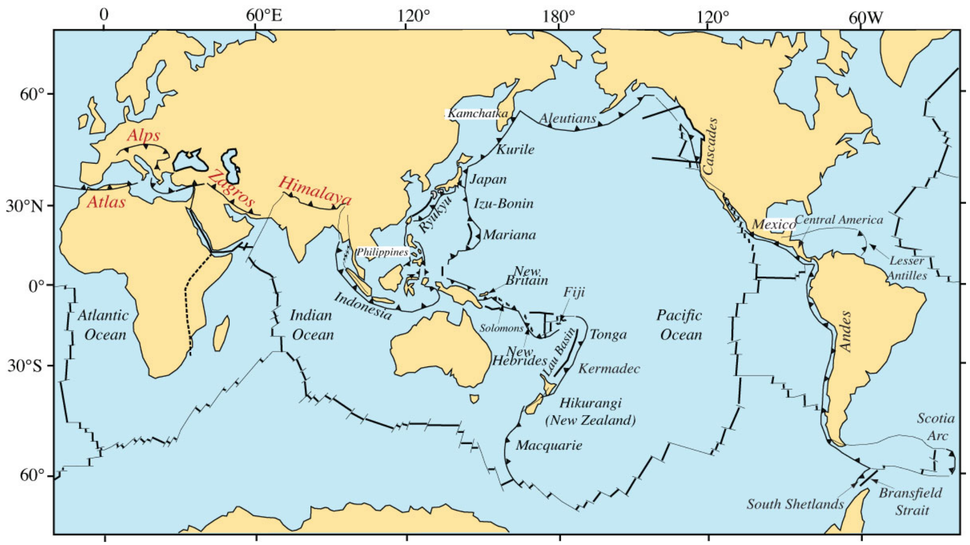


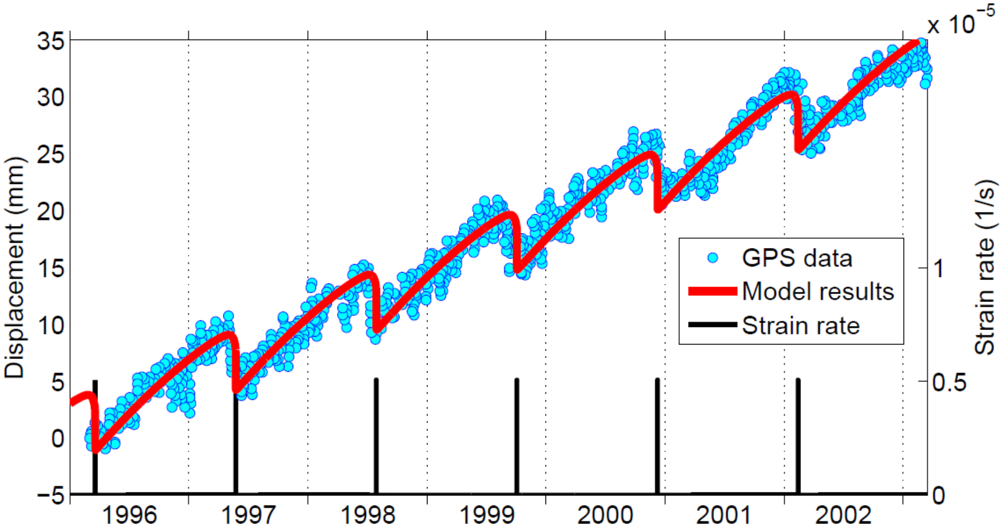
# Modelling subduction zones





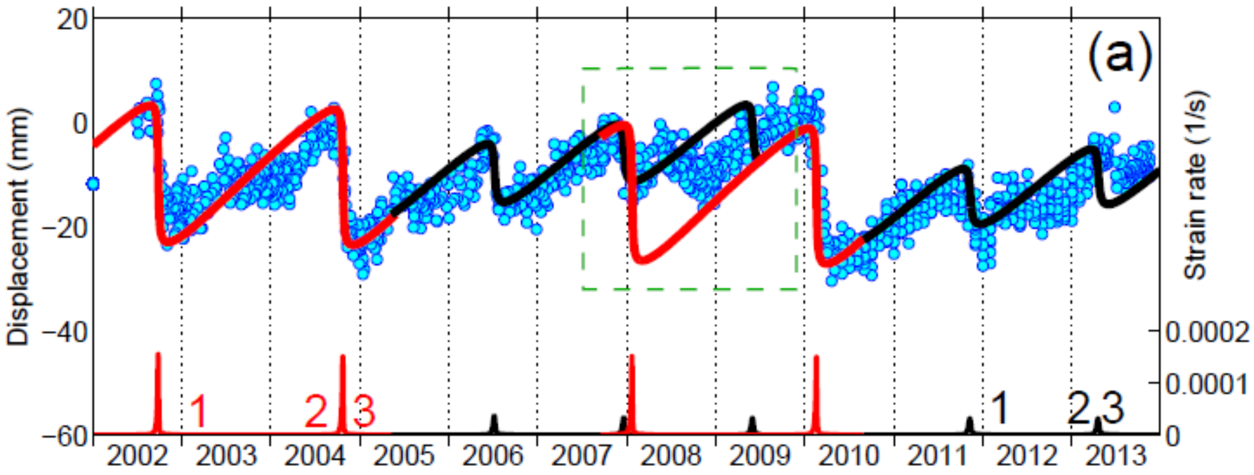
Rogers & Dragert, Science (2003)

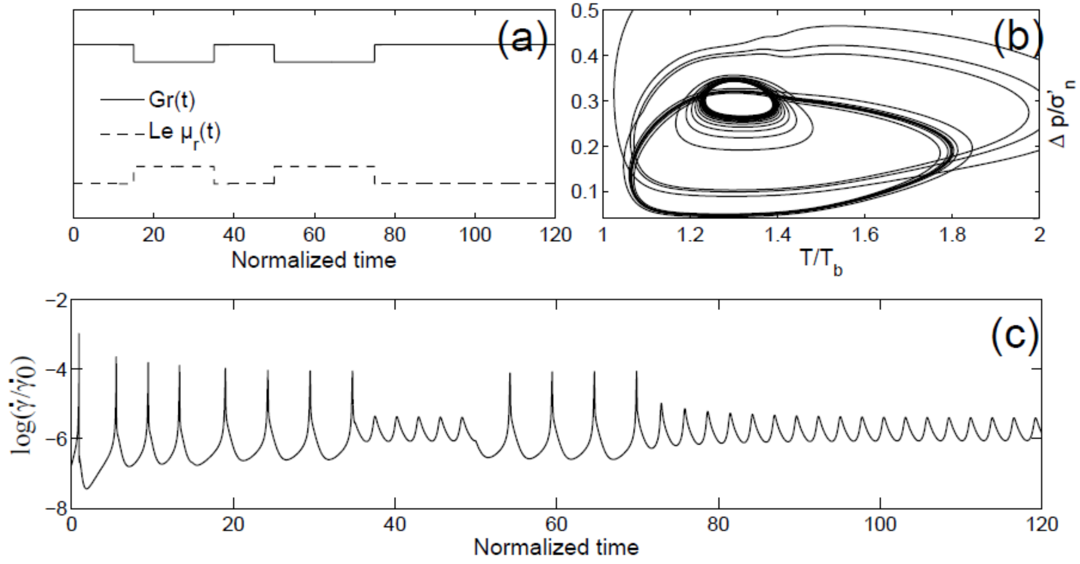


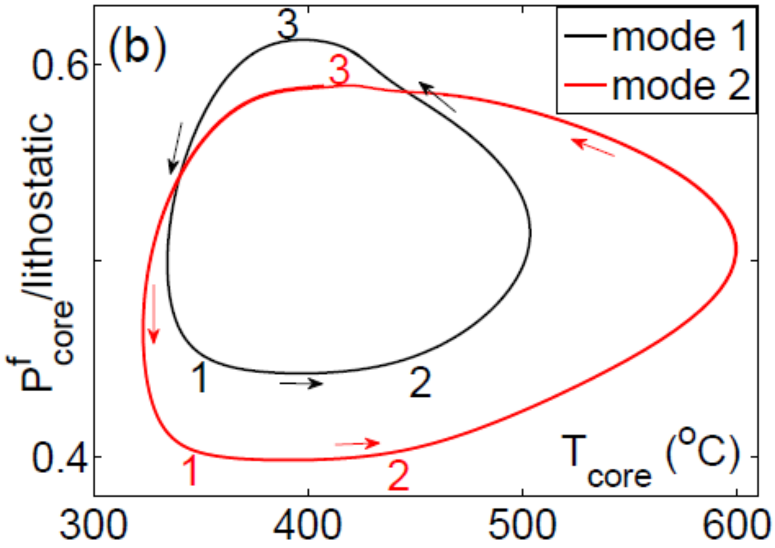


Alevizos et al, JGR (2014)

# Chaotic signals – Gisborne (New Zealand)







Poulet et al, JGR (2014)

# Matching length scales

- Intern. **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)

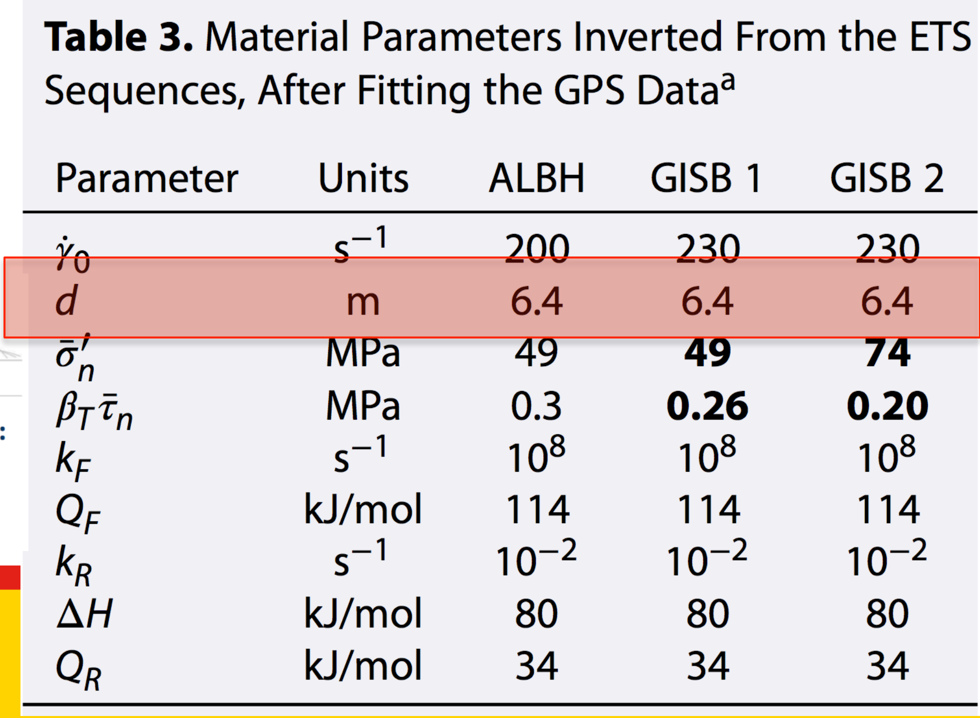
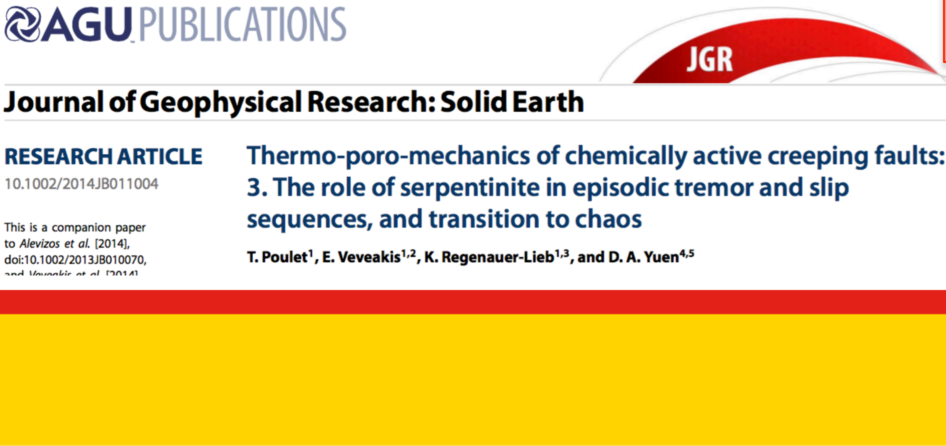


**Table 3.** Material Parameters Inverted From the ETS Sequences, After Fitting the GPS Data[a]

| 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 |
| $k_R$ | $s^{-1}$ | $10^{-2}$ | $10^{-2}$ | $10^{-2}$ |
| $\Delta H$ | kJ/mol | 80 | 80 | 80 |
| $Q_R$ | kJ/mol | 34 | 34 | 34 |



**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]**

# In Conclusion

# Thank you!

http://ugg.unsw.edu.au

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# The 6th International Conference on Coupled Thermo-Hydro-Mechanical-Chemical (THMC) Processes in Geosystems: Multiphysical instabilities across the scales

**Important dates**

Abstract submission: 15 November 2016
Abstract acceptance: 15 December 2016
Early-bird registration: 31 January 2017

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