Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

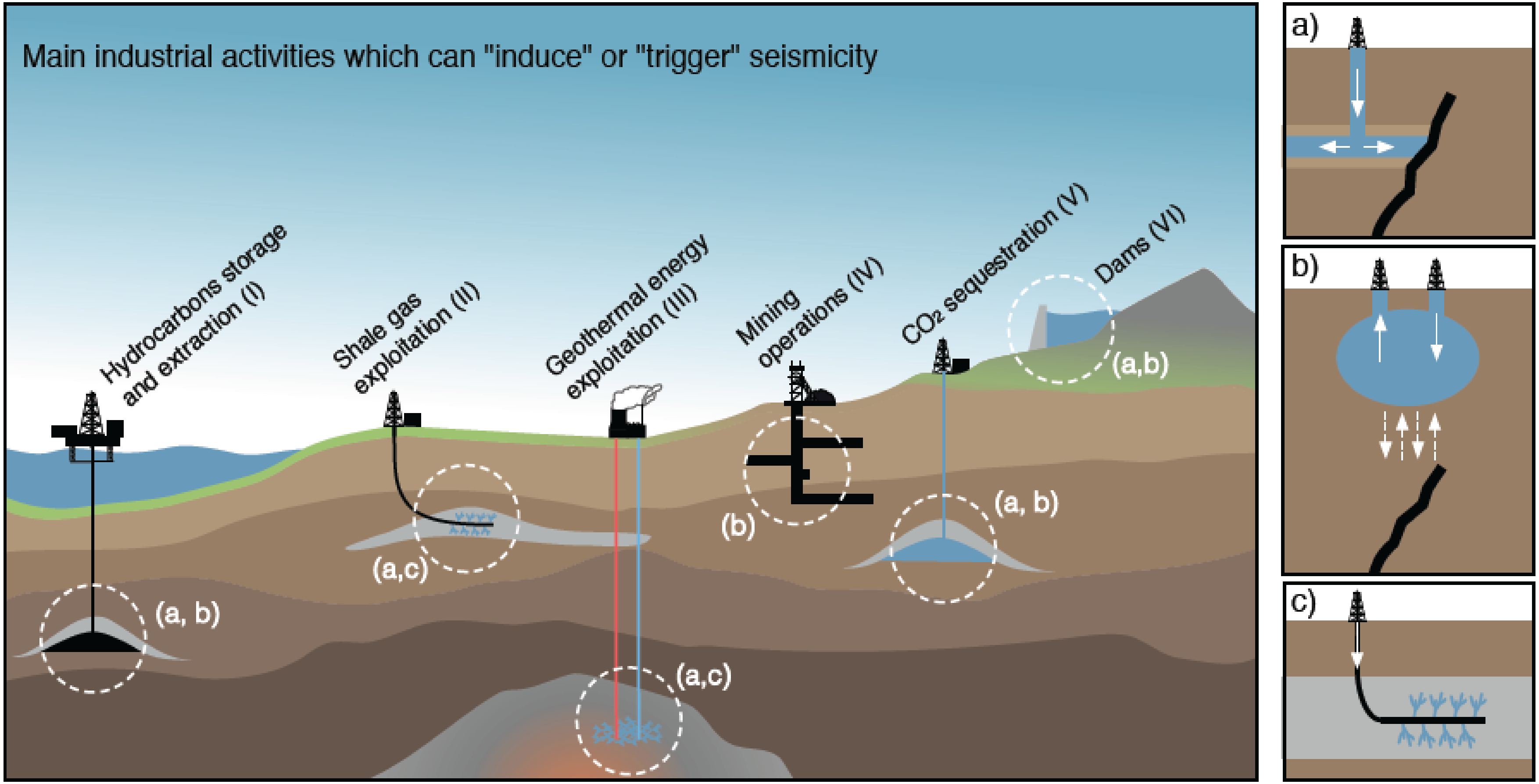
ETH zürich

Induced seismicity and GeoEnergies: lessons learned from coupled hydro-mechanical modeling

Antonio P. Rinaldi
and many others….

4th Cargèse Summer School:
Flow and Transport in Porous and Fractured Media
Cargèse, Corsica (France), 06.07.2018

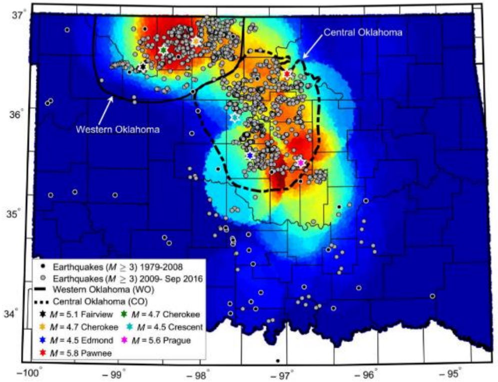
GeoEnergy applications and induced earthquakes belong together

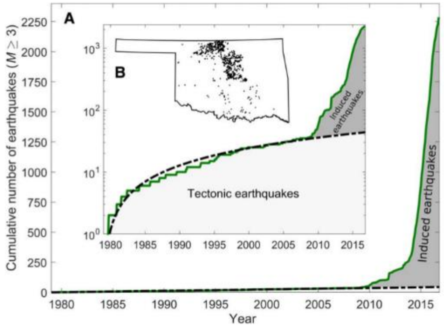


Grigoli et al. (2017)

Recent examples of induced seismicity

Wastewater injection
(e.g., Oklahoma, US)





Langebruch and Zoback, 2016

Largest event: M=5.8

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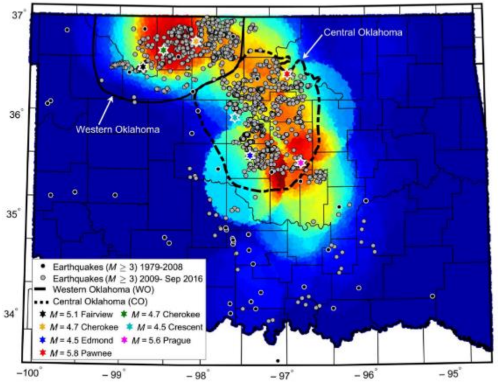
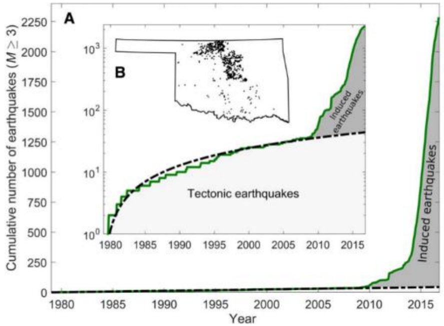
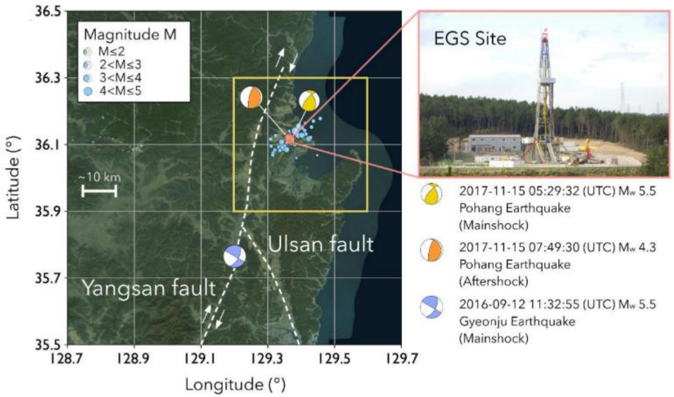




Langebruch and Zoback, 2016

Enhanced geothermal system (e.g., Pohang, South Korea)

Grigoli et al., 2018

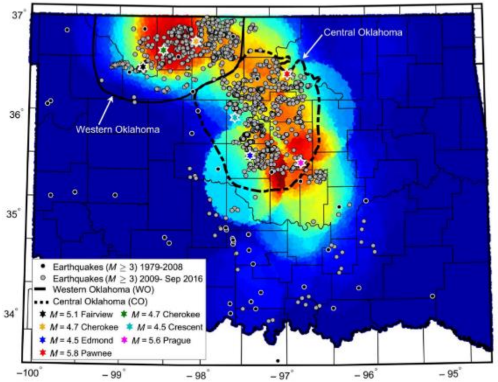


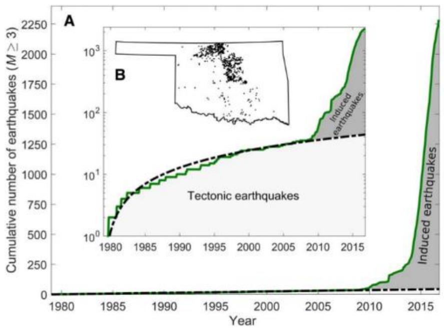
Largest event: M=5.8

Largest event: M_w=5.5

Recent examples of induced seismicity

Wastewater injection (e.g., Oklahoma, US)





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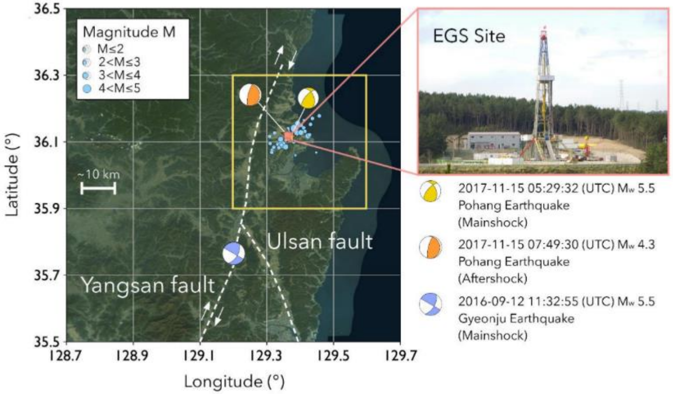
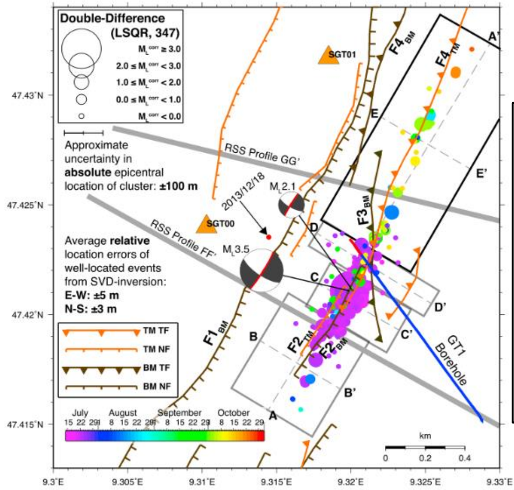
Grigoli et al., 2018



Deep geothermal energy (e.g., St. Gallen, Switzerland)



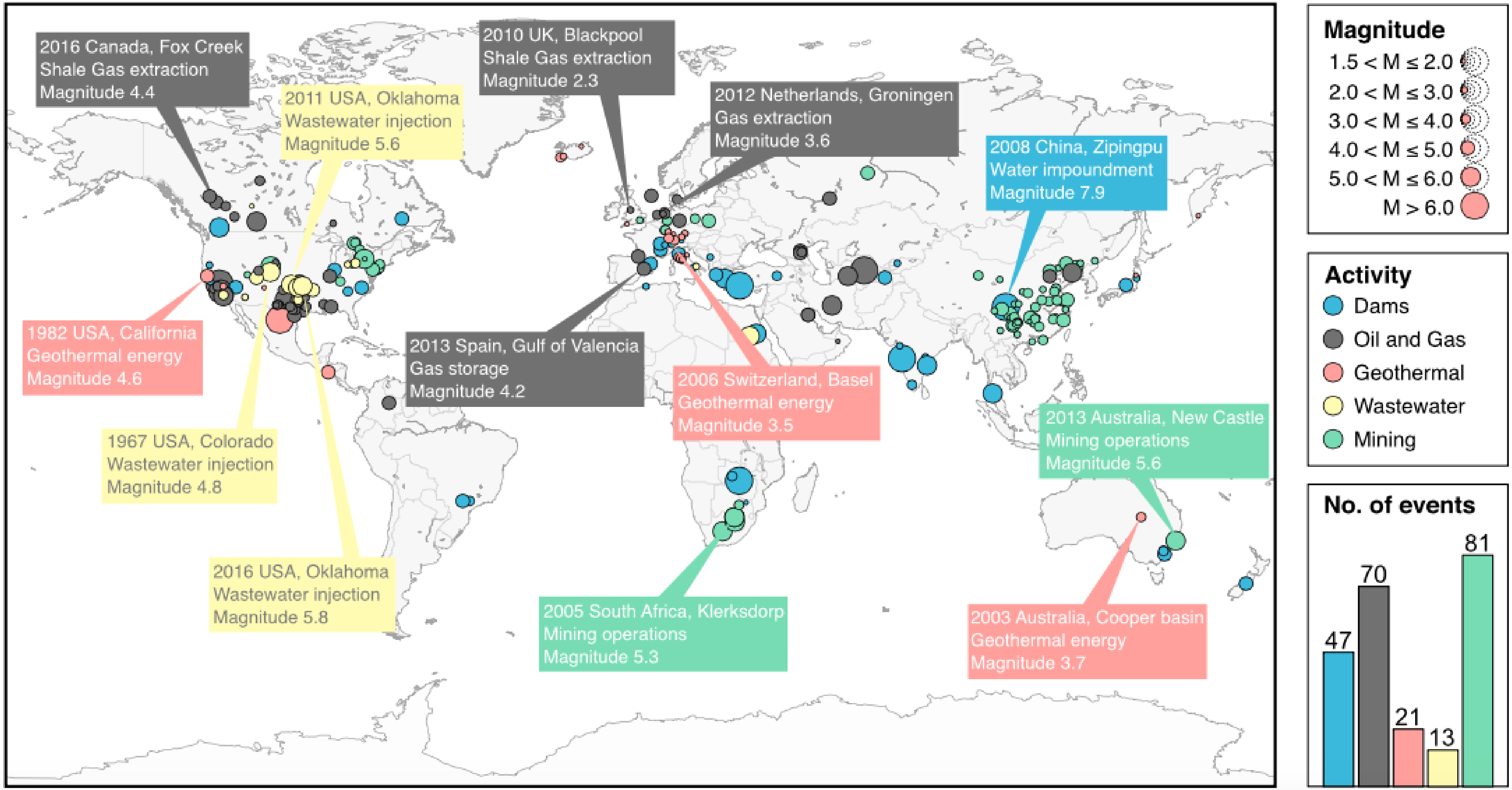
Diehl et al., 2017

Largest event: M=5.8

Largest event: M_w=5.5

Largest event: M_L=3.5

GeoEnergy applications and induced earthquakes belong together



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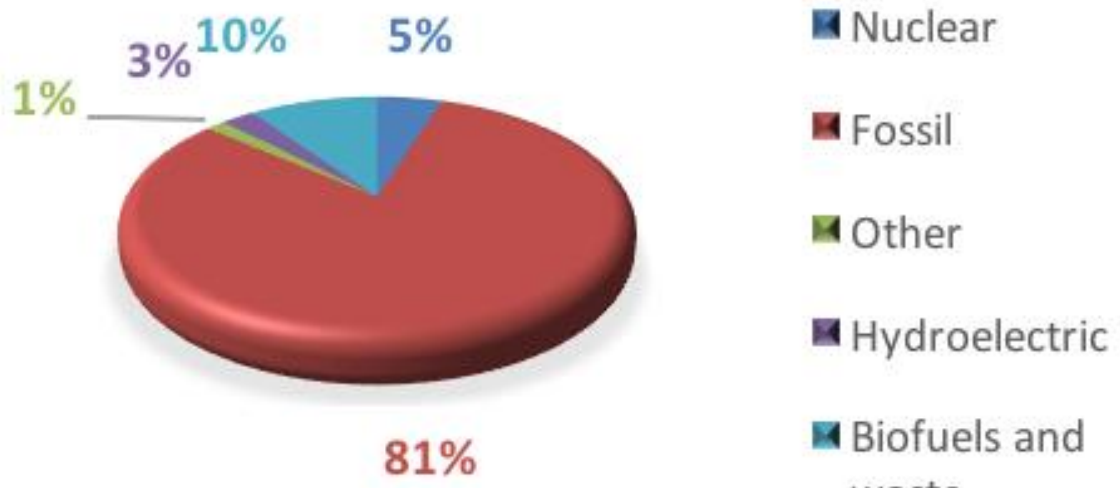
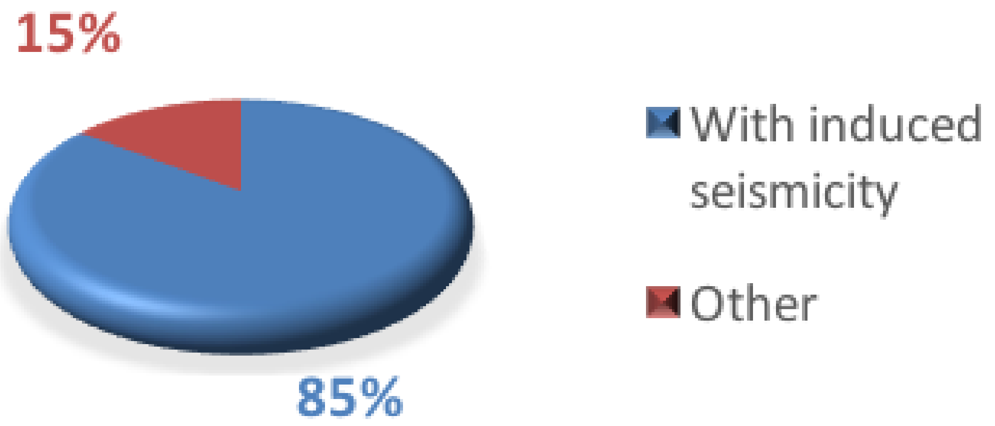
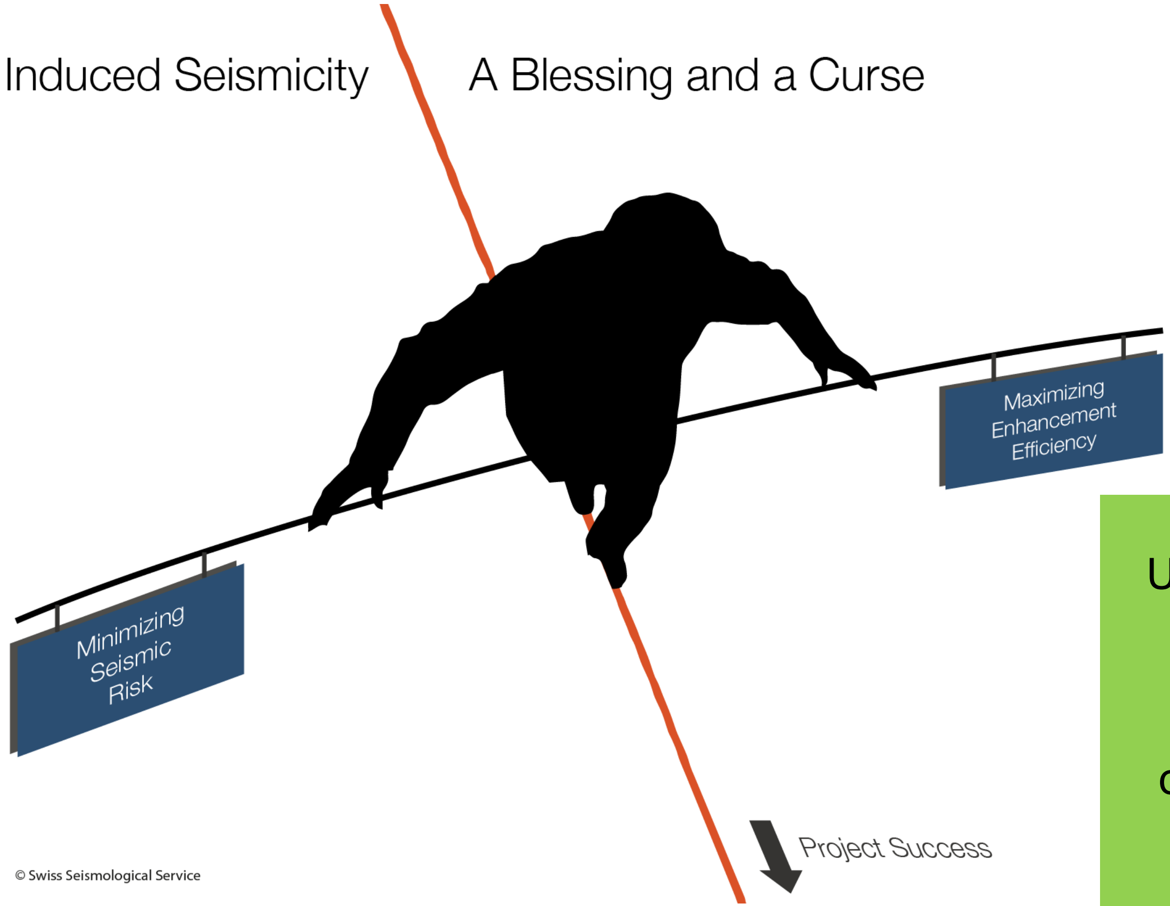




Working on Induced Earthquakes



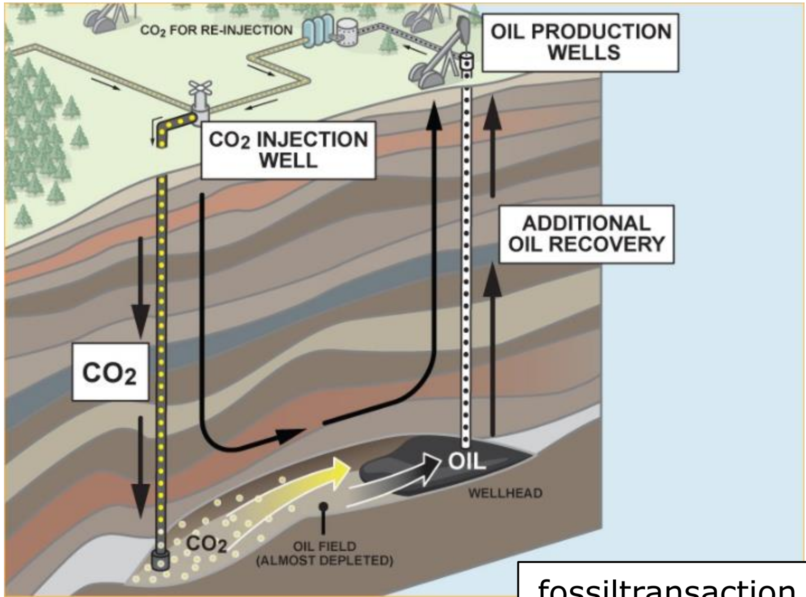
Understanding how to use and control micro-earthquakes is both an urgent need and a win-win for the team oil & gas + renewable energy

PS: It is also a fascinating science ...

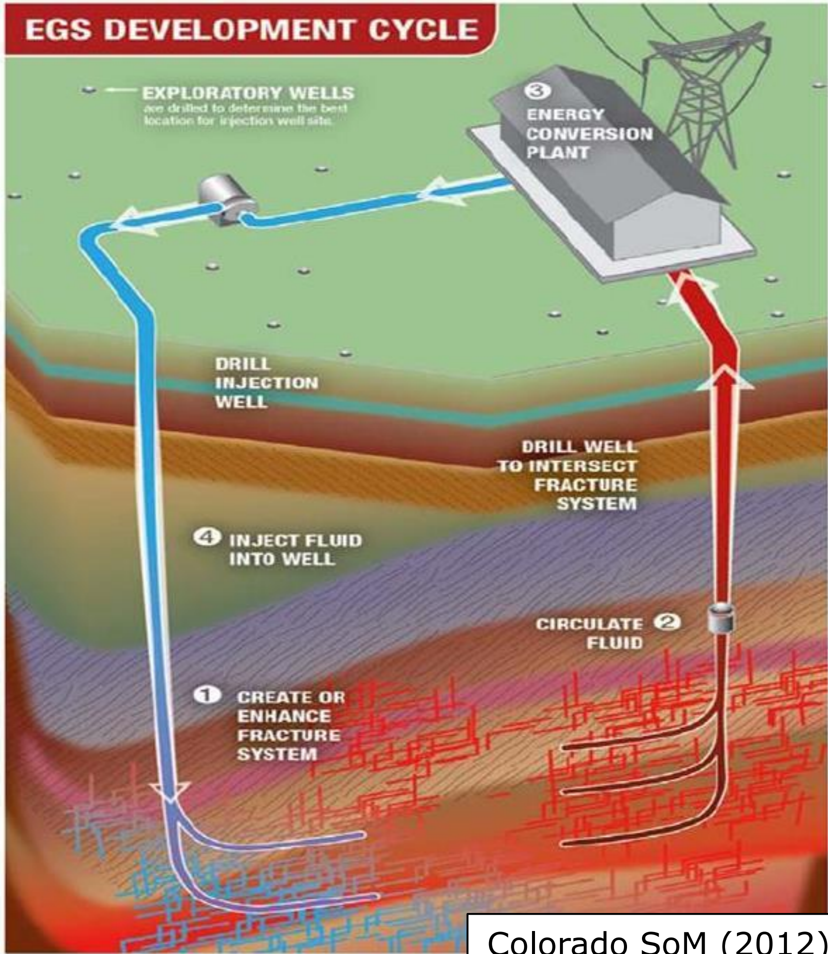
To induce or not to induce: an open problem

Induced seismicity not just a side effect but a tool.

- Enhances fluid circulation, hence **energy production**.
- Can be (somehow) **controlled**.
- Known location allows for **better monitoring**.

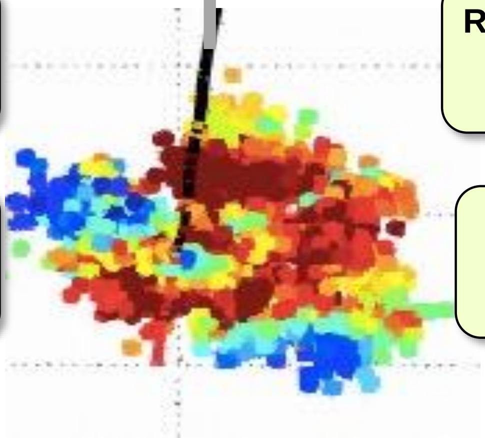


fossiltransaction.org



Colorado SoM (2012)

Interdisciplinary research at its best



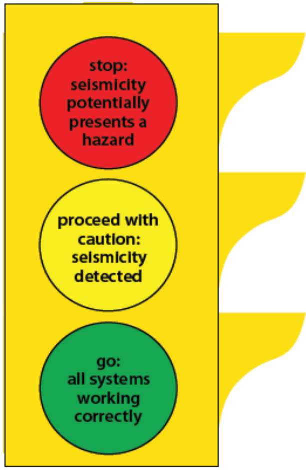
- Seismology
- Earthquake Physics
- Fluid Dynamics
- Numerical Modeling
- Social Science
- Geological Modeling
- Risk Assessment
- Exploration Geophysics
- Rock Physics
- Sensors

Relevant questions

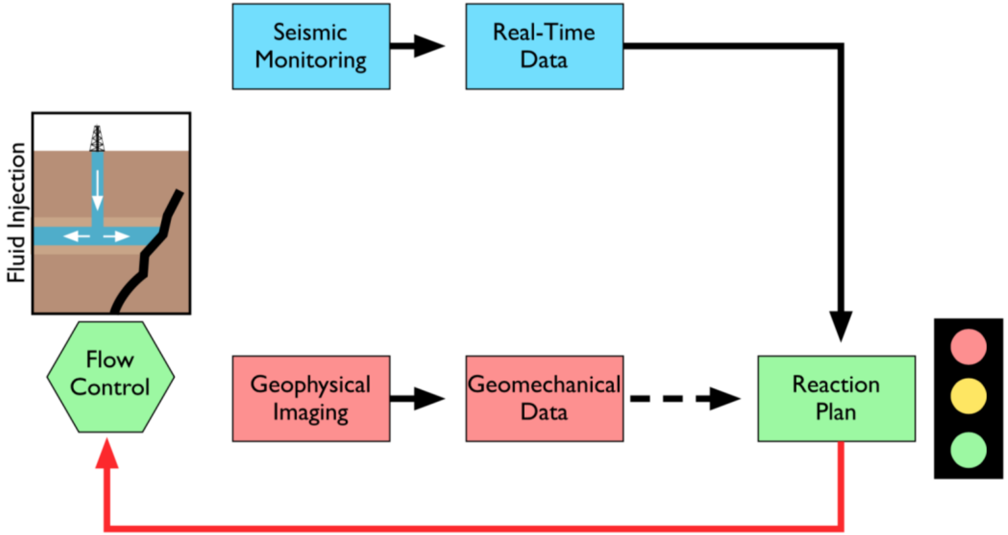
- Is my operation save and in compliance with regulations?
- How do I convince others that my operation is save?
- Is my future injection plan save and in compliance with regulations while maximizing at the same time my chance of commercial success?
- What alternative injection strategy should I follow to be save and commercially successful?
- What mitigation strategy should I follow when things develop in unfavorable ways?

State of the art: Traffic light systems

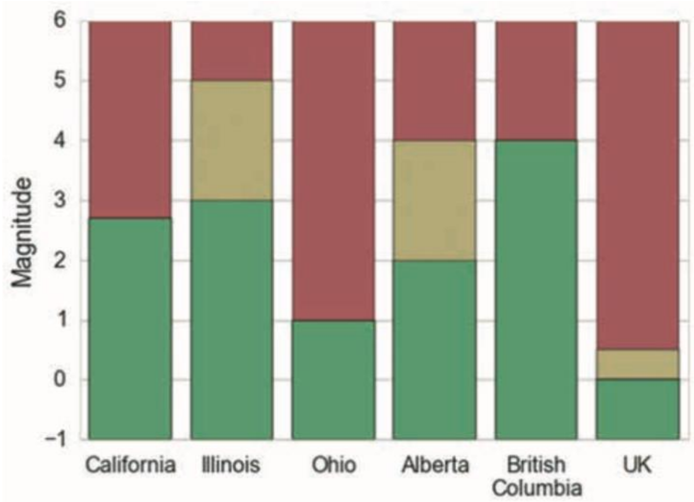
- No physical/reservoir model
- Uncertainties not accounted for
- Limited use for scenarios modeling
- Etc. …



Zoback, 2012



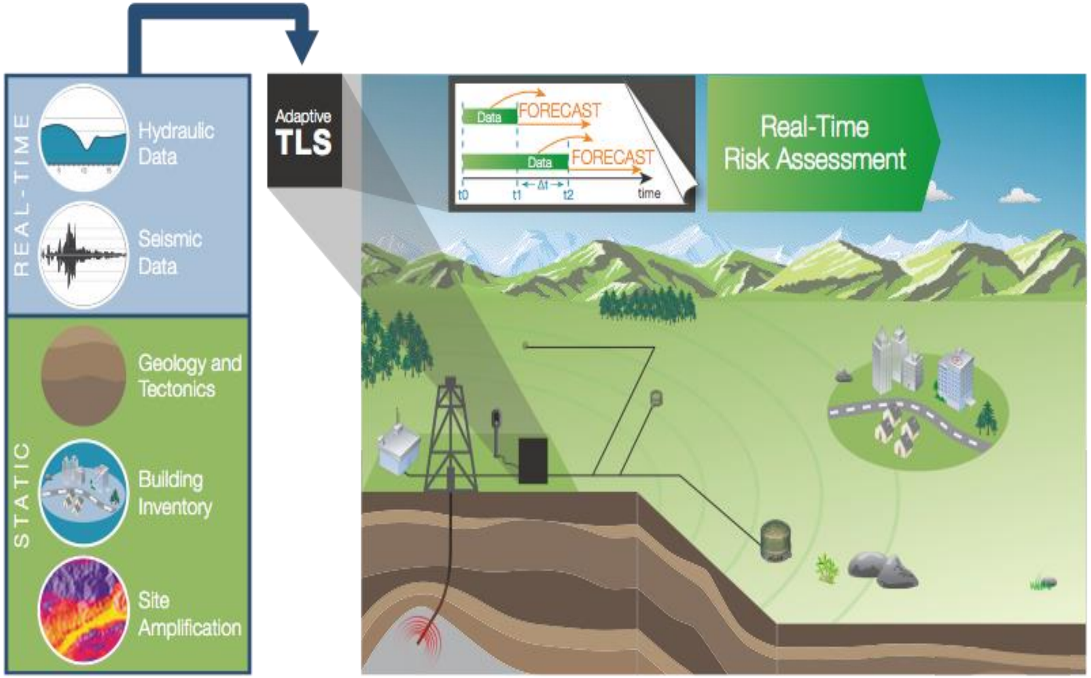
Grigoli et al., 2017



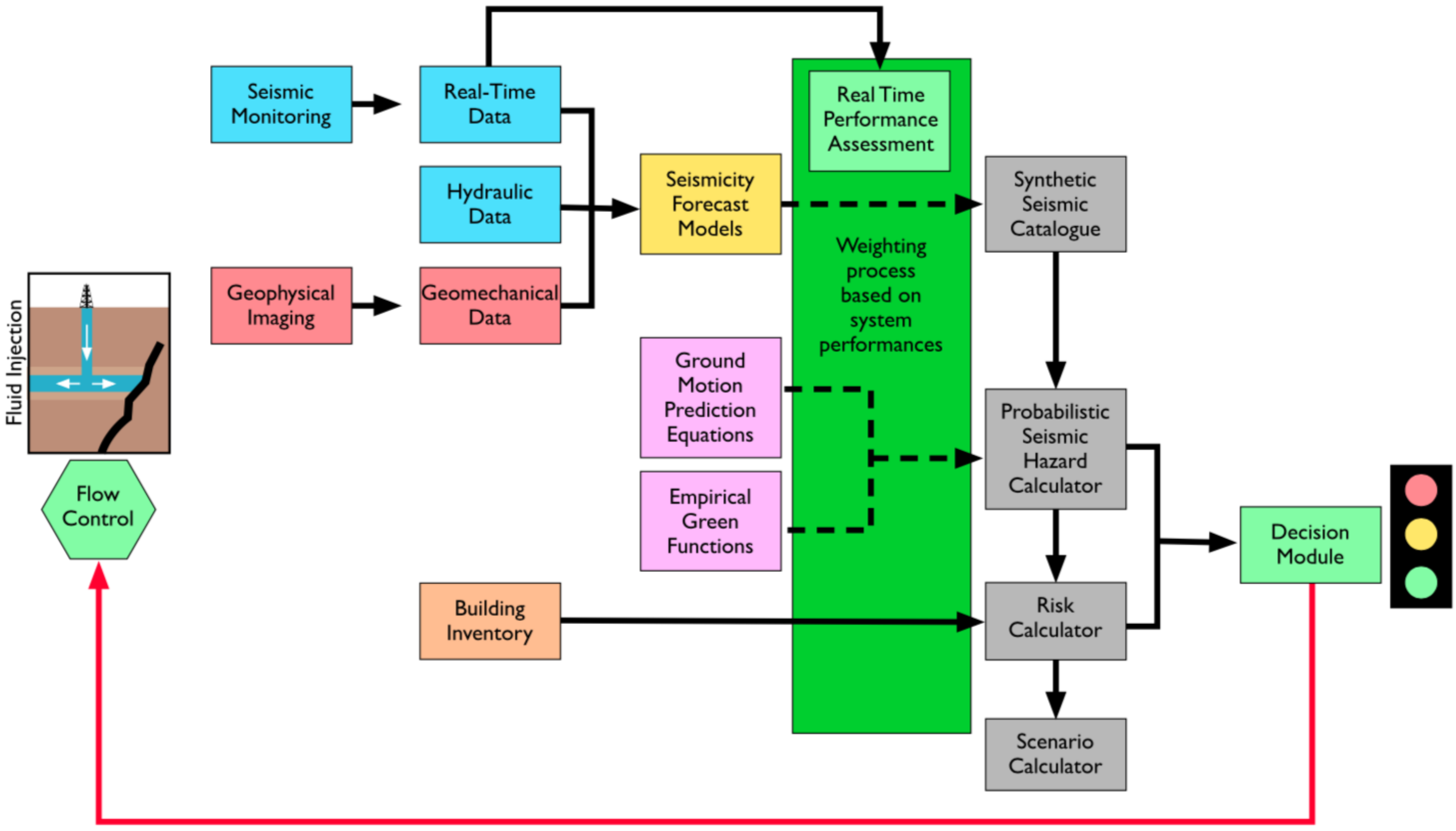
Bosman et al., 2016

Moving on to "Adaptive, data -driven Traffic Light Systems"

- ATLS are dynamically updated, forward-looking and fully probabilistic models that forecast the future seismicity and reservoir evolution based on a range of relevant key parameters (eq., K P, T, …).
- Consider also 'low probability-high consequence events'.
- Robustness through ensemble forecasting.
- Validation!



Adaptive Traffic Light System (ATLS)



Grigoli et al., 2017

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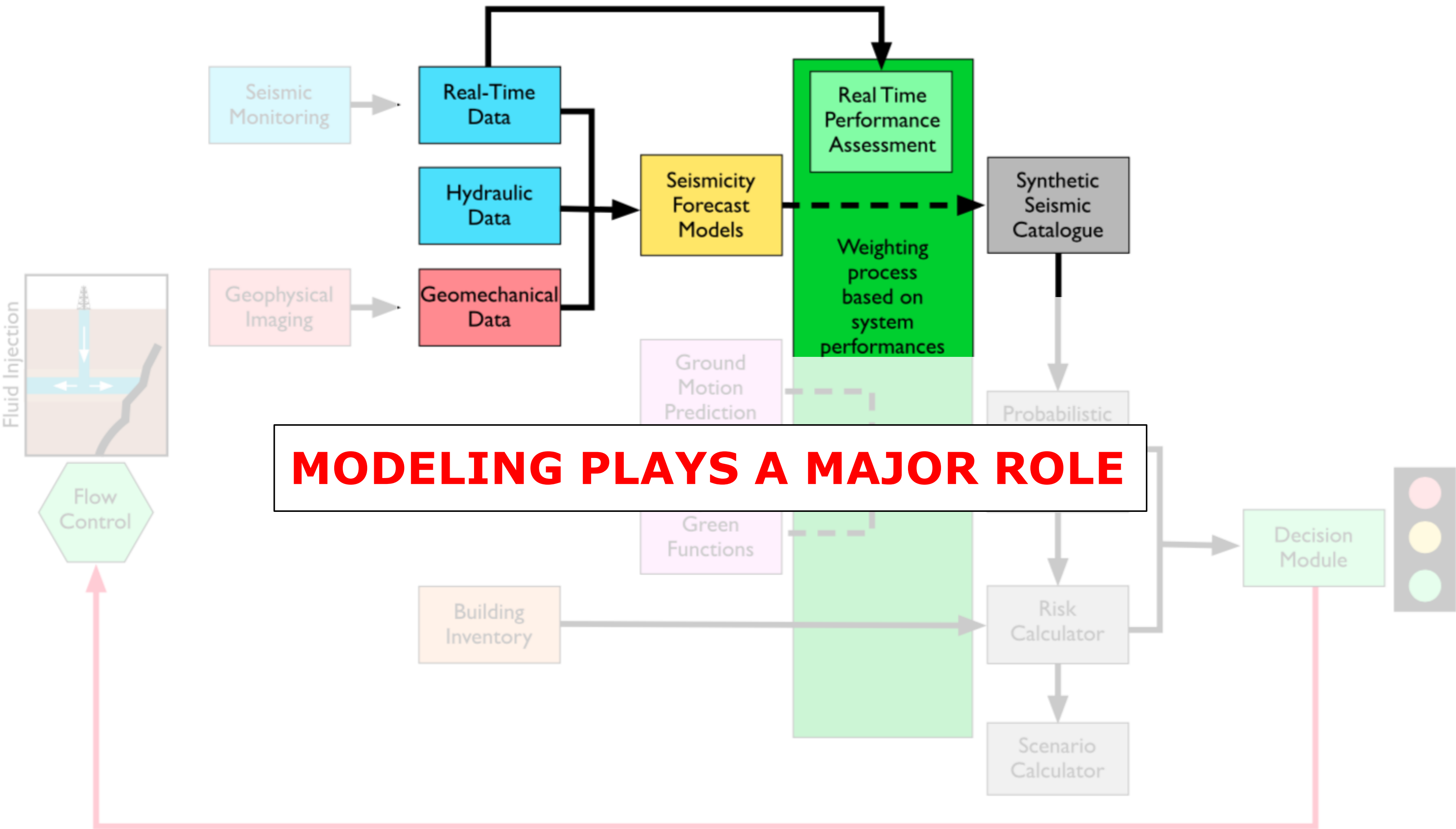


MODELING PLAYS A MAJOR ROLE

Grigoli et al., 2017

Hydromechanical simulators

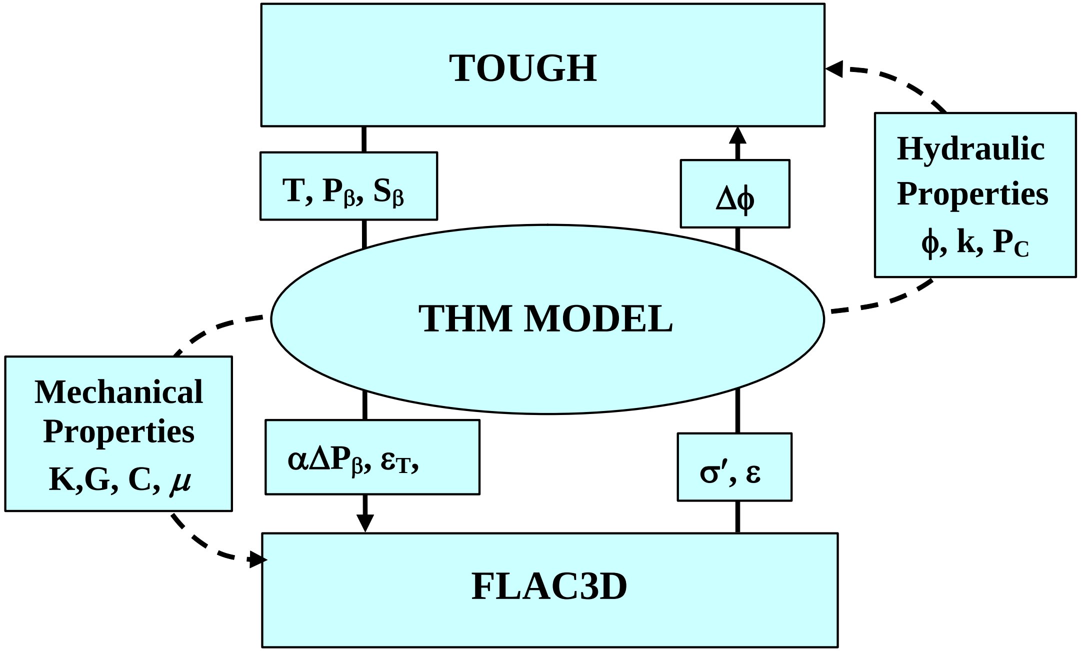
Several non-isothermal multiphase flow coupled with geomechanical processes simulators have been applied to deep geoengineering coupled modeling within the last few years

Some are based on linking established codes whereas others are stand alone

TOUGH-FLAC (Rutqvist et al. 2002), **FEMH** (Deng et al., 2011), **OpenGeoSys** (Kolditz et al., 2012), **CodeBright** (e.g. Vilarrasa et al., 2010), **STARS** (Bissell et al., 2011), **CSMP++** (e.g. Paluszny & Zimmerman, 2011), **GEOS** (Settgast et al., 2016), **FALCON** (Gaston et al., 2012), **DYNAFLOW** (Preisig and Prévost, 2011), **CFRAC** (McClure, 2012) and other linked multiphase flow codes (e.g. **TOUGH2**, **ECLIPSE**, **GEM,GPRS**) and geomechanics codes (Rohmer and Seyedi, 2010; Ferronato et al., 2010; Tran et al., 2010; Jha & Juanes, 2014)

And many more in recent years….

TOUGH-FLAC coupled simulator

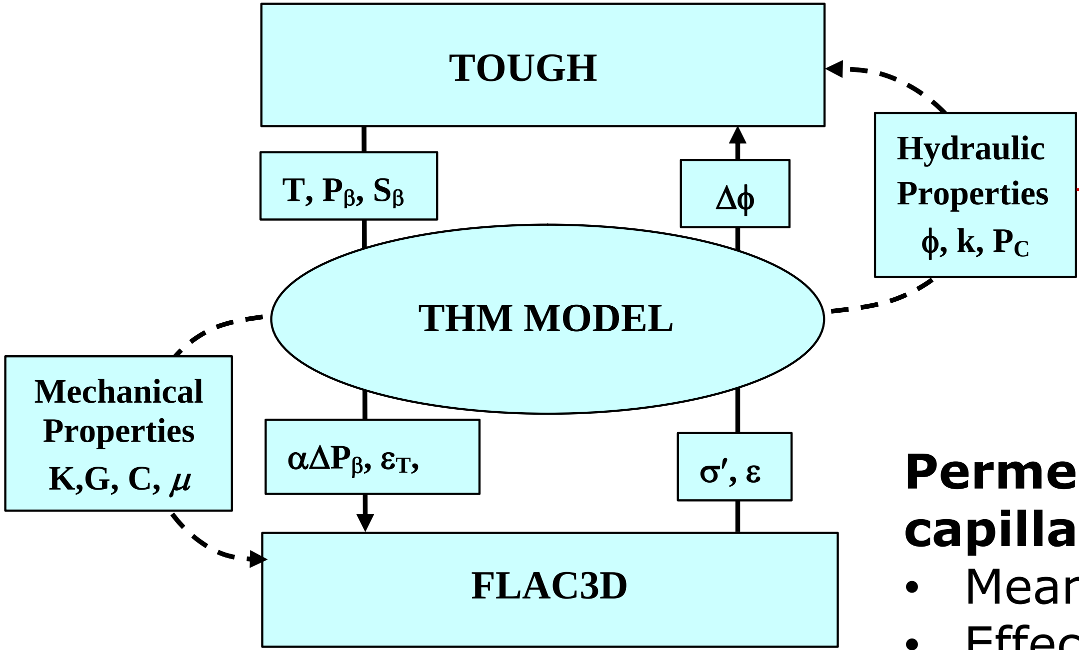


C = Cohesion
G = Shear modulus
K = Bulk modulus
k = Intrinsic permeability
P = Pressure
Pc = Capillary pressure
SH = Hydrate saturation
T = Temperature
ε = Strain
ϕ = Porosity
μ = Coefficient of friction
σ' = Effective stress

Direct couplings (solid arrow): Pore volume change, effective stress, thermal strain, and swelling

Indirect couplings (dashed arrow): Changes in mechanical and hydraulic properties

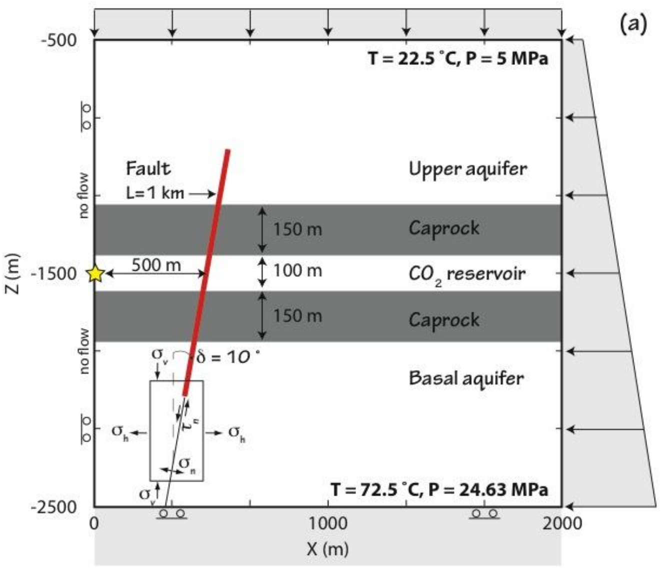
TOUGH-FLAC coupled simulator

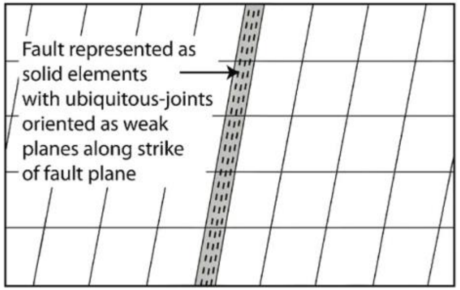


Permeability, porosity, and capillarity pressure as function of:

- Mean effective stress;
- Effective normal stress;
- Volumetric strain;
- Plastic tensile and shear strain;
- and more….

Fully-coupled models: insights on the physical processes





- 100 m storage aquifer, bounded by 150 m caprock
- Pre-existing normal fault with dip angle 80°
- CO2 injection at -1500 m, 500 m from the fault
- Isothermal with gradient 25°C/km
- Extensional stress regime $\sigma_H = 0.7\,\sigma_V$
- Damage zone as high permeability zone and Fault core with ubiquitous-joint model with oriented weak plane in a Mohr-Coulomb solid

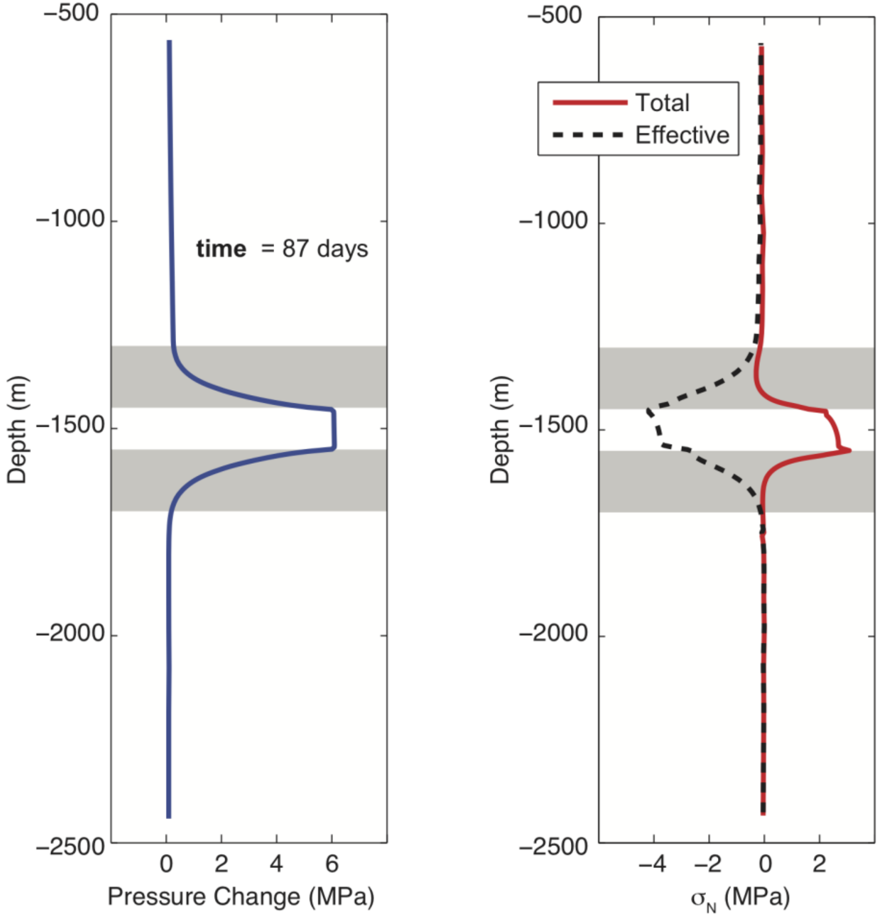
Stress and strain dependent permeability:

$$\kappa_{hm} = \kappa_0 \left[\frac{a}{c(c\sigma_n' + 1)} \sqrt{\frac{\phi_0}{12\kappa_0}} + \frac{e_{ftp} + e_{fsp}\tan\psi}{\phi_0} \right]$$

a and ***c*** empirical constants for normal-closure hyperbola (Bandis et al. ,1983)

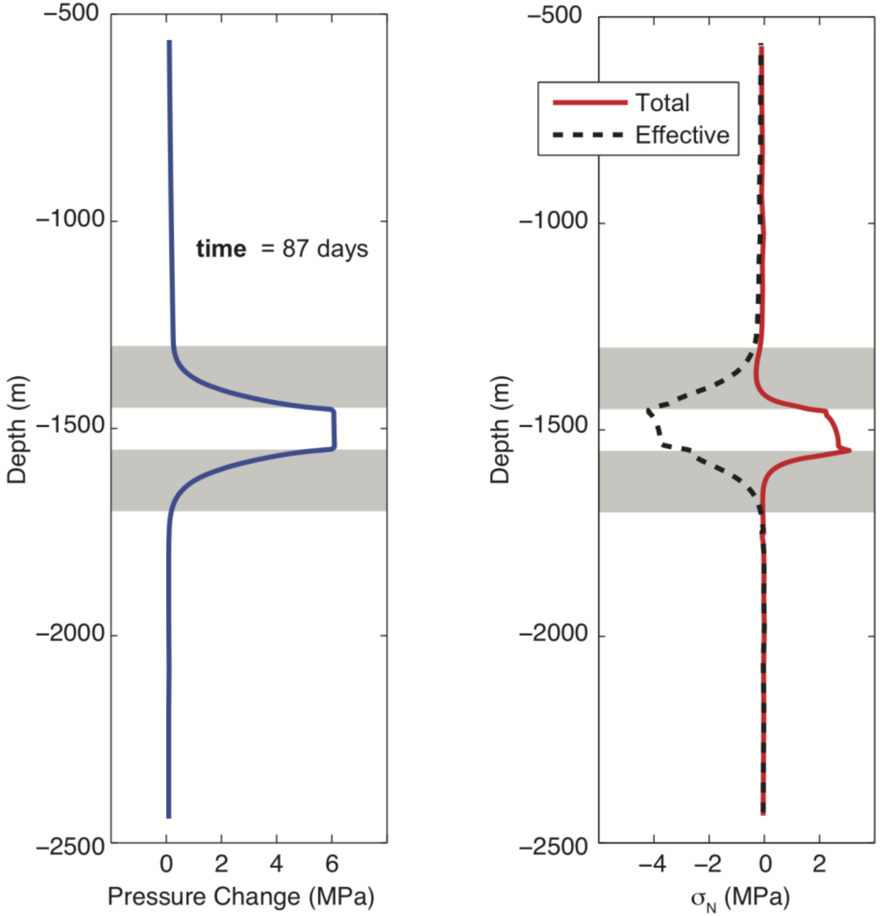
Cappa & Rutqvist, 2011,2012; Mazzoldi et al., 2012; Jeanne et al., 2014; Rinaldi et al. 2014a,b; Rutqvist et al., 2013,2014,2016; Urpi et al. 2016, 2018; Zbinden et al. 2017

Fully-coupled models: fluid injection



$$\tau \geq \tau_s = C + \mu_s \, \sigma_n{}'$$

Fully-coupled models: fluid injection



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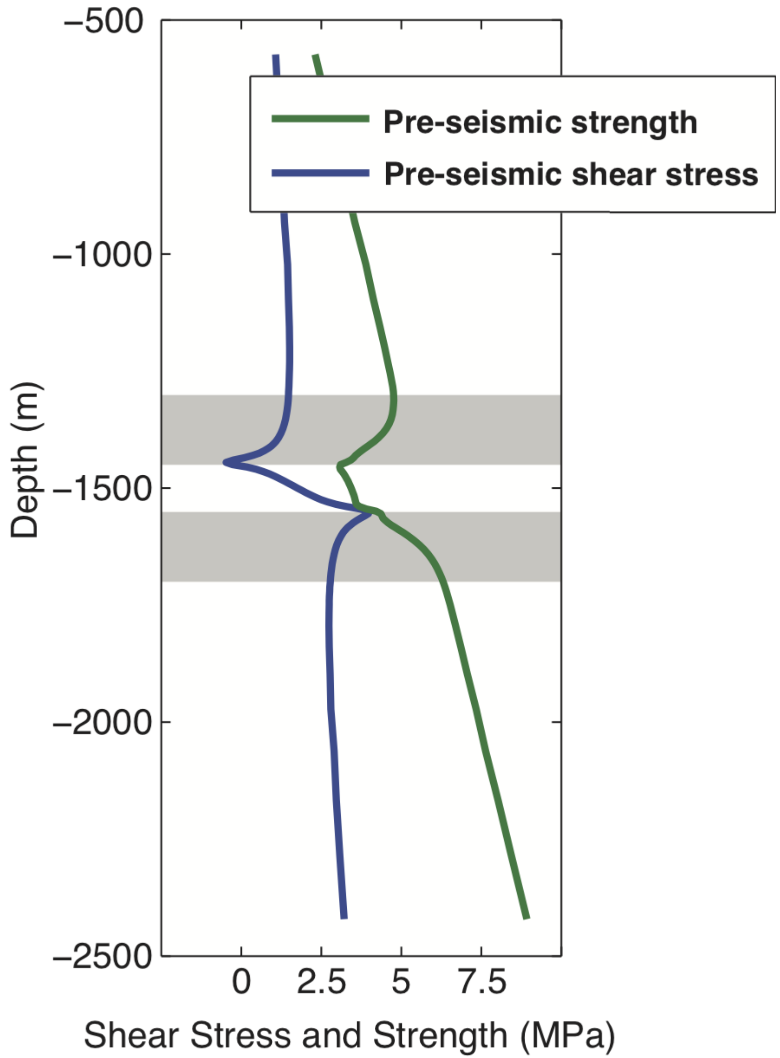
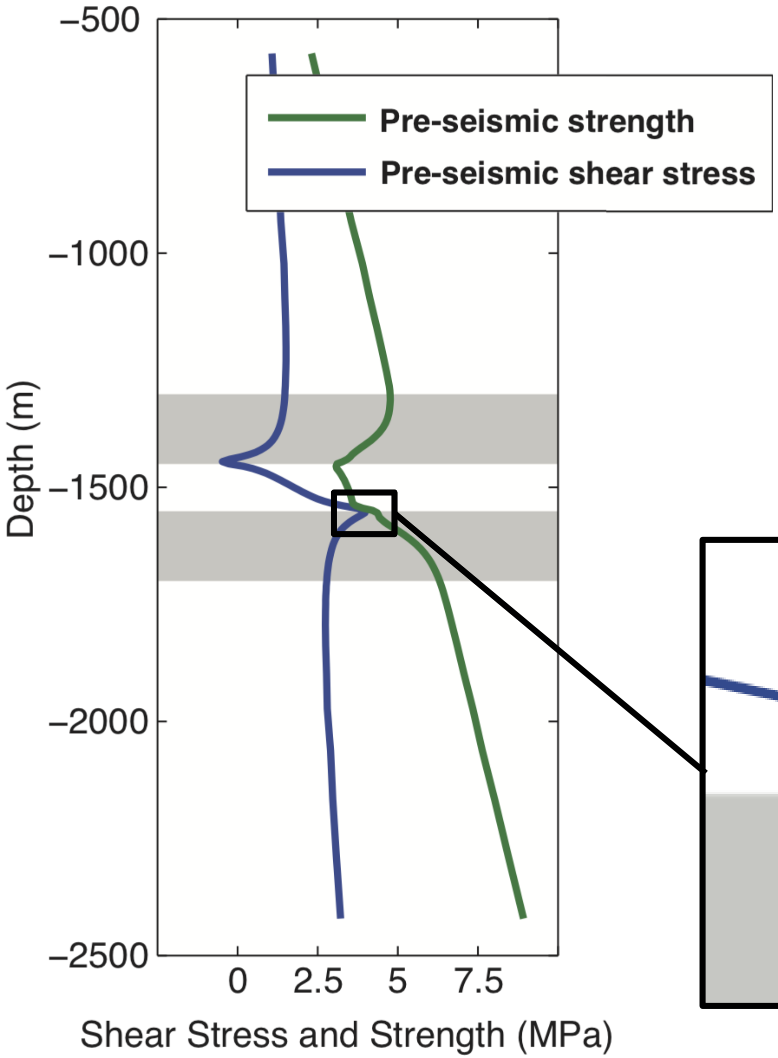
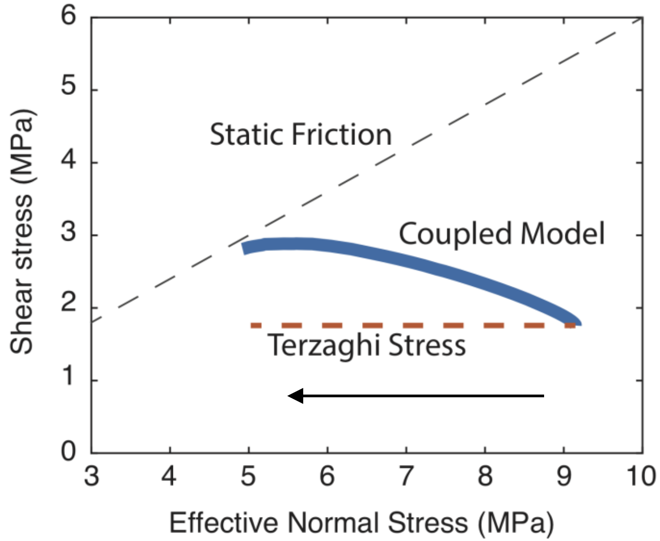


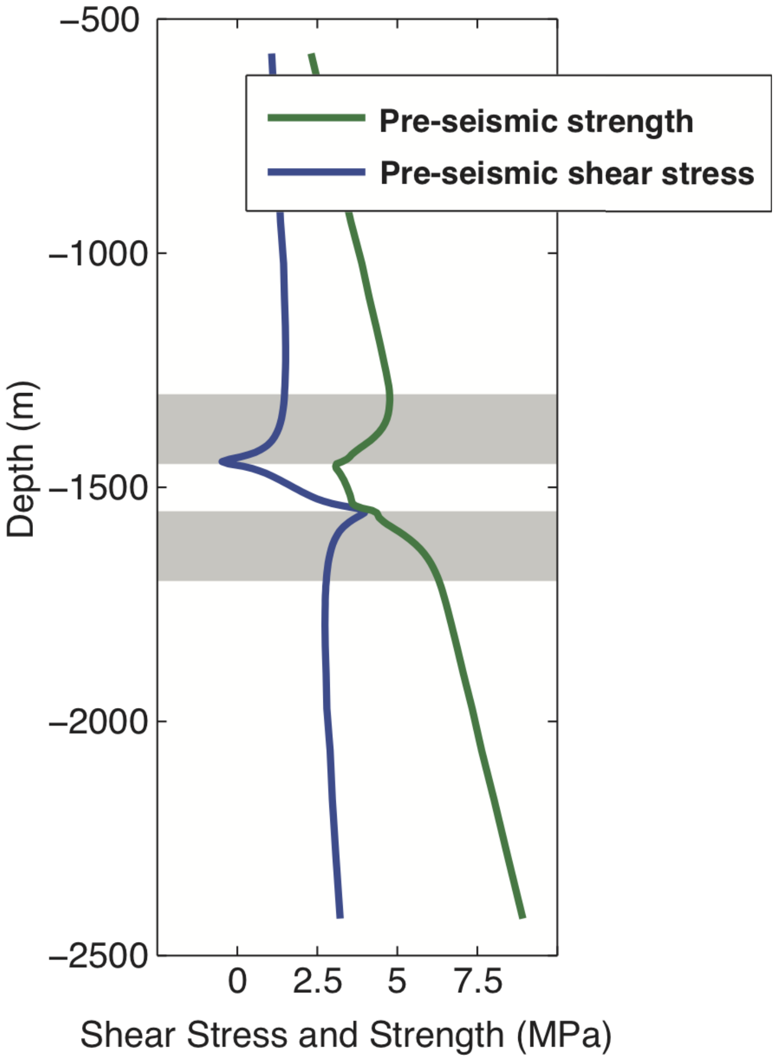
Fully-coupled models: increased pressure only?





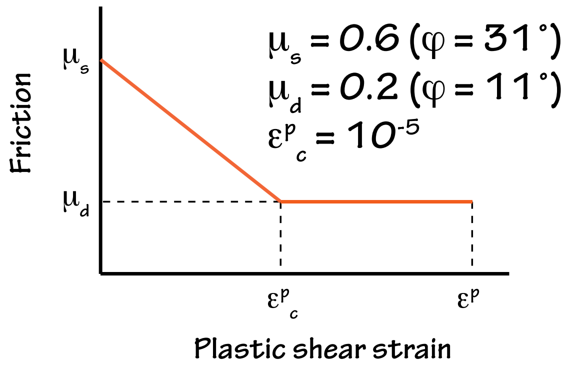
Mazzoldi et al., 2012

Fully-coupled models: stress drop



Mazzoldi et al., 2012

Strain-softening model: friction as function of plastic shear strain



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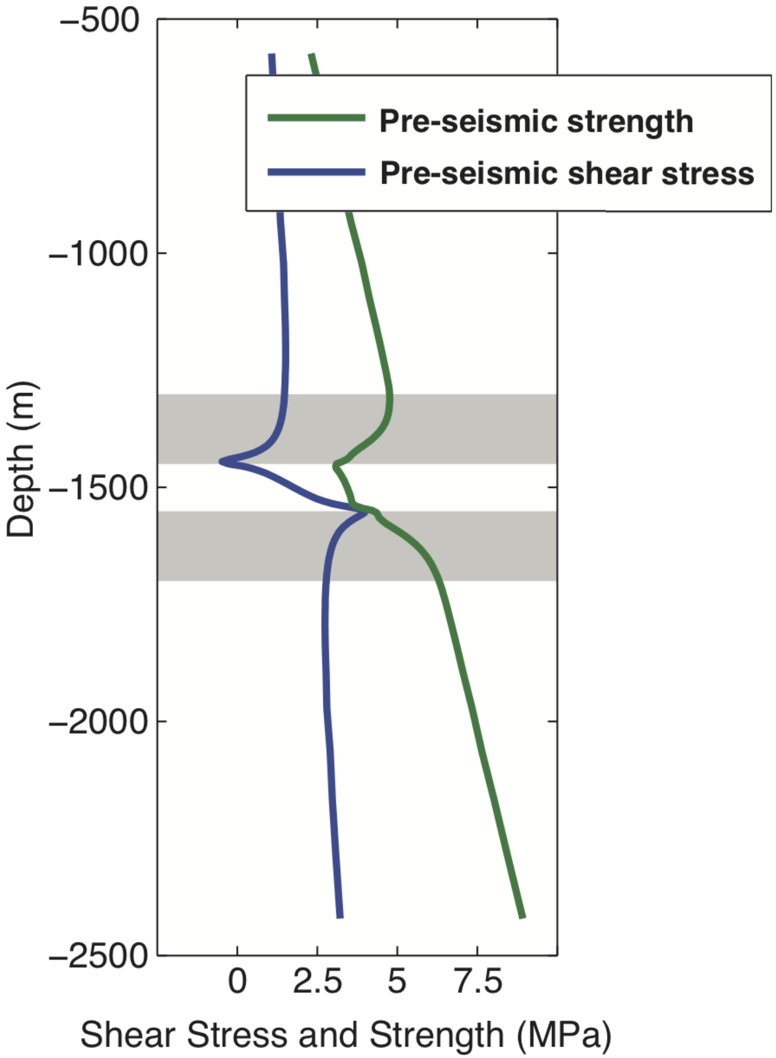
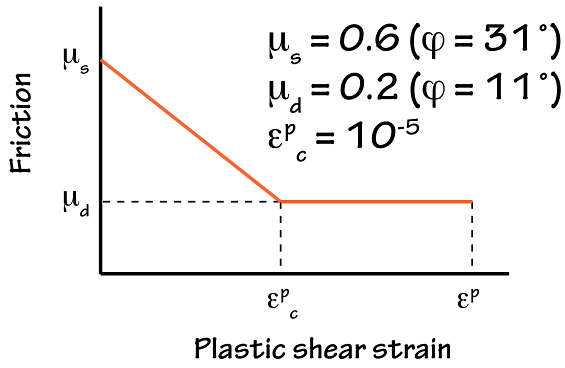
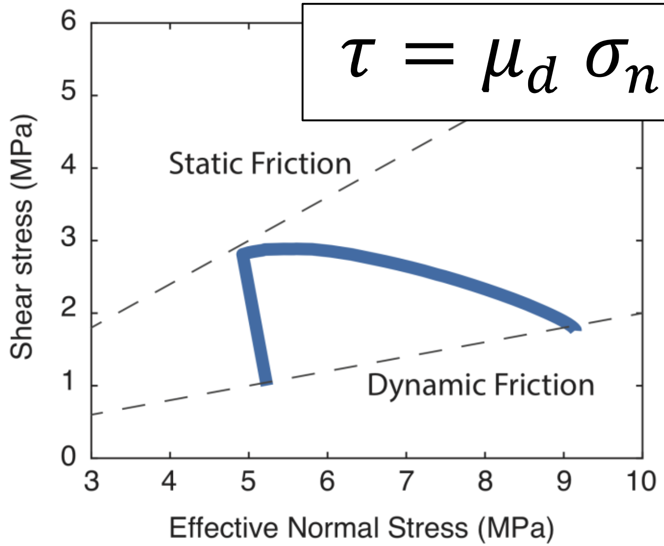


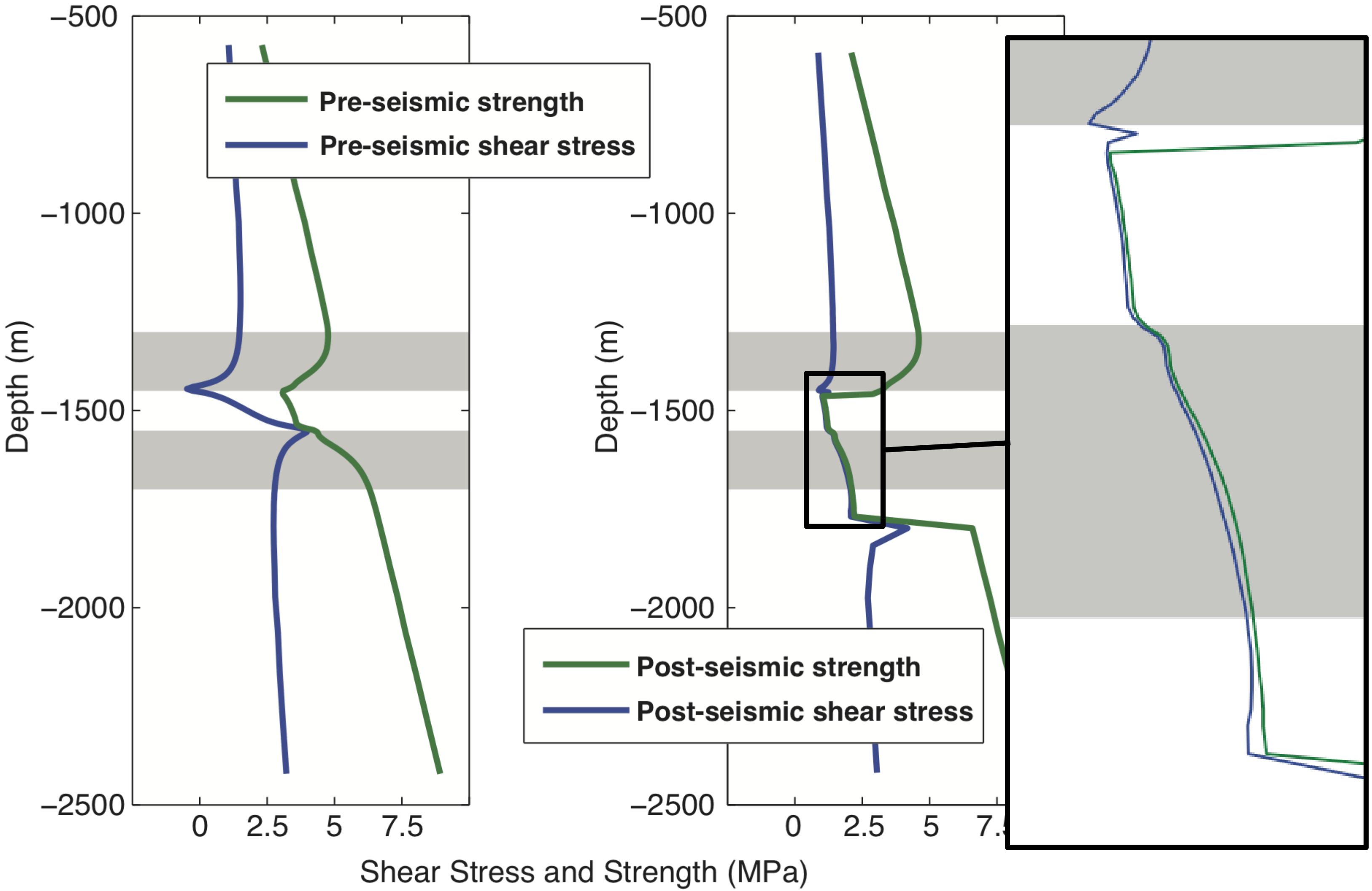




$$\tau = \mu_d\, \sigma_n'$$

Mazzoldi et al., 2012

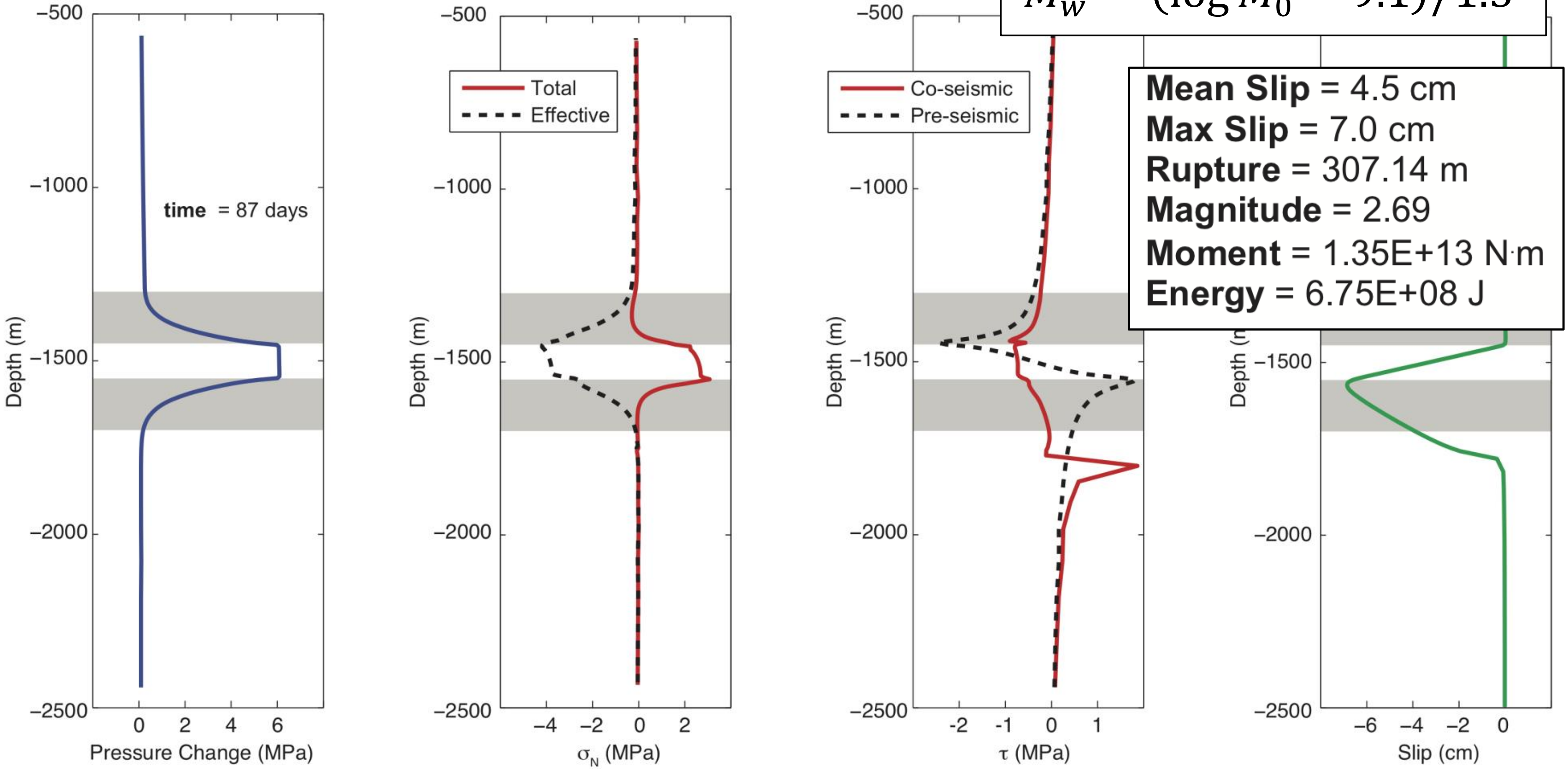
Fully-coupled models: rupture zone



Mazzoldi et al., 2012

Fully-coupled models: fluid injection

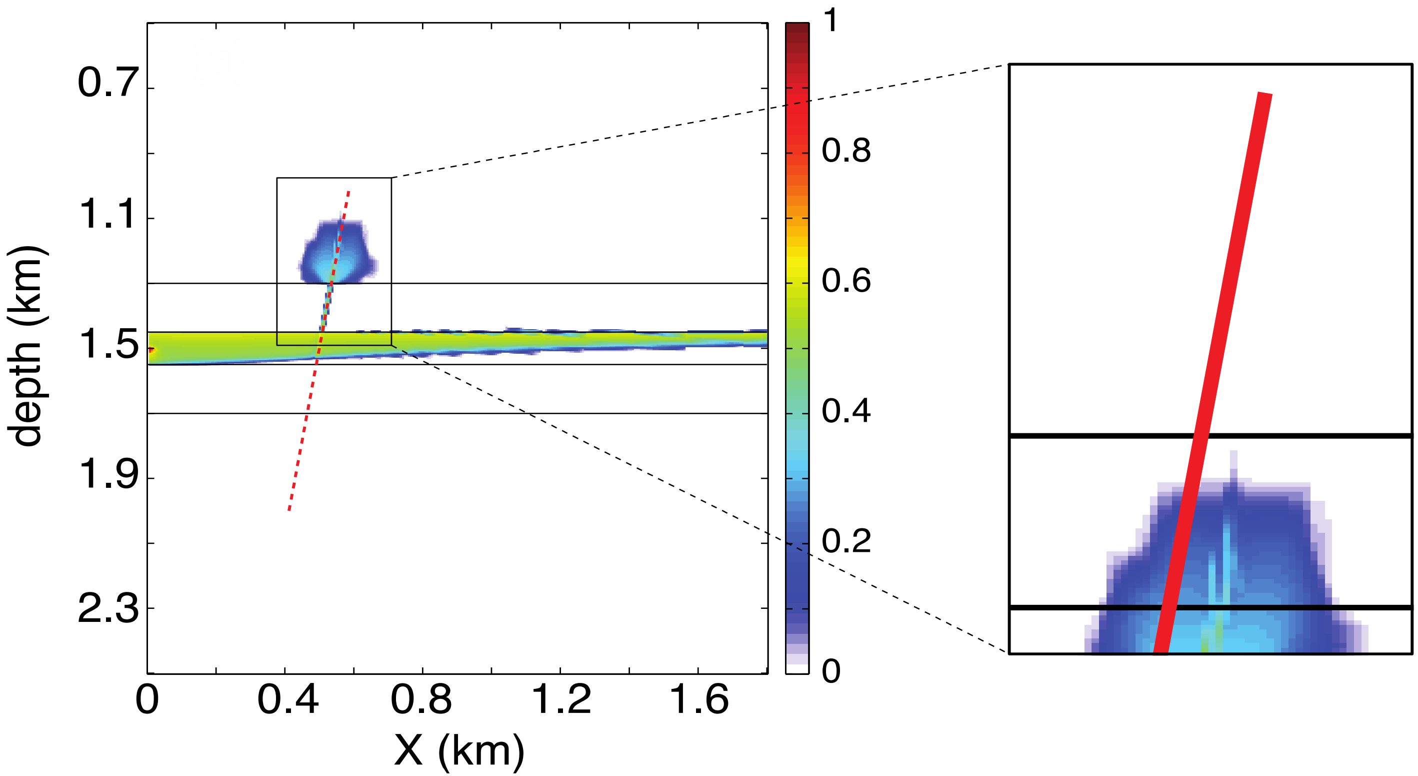
$$M_0 = G \times d_{ave} \times A$$
$$M_w = (\log M_0 - 9.1)/1.5$$



Mean Slip = 4.5 cm
Max Slip = 7.0 cm
Rupture = 307.14 m
Magnitude = 2.69
Moment = 1.35E+13 N·m
Energy = 6.75E+08 J

Mazzoldi et al., 2012

Leakage evaluation



“safe” leakage 0.1% / year
Heppe & Benson (2005)

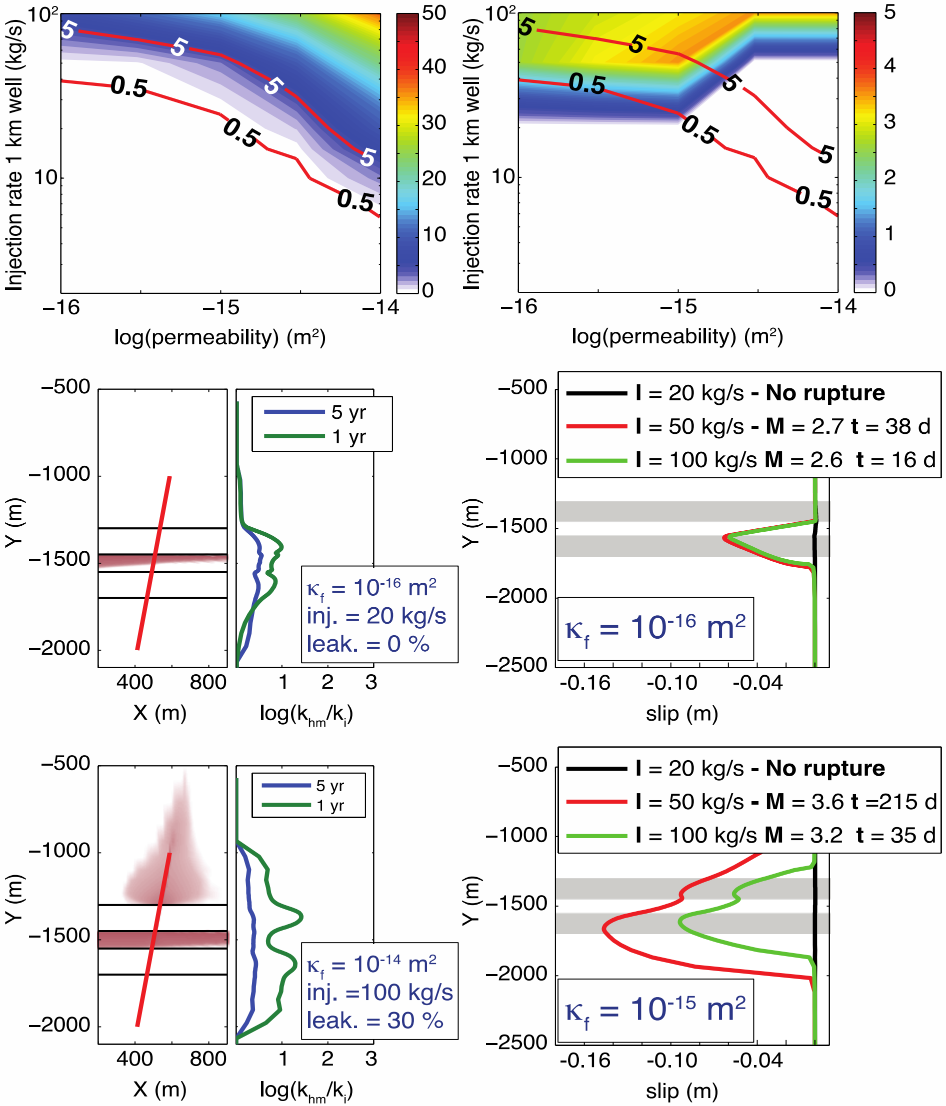
50 kg/s – 10^{-14} m^2
After 5 years of active injection
CO_2 upper aquifer: ~584 tons/m
Total injected mass: ~7800 tons/m

~7.5 % total injected mass

Induced seismicity and potential leakage (SCENARIO I)

www.seismo.ethz.ch

Rinaldi et al. (2014a)



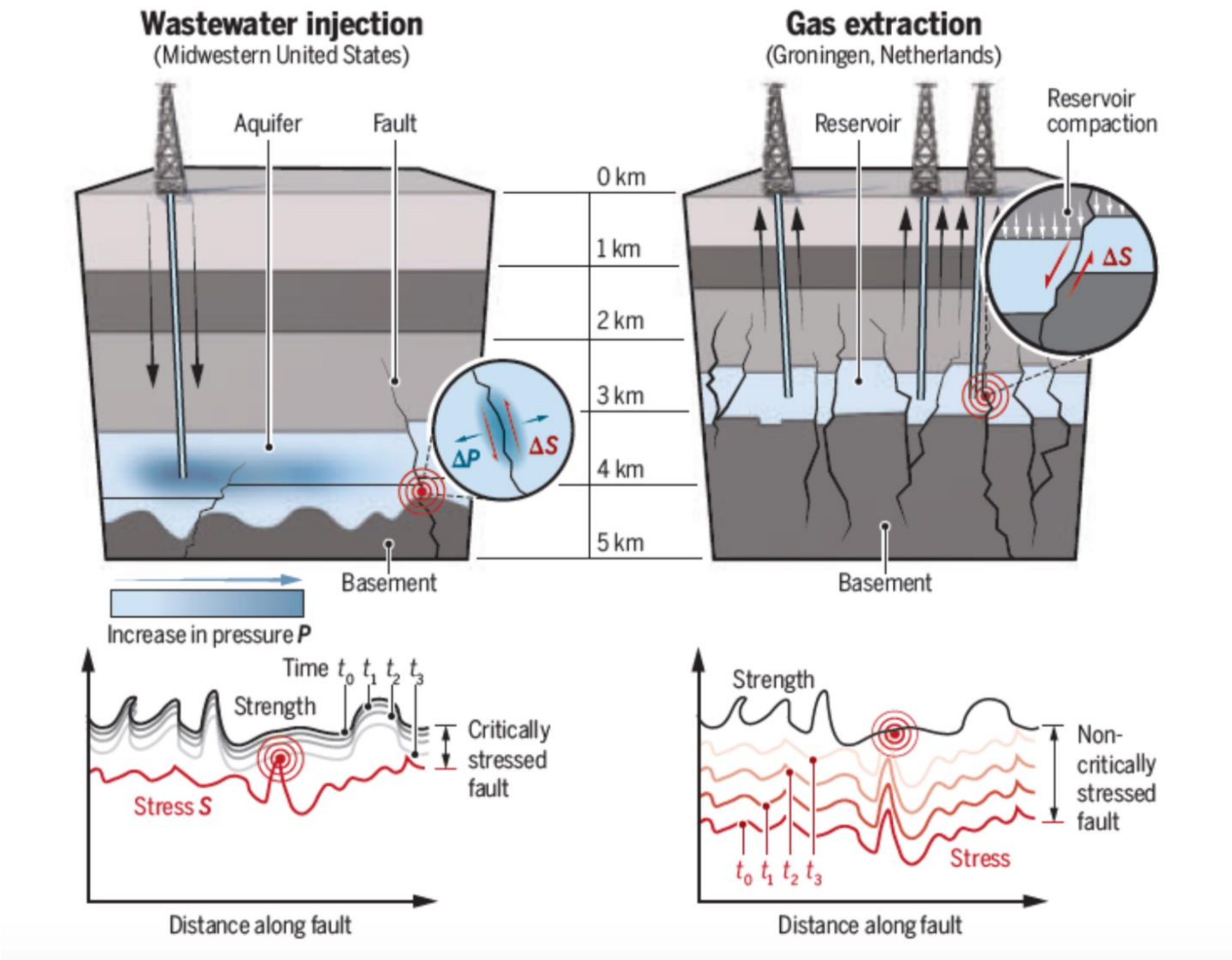
Gas saturation after 5 years

- **LEAKAGE:**
- CO_2 leakage into upper aquifer compared to total injected amount as function of injection rate (***q***=2-100 kg/s) and initial fault permeability (***κ***=10^{-16} – 10^{-14} m^2)
- High percentage only for high ***κ*** and ***q***, with about 30% in the worst case scenarios
- Fault permeability changes 1-2 orders magnitude

FAULT REACTIVATION:

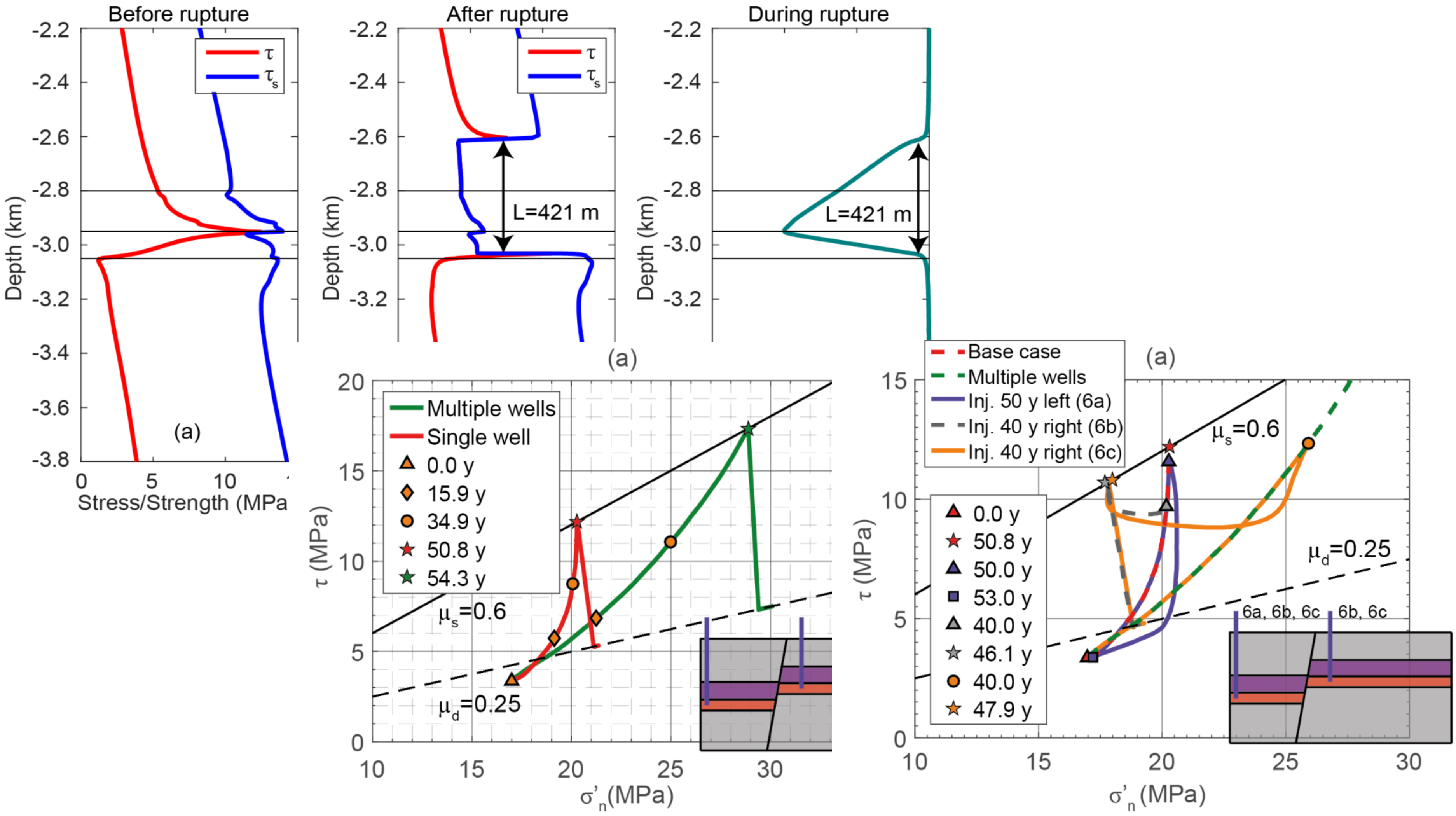
- Events only for ***q*** > 30 kg/s (M~2-3.5)
- High ***q*** requires less time for reactivation, but triggers smaller event
- High ***κ***, requires more time for reactivation, but trigger bigger events (pressure distribute more along fault)

Injection vs production



Candela et al., 2018

Fluid production: same physics, different timing



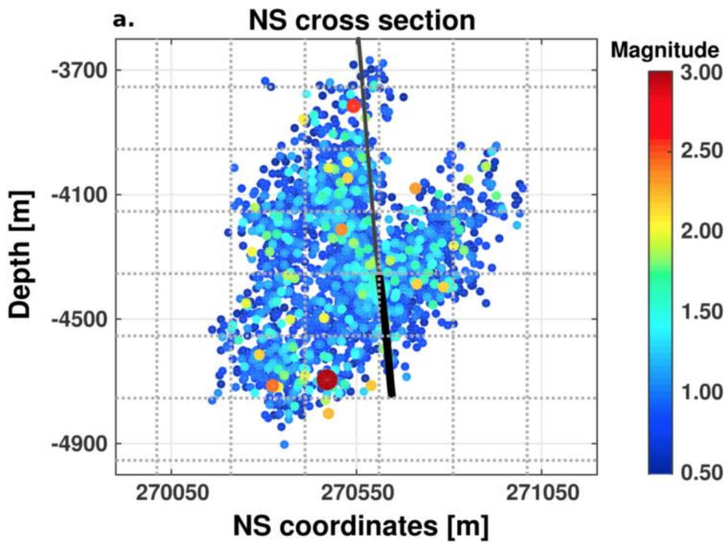
Zbinden et al., 2017

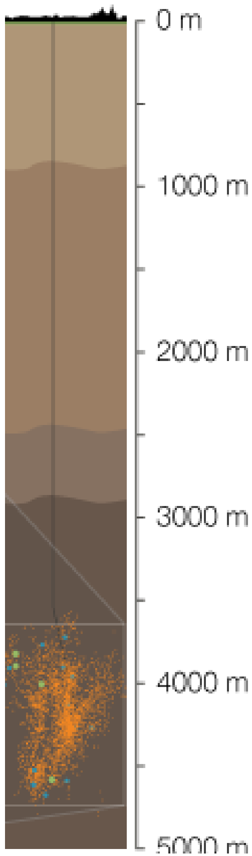
And we can learn much more…

- Effect of fault heterogeneities and/or size of caprock/aquifer
- Dynamic earthquake simulations
- Frictional laws
- Hydrofracturing/hydroshearing (with proper approximation)
- …of course can be extended to 3D

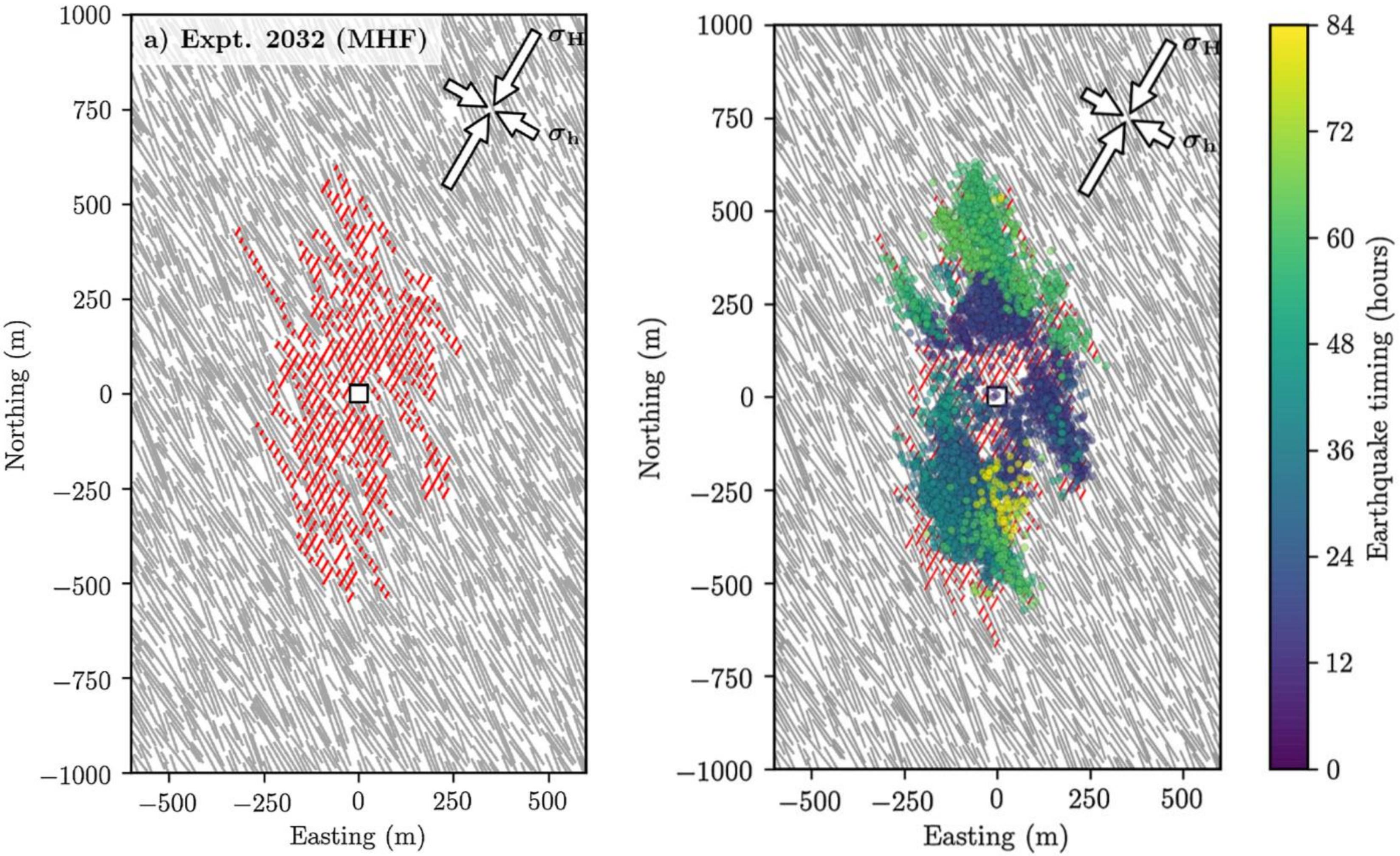
Modeling induced seismicity with fully coupled simulator

- Very complex to simulate multiple faults
- Porous medium approximation does not always hold (e.g. EGS in fractured reservoirs)





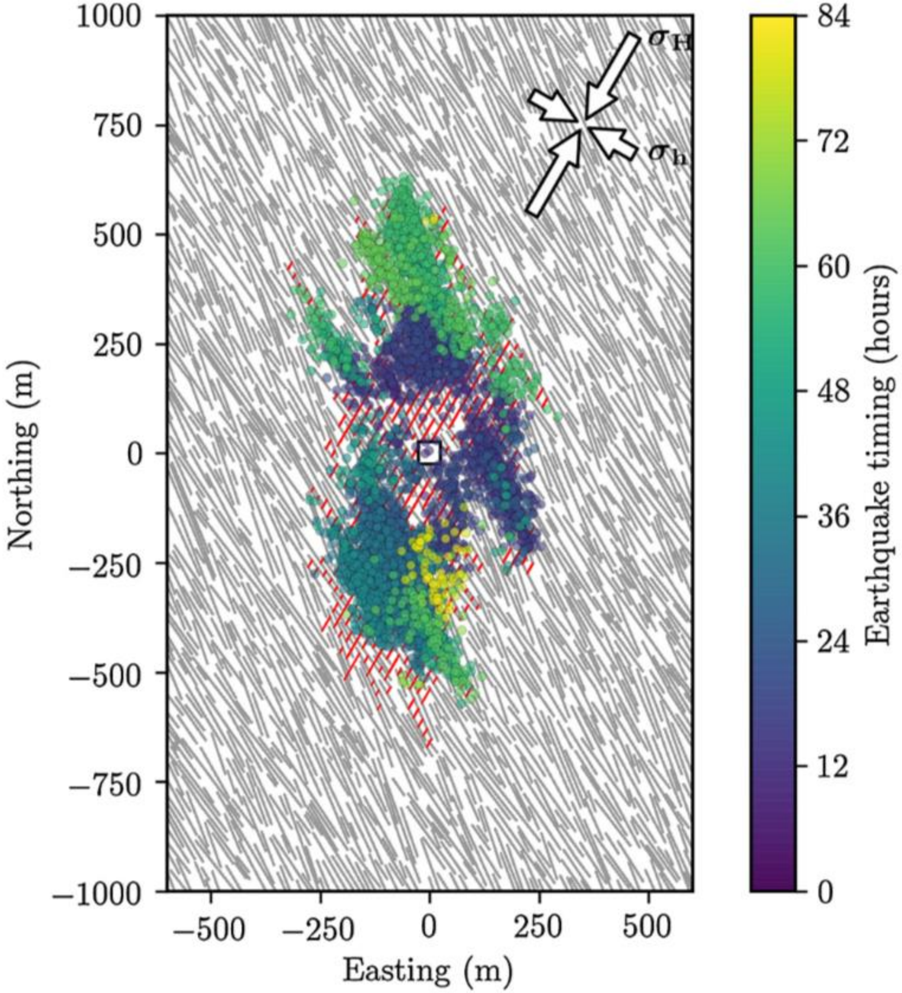
Modeling induced seismicity in fractured reservoir



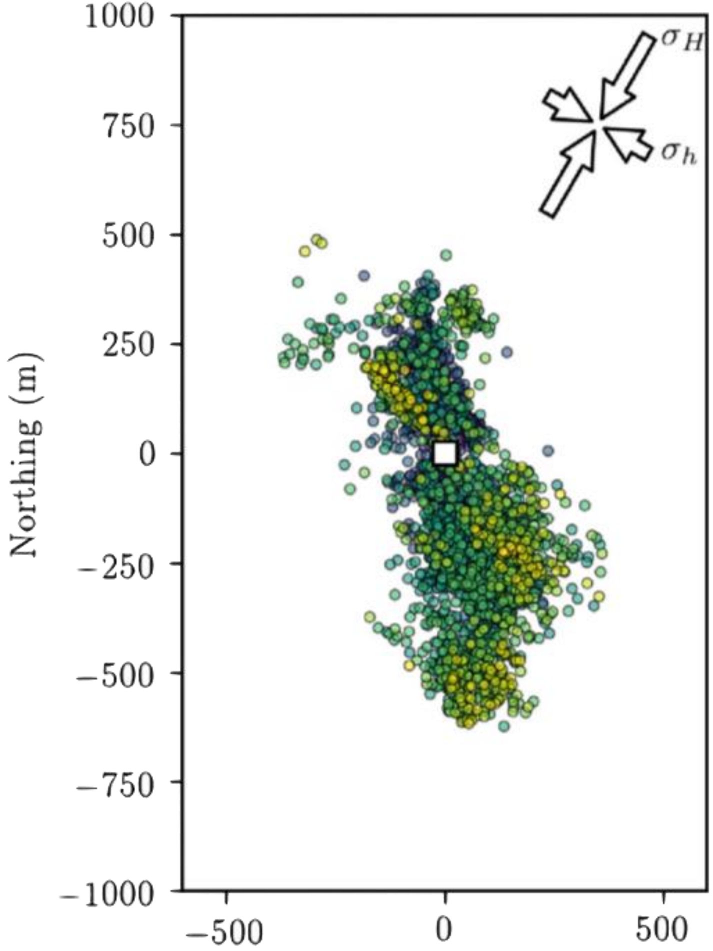
Norbeck et al., 2018

Modeling induced seismicity in fractured reservoir

Model



Observed seismicity



Norbeck et al., 2018

Modeling induced seismicity in fractured reservoir

- Quite hard to discriminate which process is more relevant.
- We don't really know the position of all the fractures (maybe the larger ones, and only if they cross the well)
- Quite computationally expensive. How can we use this in real-time for an adaptive traffic light system?

Modeling induced seismicity in fractured reservoir

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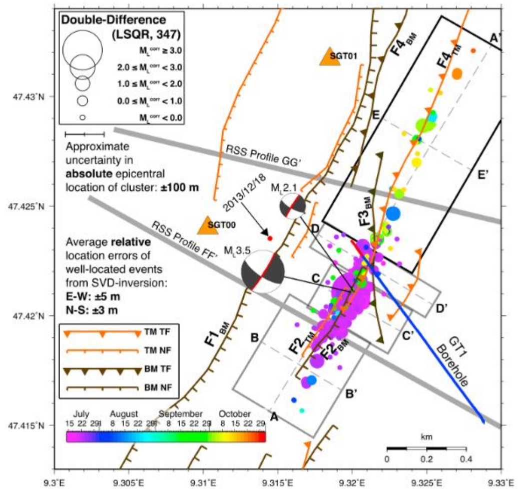
- We don't really know the position of all the fractures (maybe the larger ones, and only if they cross the well)
- Quite computationally expensive. How can we use this in real-time for an adaptive traffic light system?
- What if we have gas phase? Even more computationally expensive…



2013, Stadt St.Gallen / St.Galler Stadtwerke

Understand relevant processes and model them in a “smarter” (simpler) way

Fully coupled models
Reliable in terms of physics, but computationally expensive

Stastical models
Ideal for real-time applications, but not complete description of processes

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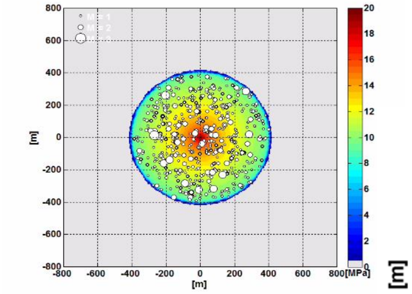
Hybrid models

Mixing some statistical approach with physics-model, not fully developed

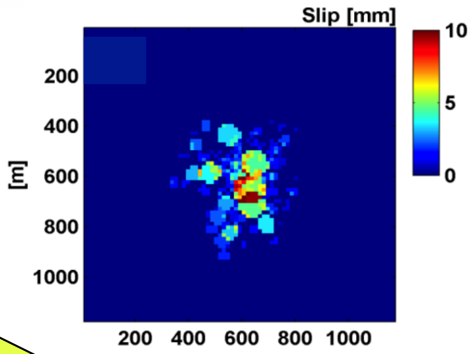
Hybrid models @ SED

- Seeds=potential earthquakes reactivating for critical pressure (Mohr-Coulomb)
- Each seed with given stress state, and local b-value from differential stress.
- At each failure a stress drop and a new stress state associated (also with CFS) and possible retriggering

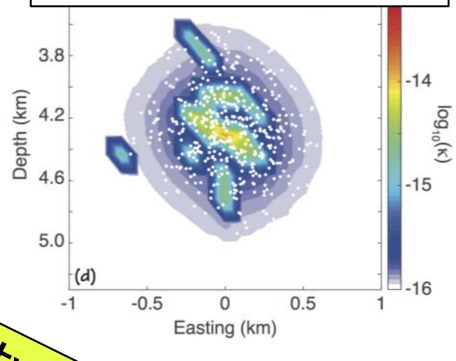
Gishig & Wiemer, 2013
Goertz-Allman & Wiemer, 2013



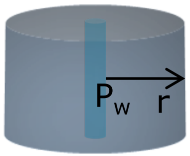
Gishig et al., 2014



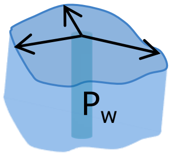
Rinaldi & Nespoli, 2017



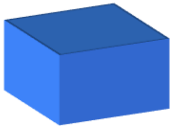
Model Complexity



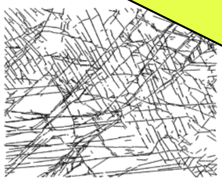
1D with COMSOL & Seed model



2D with SUTRA & Seed model

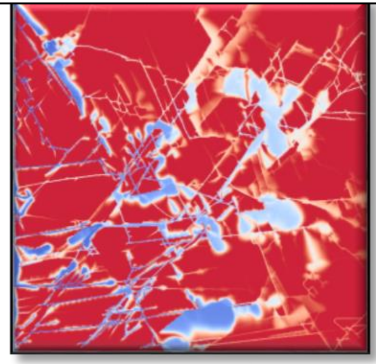


TOUGH2-Seed Full 3D model With k change



HFR-Sim: 3D Discrete Fracture Modeling & Seed model

Karvounis & Wiemer, 2018



TOUGH2-seed: permeability changes

Reversible Pressure dependent permeability

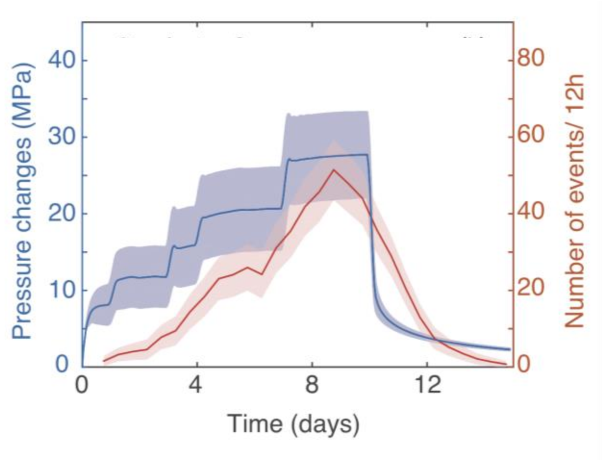
$$\phi_{hm}=(\phi_0-\phi_r)e^{\alpha\Delta P}+\phi_r$$

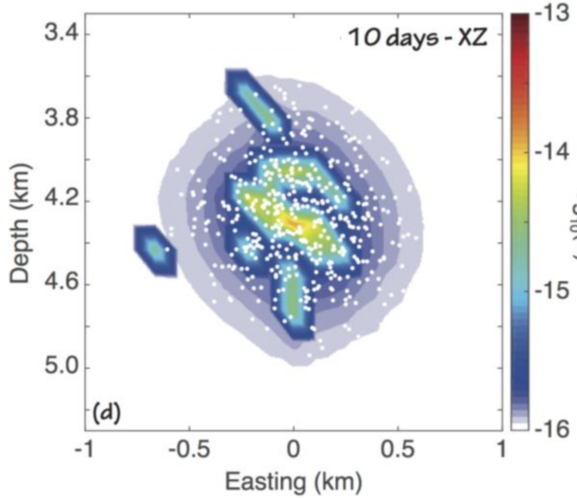
$$\kappa_{hm} = \kappa e^{C_1\left(\frac{\phi_{hm}}{\phi_0}-1\right)},$$

Irreversible slip-dependent permeability (assigned to grid block where seed is reactivating)

$$\Delta d = \frac{M_0}{G\pi}\left(\frac{16\Delta\tau}{7M_0}\right)^3,$$

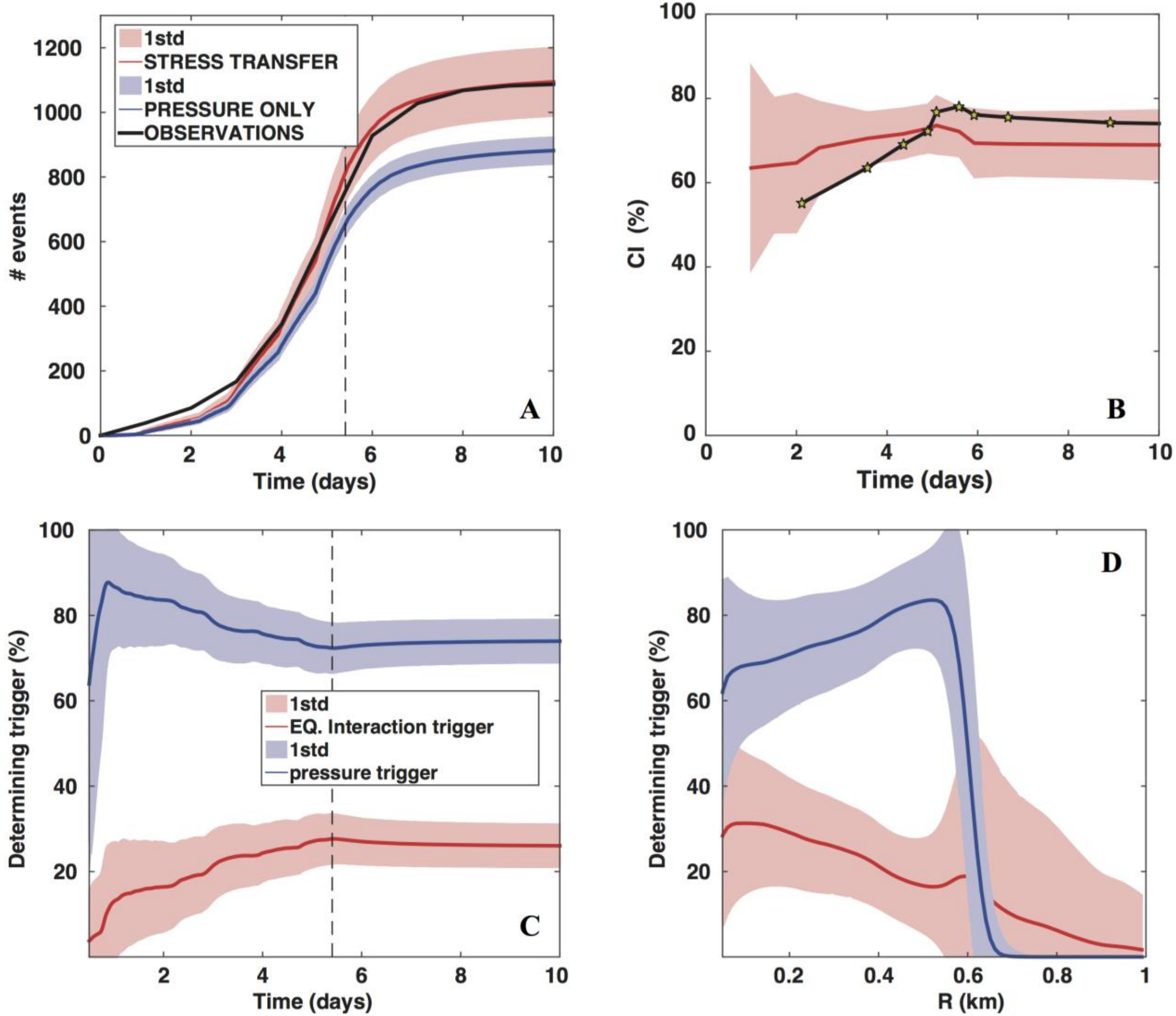
$$\kappa_{hm} = \kappa_0\left[1 + C_2\left(1 - \frac{e^{-\Delta d}}{d^*}\right)\right]^n$$





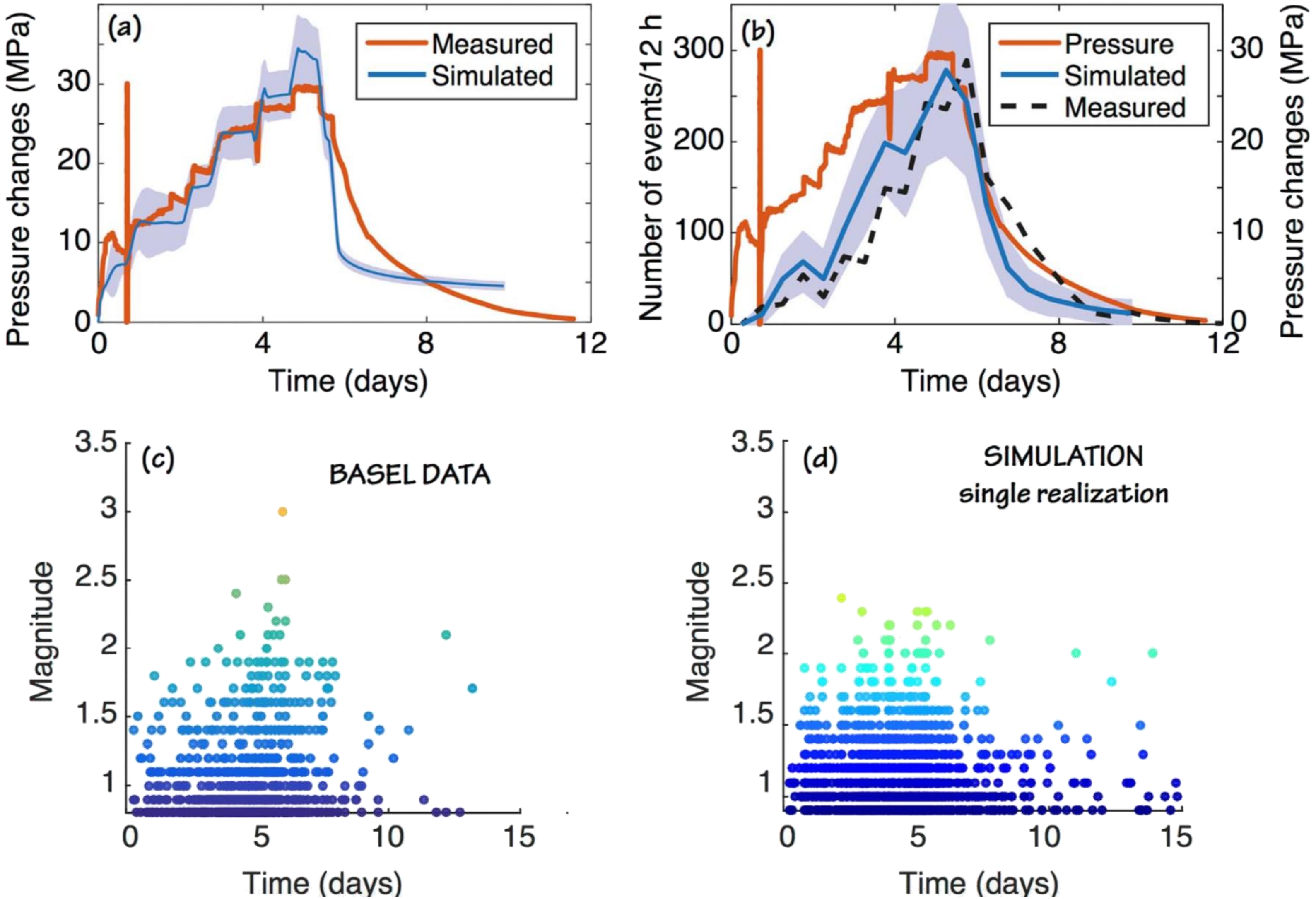
Rinaldi & Nespoli, 2017

TOUGH2-seed: Earthquakes interaction



Catalli et al., 2016

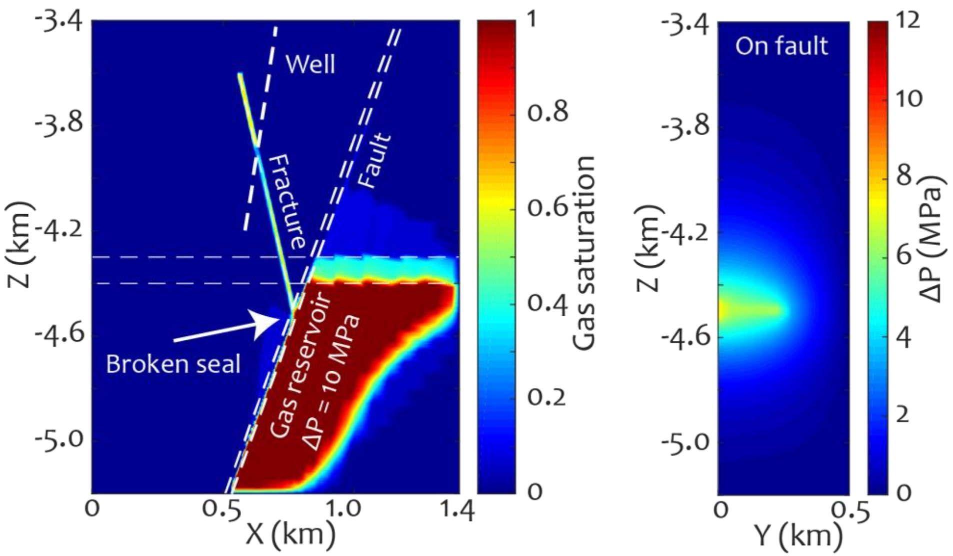
Application to Basel EGS

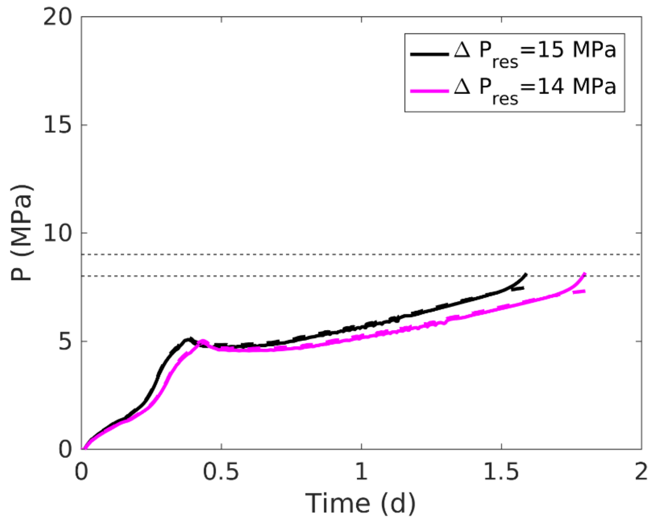


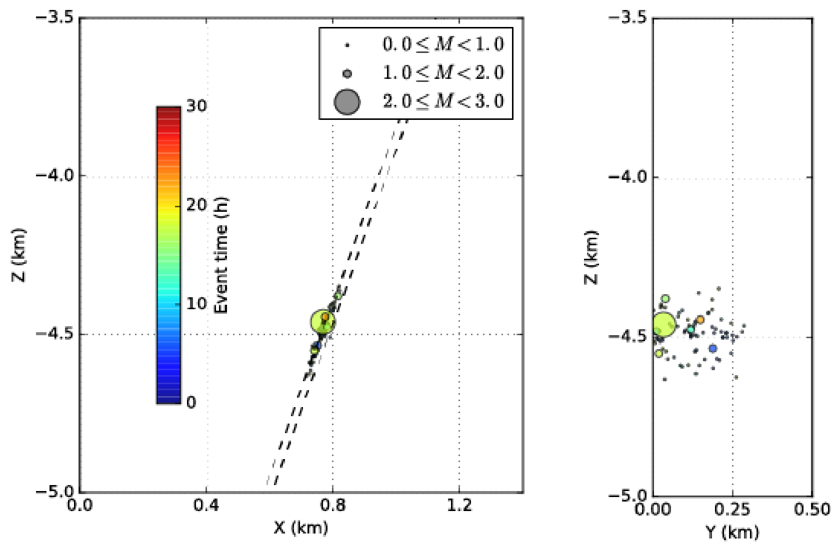
Rinaldi & Nespoli, 2017

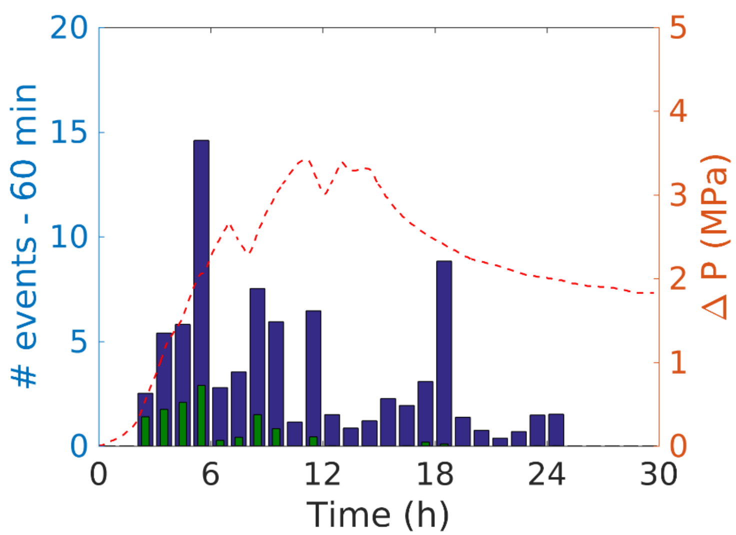
Modeling two-phase fluid flow: the case of St. Gallen

Zbinden et al., in prep

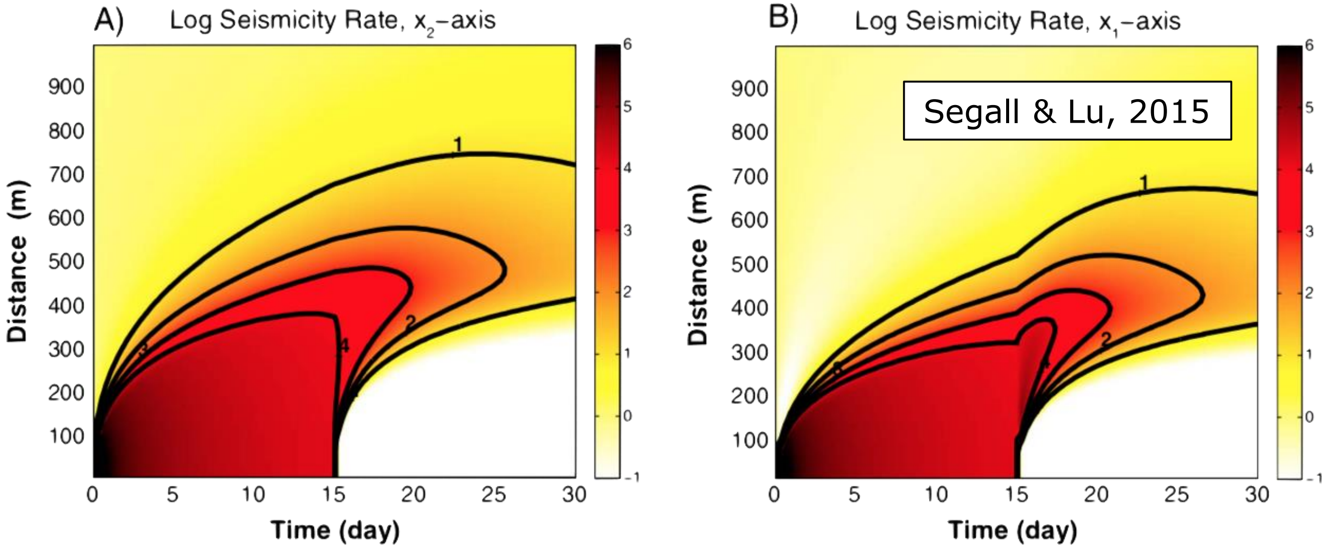


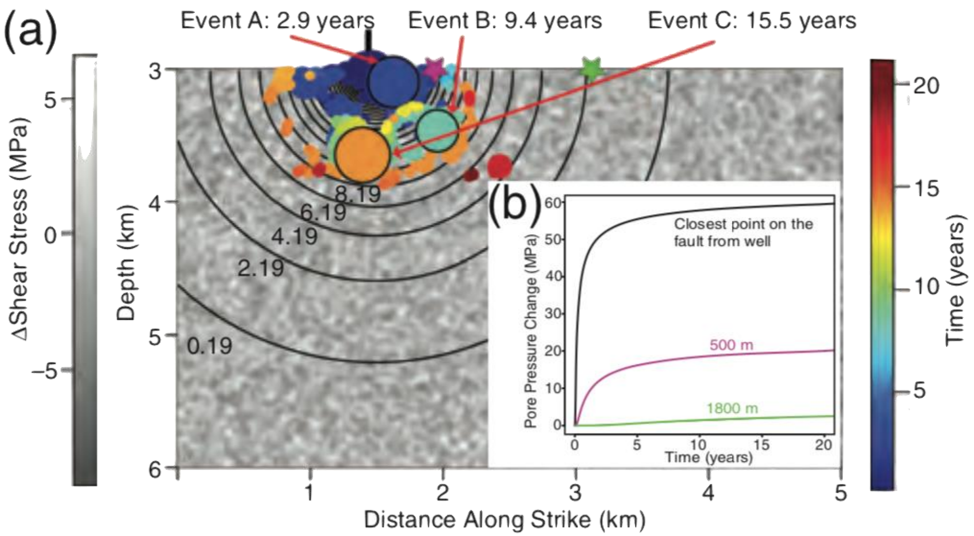


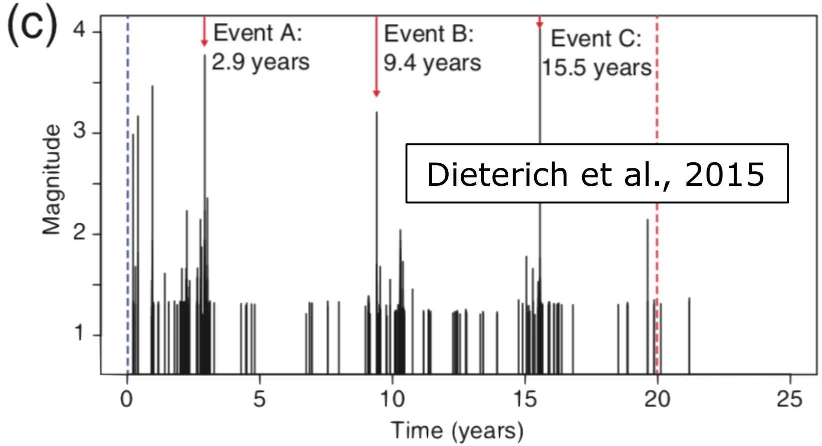




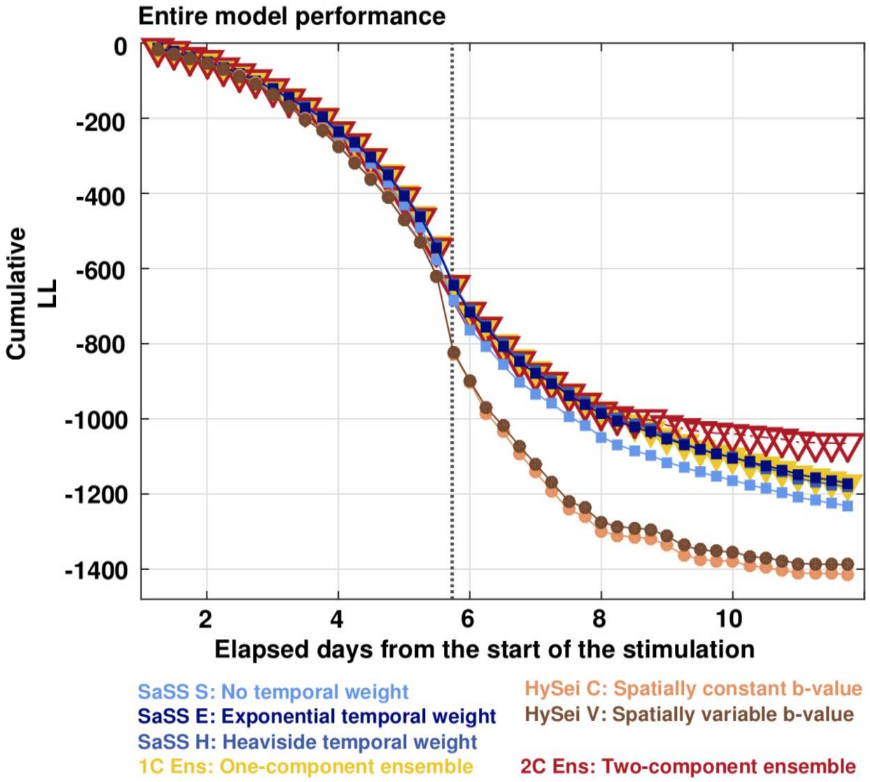
Other “hybrid” models

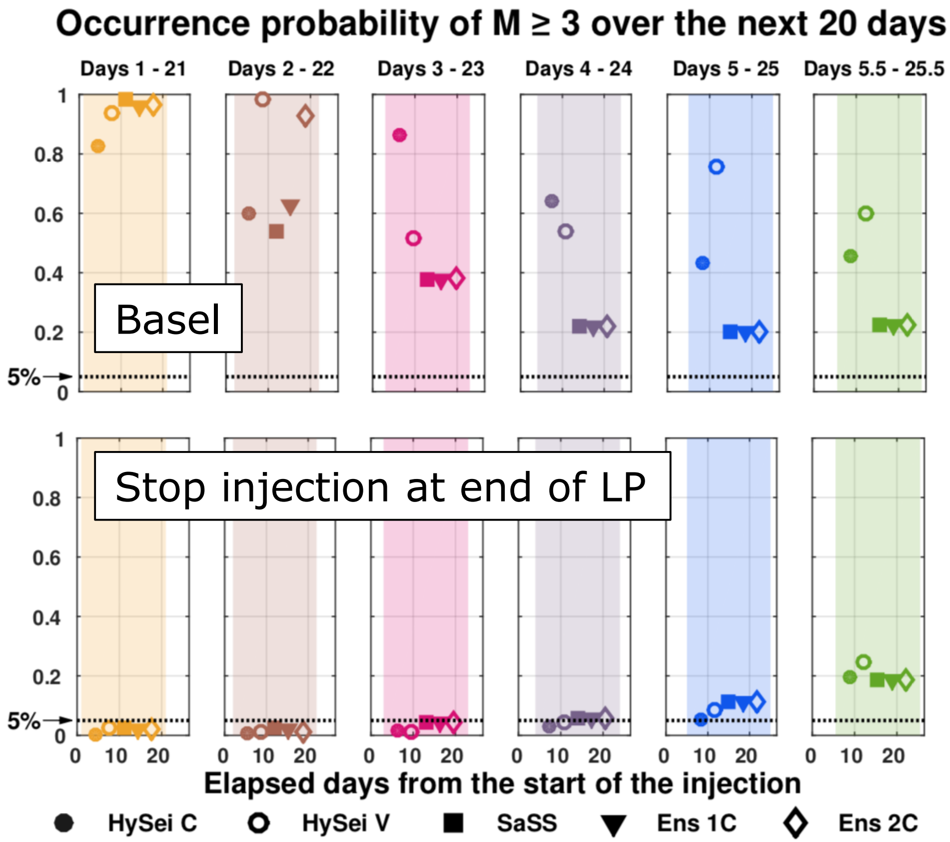






Prototype ATLS based on models





Kiraly-Proag et al., 2018

What do we need for a full development of ATLS?

- ✓ A multidisciplinary approach is essential: we still lack a complete physical understanding of the induced seismicity (from hydrogeology to seismic waves!)
- ✓ We do need a combination of probabilistic and deterministic modeling (e.g. more sophisticated hybrid models) and we do need to compare several models.
- ✓ Model learning from data:
  - ➢ Data stream and analysis in real-time is essential for building up reliable and adaptive models, based on physical processes
  - ➢ For testing and evaluating future performances
- ✓ Current models applied to past datasets are solid, but we miss applications in real time:
  - ➢ Underground labs
  - ➢ Pilot/test projects