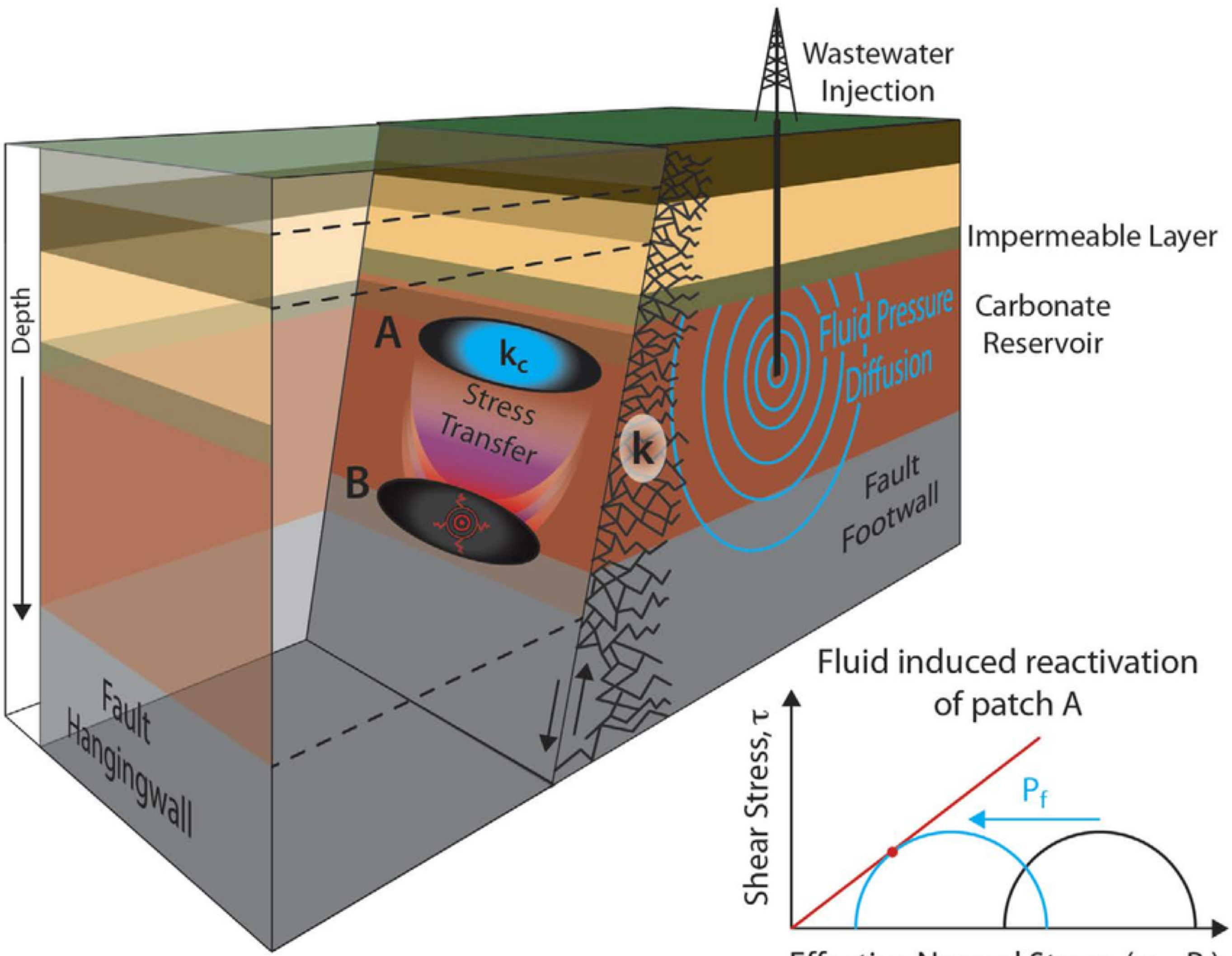
Induced seismicity and fault reactivation as a THMC problem

by

Manolis Veveakis

Multiphysics Geomechanics group, Duke University

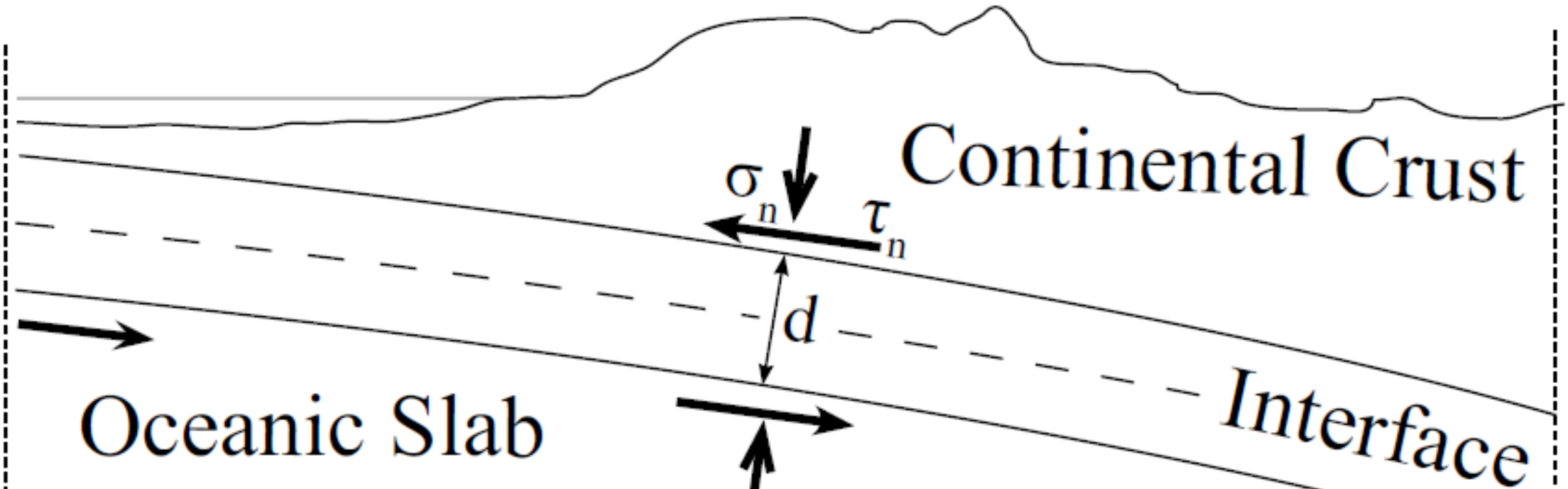
Fault Reactivation in a nutshell



Scuderi and Collettini 2016

Mechanics of Faults

The theoretical approach



Science AAAS

Nonvolcanic Deep Tremor Associated with Subduction in Southwest Japan
Kazushige Obara
Science **296**, 1679 (2002);
DOI: 10.1126/science.1070378

REPORTS

Nonvolcanic Deep Tremor Associated with Subduction in Southwest Japan

Kazushige Obara

Deep long-period tremors were recognized and located in a nonvolcanic region in southwest Japan. Epicenters of the tremors were distributed along the strike of the subducting Philippine Sea plate over a length of 600 kilometers. The depth of the tremors averaged about 30 kilometers, near the Mohorovic discontinuity. Each tremor lasted for at most a few weeks. The location of the tremors within the subduction zone indicates that the tremors may have been caused by fluid generated by dehydration processes from the slab.

Depth

Duration

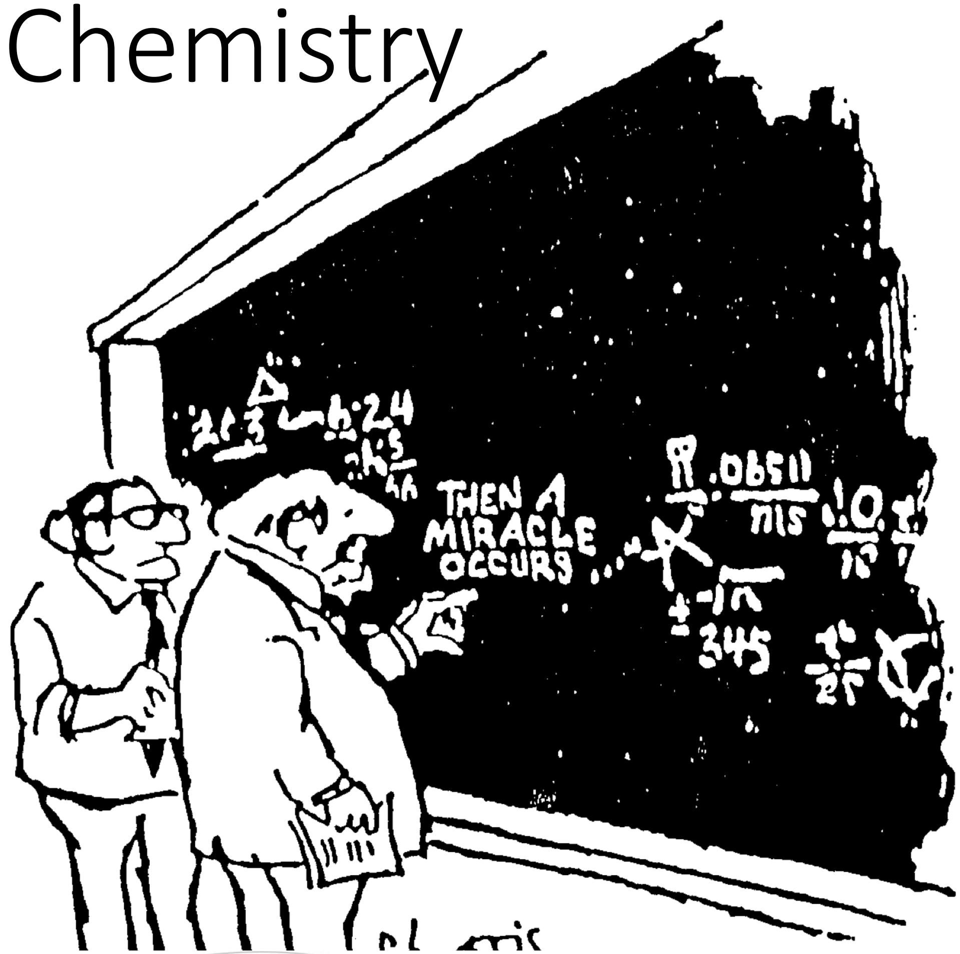
Origin

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

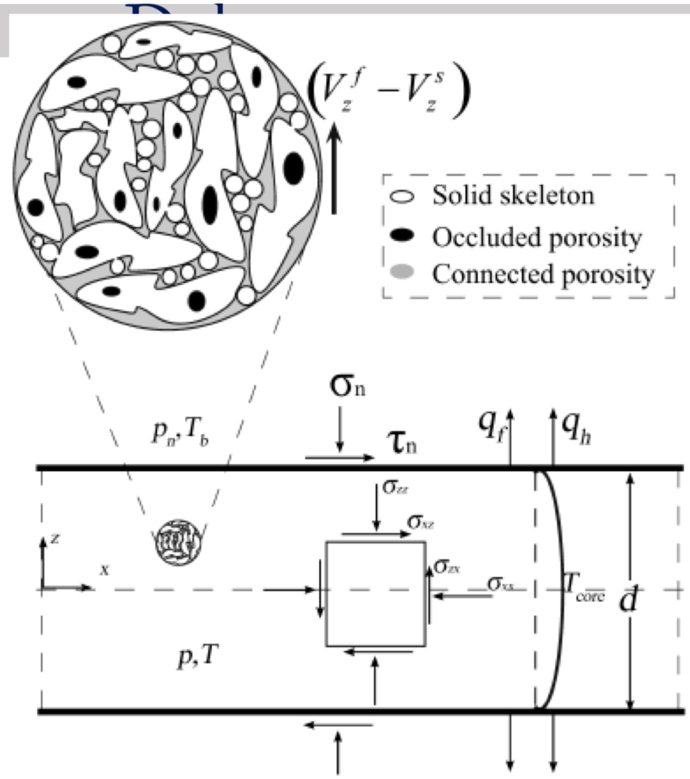
This is a companion paper to *Alevizos et al.* [2014], doi:10.1002/2013JB010070, and *Veveakis et al.* [2014].

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]

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



- Porosity and permeability linked with Kozeny-Carman law

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

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

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

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

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

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

The mathematical system

- Normalised and reduced system of equations

$$\tau = \tau_d(t)\ ,\ \ \sigma' = \sigma'_n(t)$$

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

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

- Dimensionless Groups:

Lewis number

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

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

Gruntfest number

The mathematical system

- Normalised and reduced system of equations

$$\tau = \tau_d(t) \ , \ \sigma' = \sigma'_n(t)$$

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

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

- Dimensionless Groups:

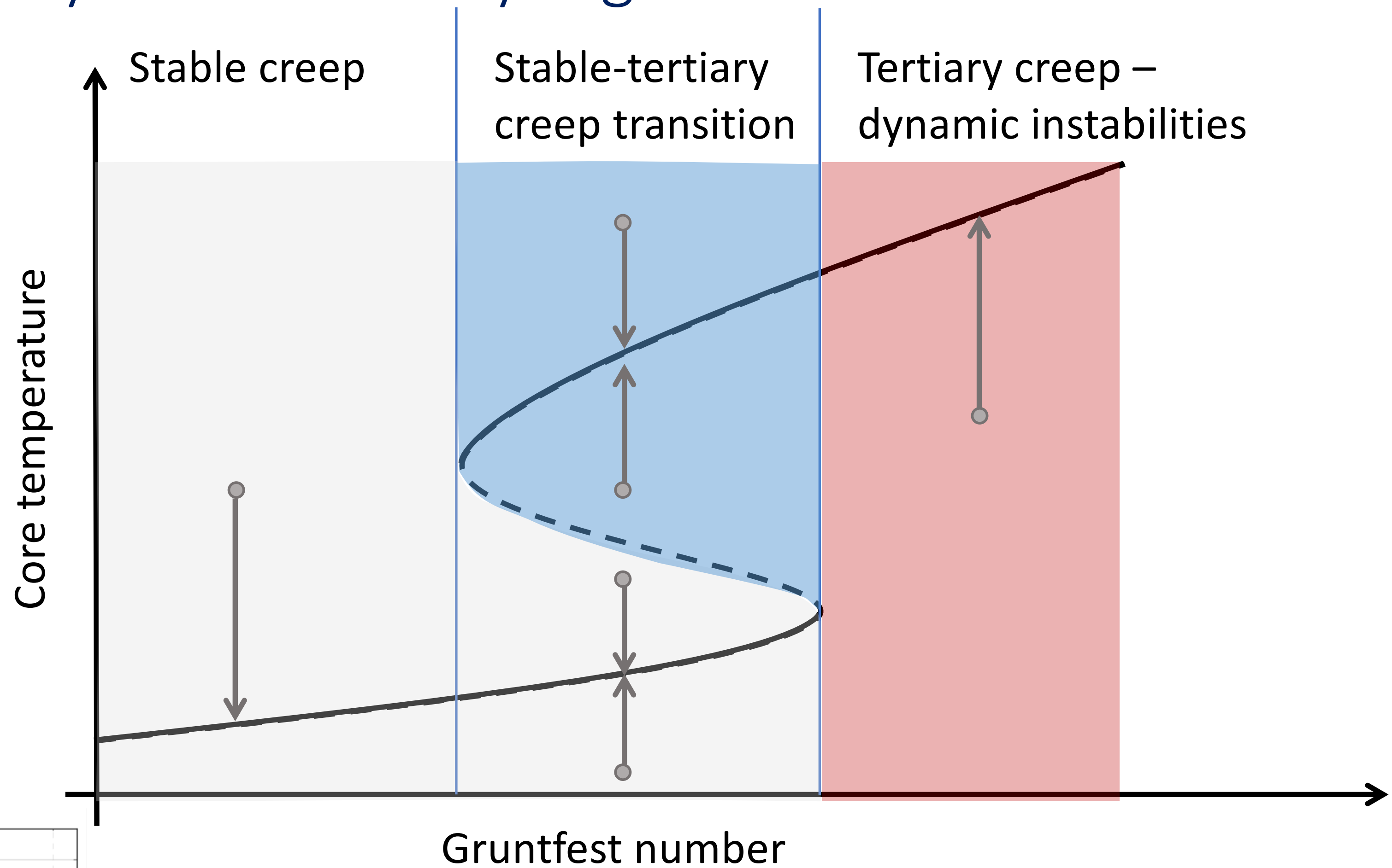
Lewis number

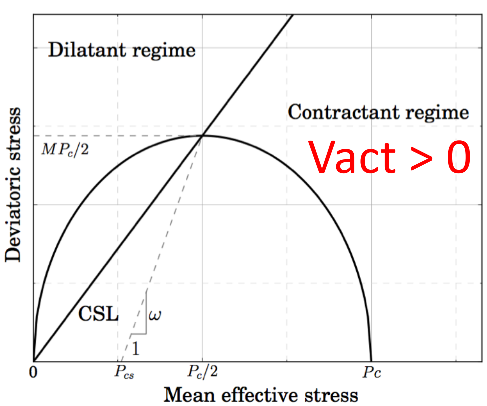
$$Le = \frac{\text{heat diffusion}}{\text{mass diffusion}}$$

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

Gruntfest number

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

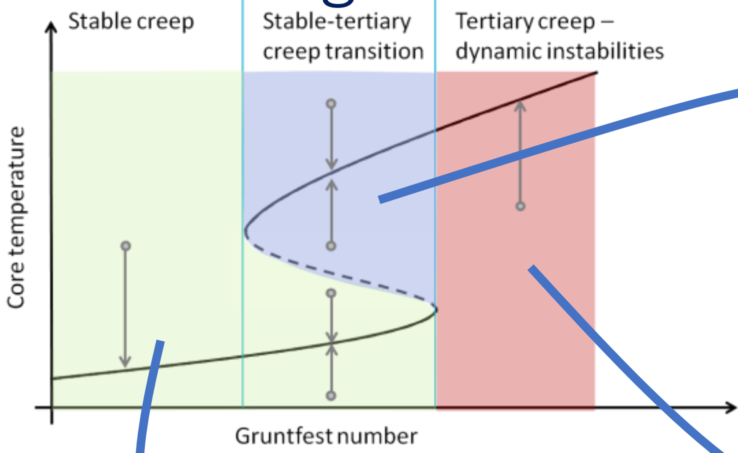


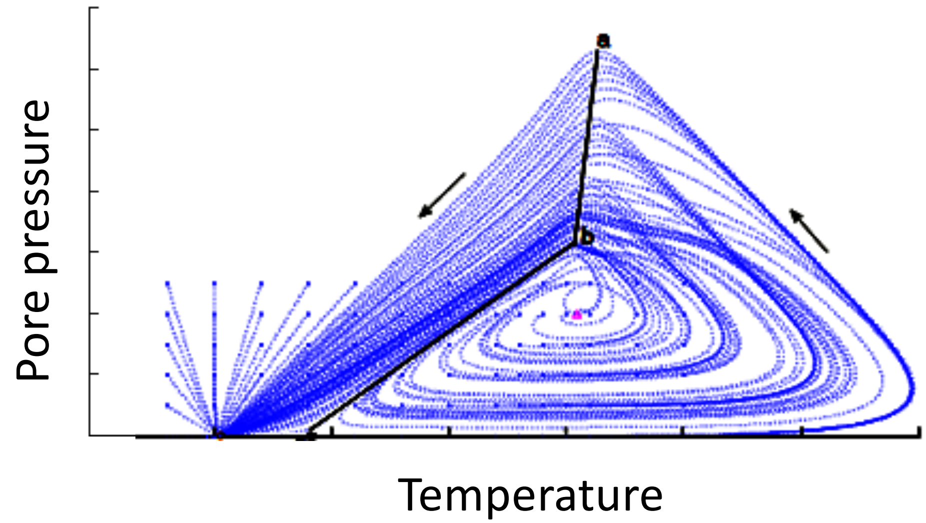


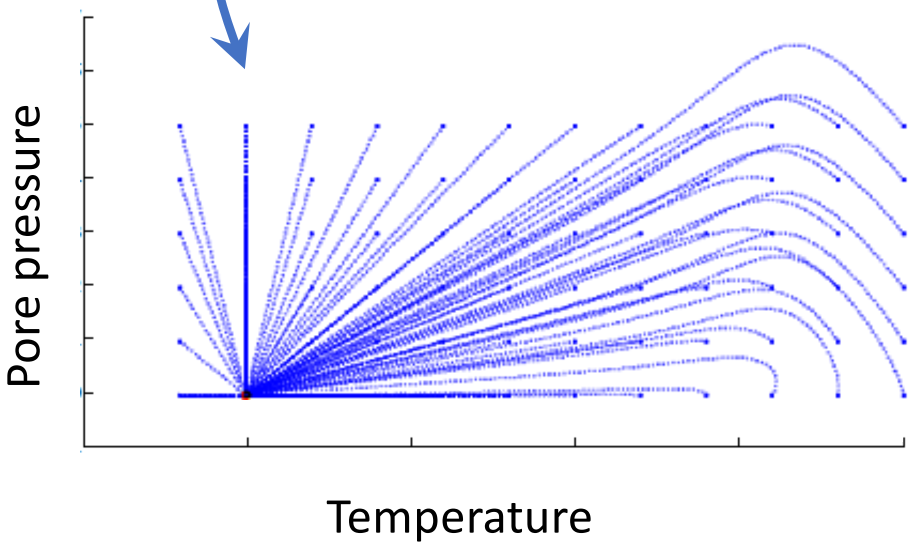
$$Gr = \frac{\text{char. time scale heat production}}{\text{char. time scale energy transfer}}$$

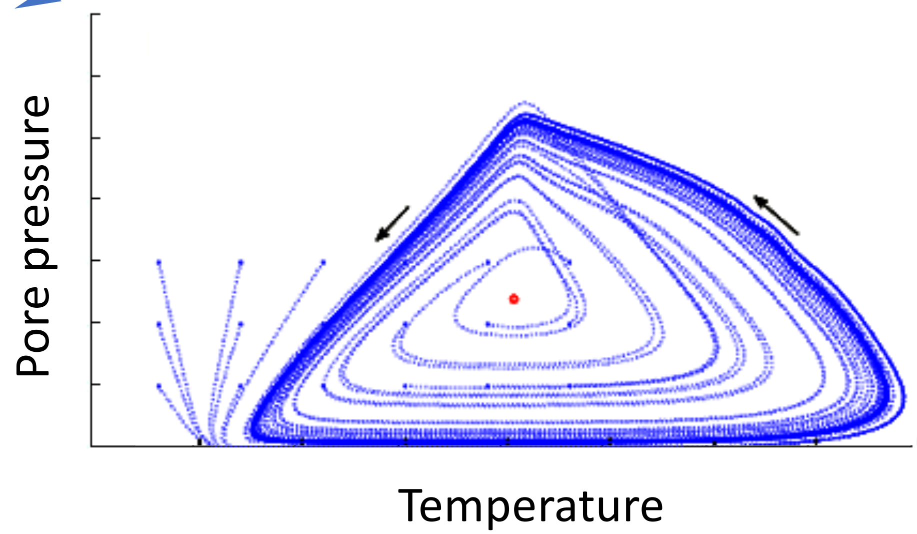
Natural localised instability

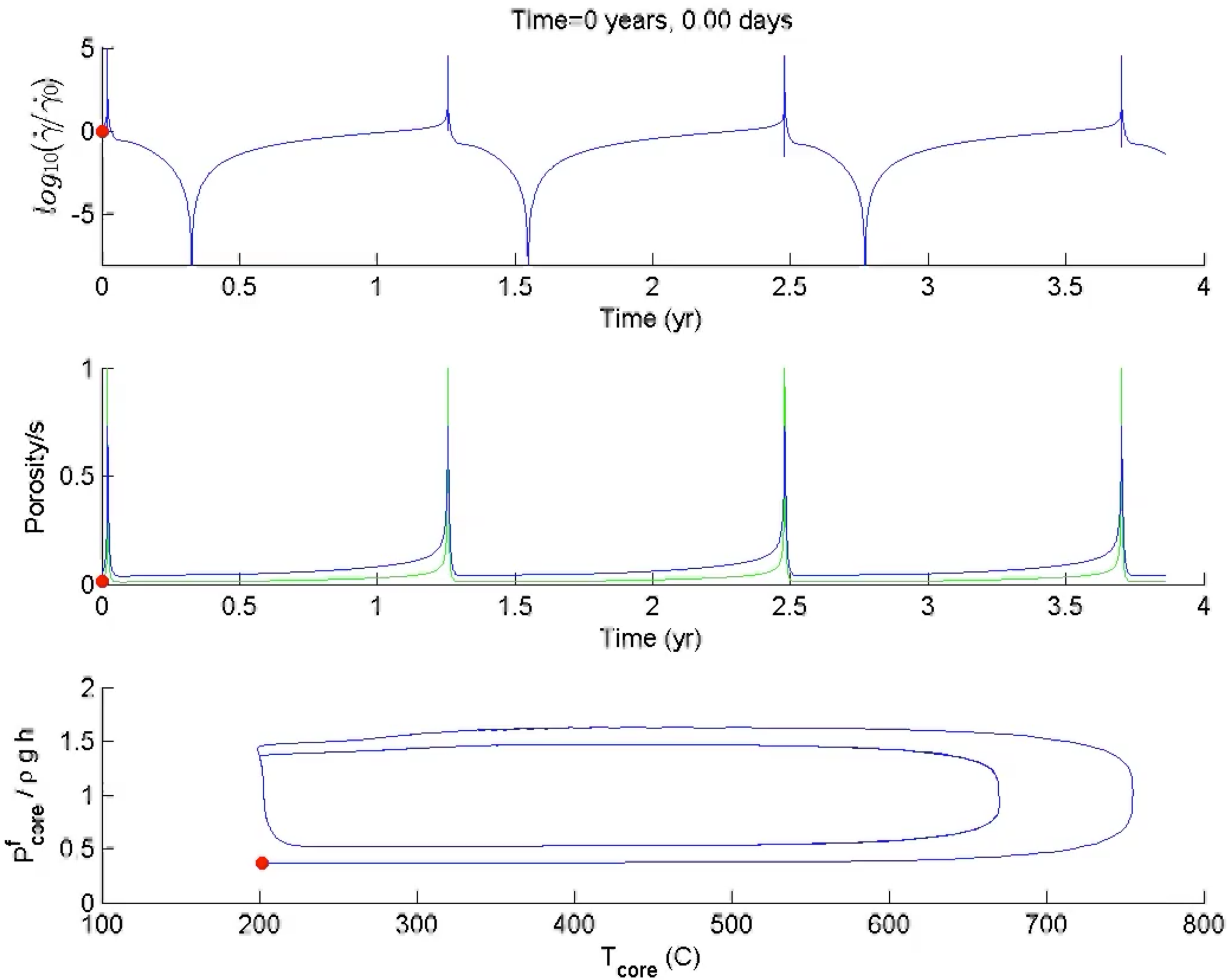
Phase diagrams





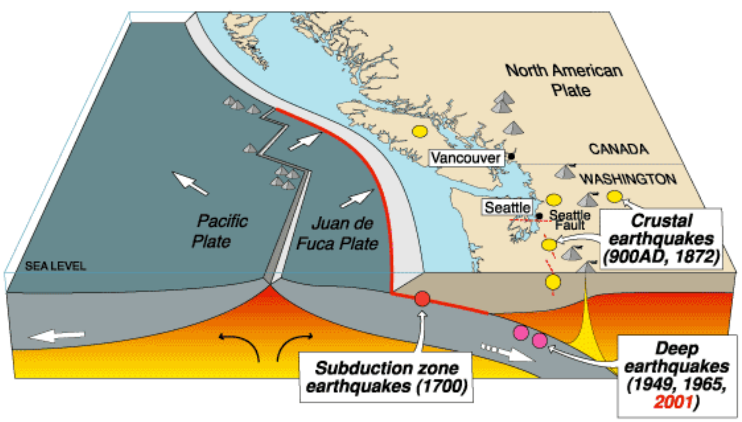





Time=0 years, 0.00 days
$log_{10}(\dot{\gamma}/\dot{\gamma}_0)$
Time (yr)
Porosity/s
Time (yr)
$P^f_{core} / \rho g h$
T_{core} (C)

Subduction zones
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
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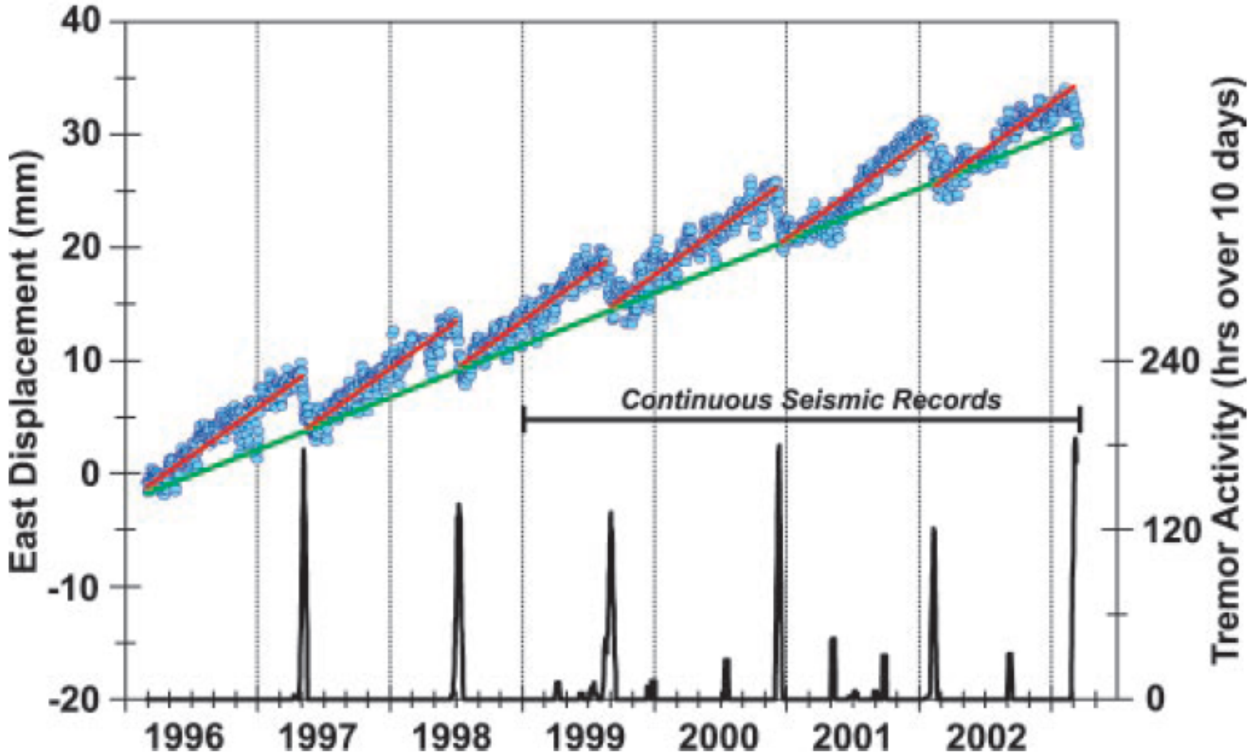
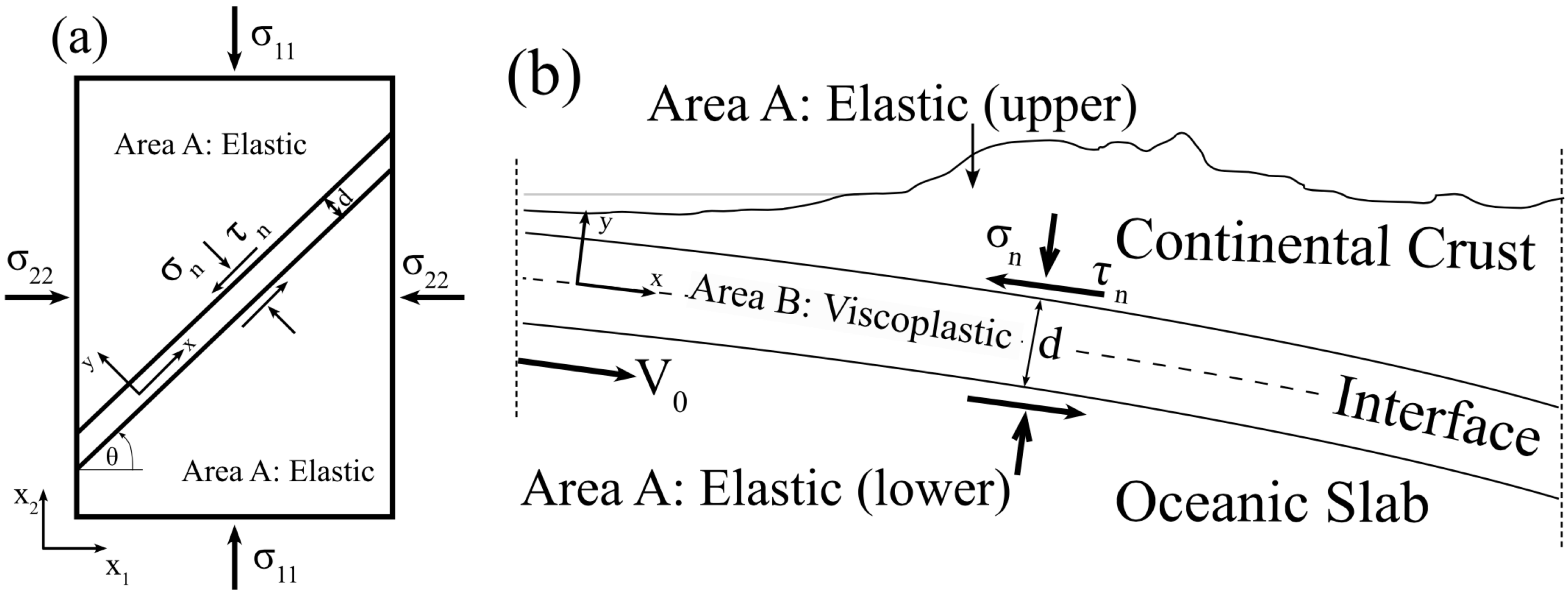
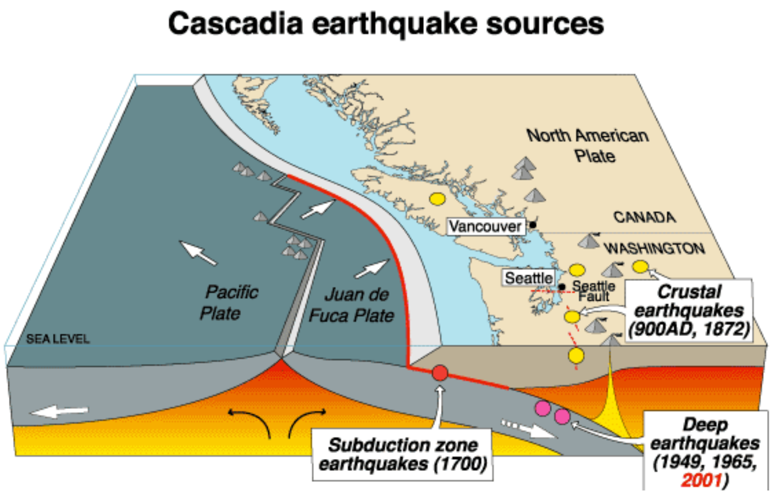


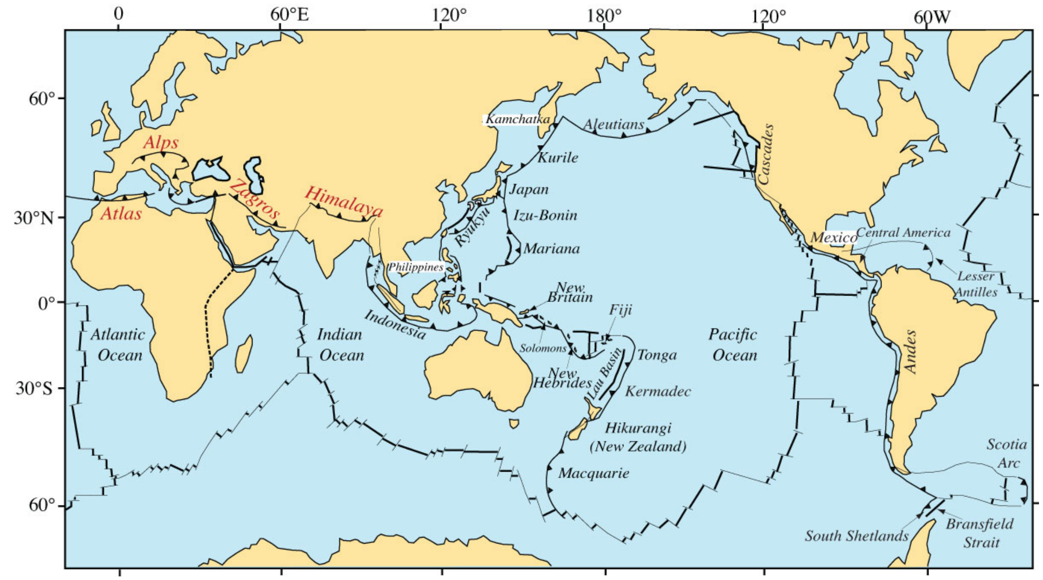
Modelling Subduction zones: Serpentinite dehydration oscillator

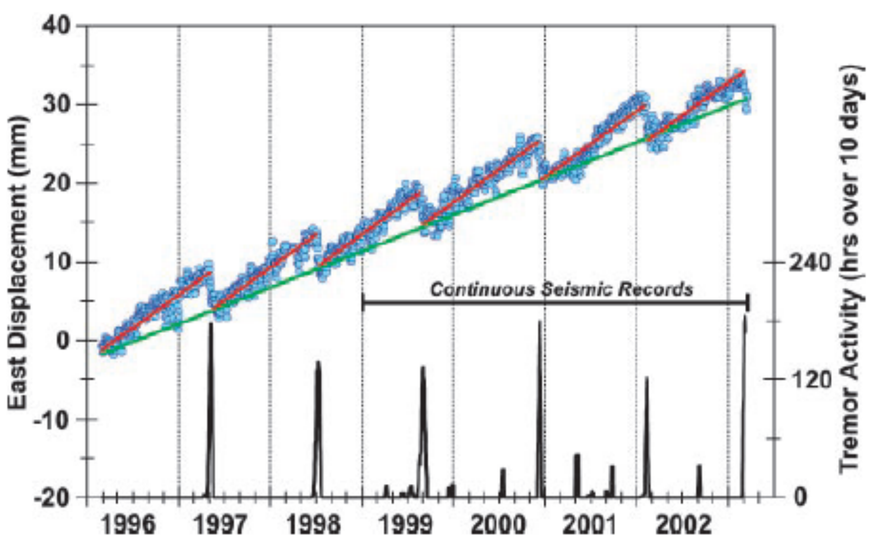


The problem: we require stress continuity at the shear band interface, because of the definition of the shear band as zone of velocity gradient discontinuities. So which BCs do we use?

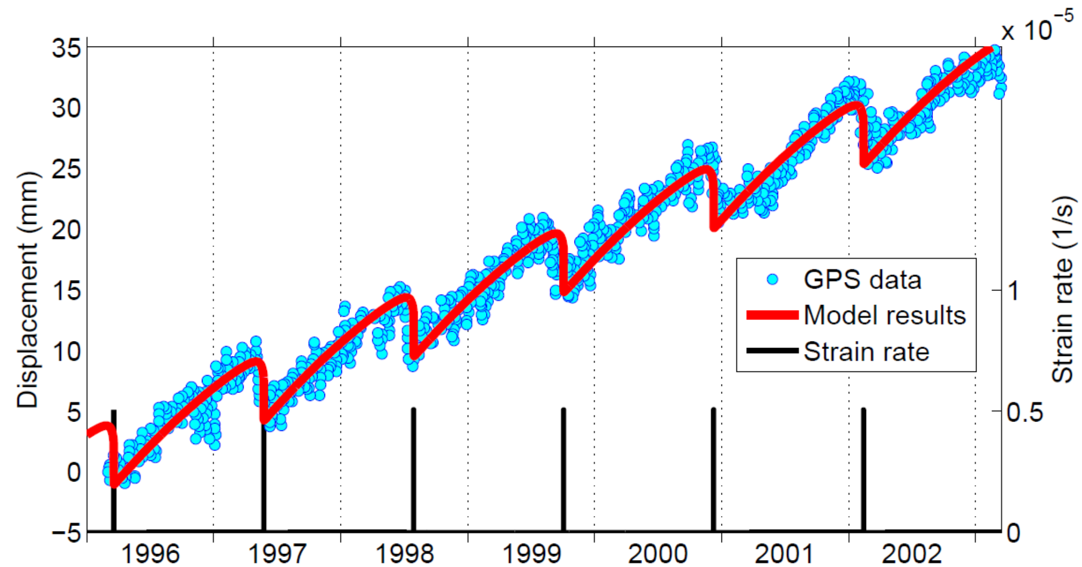
Modelling subduction zones





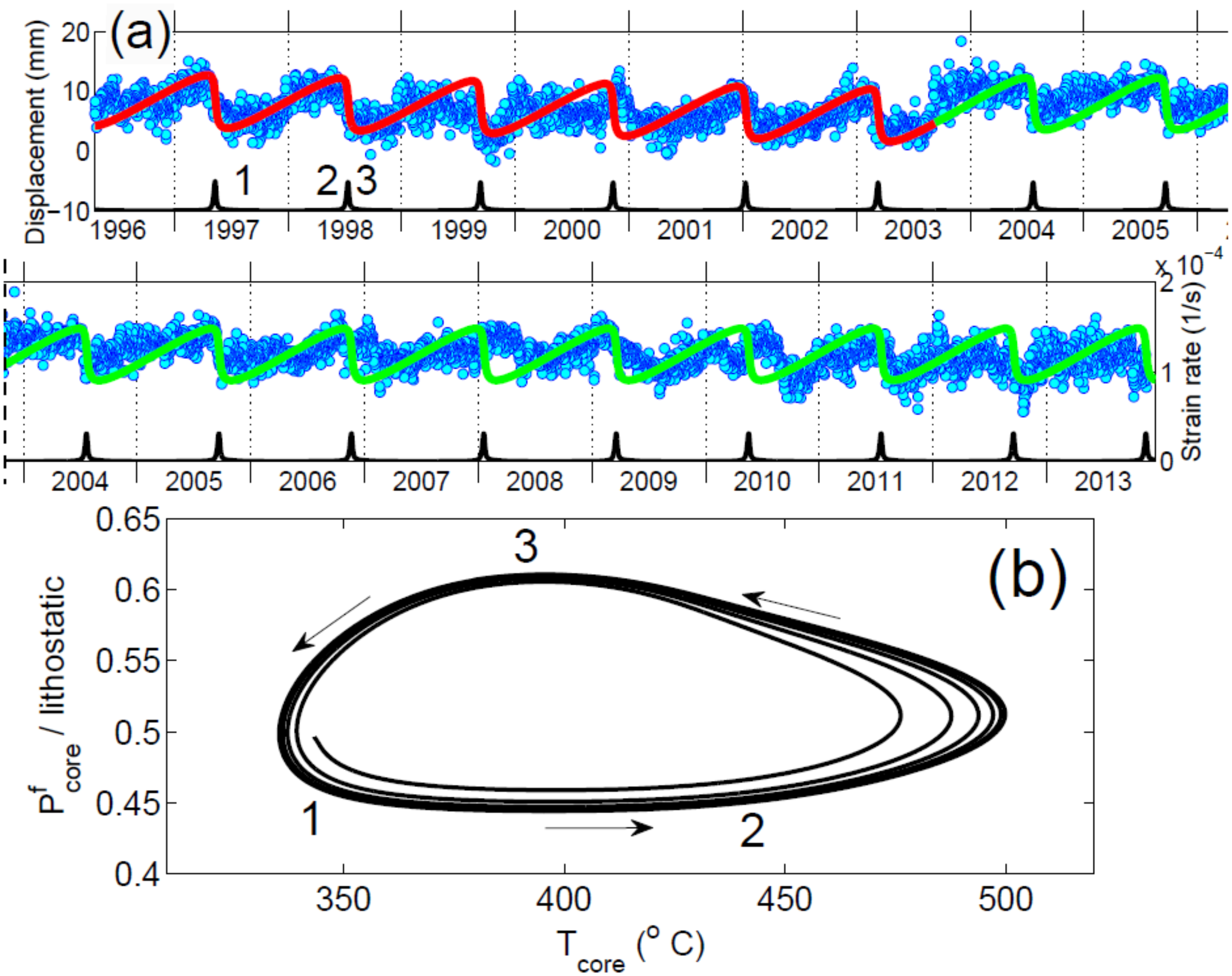


Rogers & Dragert, Science (2003)

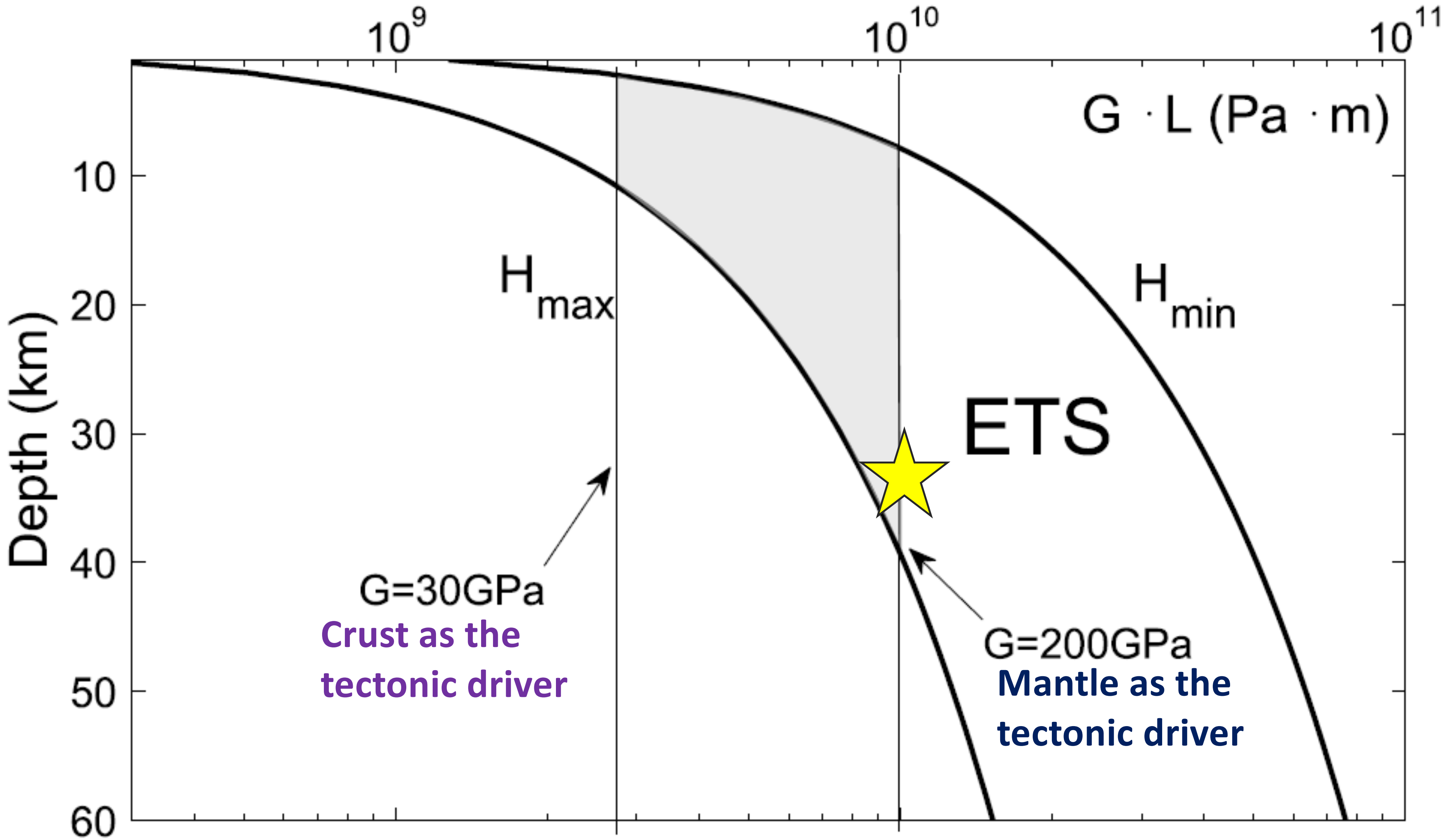


Alevizos et al, JGR (2014)

Oscillator cycles, Earth's heartbeat

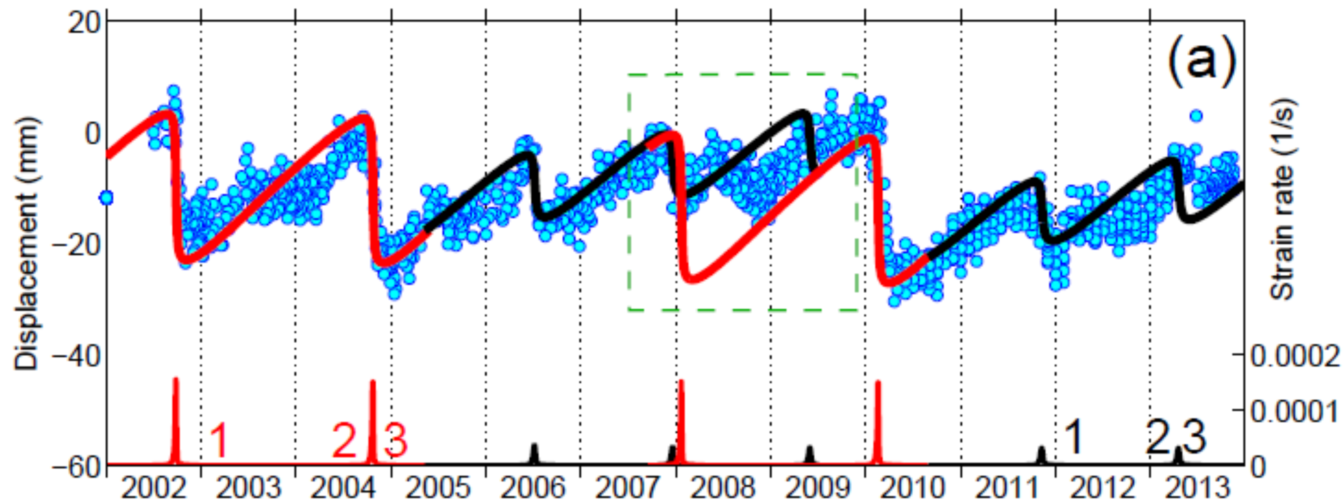


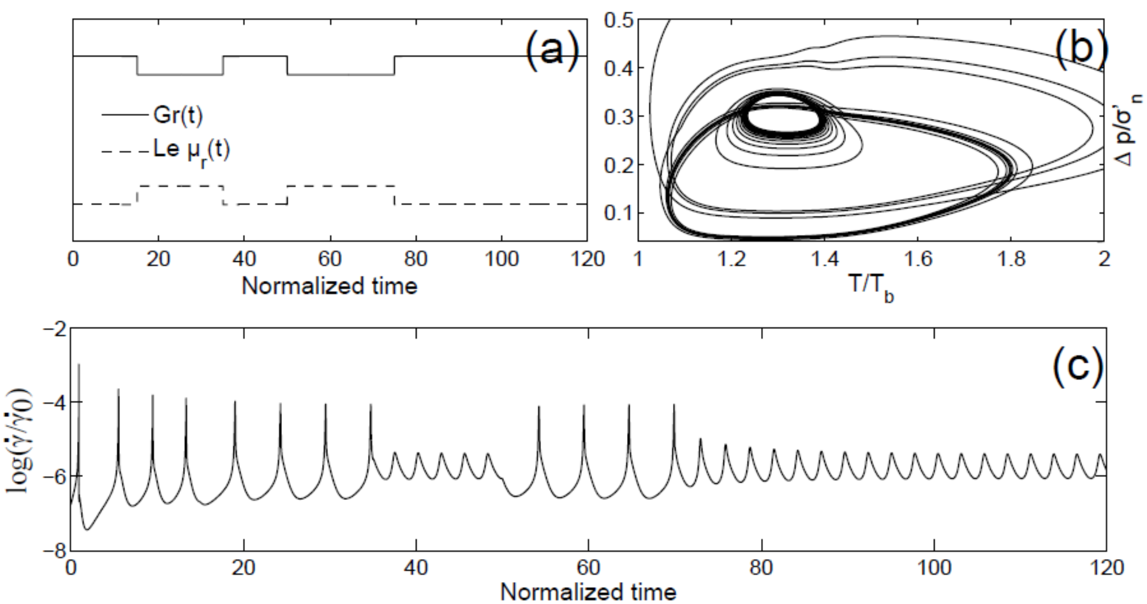
ETS location and tectonic driver: Cascadia

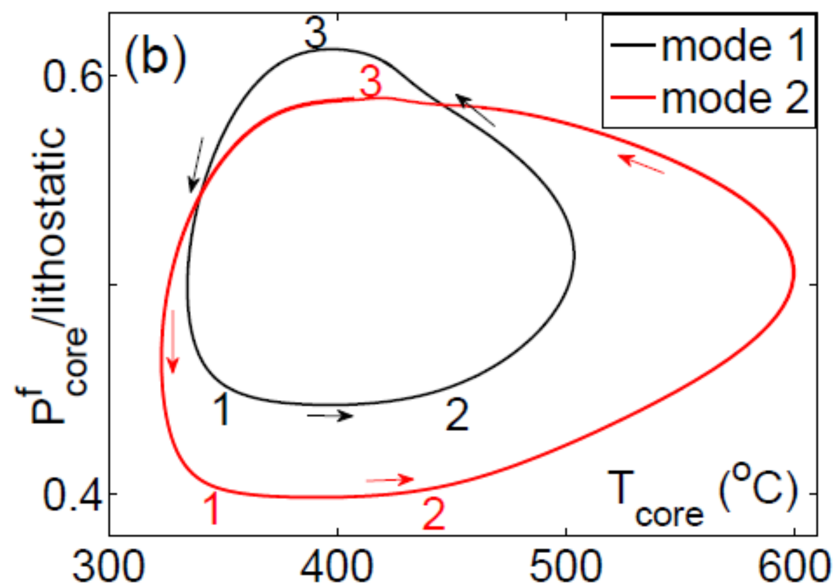


Poulet, Veveakis, Regenauer-Lieb & Yuen , JGR (2014)

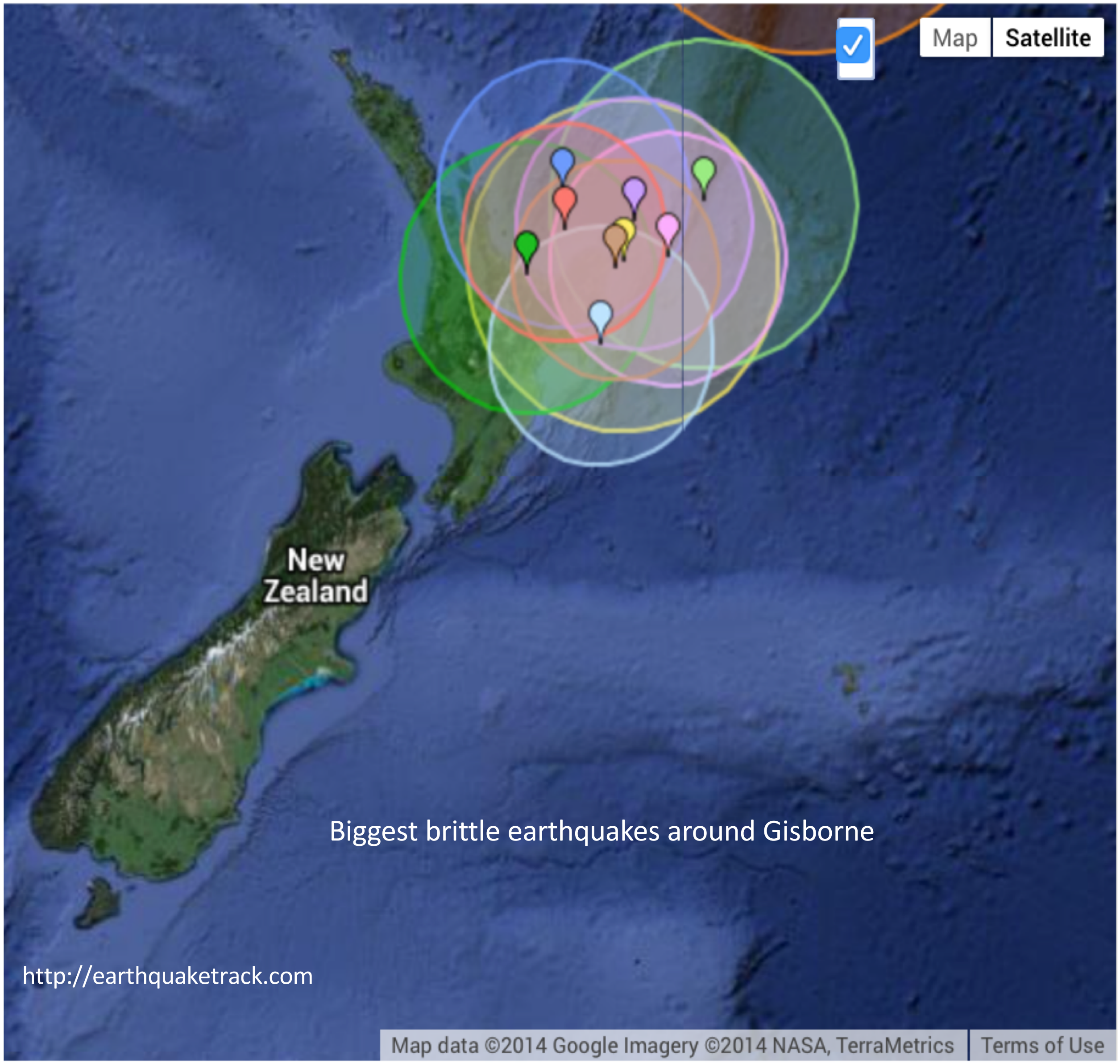
Chaotic signals – Gisborne (New Zealand)



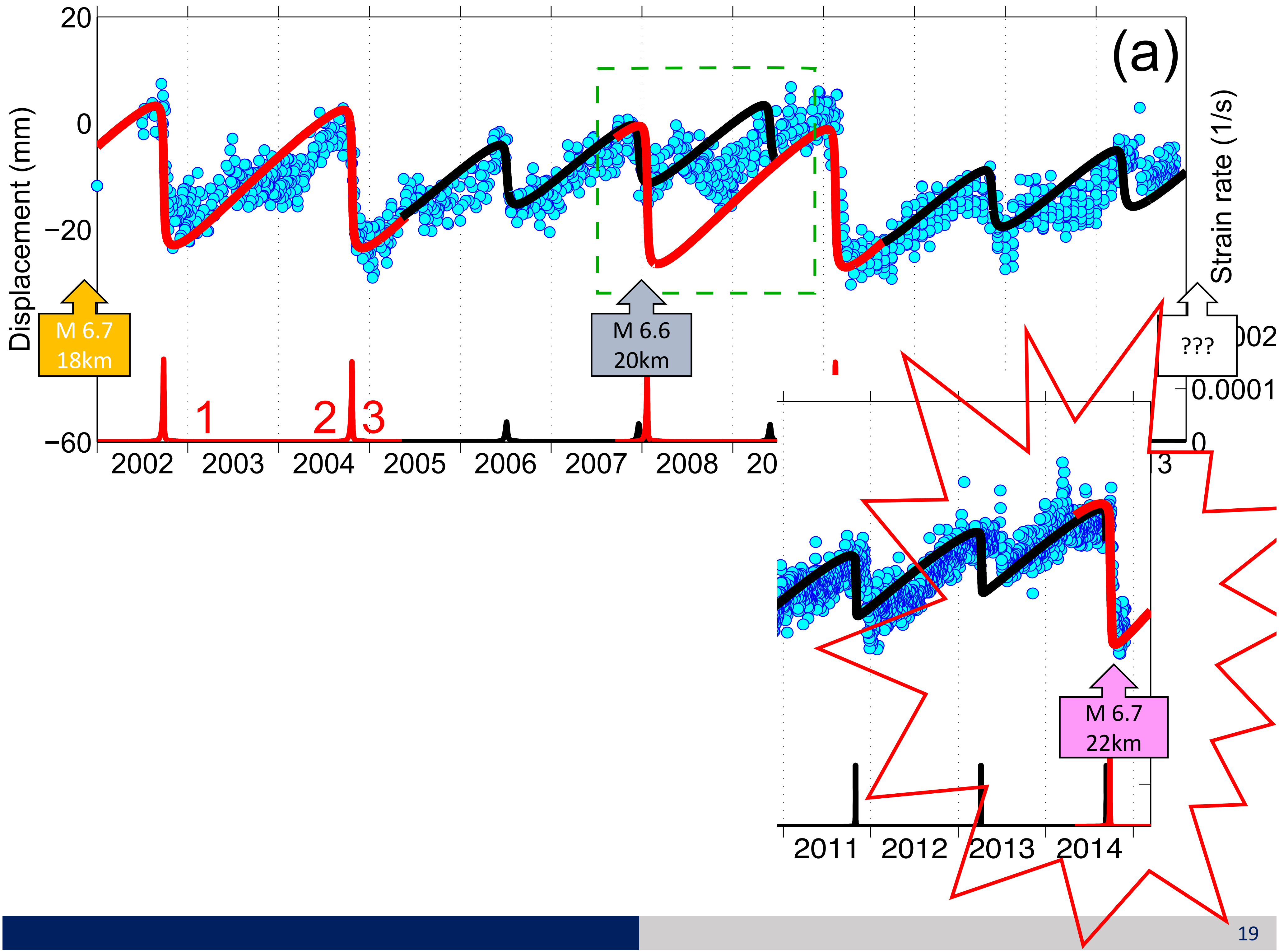




Can we predict brittle earthquakes? (NO, but still…)



- 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


20
0
−20
−60
Displacement (mm)
Strain rate (1/s)
(a)
M 6.7
18km
M 6.6
20km
???
M 6.7
22km
1
2
3
0.0001
0
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)

AGU PUBLICATIONS

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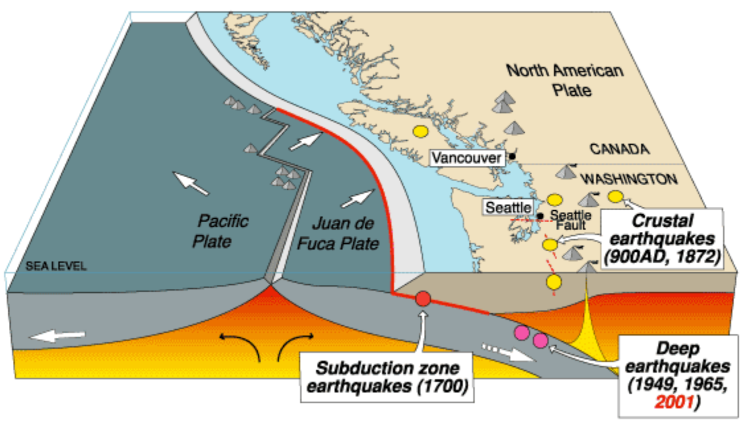
T. Poulet[1], E. Veveakis[1,2], K. Regenauer-Lieb[1,3], and D. A. Yuen[4,5]

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

Episodic tremor and Slip (ETS)
Could we do it data-driven?

Cascadia earthquake sources



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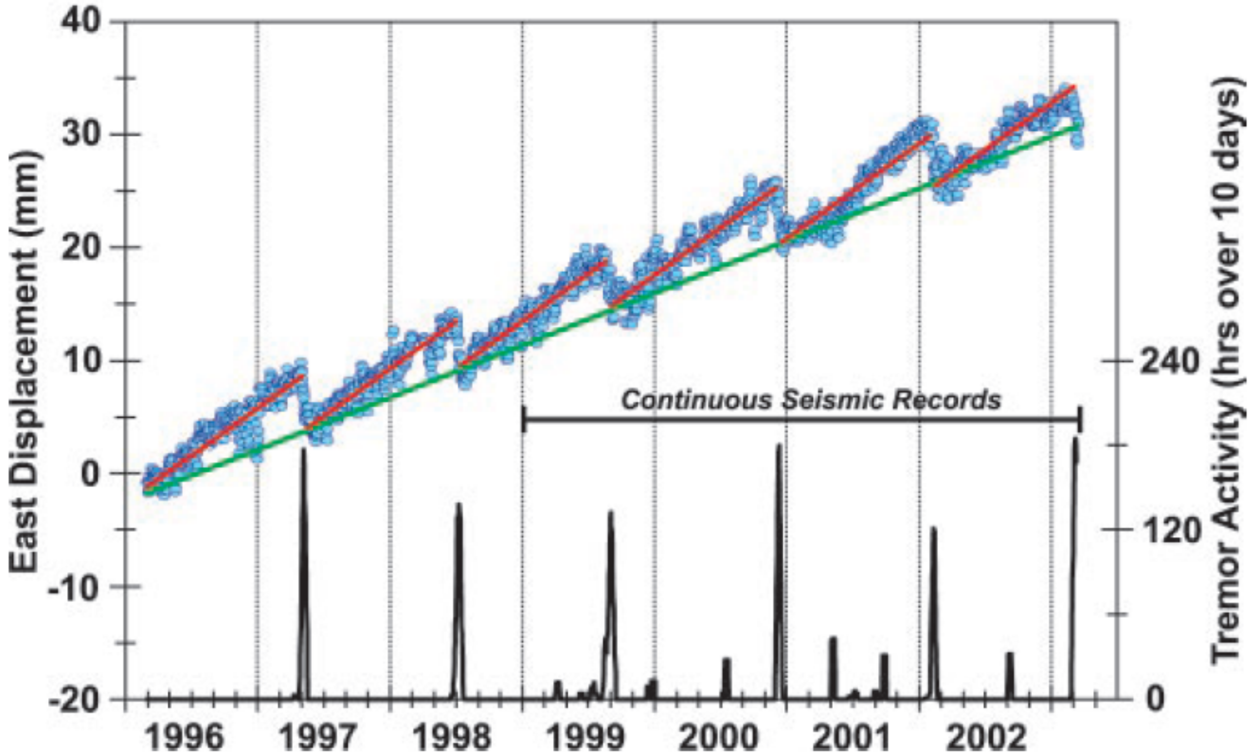
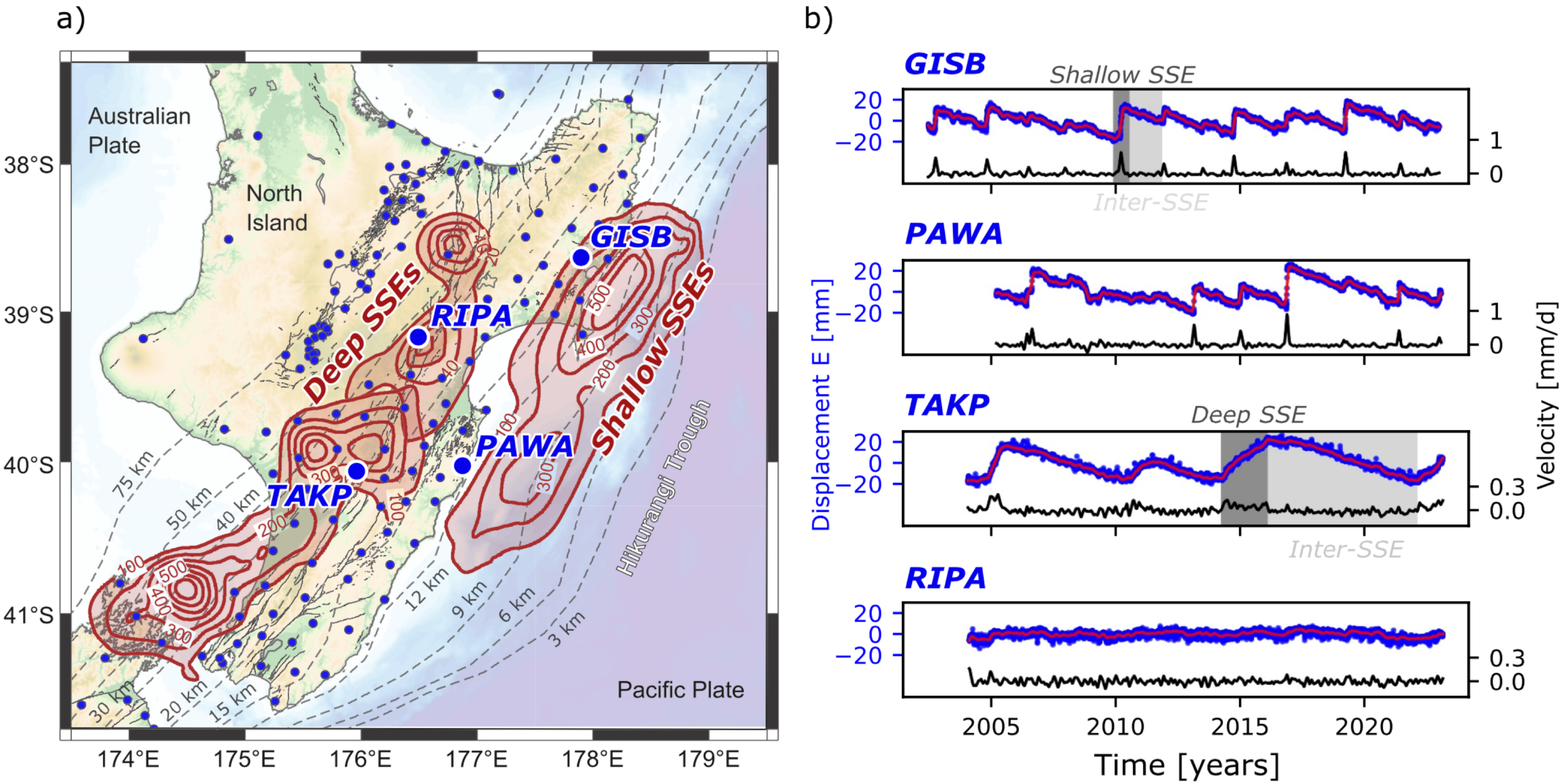
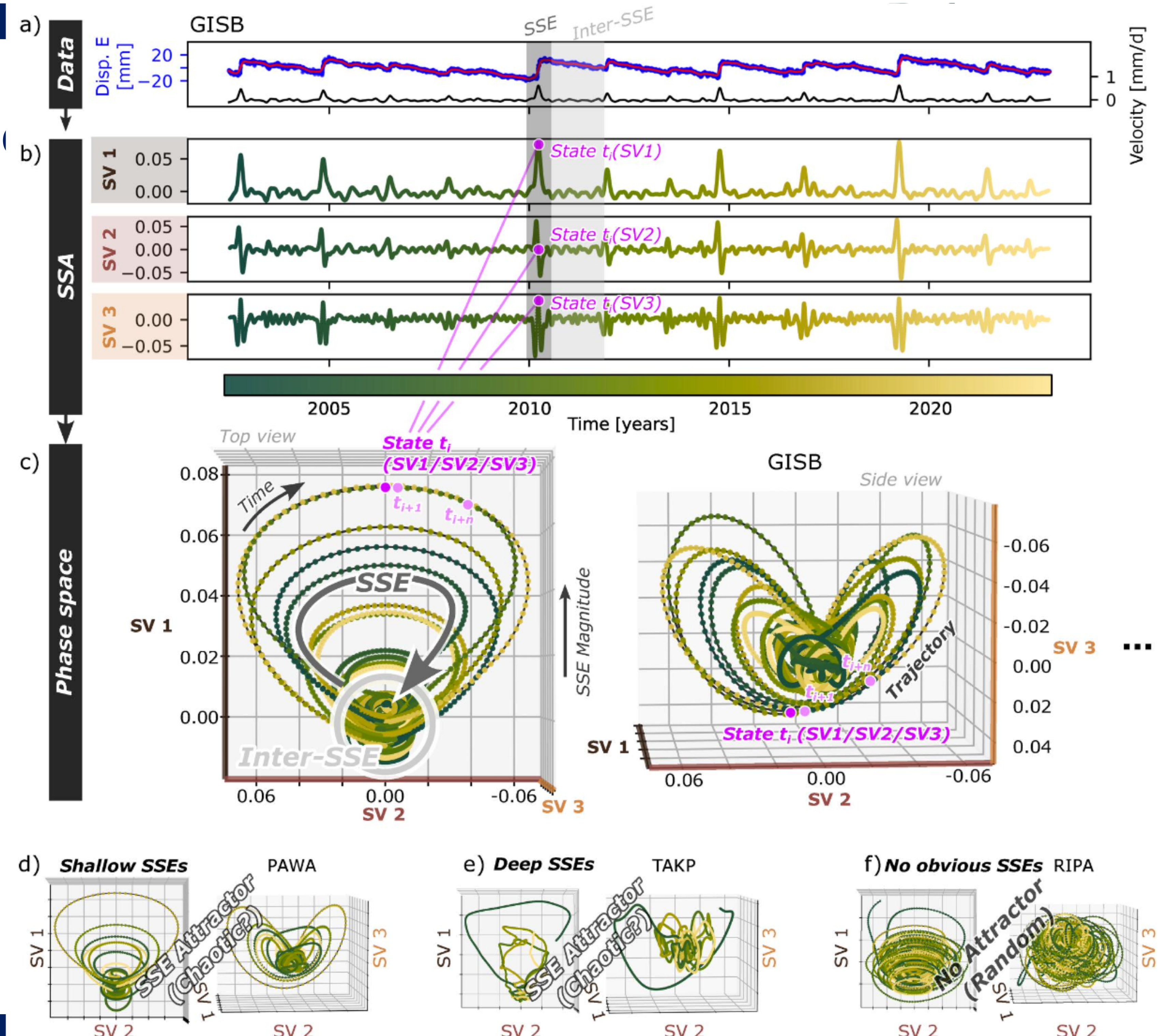


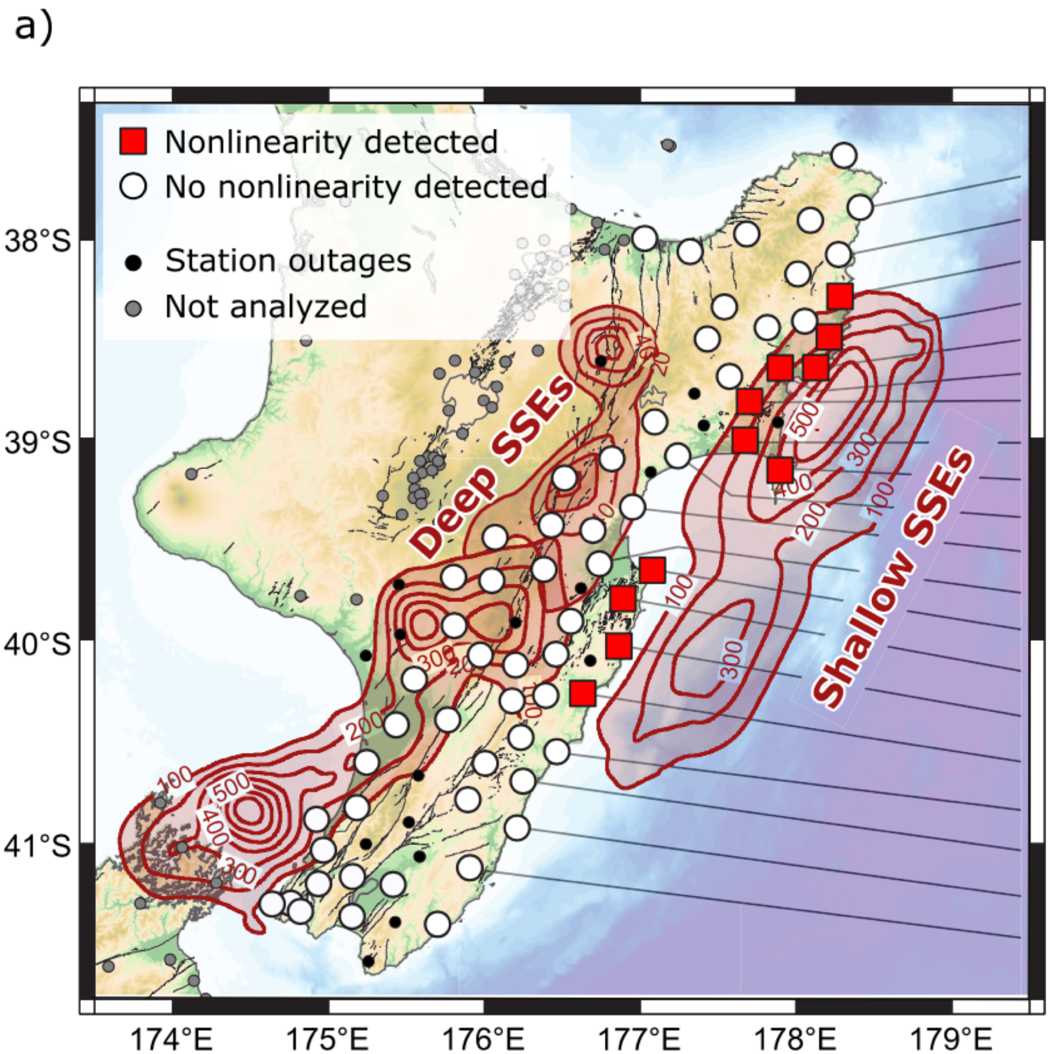
Nonvolcanic Tremor in Cascadia

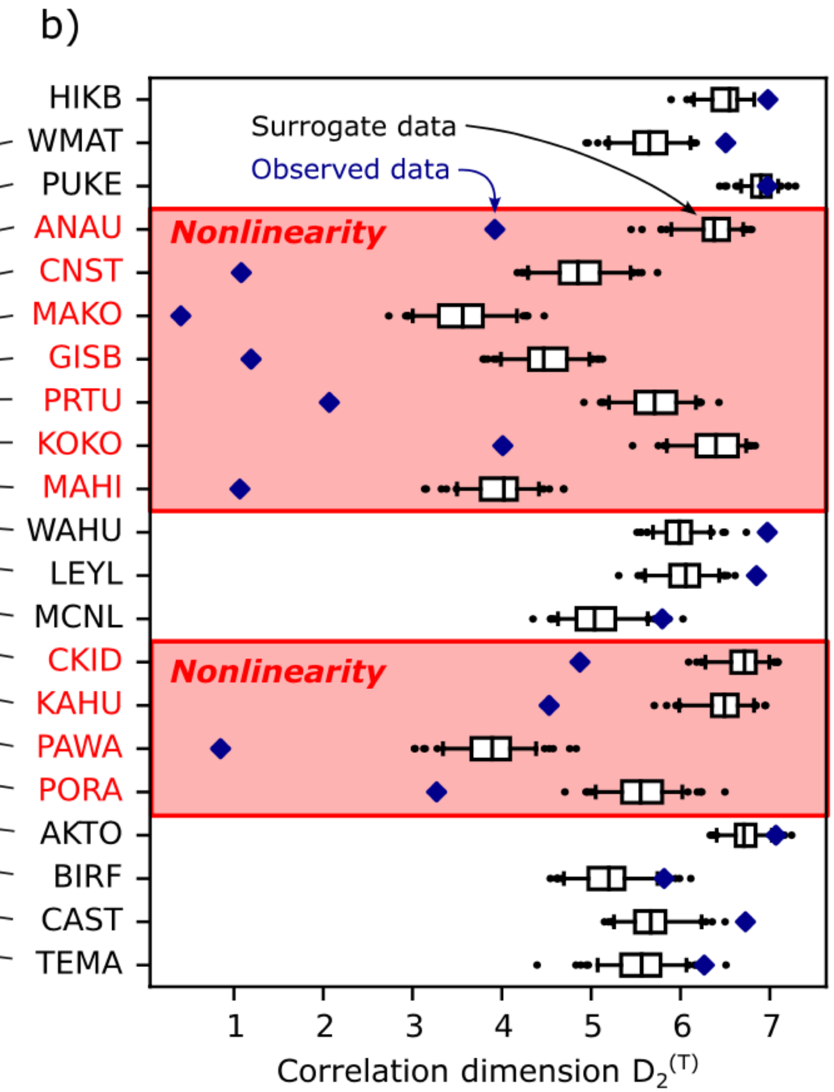
Graph CNN –based analysis of ETS series in New Zealand




a)
Data
GISB
SSE
Inter-SSE
Disp. E [mm]
20
−20
Velocity [mm/d]
1
0
b)
SSA
SV 1
0.05
0.00
State ti(SV1)
SV 2
0.05
0.00
−0.05
State ti(SV2)
SV 3
0.00
−0.05
State ti(SV3)
2005
2010
2015
2020
Time [years]
c)
Phase space
Top view
State ti (SV1/SV2/SV3)
Time
ti+1
ti+n
SSE
Inter-SSE
SV 1
0.08
0.06
0.04
0.02
0.00
0.06
0.00
-0.06
SV 2
SV 3
SSE Magnitude
GISB
Side view
Trajectory
-0.06
-0.04
-0.02
0.00
0.02
0.04
SV 3
SV 1
SV 2
...
d) Shallow SSEs
PAWA
SSE Attractor (Chaotic?)
e) Deep SSEs
TAKP
f) No obvious SSEs
RIPA
No Attractor (Random)

Graph CNN –based analysis of ETS series in New Zealand





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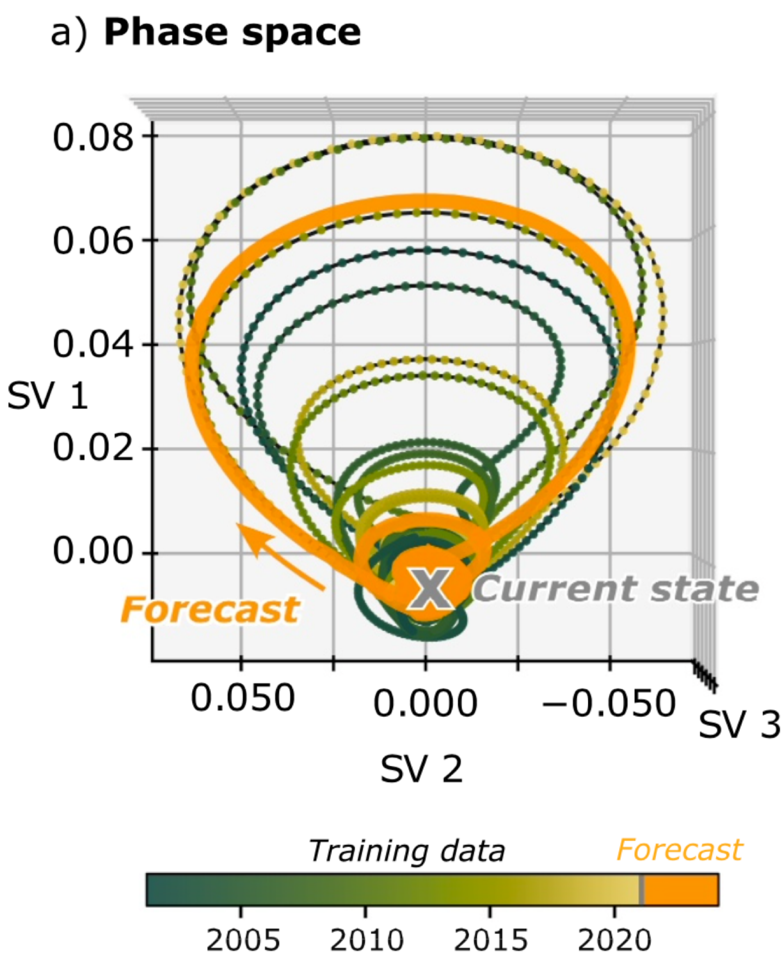
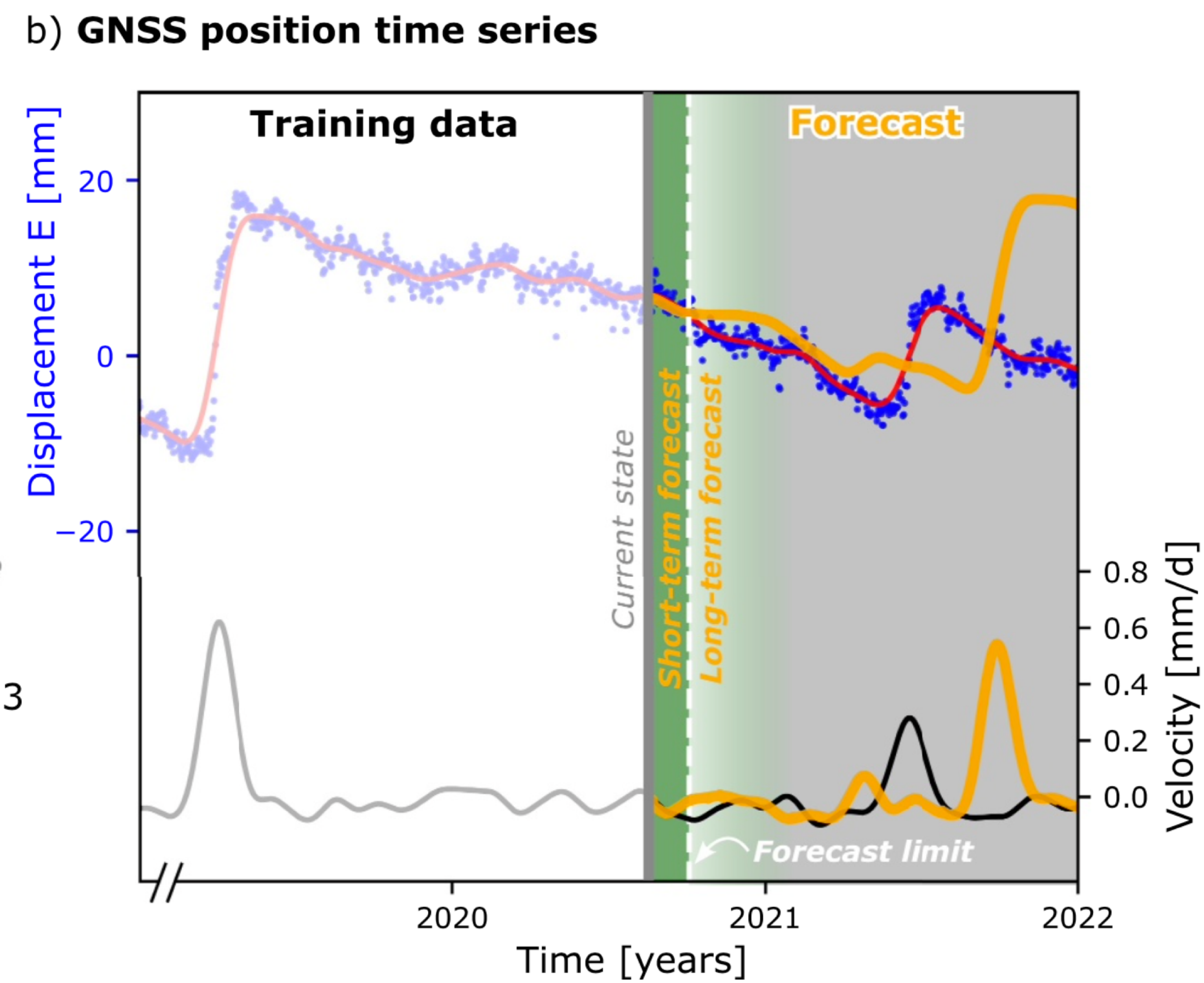
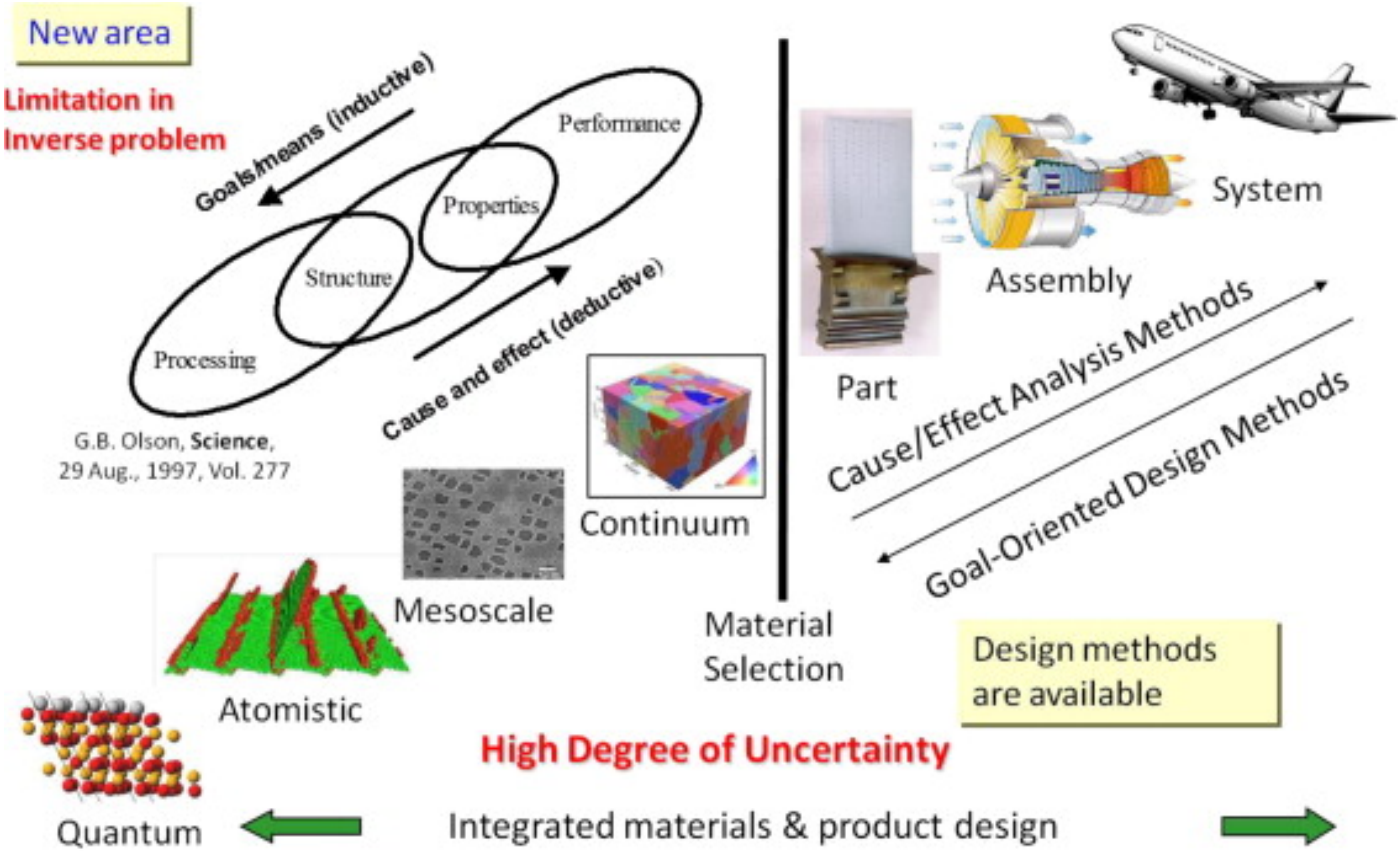




The question still is:

How can we use these concepts for fault reactivation?

Integrated Computational Materials Engineering (ICME)



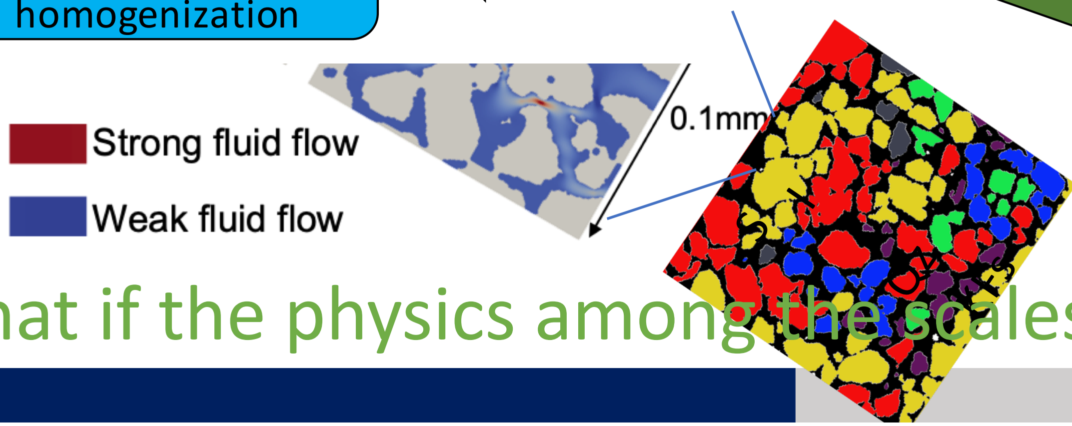
3-scale ICME for Geomaterials under environmental loading

Thermo-hydro-mechanical-chemical (THMC) couplings across the scales

Macro
- Darcy flow: pressure depletion/equilibration → Stress Path: fault shear stress

Meso
- Fault slip ⟷ Fault activation/healing

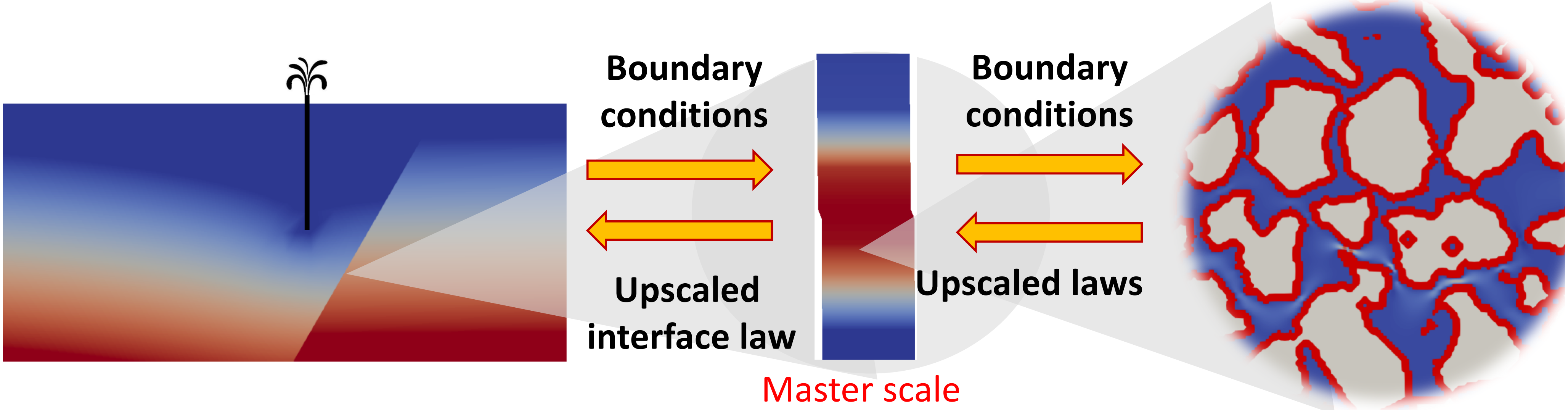
Micro
- Chemical dissolution/precipitation → Stokes flow: permeability homogenization



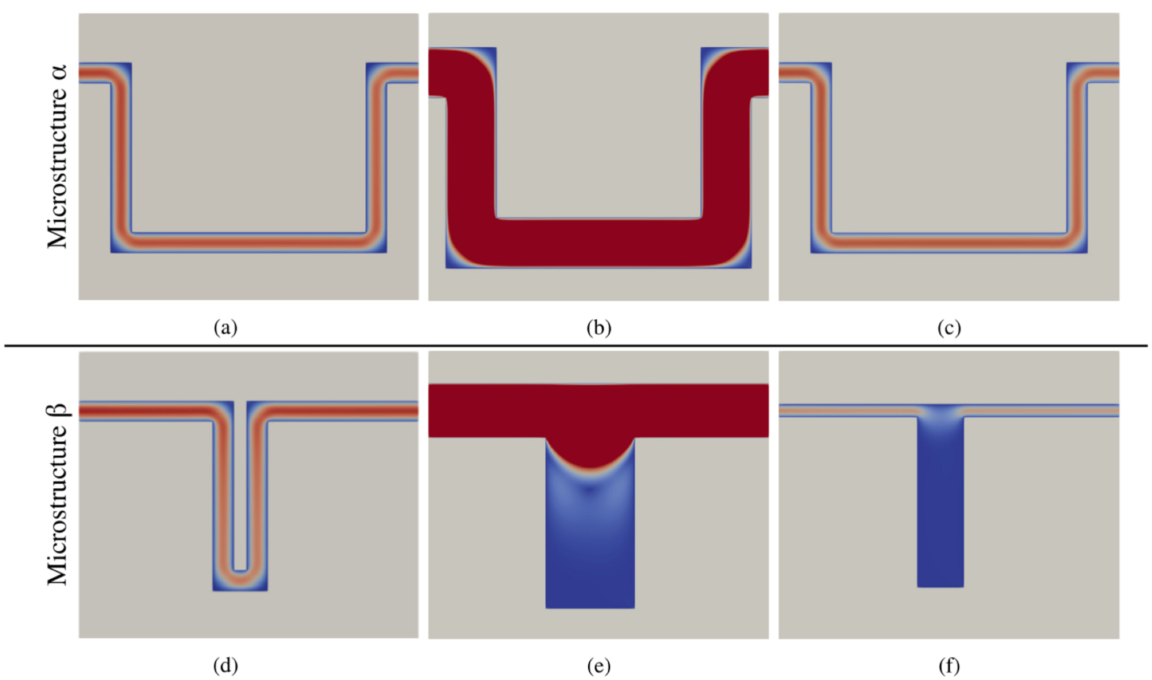
MICRO

What if the physics among the scales are not separated?

Three-scale nested schemes: On-the-fly homogenization



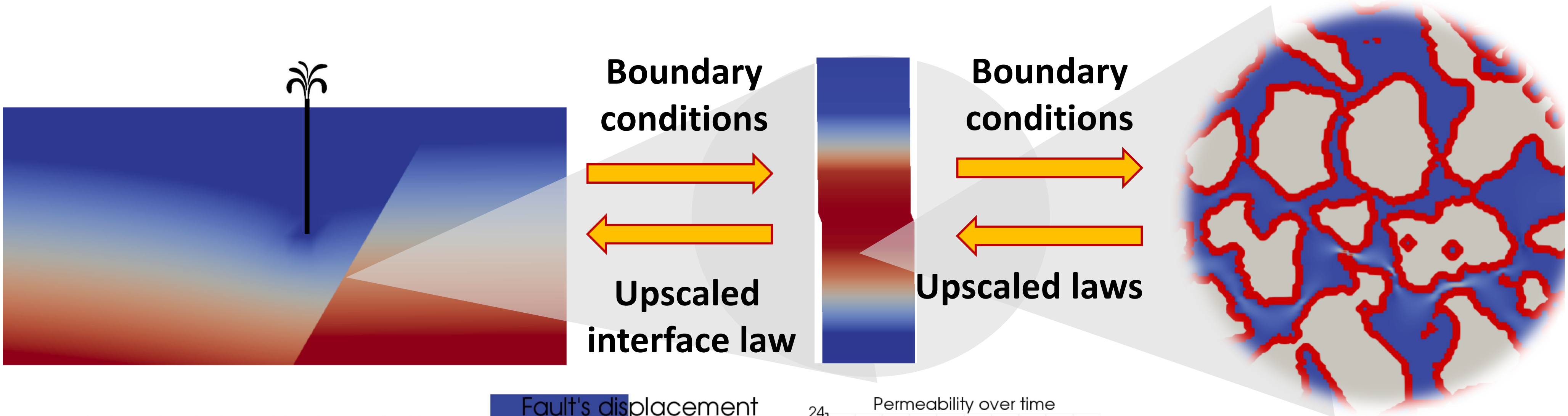
M. Lesueur, T. Poulet and M. Veveakis / Computer Methods in Applied Mechanics and Engineering 365 (2020) 112988

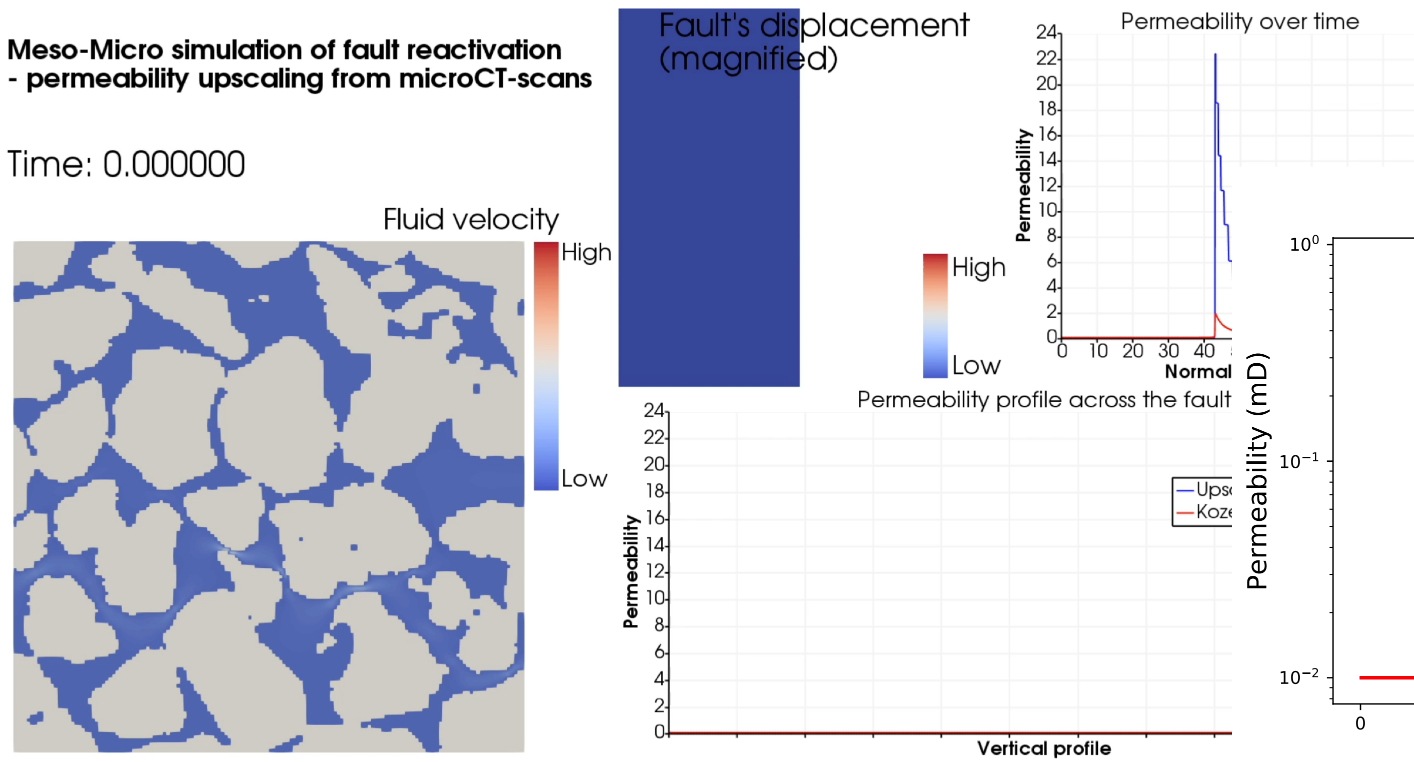


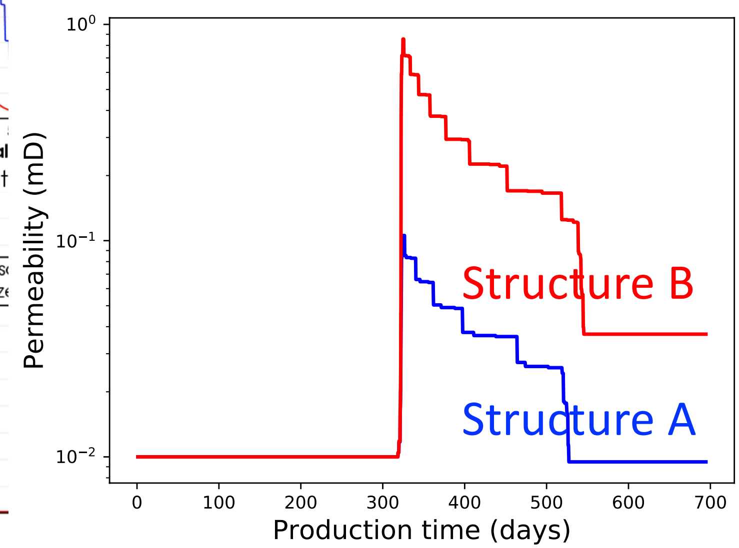
Structure A

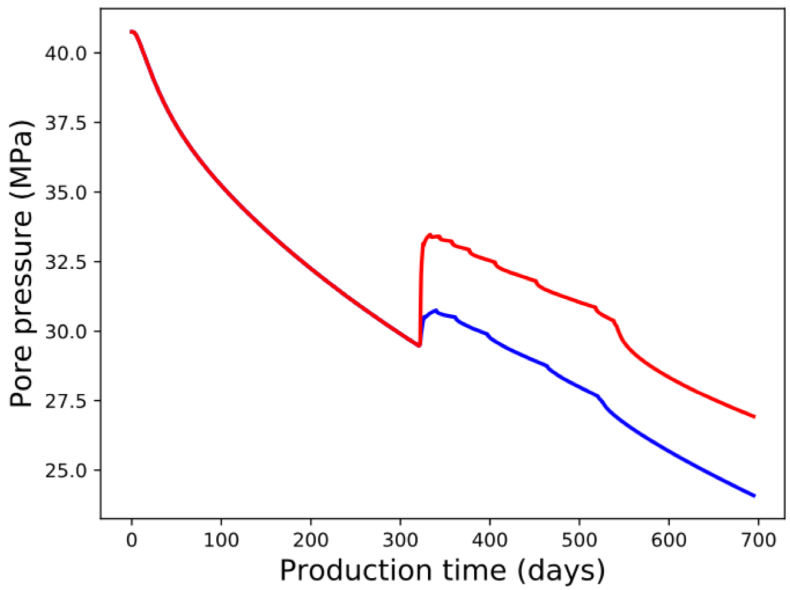
Structure B

Three-scale nested schemes: On-the-fly homogenization

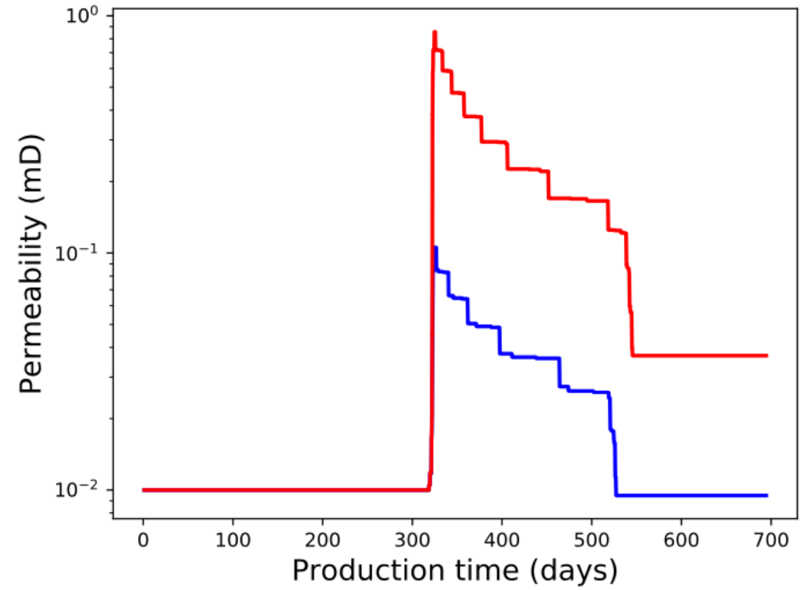




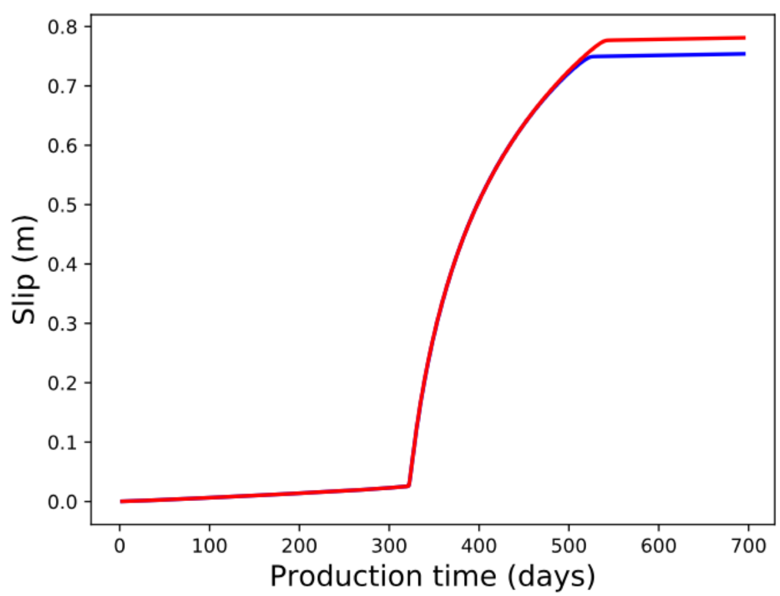




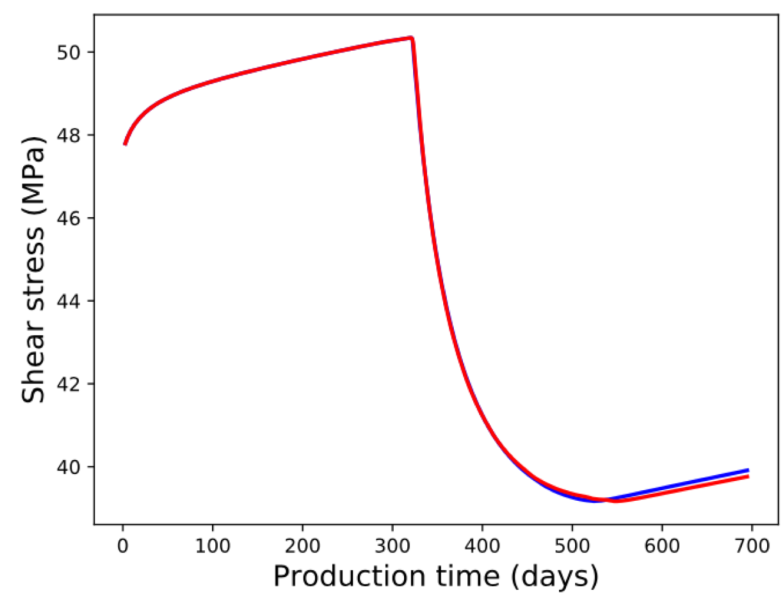
(a) Evolution of pore pressure on the left side of the fault.



(b) Evolution of the fault permeability.



(c) Evolution of the fault slippage.



(d) Evolution of the fault shearing stress (Von Mises stress).

Thank you!