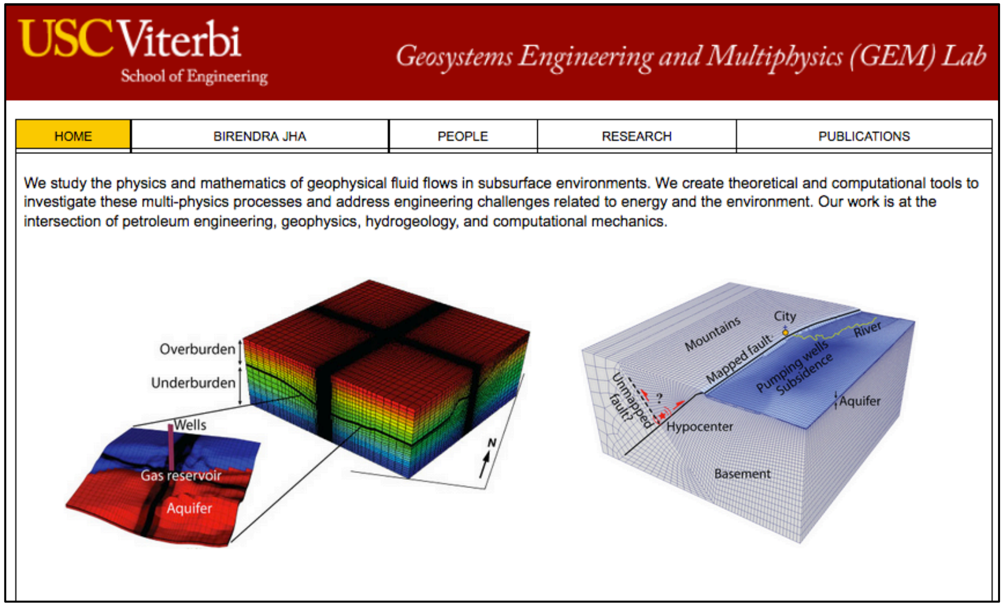
Coupled flow and geomechanics of petroleum reservoirs, aquifers and faults

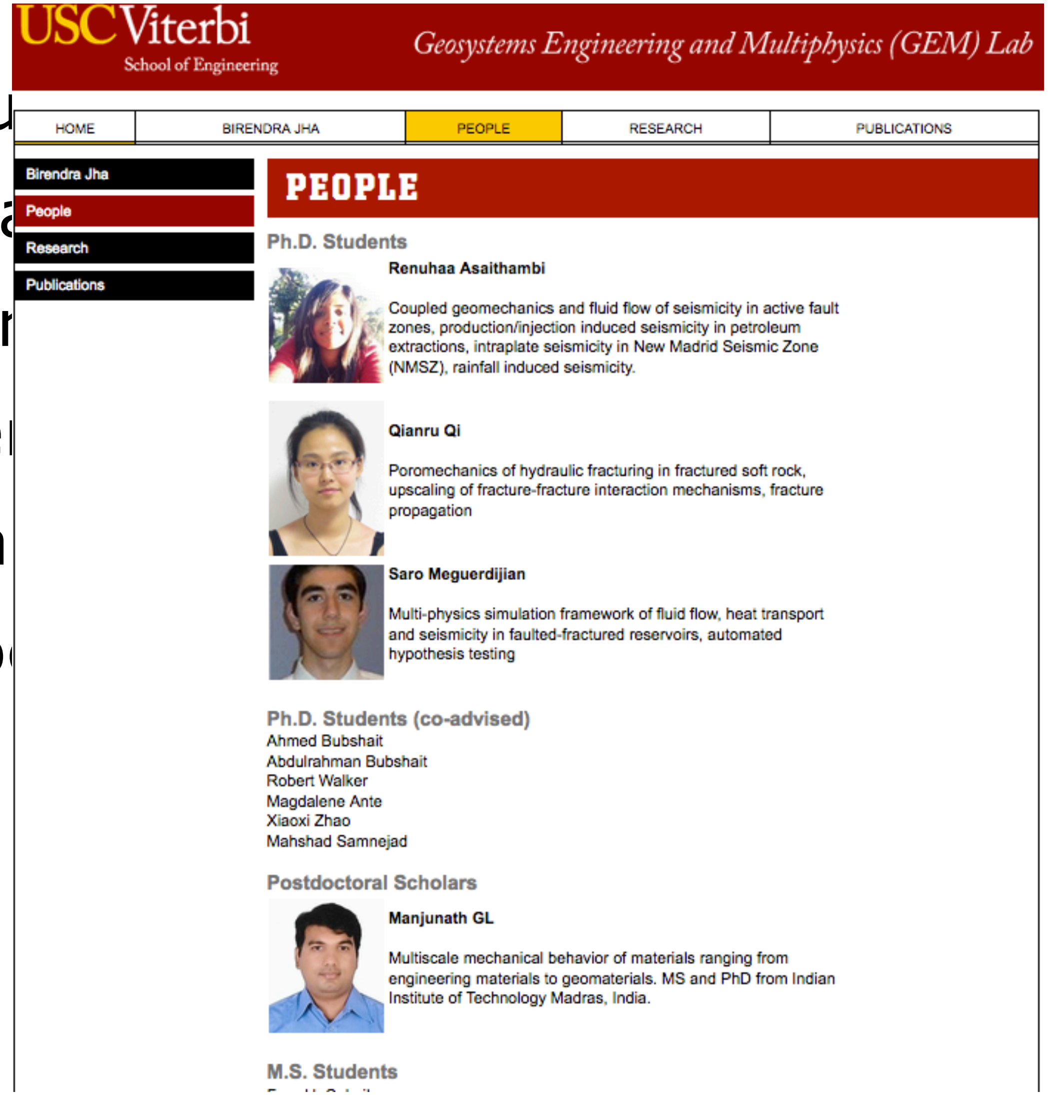
gemlab.usc.edu



Birendra Jha
Assistant Professor, Petroleum Engineering
MFD Chemical Engineering and Materials Science
University of Southern California

Computational modeling of flow, transport and deformation

- Induced earthqu
- Leakage along fa
- Hydraulic fractur
- Geothermal ener
- Underground ga
- Enhanced hydro
injection
- …



Injection-Induced Earthquakes

William L. Ellsworth

Science JULY 2013

Human Activity May Have Triggered Fatal Italian Earthquake

Science APRIL 20

ROME—A pair of d... struck the north of Italy in 2012 could have been triggered by the extraction of petroleum ... in the Un... Terlizzes...

INDUCED EARTHQUAKES Science July 3, 2014

Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection

K. M. Keranen,[1*] M. Weingarten,[2] G. A. Abers,[3†] B. A. Bekins,[4] S. Ge[2]

PNAS

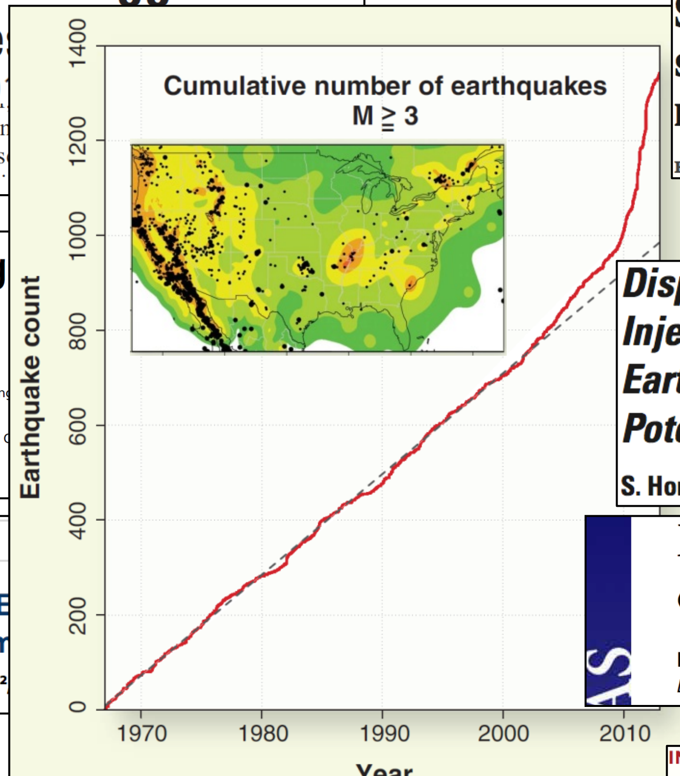
Gas injection may have trig... Cogdell oil field, Texas

Wei Gan[a,b] and Cliff Frohlich[b,1]

[a]School of Earth Sciences and Resources, China University of Geosciences, Beijing ... University of Texas at Austin, Austin, TX 78758-4445

Edited by Donald W. Forsyth, Brown University, Providence, RI, and approved ...

Between 1957 and 1982, water flooding was conducted to improve petroleum production in the Cogdell oil field north of ...



Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake

S. Horton[1] Seismological Research Letter March/April 2012

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL069284

Key Points:

- Coupled flow-geomechanics

Were the May 2012 E... A coupled flow-geom...

R. Juanes[1,2], B. Jha[1,3], B. H. Hager[2]...

PNAS

Earthquake triggering and large-... carbon dioxide

Mark D. Zoback[a,1] and Steven M. Gorelick[b]

Departments of [a]Geophysics and [b]Environmental Earth System Science, Stan...

The Dallas–Fort Worth Earthquake Sequence: October 2008 through May 2009

February 2011

by Cliff Frohlich, Chris Hayward, Brian Stump, and Eric Potter

INDUCED SEISMICITY Science JUNE 2015

High-rate injection is associated with the increase in U.S. mid-continent seismicity

M. Weingarten,[1*] S. Ge,[1] J. W. Godt,[2] B. A. Bekins,[3] J. L. Rubinstein[3]

Geomechanical Analysis to Evaluate Production-Induced Fault Reactivation at Groningen Gas Field

Society of Petroleum Engineers

Pablo F. Sanz, ExxonMobil Upstream Research Co. (EMUF... EMURC, Sheng-Yuan Hsu, EMURC, Jorge L. Garzon, EMU... Co., William E. Kline, EMURC, Bruce A. Dale, ExxonMobil ...

Causal factors for seismicity near Azle, Texas

nature Apr 2015

Matthew J. Hornbach[1], Heather R. DeShon[1], William L. Ellsworth[2], Brian W. Stump[1], Chris Hayward[1], Cliff Frohlich[3], Harrison R. Oldham[1], Jon E. Olson[4], M. Beatrice Magnani[1], Casey Brokaw[1] & James H. Luetg...

Natural or induced?

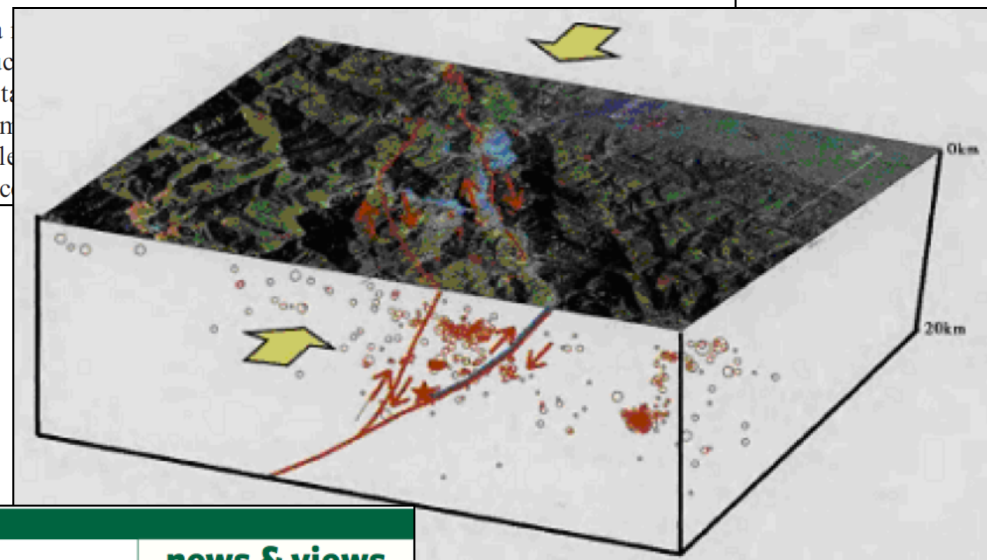
NEWS OF THE WEEK

16 JANUARY 2009 VOL 323 **SCIENCE** www.sciencemag.org

SEISMOLOGY

A Human Trigger for the Great Quake of Sichuan?

Natural disasters are often described as "acts of God," but within days of last May's devastating earthquake in China's Sichuan Province, seismologists in and out of China were quietly wondering whether humans might have had a hand in it. Now, the first researchers have gone



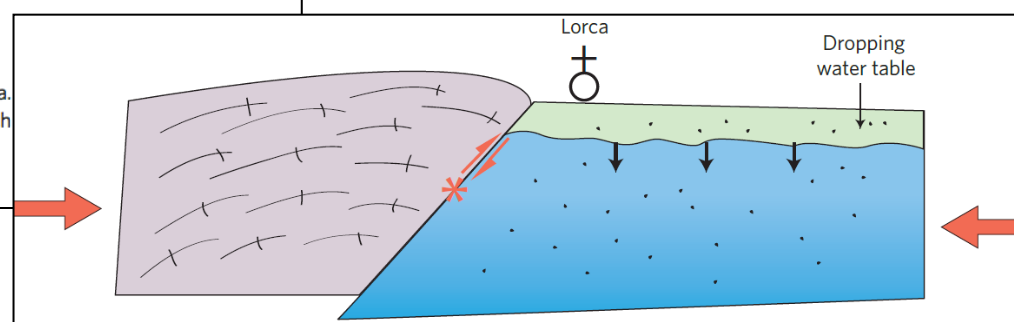
news & views

EARTHQUAKES

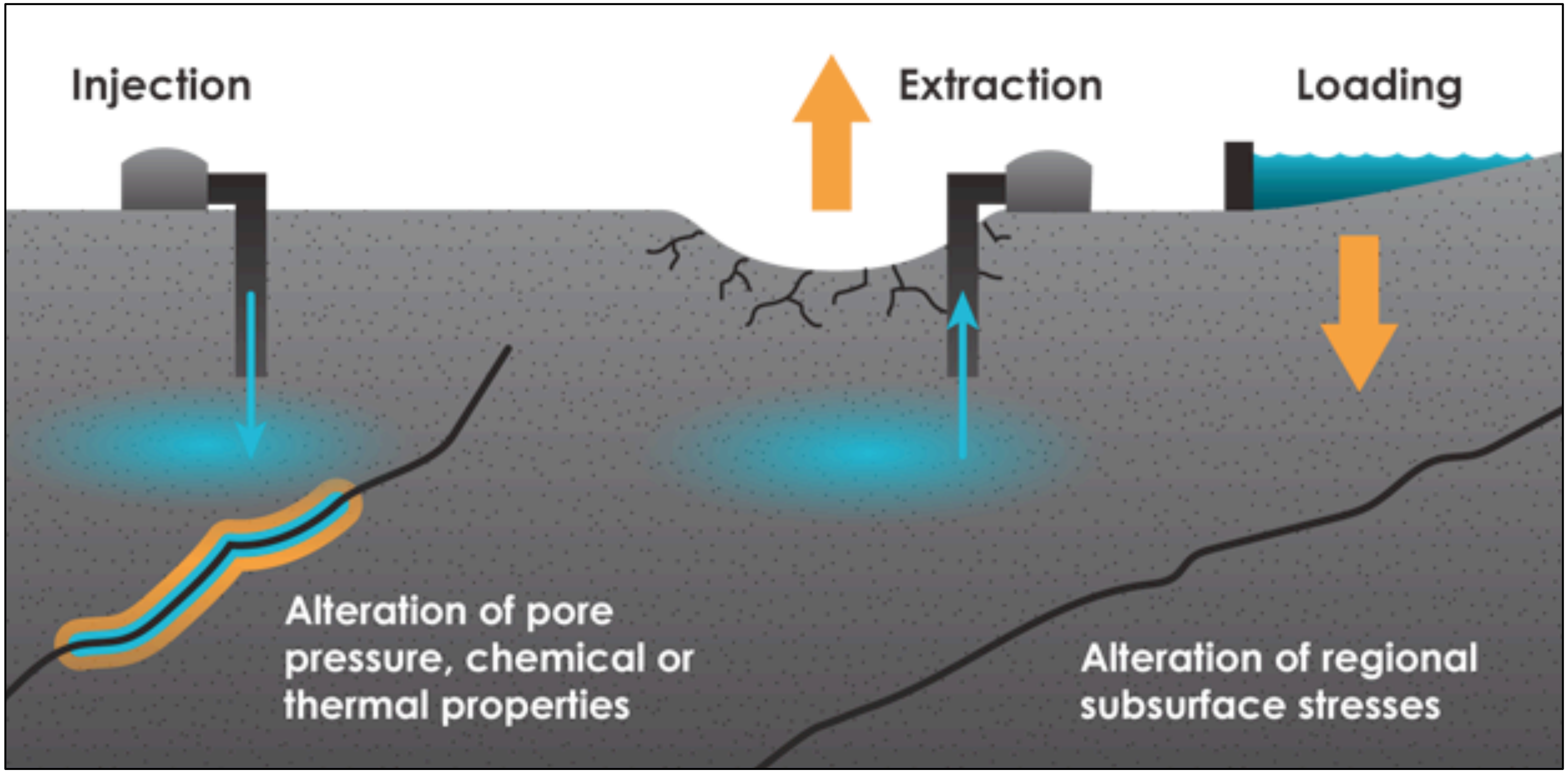
Human-induced shaking

In 2011, a modest earthquake in southern Spain seriously damaged the city of Lorca. deformation suggests that the quake was caused by rupture of a shallow fault patch pumping of water from a nearby aquifer.

Jean-Philippe Avouac



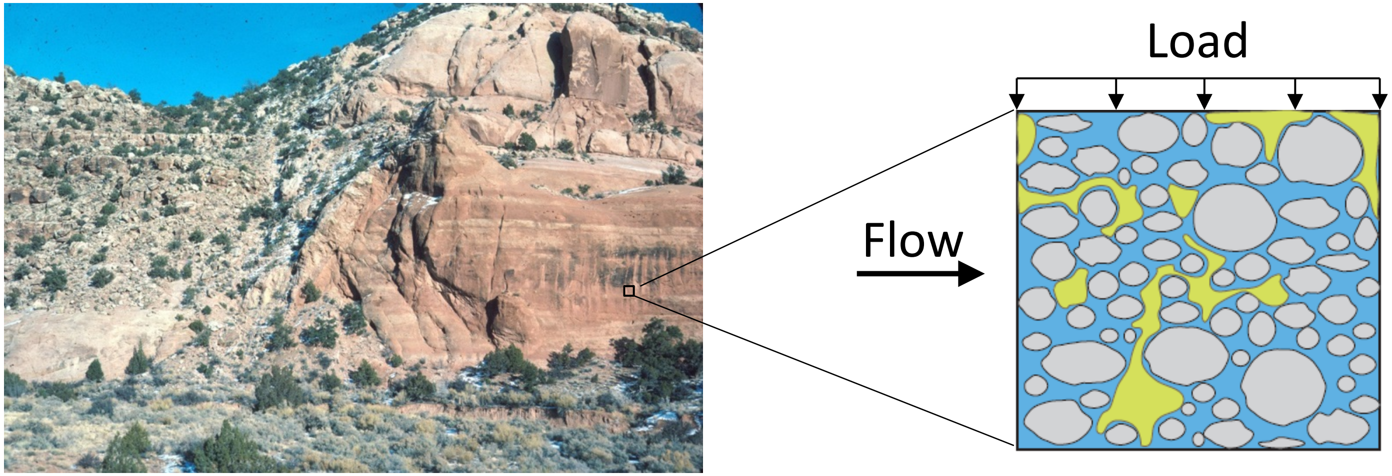
Induced earthquakes mechanisms



Healy et al., *Science* 1968
Segall, *JGR* 1985
Chander and Kalpana, *EG* 1997

Multiphase fluid flow and geomechanics

Biot, *JAP* 1941
Rice et al, *RGSP* 1976
Coussy, 1995



Oil, water, gas have different pressures and densities.

Governing equations

Force balance (quasi-static):

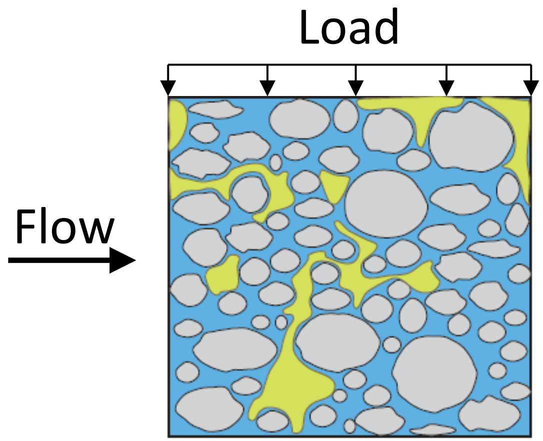
$$\nabla \cdot \boldsymbol{\sigma} + \rho_b \boldsymbol{g} = 0 \qquad \rho_b = (1-\phi)\rho_s + \phi \sum_\alpha \rho_\alpha$$

Fluid mass balance:

$$\frac{\partial}{\partial t}\left(\rho_\alpha \sum_\beta \left(N_{\alpha\beta} + \frac{b_\alpha b_\beta}{K_{dr}}\right) p_\beta\right) + \frac{1}{K_{dr}}\frac{\partial}{\partial t}\left(\rho_\alpha b_\alpha \sigma_v\right) + \nabla \cdot \boldsymbol{w}_\alpha = \rho_\alpha f_\alpha$$

α, β = Oil, water, gas

Multiphase fluid flow and geomechanics



$$N_{gg} = -\phi \frac{\partial S_w}{\partial P_{wg}} + \phi S_g c_g + S_g^2 N,$$

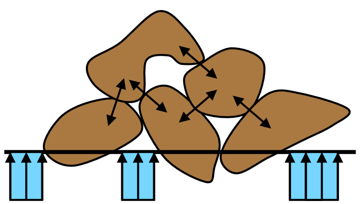
$$N_{gw} = N_{wg} = \phi \frac{\partial S_w}{\partial P_{wg}} + S_g S_w N,$$

$$N_{ww} = -\phi \frac{\partial S_w}{\partial P_{wg}} + \phi S_w c_w + S_w^2 N,$$

Constitutive equations

Poroelasticity: $$\left(\frac{dm}{\rho}\right)_\alpha = b_\alpha d\varepsilon_v + \sum_\beta N_{\alpha\beta} dp_\beta$$

Effective stress:



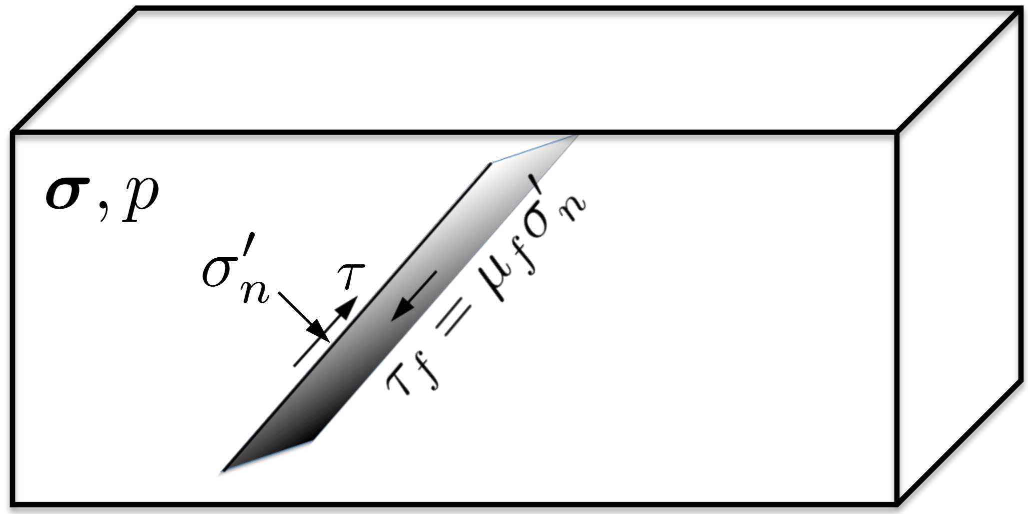
$$\delta\boldsymbol{\sigma} = \delta\boldsymbol{\sigma}' - b\delta p_E \mathbf{1}$$

$$\delta\boldsymbol{\sigma}' = \boldsymbol{C}_{dr} : \boldsymbol{\varepsilon}$$

Darcy flux: $$\boldsymbol{w}_\alpha = -\frac{\boldsymbol{k} k_\alpha^r \rho_\alpha}{\mu_\alpha}(\nabla p_\alpha - \rho_\alpha \boldsymbol{g})$$

Coupling between flow and deformation through parameters (poroelastic properties) and processes (PDE terms)

Geomechanics of a fault



Effective normal stress: $\sigma'_n = \sigma_n - bp$

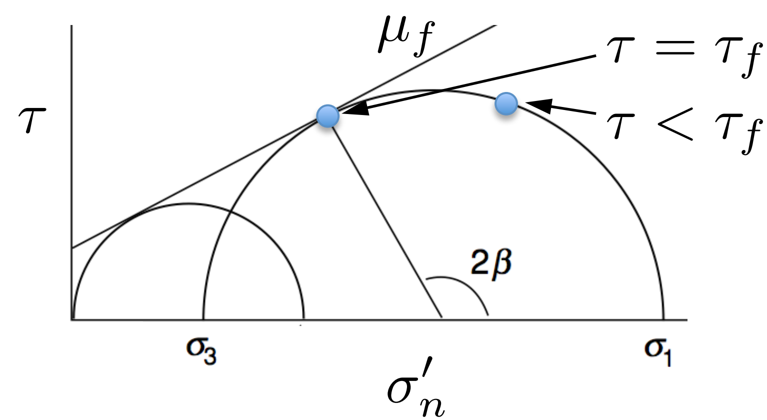
Friction stress: $\tau_f = \mu_f \sigma'_n$

Shear failure criterion: $\tau \geq \tau_f$

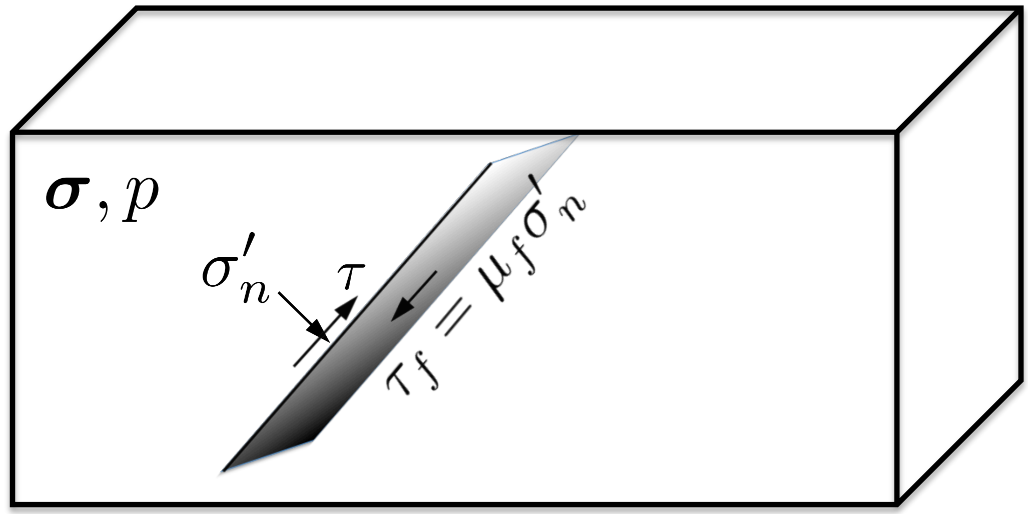
Coulomb Failure Function:

$$\mathrm{CFF} = \tau - \mu_f \sigma'_n$$

Mohr-Coulomb theory



Induced seismicity mechanisms

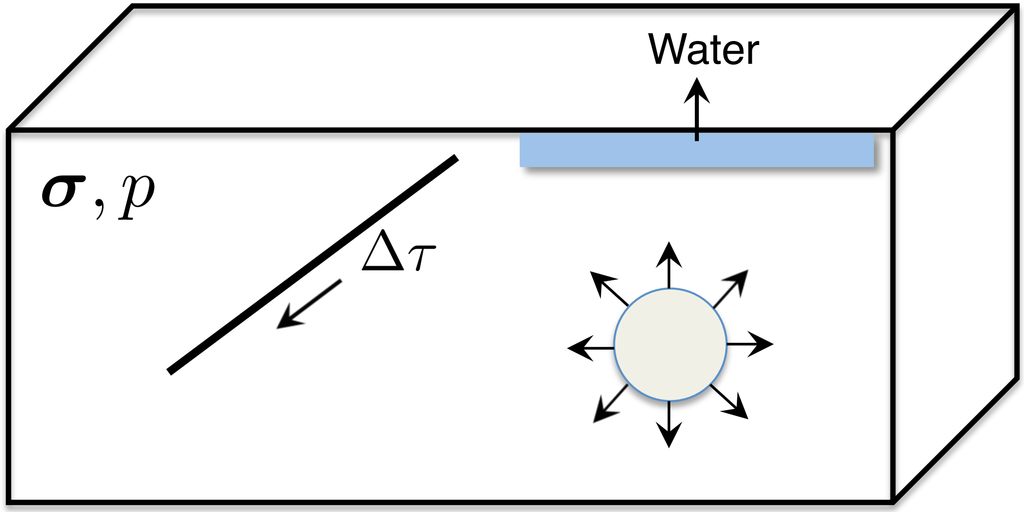


Tendency to slip if:

$$\Delta \mathrm{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right] > 0$$

$$\begin{array}{ll} \Delta\tau > 0 & \text{(poroelastic loading)} \\ \Delta\sigma_n < 0 & \text{(poroelastic unloading)} \\ \Delta p > 0 & \text{(fluid injection)} \\ \Delta\mu_f < 0 & \text{(fault weakening)} \end{array}$$

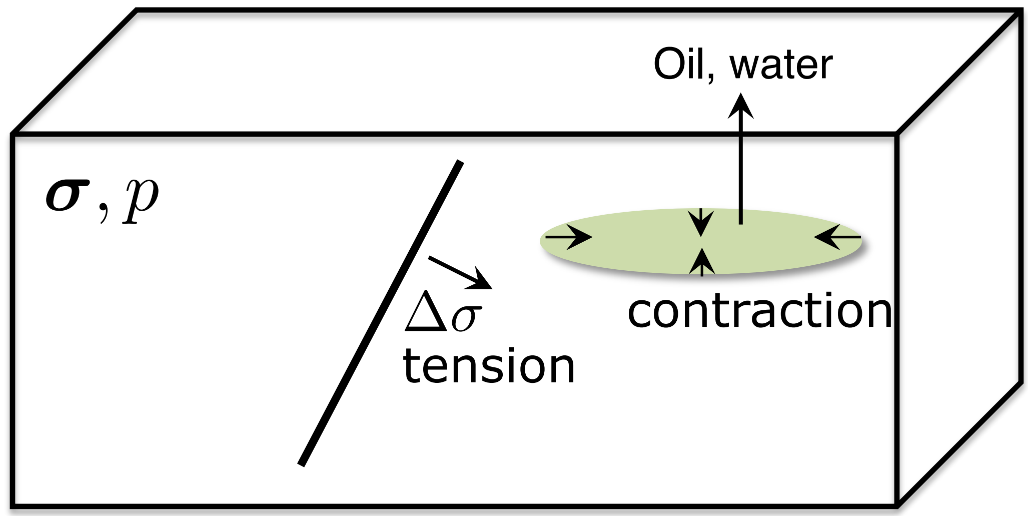
Water extraction from unconfined aquifer



$$\Delta \mathrm{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right] > 0$$

$\Delta\tau > 0$	(poroelastic loading)
$\Delta\sigma_n < 0$	(poroelastic unloading)
$\Delta p > 0$	(fluid injection)
$\Delta\mu_f < 0$	(fault weakening)

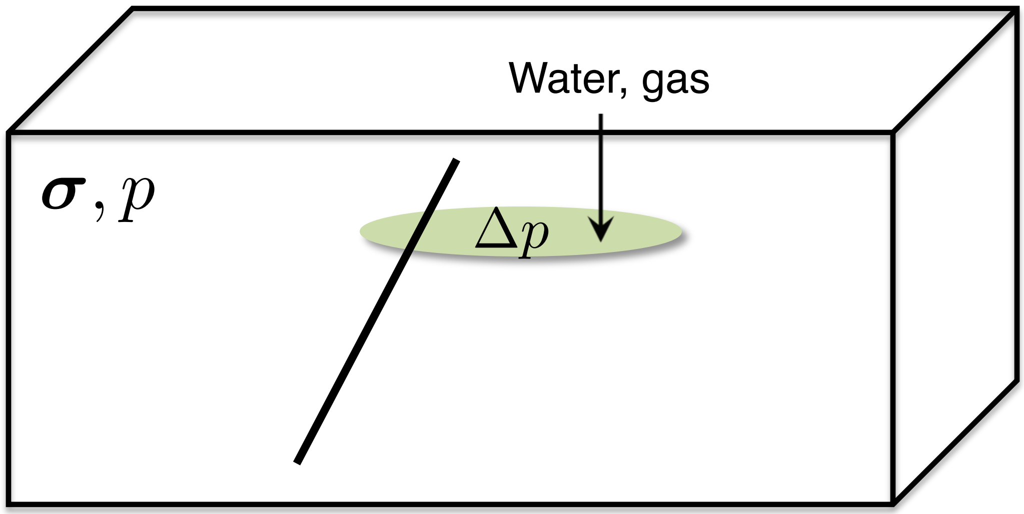
Hydrocarbon production from confined reservoir



$$\Delta \mathrm{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right] > 0$$

$\Delta\tau > 0$	(poroelastic loading)
$\Delta\sigma_n < 0$	(poroelastic unloading)
$\Delta p > 0$	(fluid injection)
$\Delta\mu_f < 0$	(fault weakening)

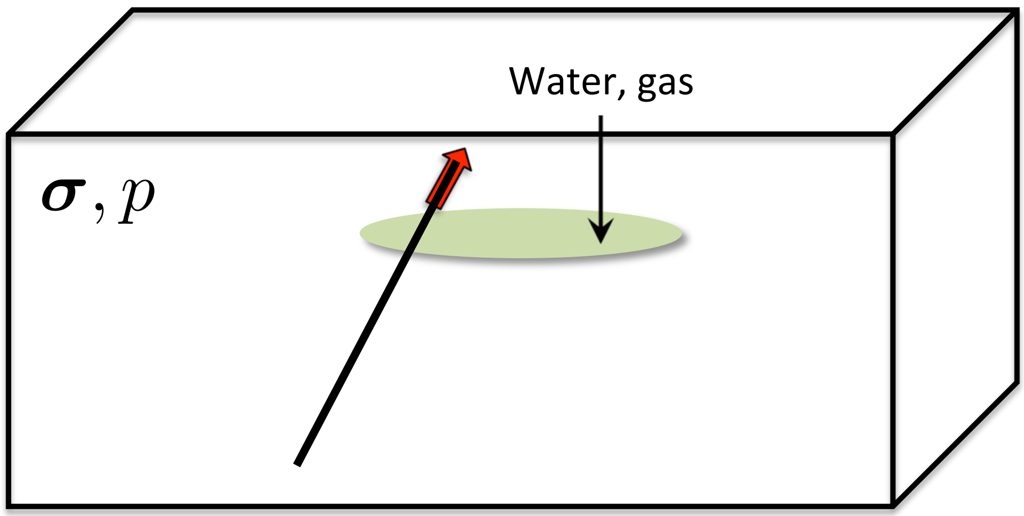
Fluid injection into a confined reservoir



$$\Delta \mathrm{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right] > 0$$

$$
\begin{array}{ll}
\Delta\tau > 0 & \text{(poroelastic loading)} \\
\Delta\sigma_n < 0 & \text{(poroelastic unloading)} \\
\Delta p > 0 & \text{(fluid injection)} \\
\Delta\mu_f < 0 & \text{(fault weakening)}
\end{array}
$$

Fault slip can lead to leakage



Fluid leakage if: $\Delta k_f > 0$

$\Delta k_f = f$ (fault slip, fault compression)

$\Delta \tau > 0$ (poroelastic loading)

$\Delta \sigma_n < 0$ (poroelastic unloading)

$\Delta p > 0$ (fluid injection)

$\Delta \mu_f < 0$ (fault weakening)

Key questions in subsurface energy production

- How much can be extracted/stored, and at what rate?
- What is the risk of induced seismicity? What is the risk of leakage?
- How do we mitigate the risk?

Geomechanical modeling of reservoirs with faults is essential.

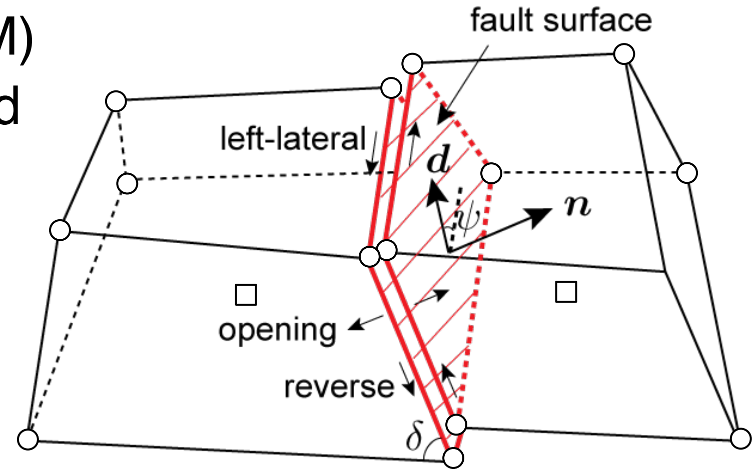
Settari and Mourits, *SPEJ* 1998; Bourne et al., *J Struct Geol* 2001
Birkholzer and Zhou, *IJGGC* 2009; Morris et al., *IJGGC* 2011;
Cappa and Rutqvist, *GRL* 2011; Jha and Juanes, *WRR* 2014

Computational model

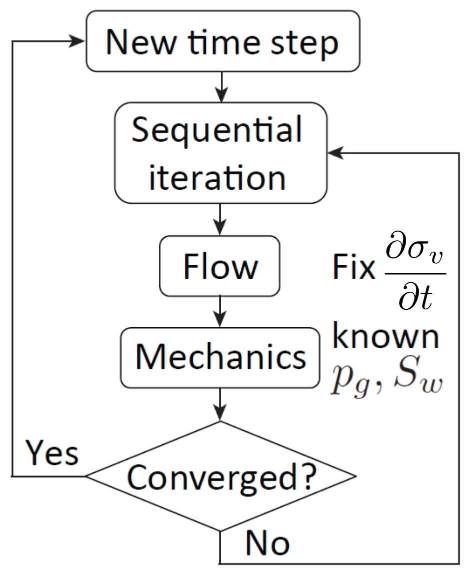
Jha and Juanes, *Acta Geotech.* 2007
Kim, Tchelepi and Juanes, *CMAME* 2011
Jha and Juanes, *WRR* 2014

- **Discretization**
  - Stable, convergent scheme (FEM-FVM)
  - Single, unstructured computational grid

□ Pressure node
○ Displacement node



- **Coupling strategies**
  - Efficient, unconditionally stable sequential solution scheme



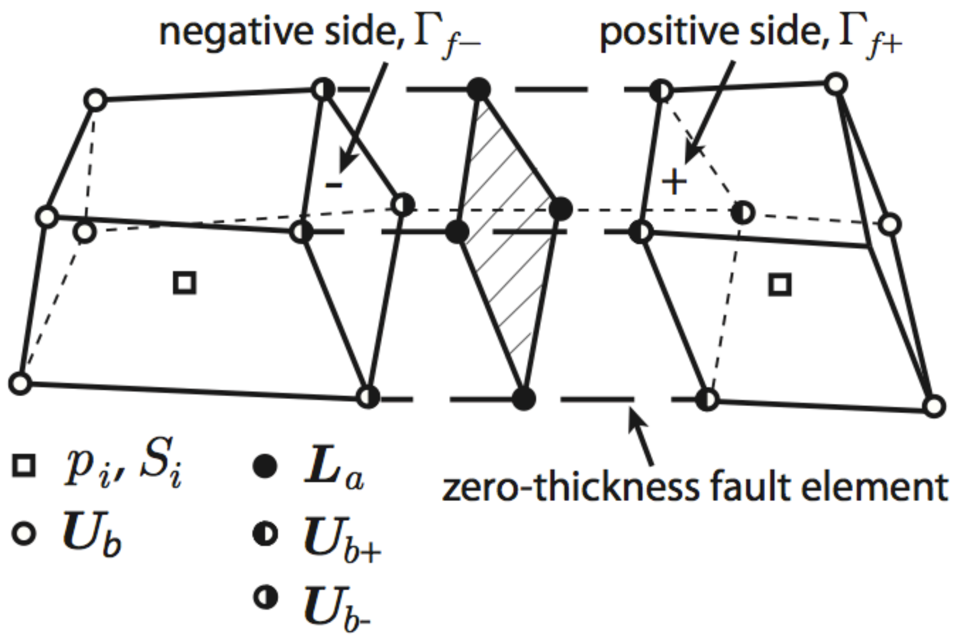
$$\left(\frac{b^2}{K_{dr}} + \frac{1}{M} \right) \frac{\partial p}{\partial t} + \frac{b}{K_{dr}} \frac{\partial \sigma_v}{\partial t} + \nabla \cdot \boldsymbol{v} = f$$

$$\nabla \cdot \boldsymbol{\sigma} + \rho_b \boldsymbol{g} = \mathbf{0}$$

Aagaard, Knepley and Williams, *JGR* 2013

Computational model

Fault is discretized with interface finite elements.



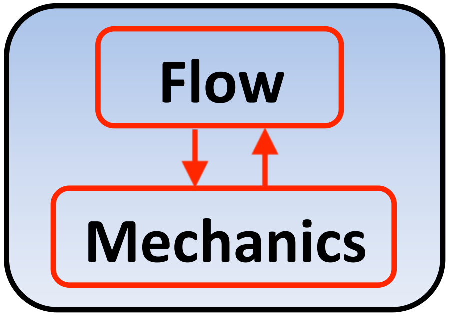
- Lagrange multiplier approach to solve the contact problem

$$\begin{bmatrix} \boldsymbol{K} & \boldsymbol{C}^T \\ \boldsymbol{C} & \boldsymbol{0} \end{bmatrix}^{(k)} \begin{bmatrix} \delta \boldsymbol{U} \\ \delta \boldsymbol{L} \end{bmatrix}^{(k)} = - \begin{bmatrix} \boldsymbol{R}_u \\ \boldsymbol{R}_l \end{bmatrix}^{(k)}$$

U is displacement.
L is Lagrange multiplier (fault traction)

Aagaard, Knepley and Williams, *JGR* 2013
Jha and Juanes, *WRR* 2014

Coupled multiphase flow and geomechanics simulator



- Computationally efficient sequential solution
- Sophisticated formulation for fault deformation and slip
- Flow along and across fault, fracture propagation
- Viscoelastic, elastoplastic, and viscoplastic rheology. Rate and State fault friction
- Field-scale (unstructured grid, complex production-injection scenarios, parallel computing)

Post mortem analysis of the 2011 Lorca earthquake


nature geoscience

LETTERS

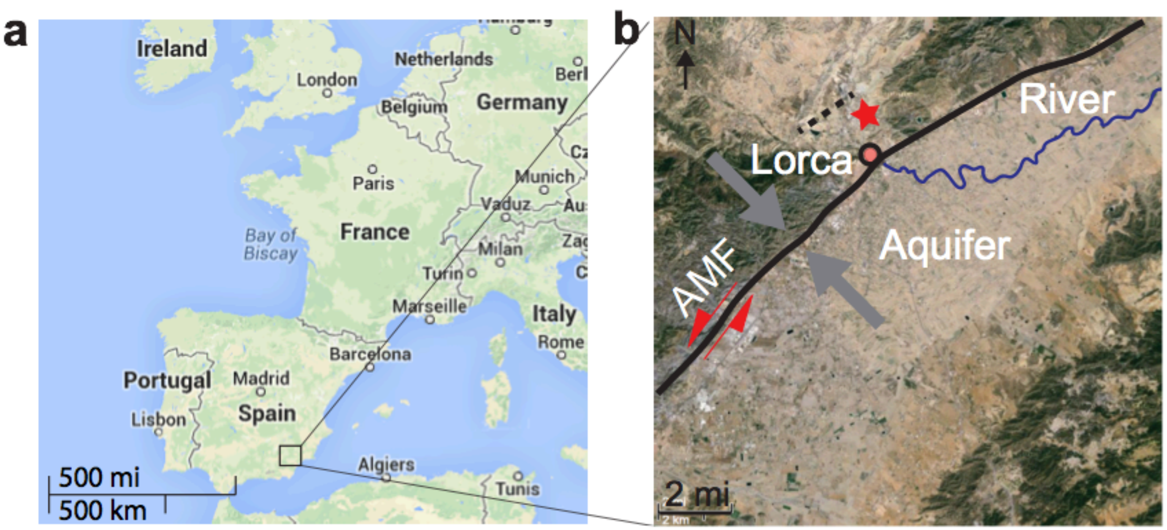
PUBLISHED ONLINE: 21 OCTOBER 2012 | DOI: 10.1038/NGEO1610

The 2011 Lorca earthquake slip distribution controlled by groundwater crustal unloading

Pablo J. González[1]*, Kristy F. Tiampo[1], Mimmo Palano[2], Flavio Cannavó[2] and José Fernández[3]

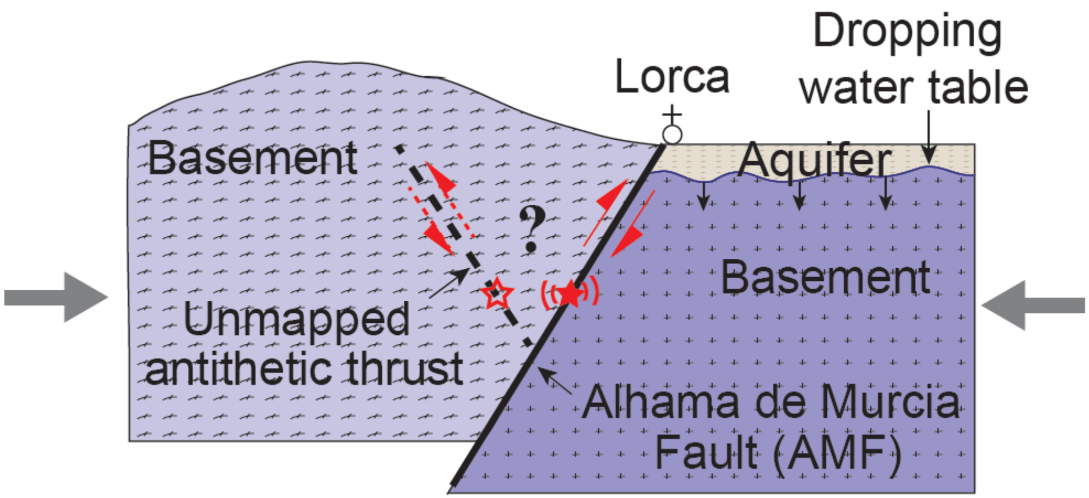
Earthquake initiation, propagation and arrest are influenced by fault frictional properties[1,2] and preseismic stress[3,4]. Studies of triggered and induced seismicity[5–7] can provide unique

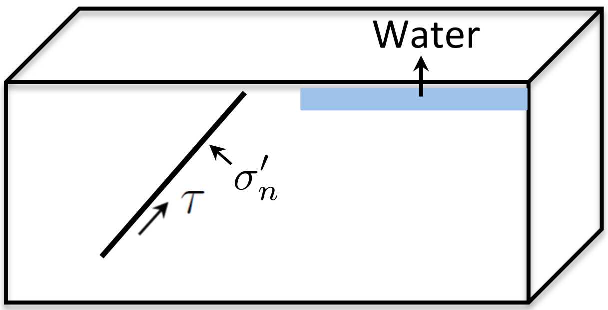
Methods). Two different ENVISAT descending satellite tracks (I2 and I6) imaged the area before and after the event, providing estimates of the displacement field from two different look angles



- 1960-2010 groundwater extraction
- Mw = 5.1 in May 2011

Effect of water withdrawal - Conceptual model





Drop in water table in aquifer: Δz

Unloading of basement: $\Delta \boldsymbol{\sigma} = \boldsymbol{f}(\phi \rho_w \Delta z A, \ldots)$

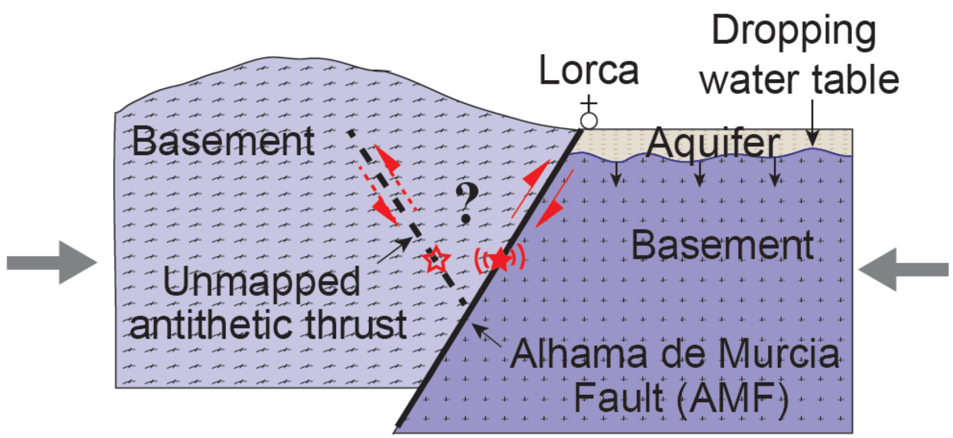
Drop in pressure in basement: $\Delta p = \Delta p_c + \Delta p_d$

(Pore expansion + pressure diffusion)

Previous interpretation

(Gonzalez et al., *Nature Geosci.* 2012
de Michele et al., *Seism. Res. Lett.* 2013)

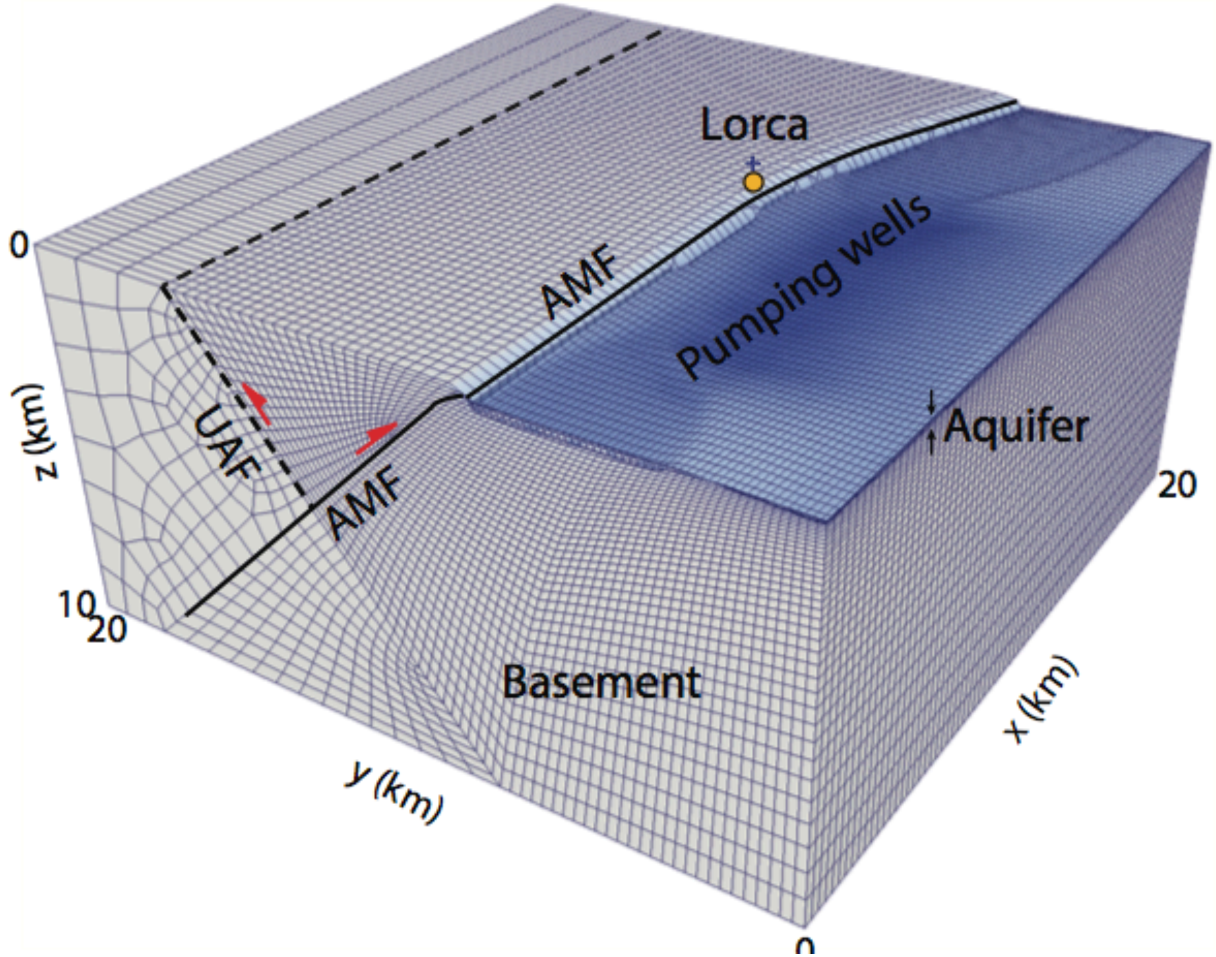
- Ignored coupling between flow and deformation
- Ambiguous regarding which fault sourced the earthquake



Can we ignore flow-deformation coupling?

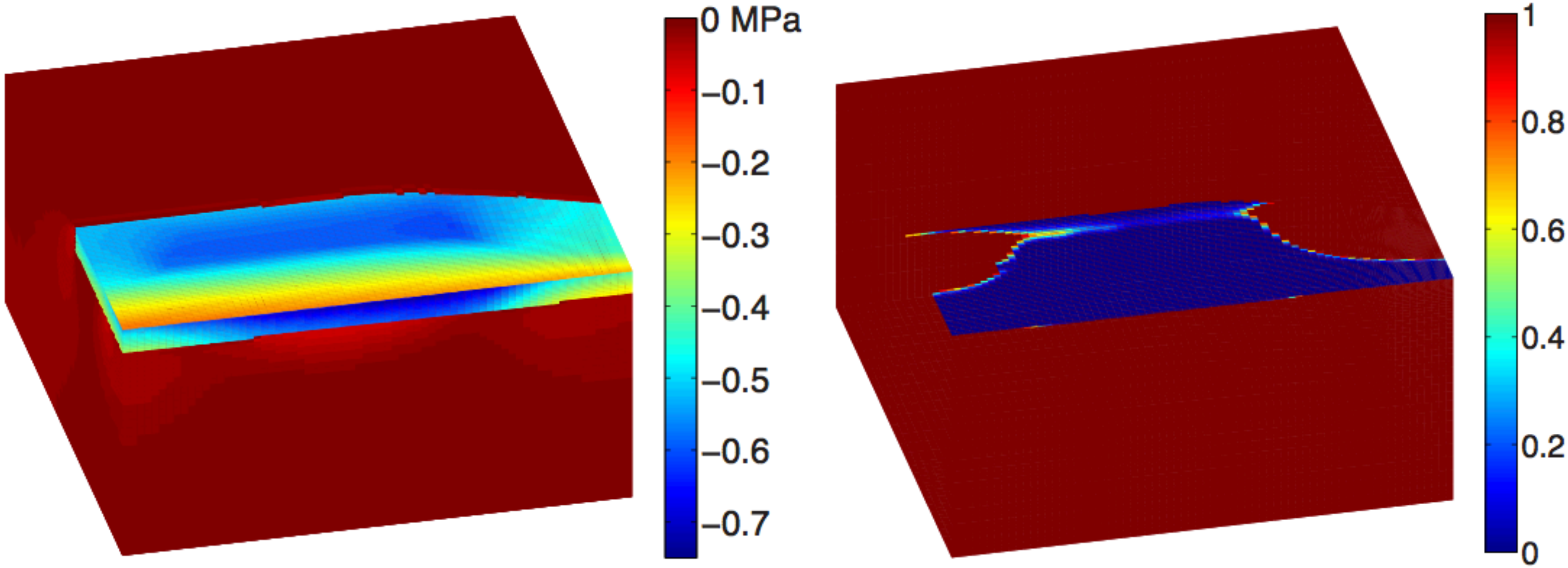
Which fault ruptured and how?

Computational model



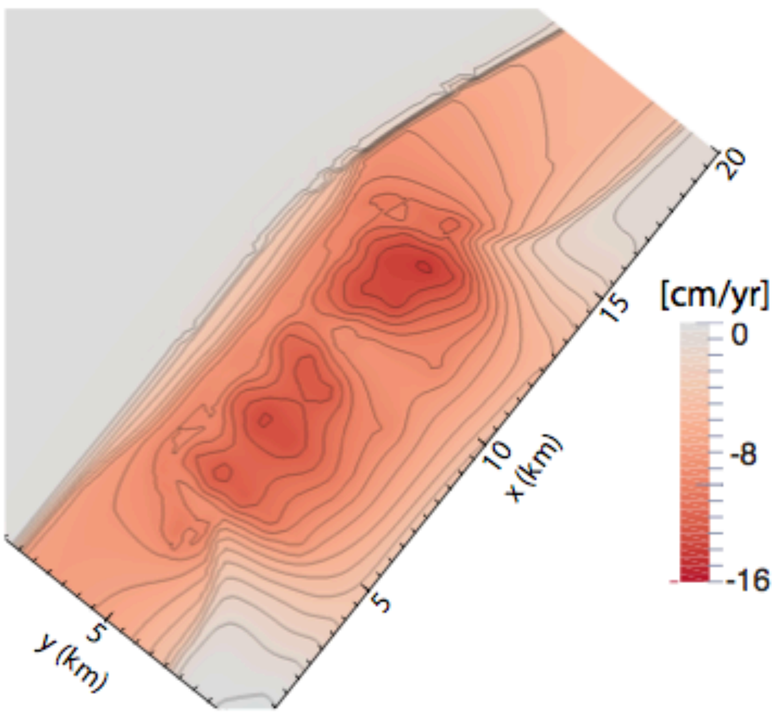
Jha et al, *AGU* 2013

Drop in pressure and water table

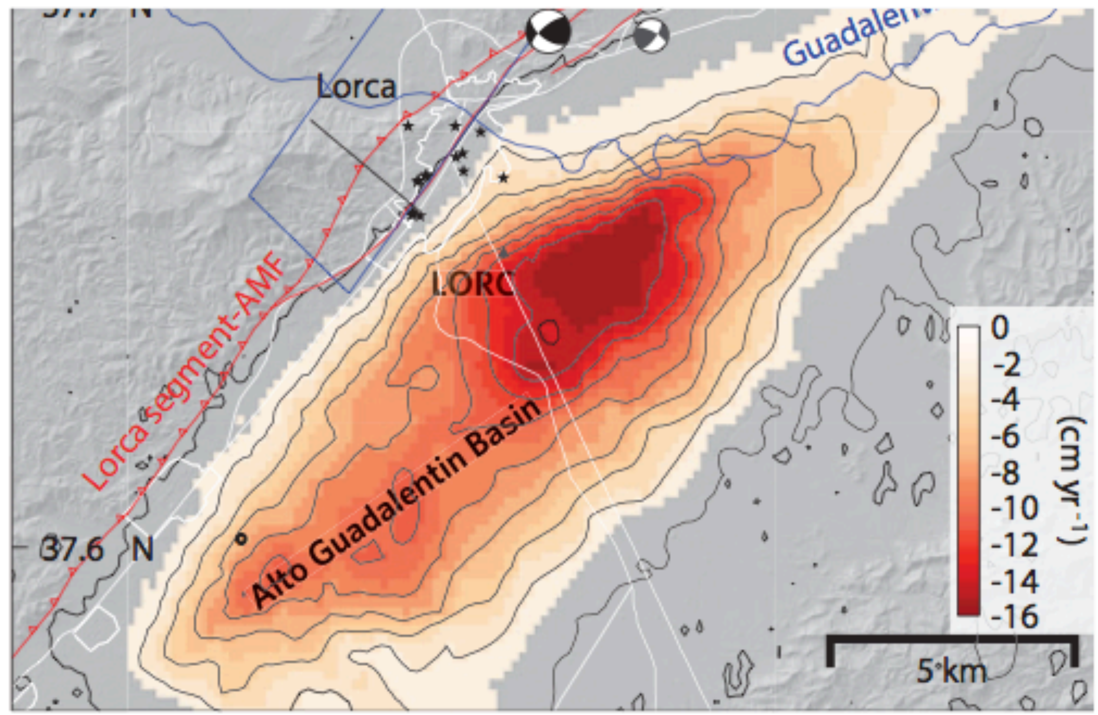


Subsidence due to groundwater withdrawal

Model

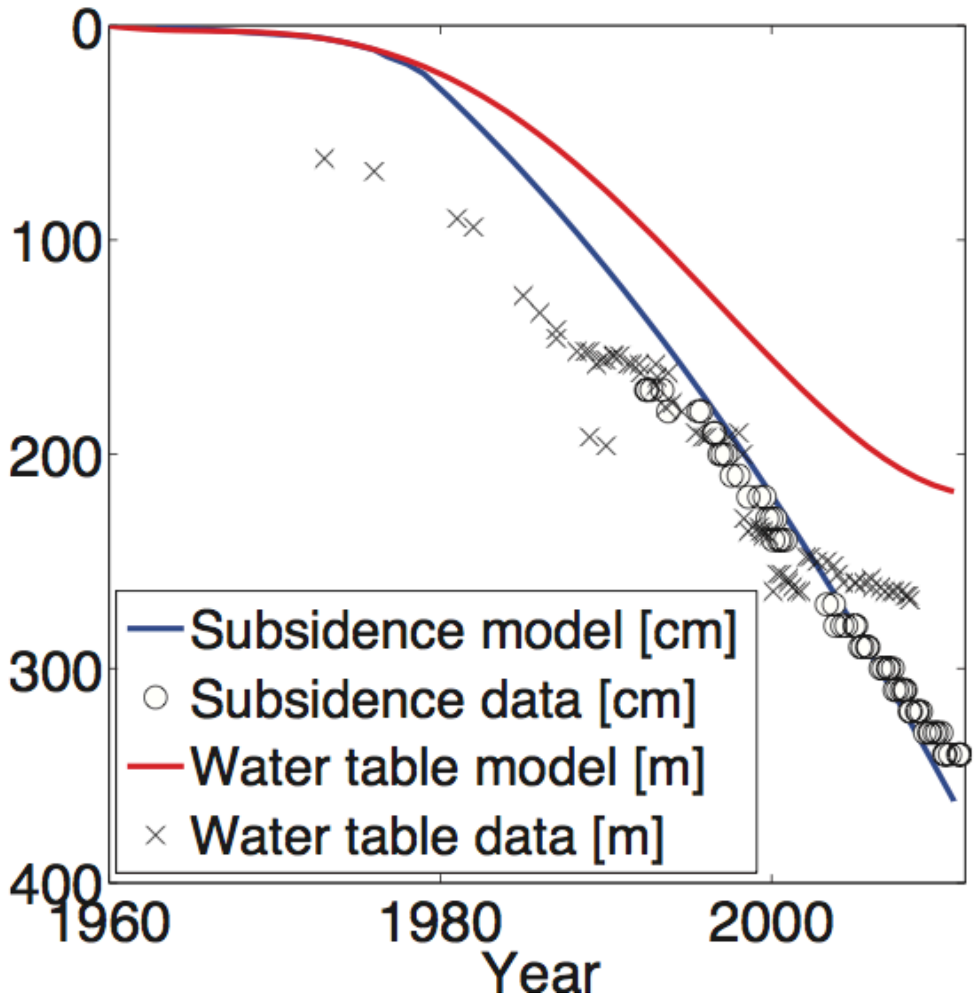


InSAR data



Jha et al, *AGU* 2013

Decrease in water table and ground subsidence

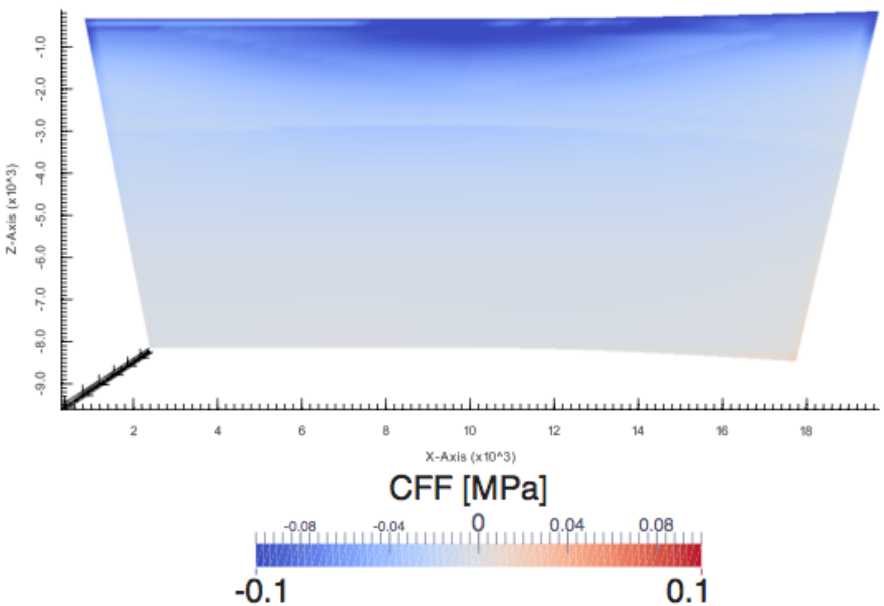


Good agreement between data and model

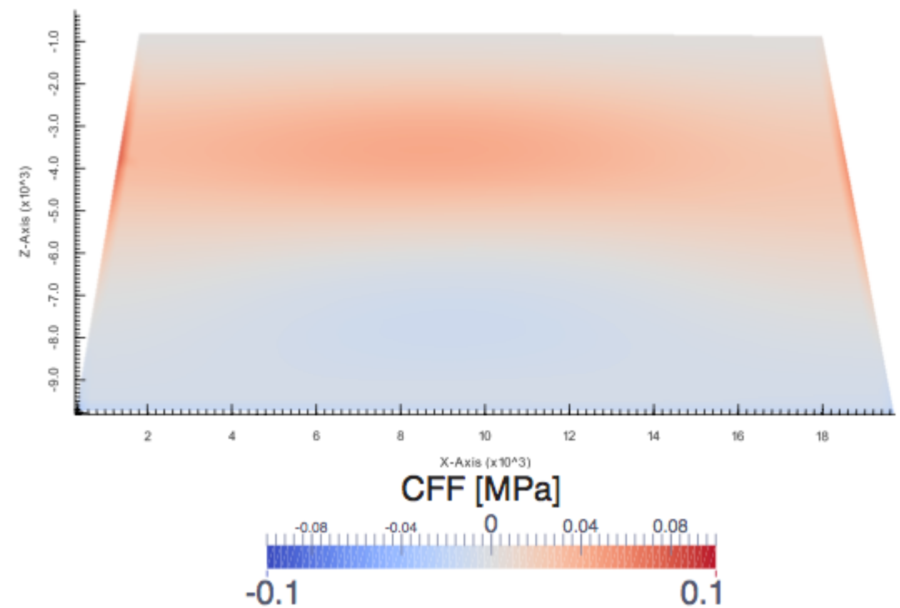
Water table model is averaged over the aquifer.
Water table data is from a few wells.

Change in fault stability due to water extraction

AMF

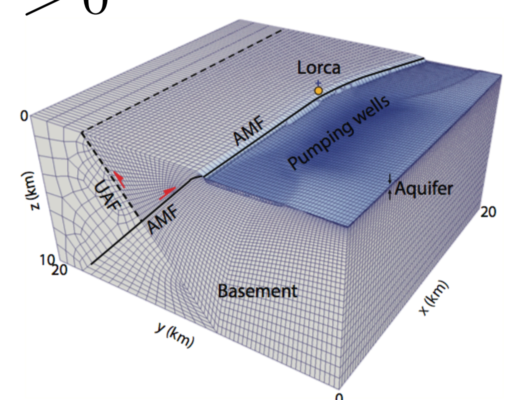


UAF



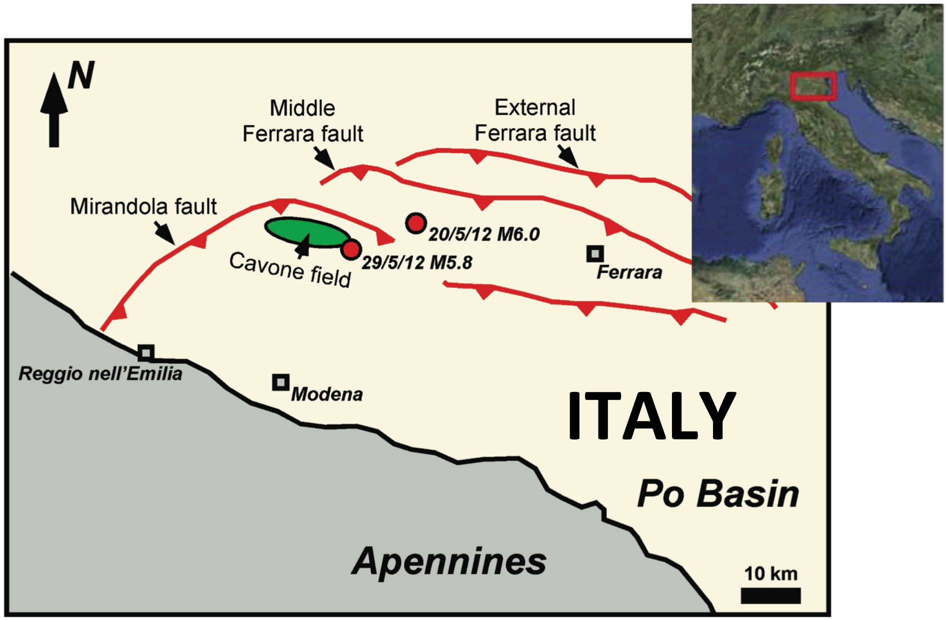
Tendency to slip if: $\Delta \mathrm{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right] > 0$

AMF fault is actually *stabilized*.



The 2012 Emilia-Romagna earthquakes

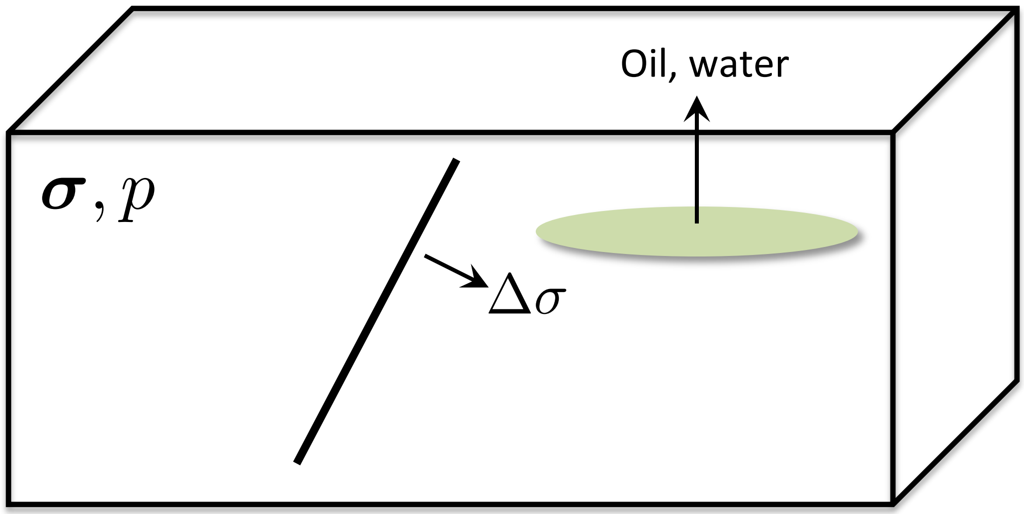
- Sequence of earthquakes (M_w= 6, M_w= 5.8) in May 2012 near the Cavone oil field in Italy



- Raised the question: *Was it induced by production/injection?*
- We address this question by means of computational modeling of coupled flow and geomechanics, integrating geologic constraints, seismic observations, and historical production

Juanes et al., *GRL* 2016

Effect of production - Conceptual model



Tendency to slip if:

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$\Delta\tau > 0$ (poroelastic loading)

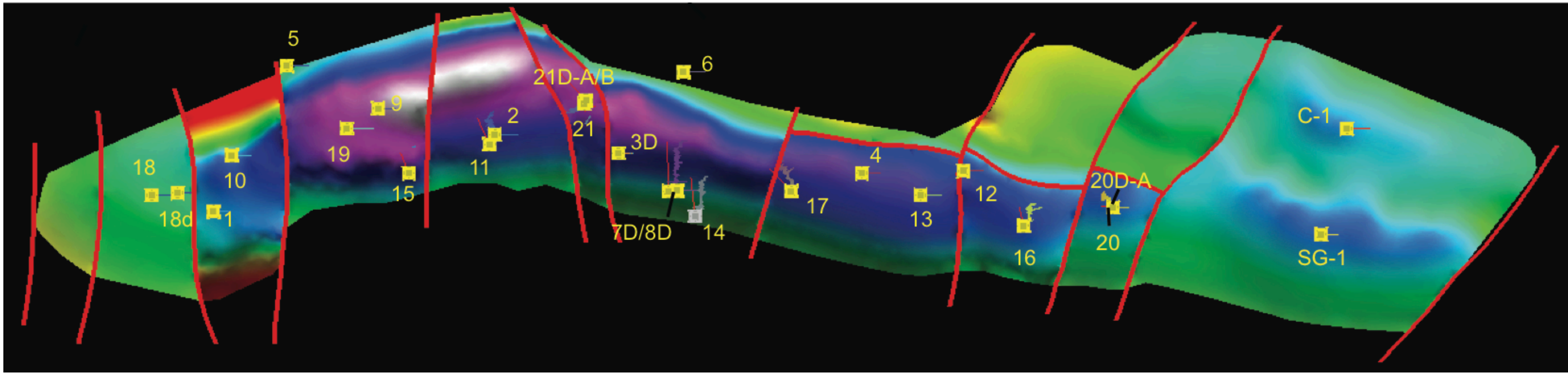
$\Delta\sigma_n < 0$ (poroelastic unloading)

$\Delta p > 0$ (fluid injection)

$\Delta\mu_f < 0$ (fault weakening)

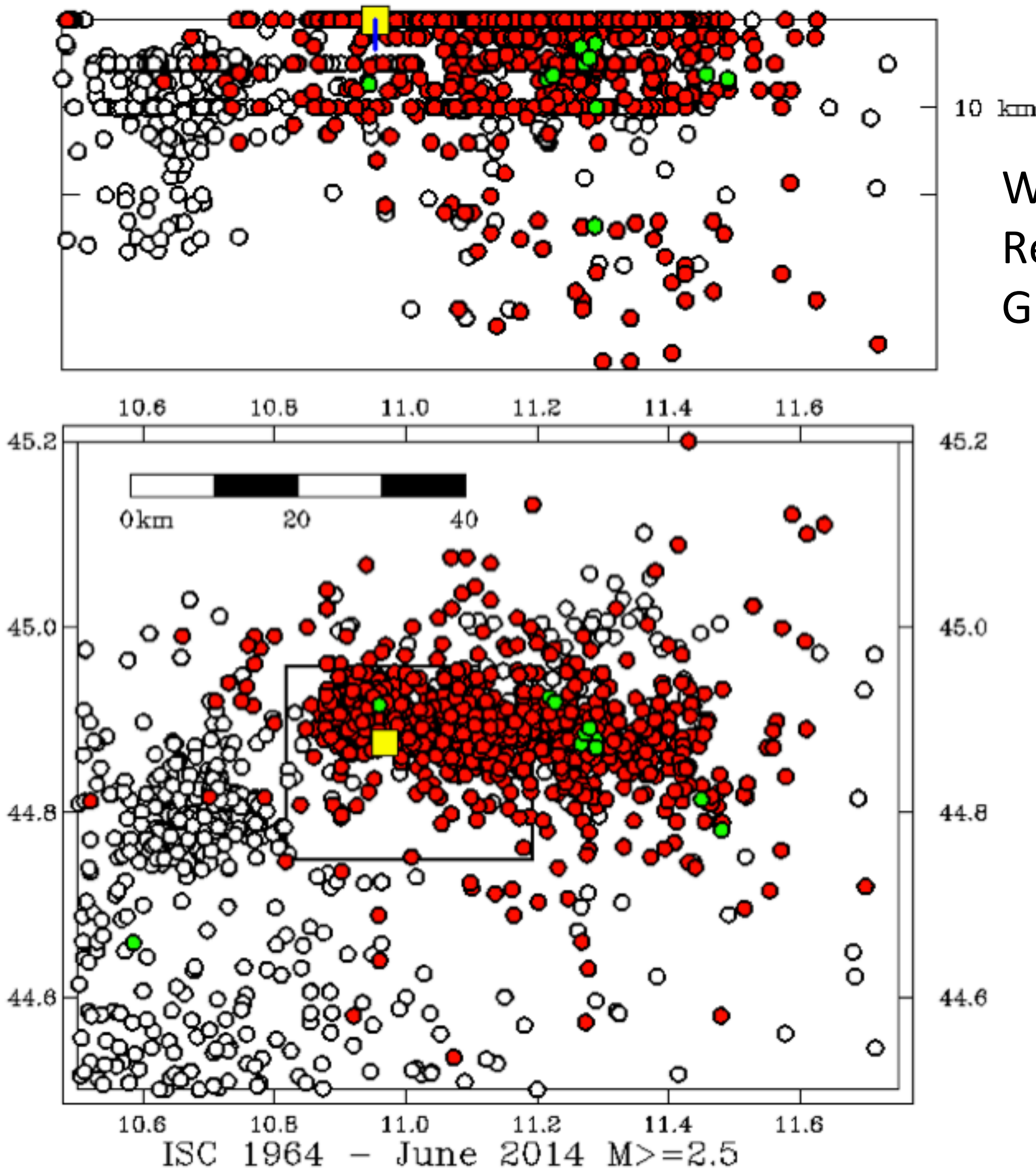
The Cavone oilfield

Map view



- Reservoir is compartmentalized by several faults.
- Strong aquifer support from underneath the reservoir.
- Oil production started in 1980. Injection of produced/ waste water began in 1993. 16 producers, 1 injector.

Regional seismicity



Cross-section view

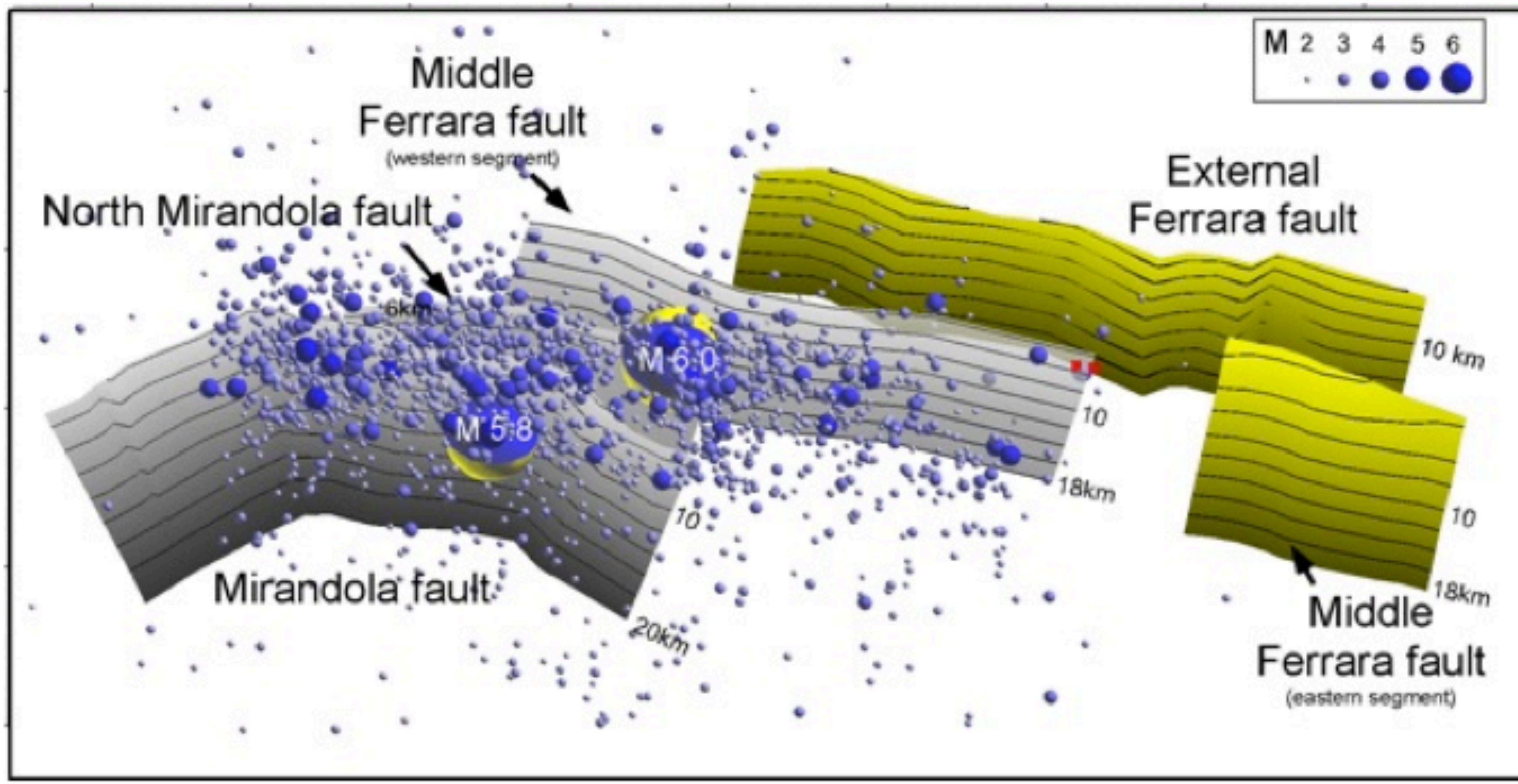
White circle: 1964 - 04/2012

Red circles: 05/2012 - 06/2012

Green circles: 07/2012 - 06/2014

Map view

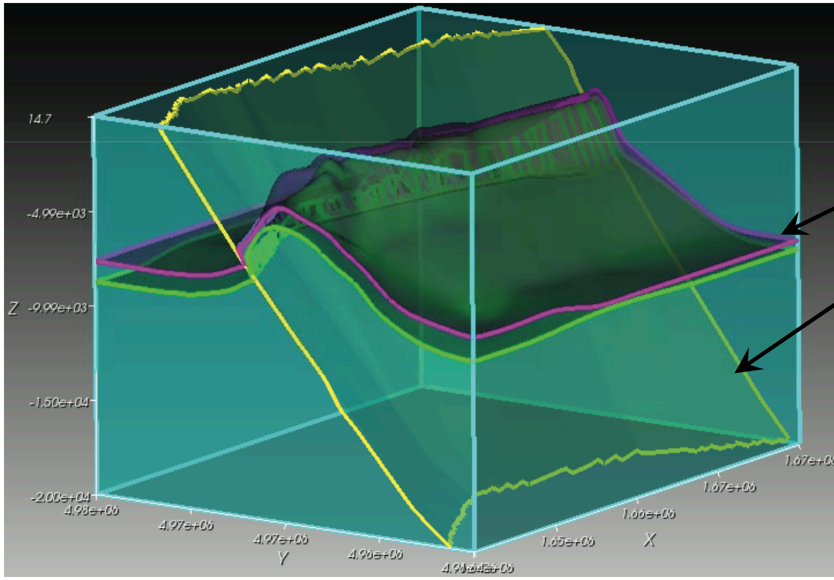
Seismicity on regional faults



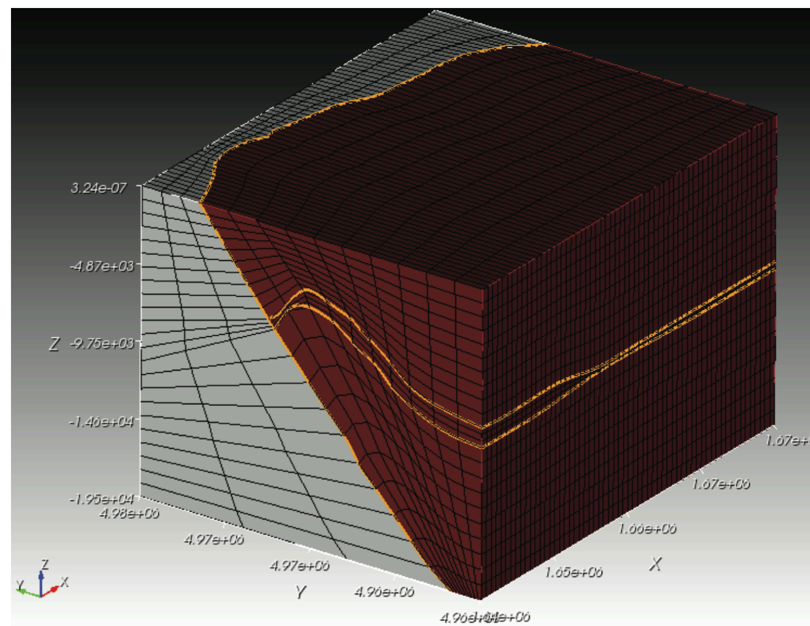
Seismicity data from Jan 2011 – Feb 2013

Computational model

Structural model

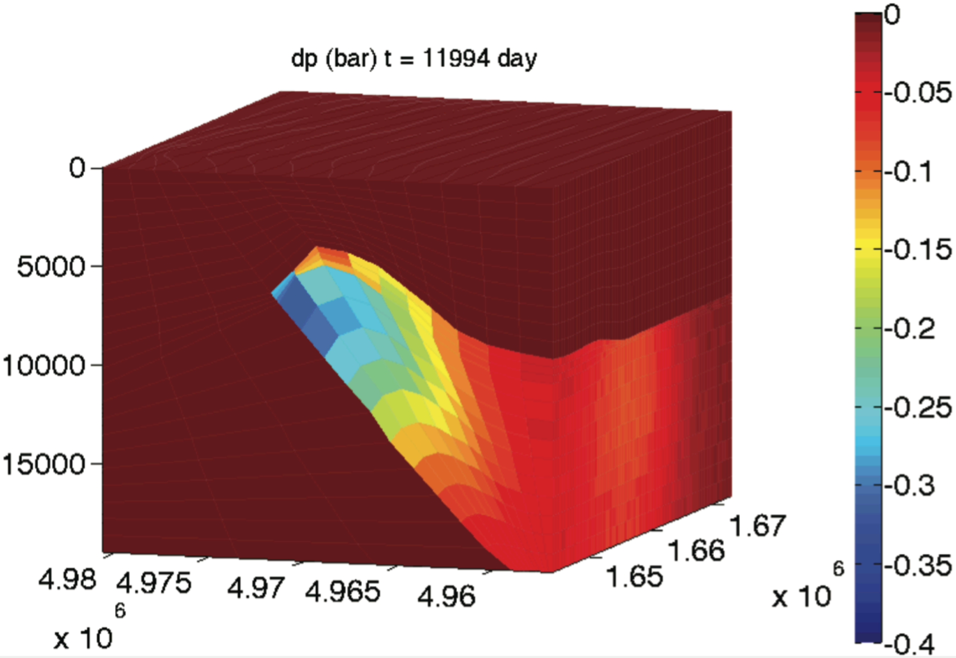


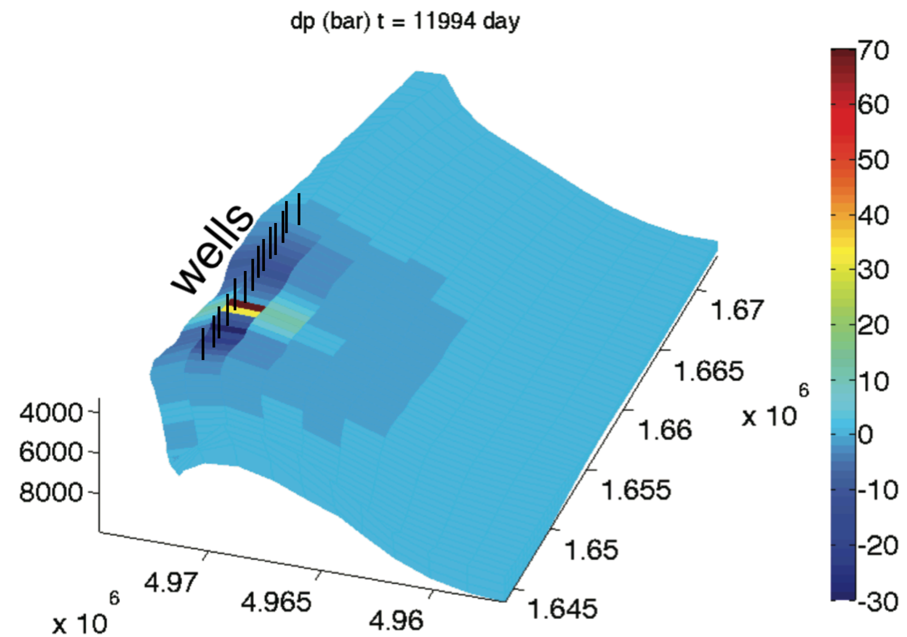
Geomechanical grid



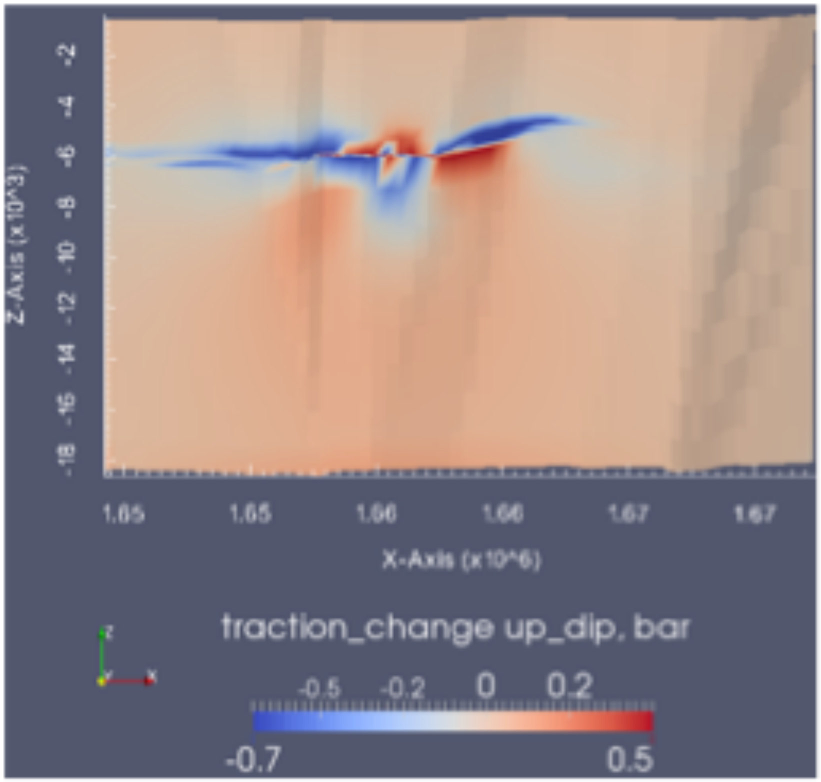
Jha et al, *AGU* 2014

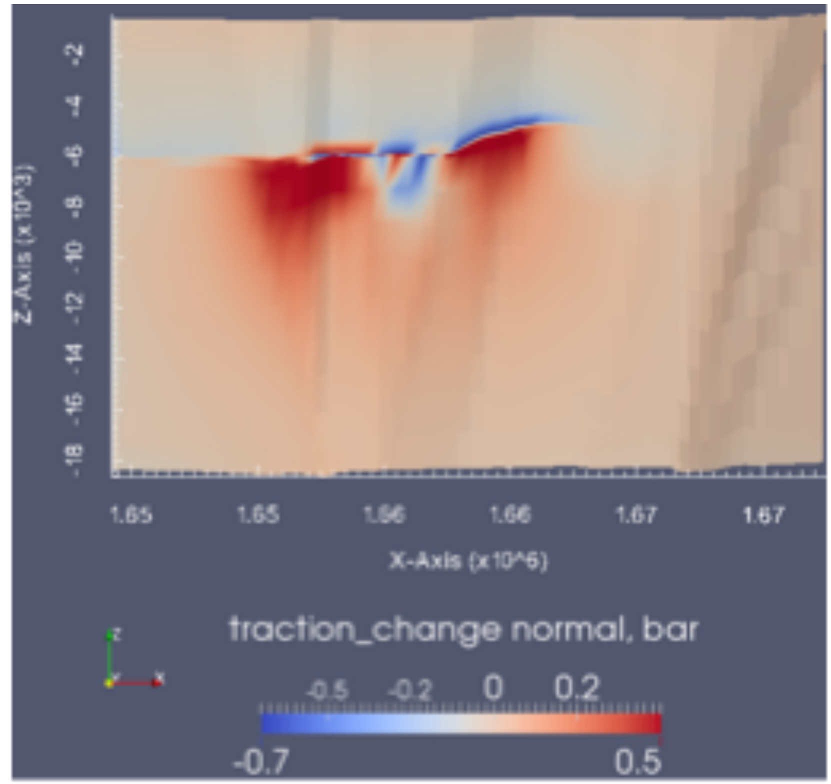
Reservoir pressure changes due to production and injection

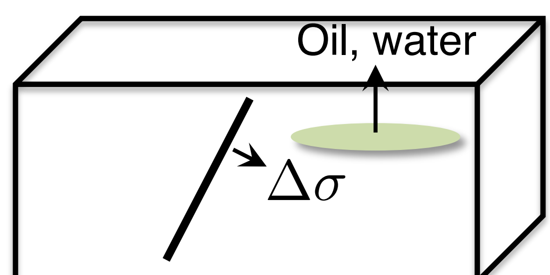




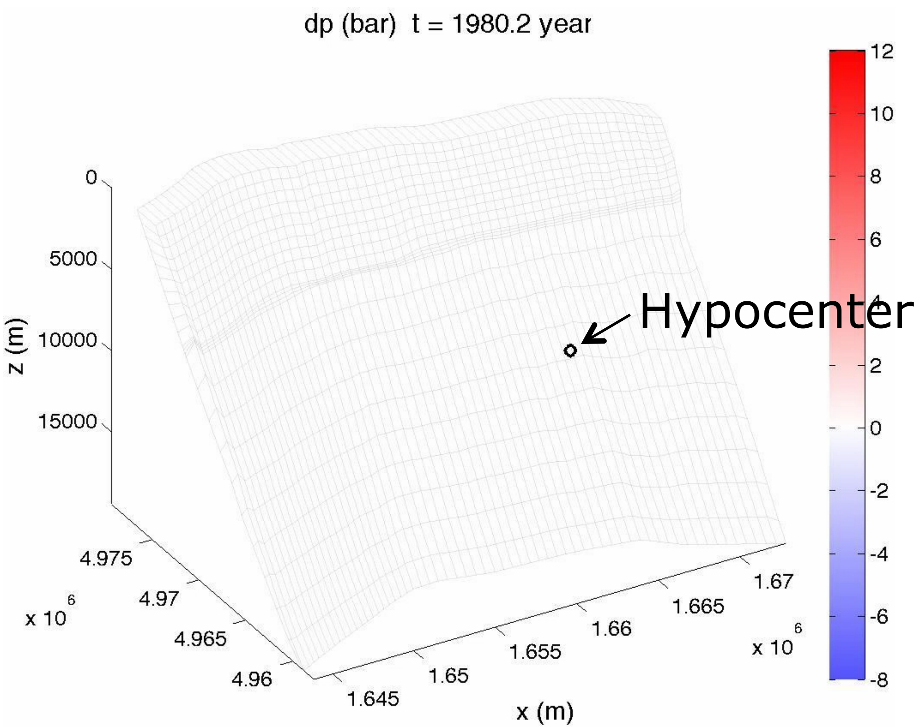
Shear and normal fault tractions change due to prod/inj



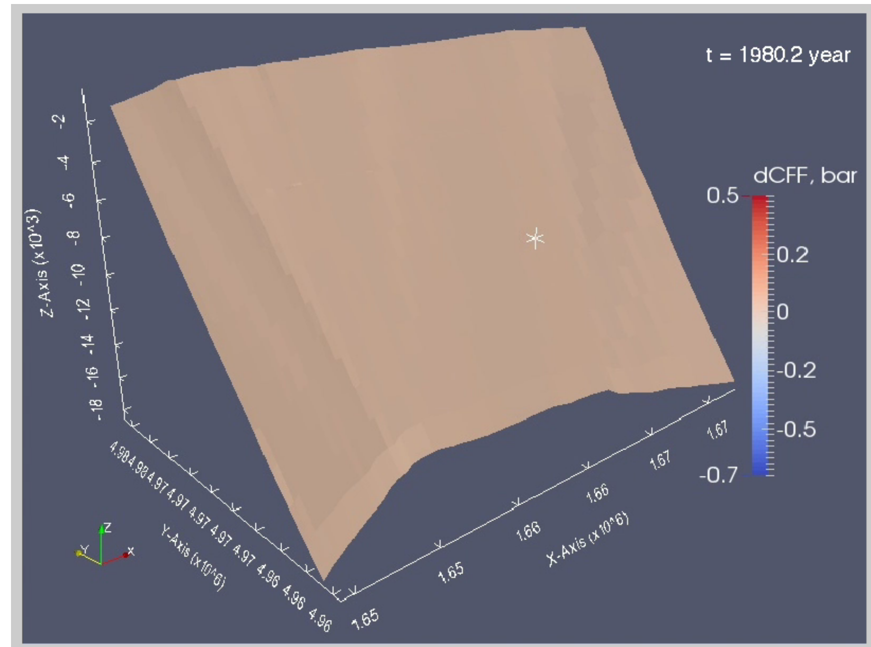




Evolution of pressure and stress on fault



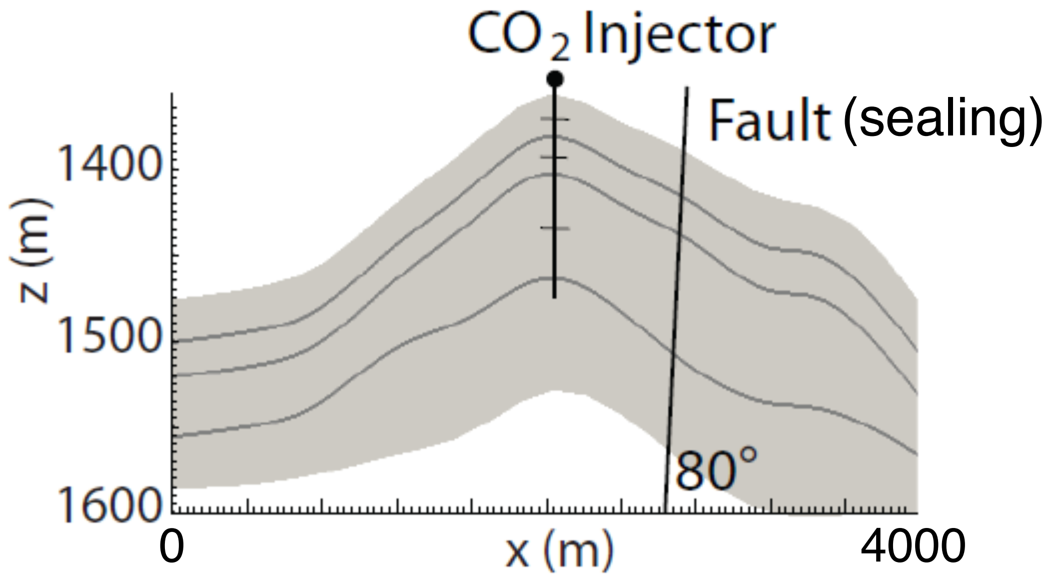
$$\Delta \mathrm{CFF} = \Delta\tau - \Delta\left[\mu_f(\sigma_n - bp)\right]$$

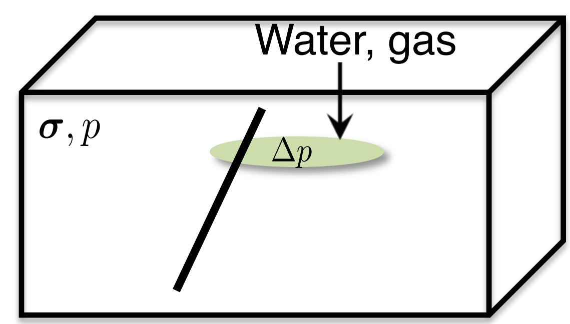


- Increase in Coulomb stress not enough to trigger seismicity
- Injection *stabilized* the fault.

Seismicity induced by CO_2 injection

Can CO_2 injection induce seismicity? Largest magnitude?



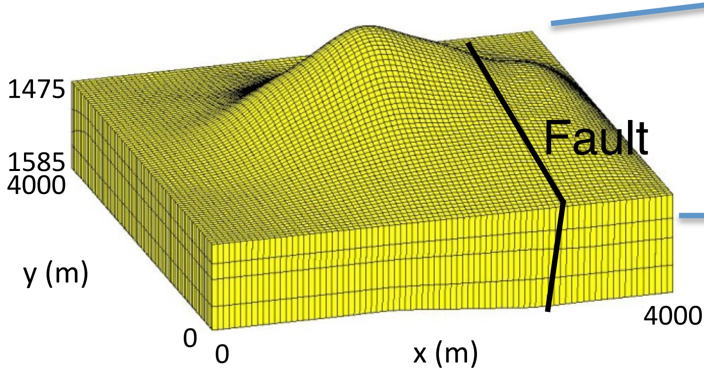


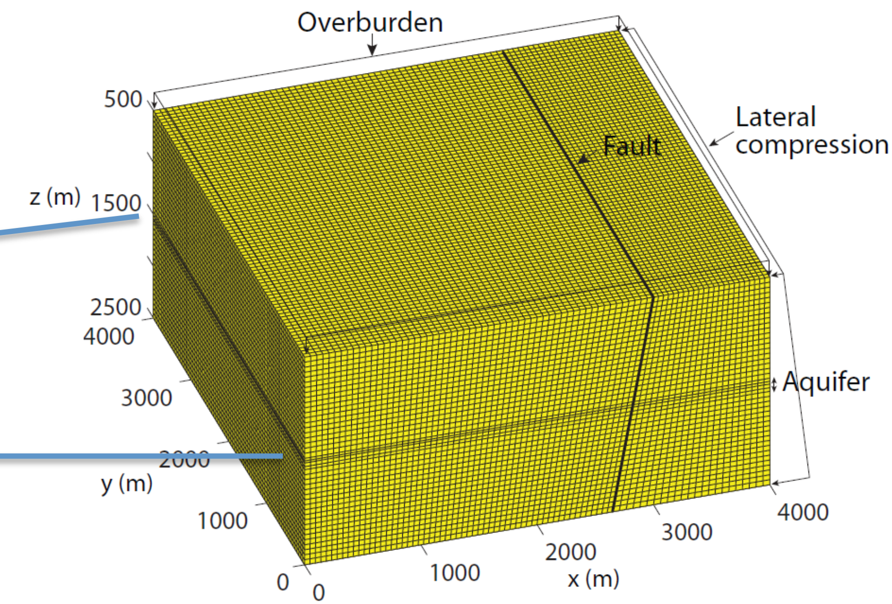
Computational model

Jha and Juanes, *WRR* 2014

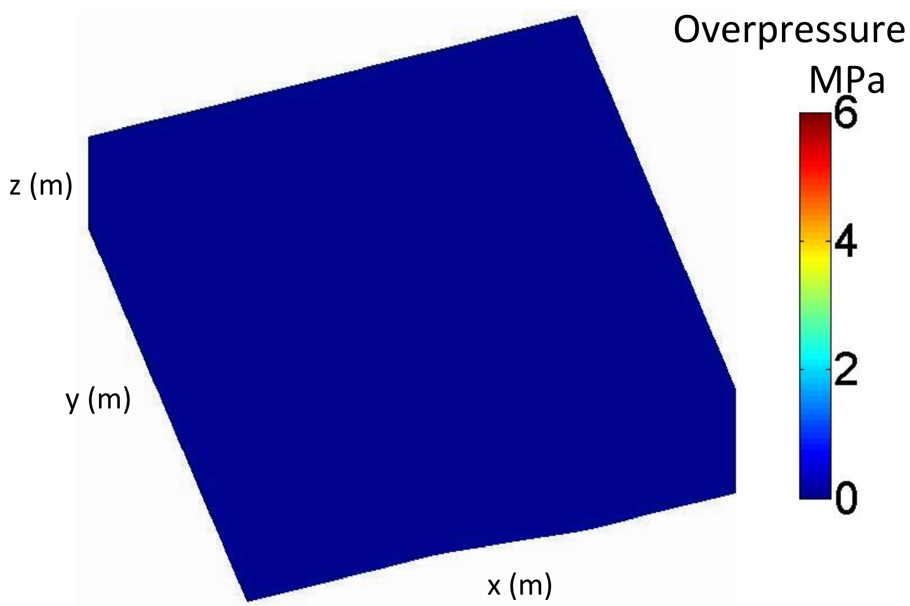
Geomechanical domain

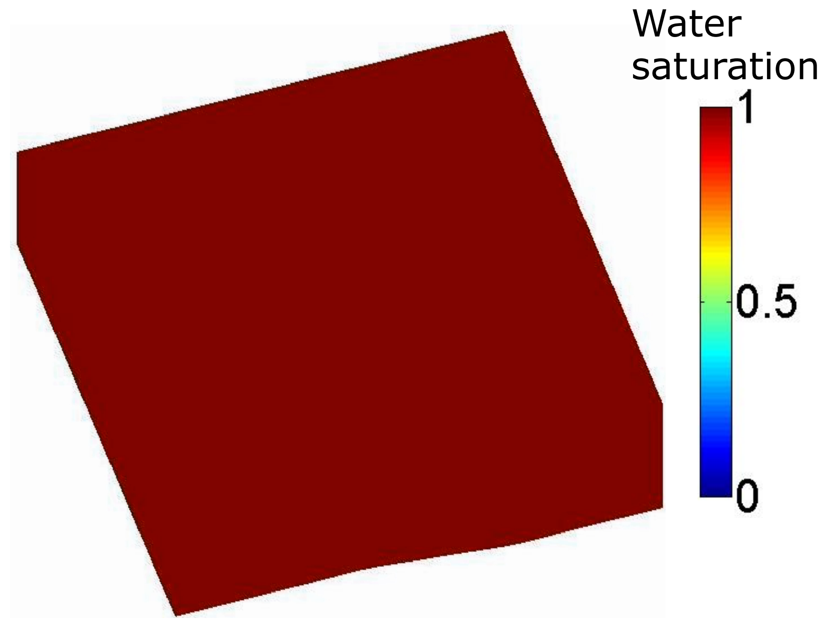
Aquifer domain





Over-pressurization due to injection

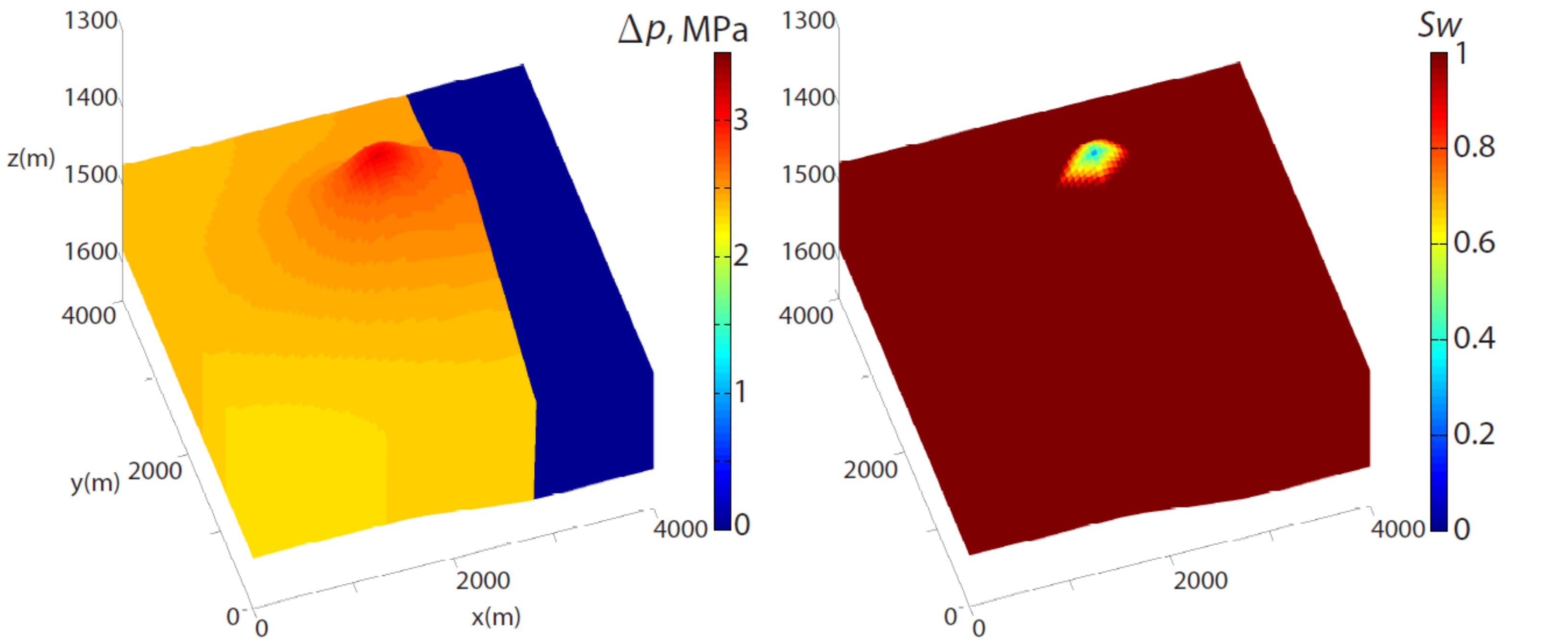




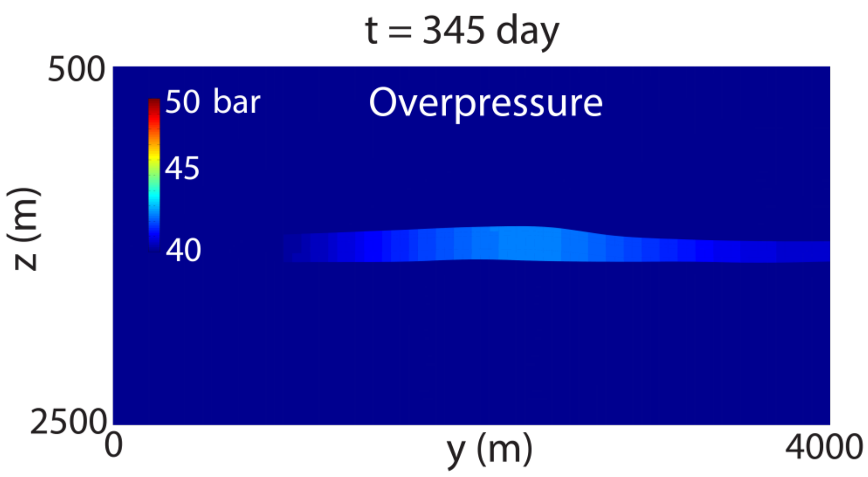
Pressure rises in the fault block where the injector is located.

CO_2 accumulates near the top because of buoyancy.

Over-pressurization due to injection

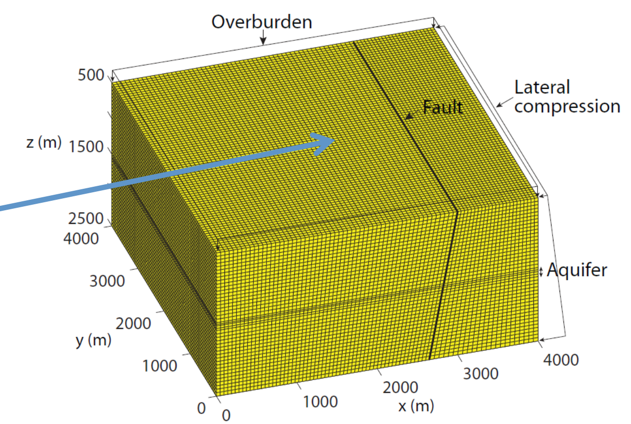


Fault pressure

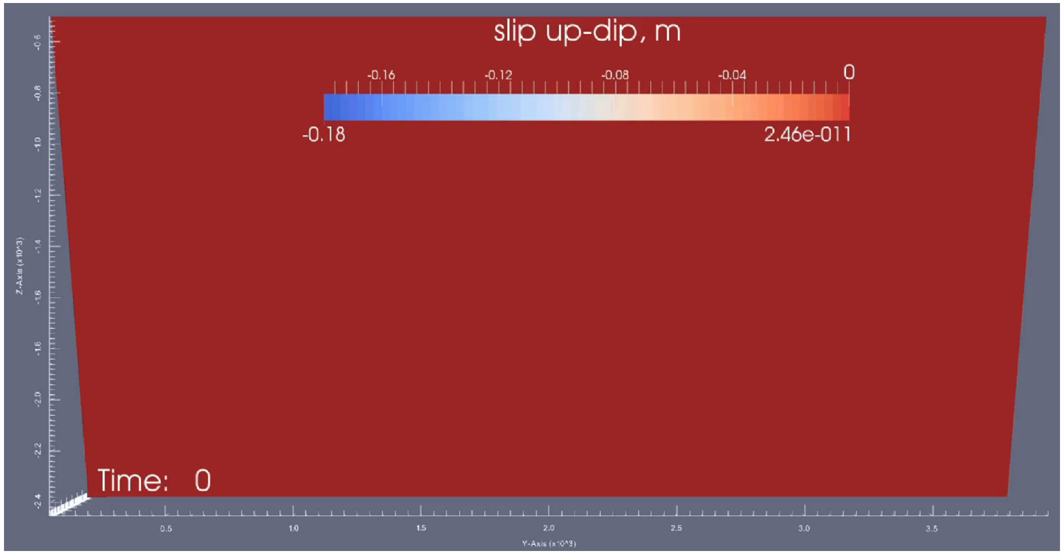


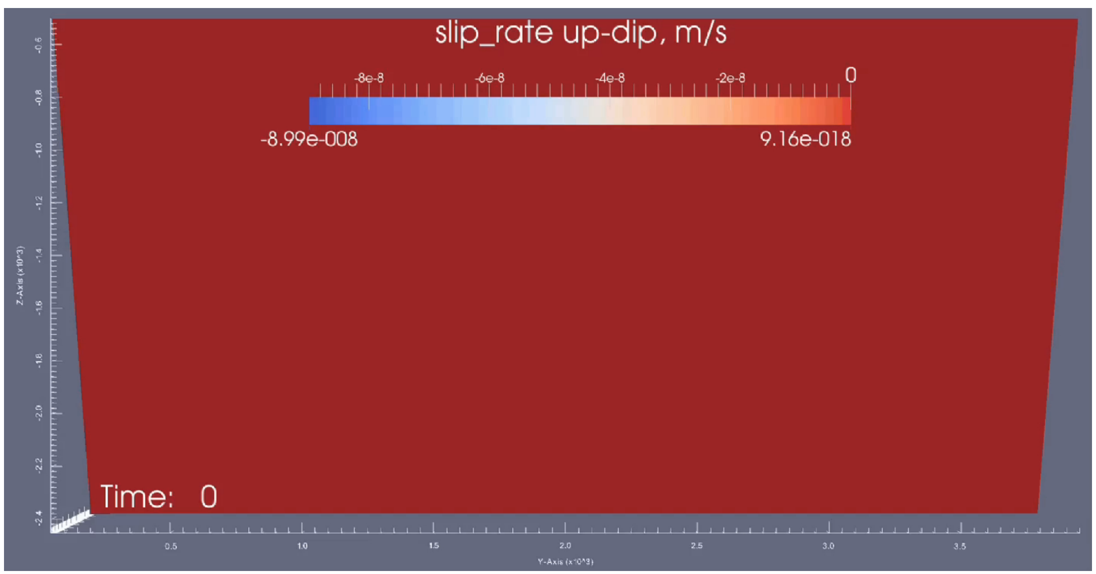
Pressure on the fault also increases in the reservoir depth interval.

View angle for images above

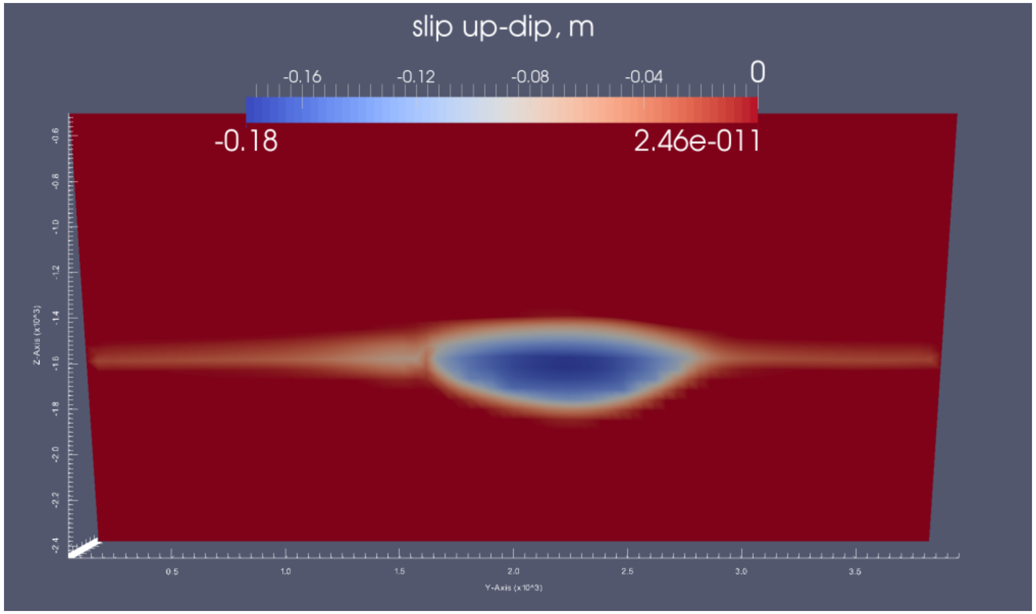


Fault slips due to over-pressurization

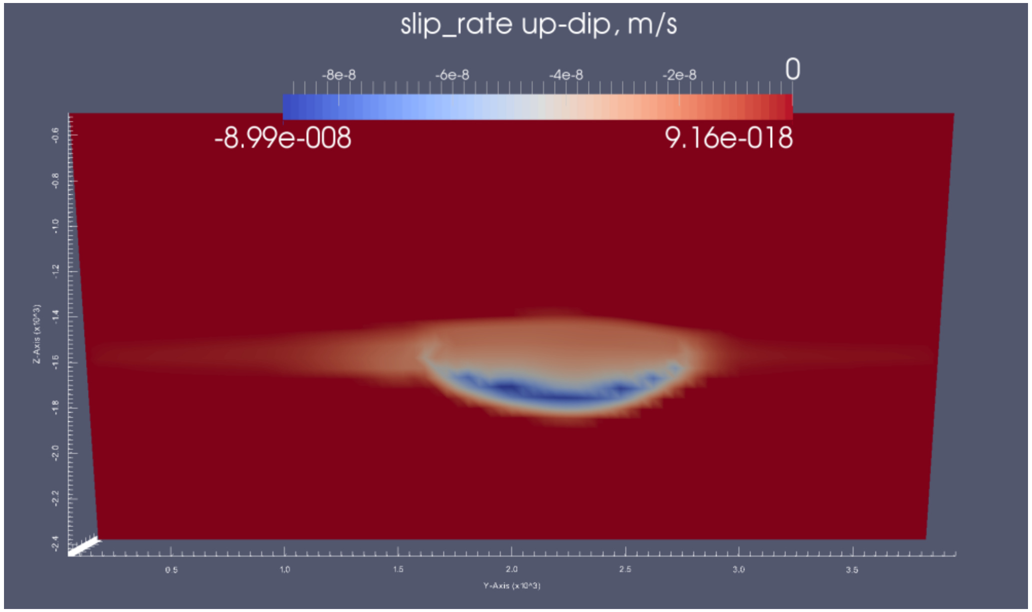




Fault slips due to over-pressurization

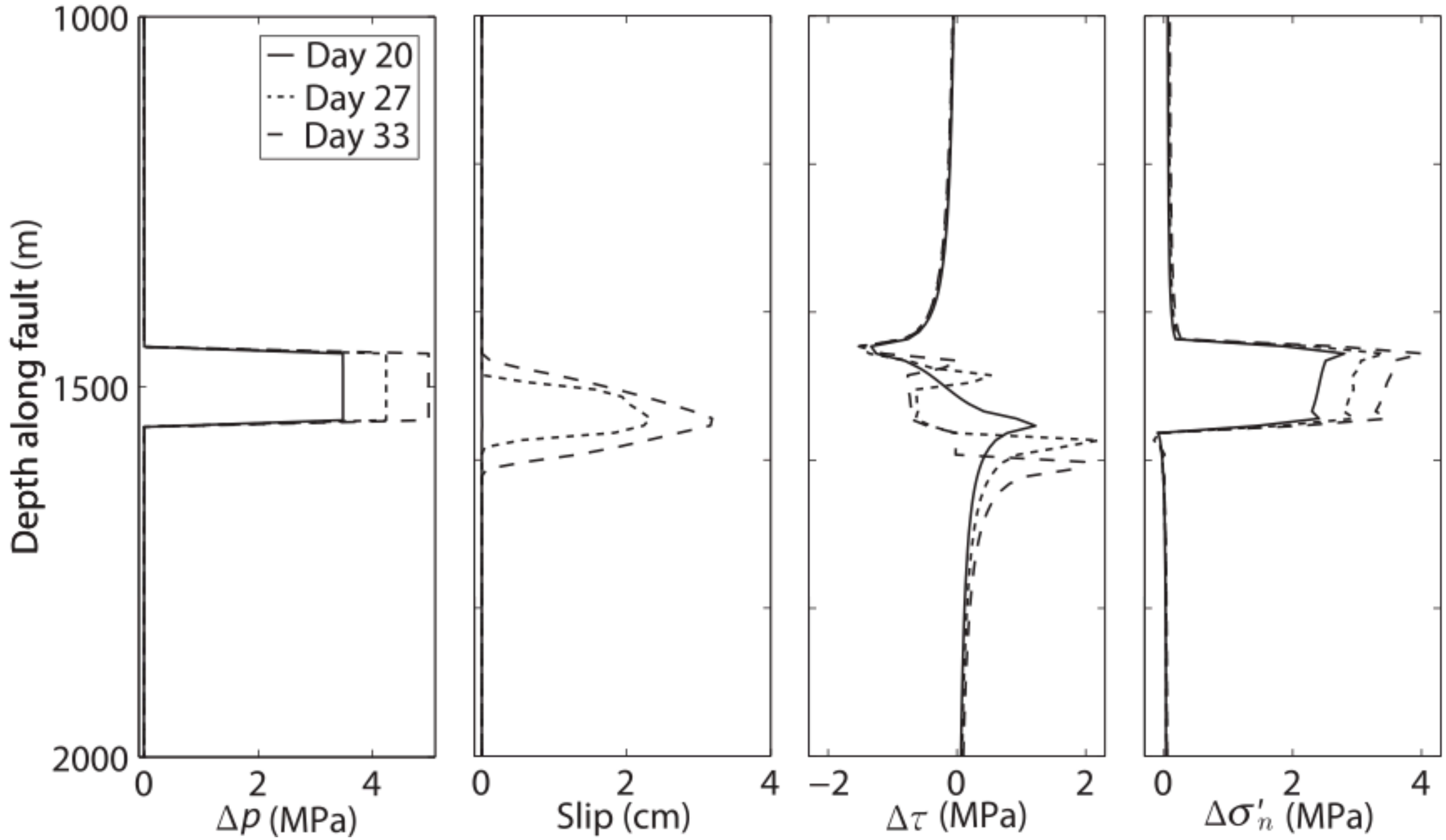


Slip area gives magnitude of seismicity

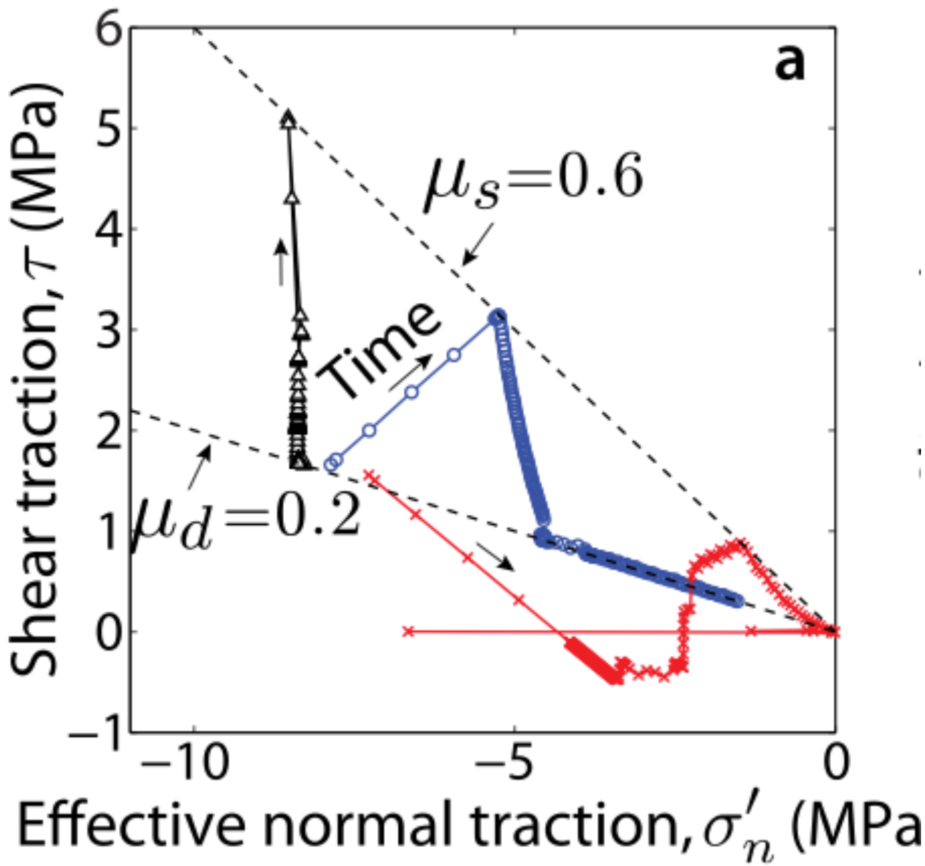


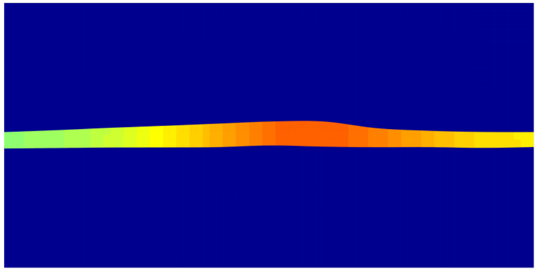
Slip direction gives directivity of seismic energy released

Depth profiles of pressure and stresses along the fault



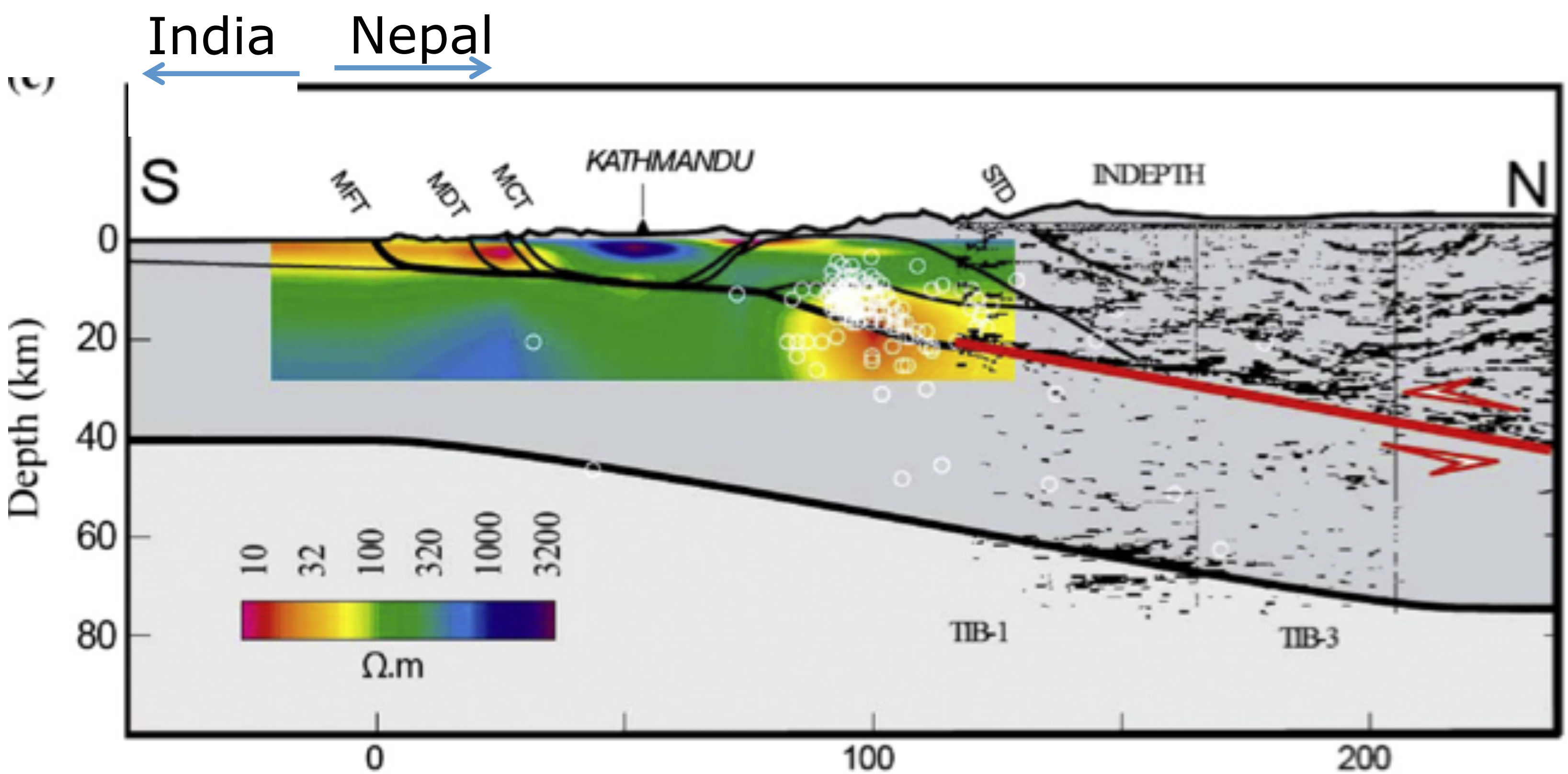
Stress paths of specific points on the fault





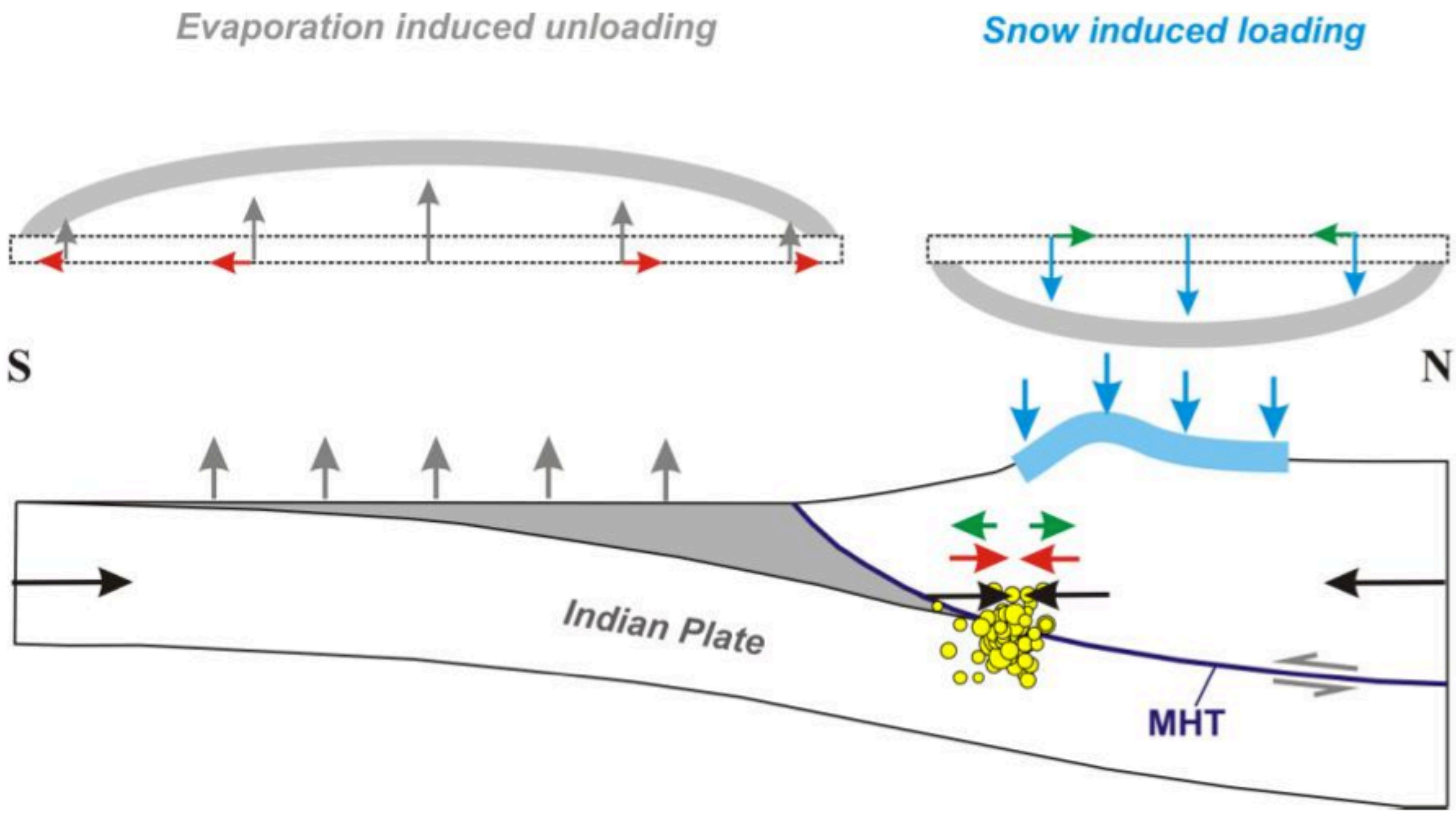
Influence of meteorological cycle in mid-crustal seismicity of the Nepal Himalaya

Kundu et al., *JAES* 2017



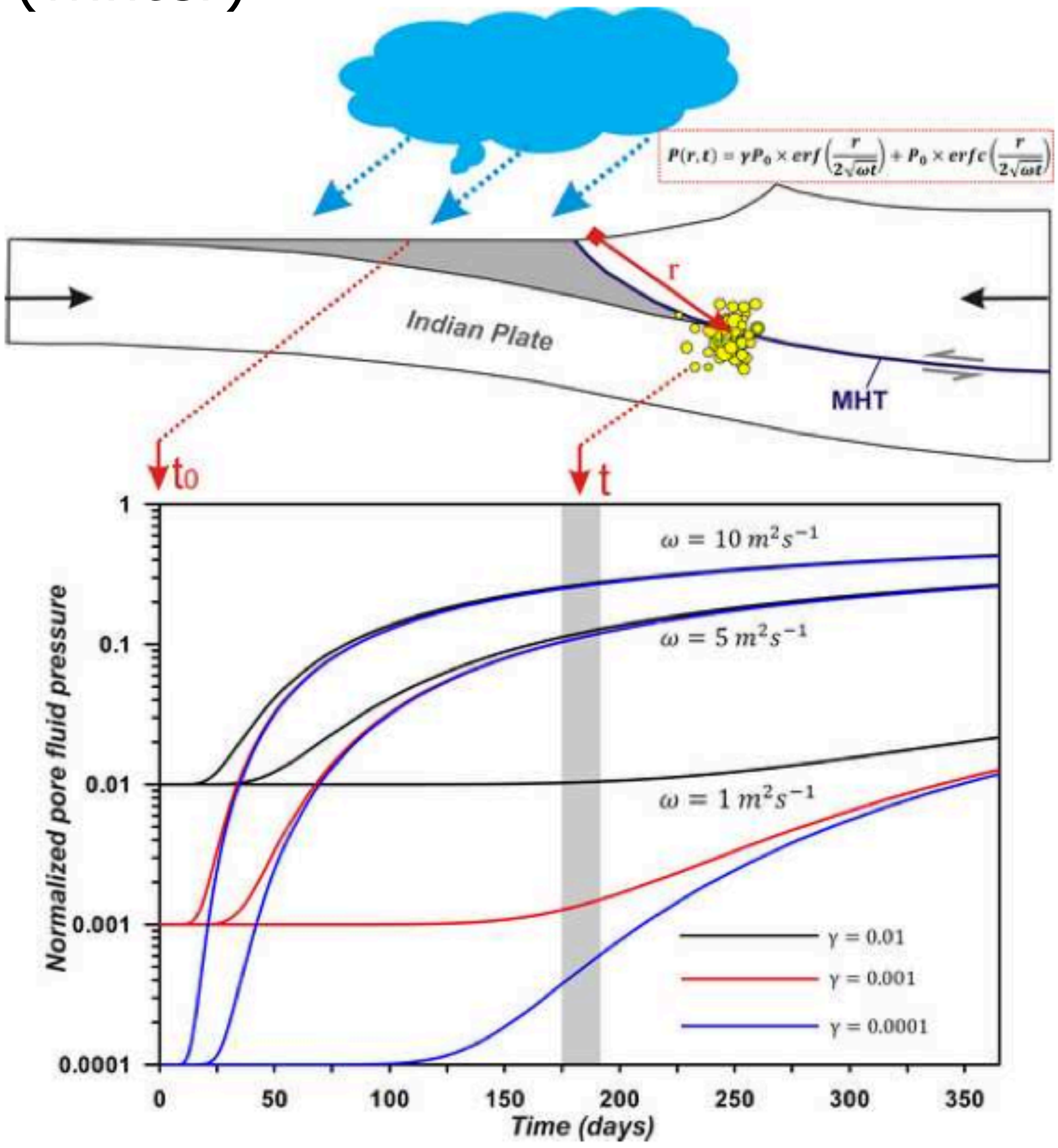
Bettinelli et al., *EPSL*, 2008

Evaporation induced unloading and snowfall-induced loading of the MHT fault



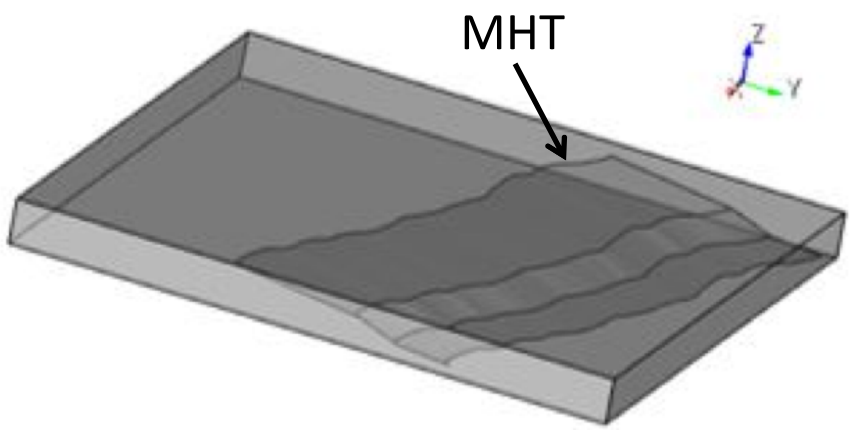
Kundu et al., JAES 2017;
Bettinelli et al., *EPSL*, 2008

Time lag between monsoon rainfall (summer) and mid-crustal seismicity (winter)

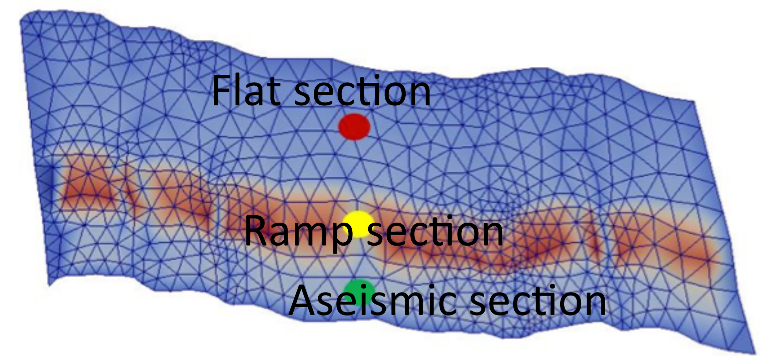


Pressure change =
change due to diffusion
+
change due to poroelastic deformation

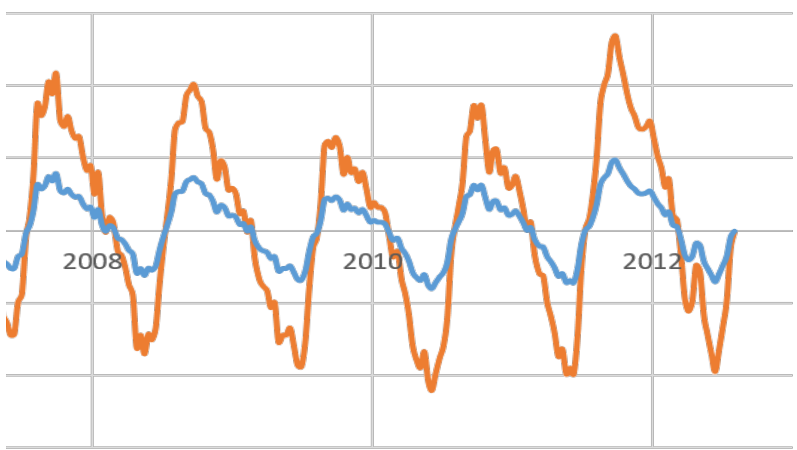
Coupled flow and geomechanical model



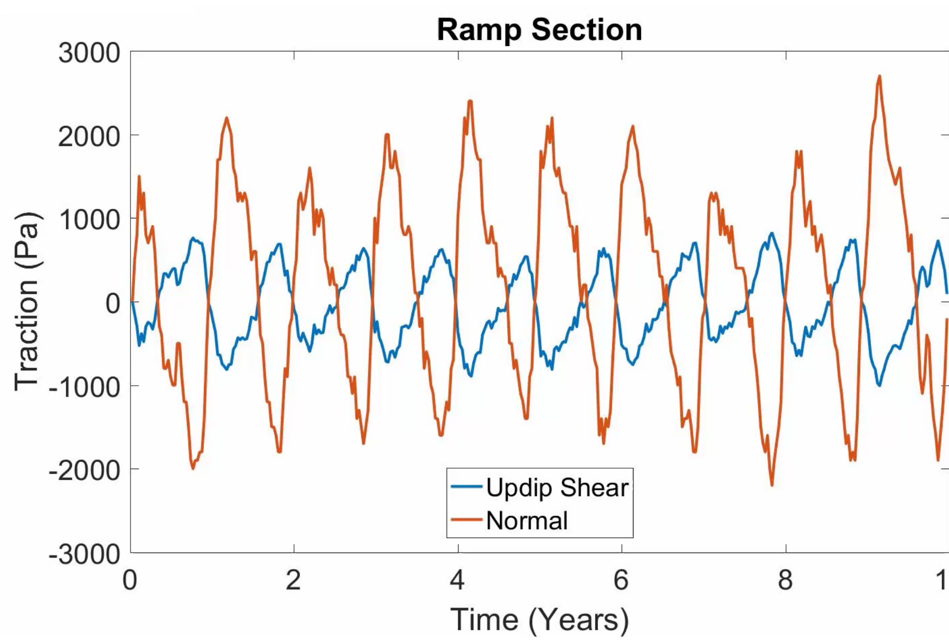
Three sections of MHT



Rainfall load from Equivalent Water Height



Induced changes in fault tractions

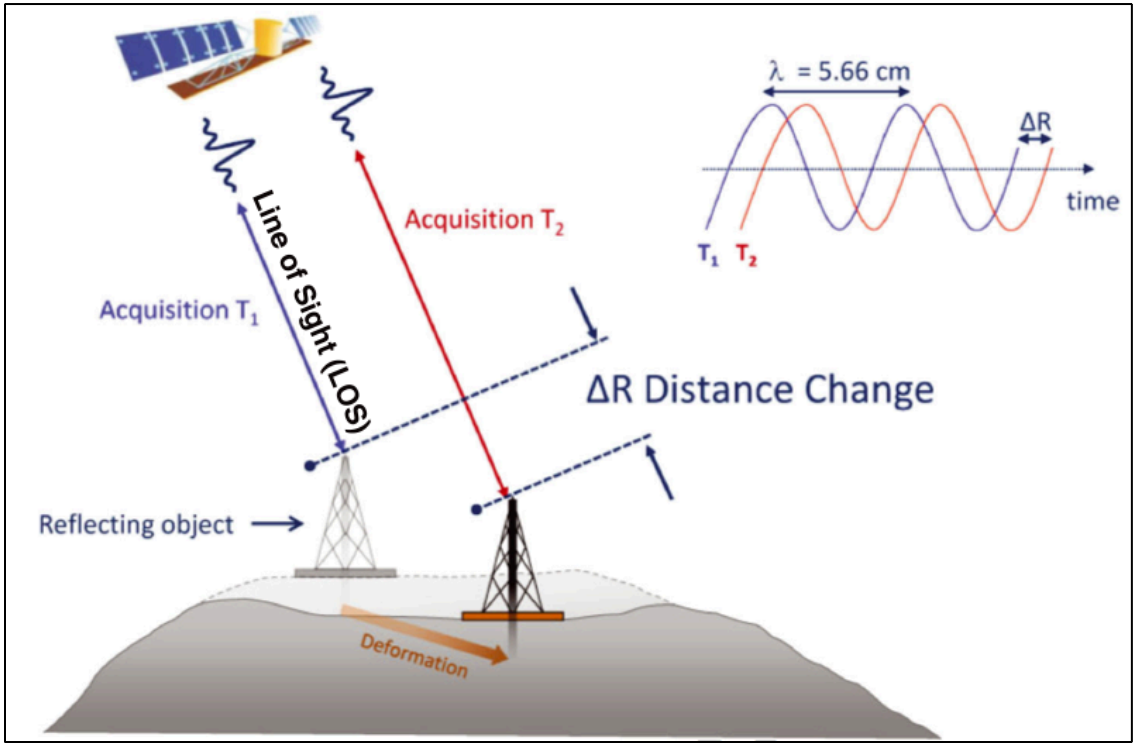


Conclusions

Computational modeling of coupled flow and geomechanics is a powerful tool:

- Provides mechanistic explanation of seismicity, fluid flow, and ground deformation observed around reservoirs
- Identifies energy and groundwater extraction strategies that can mitigate seismic risk

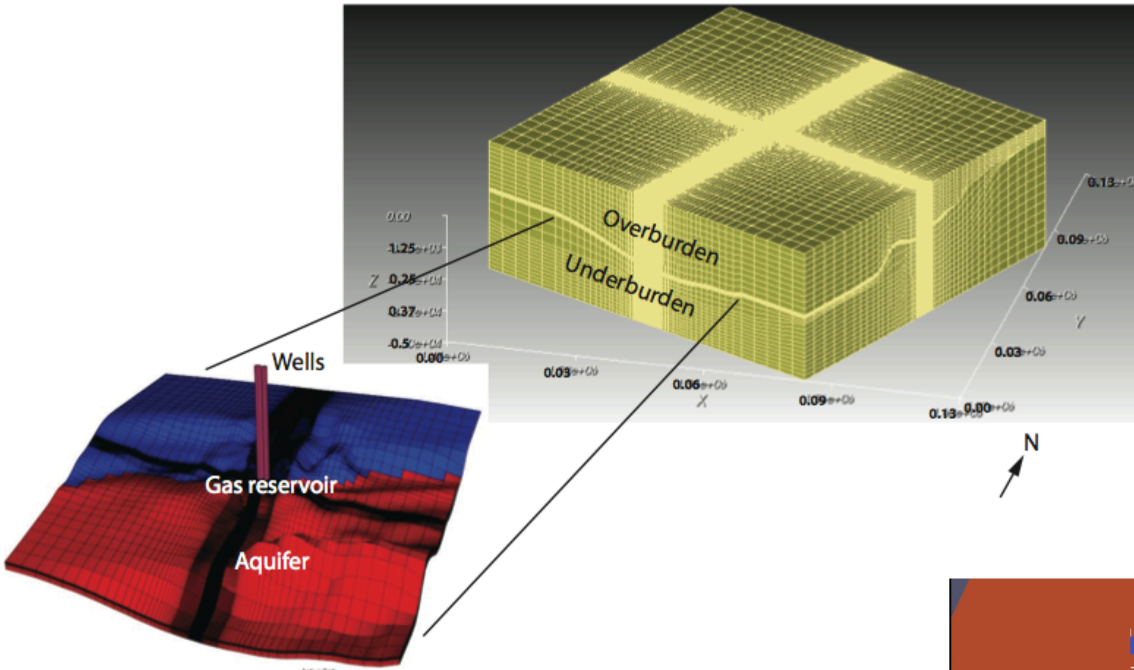
Underground gas storage

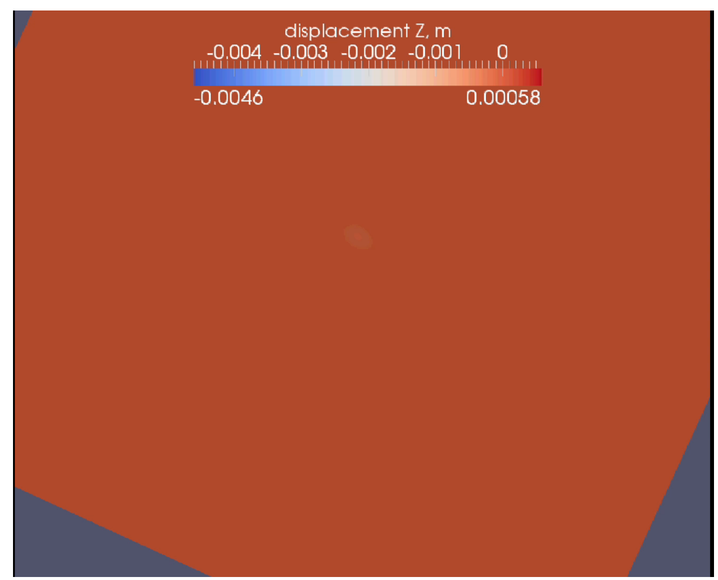


Side view

Store in summer, produce in winter.
How much can be stored and how fast?

Finite element modeling and simulation





Top view

Compare model results with satellite data