The influence of fault hydromechanical properties and stress state on injection-induced seismicity

Nicolas Wynants-Morel[1], Frédéric Cappa[1,2] and Louis De Barros[1]

(wynants@geoazur.unice.fr)

[1] Geoazur, France

[2] Lawrence Berkeley National Laboratory, USA

EGU General Assembly 2019
Vienna | Austria | 7–12 April 2019

Abstract Number: EGU2019-7324

Web site: hydroseis.oca.eu

Nicolas Wynants-Morel is supported by a fellowship from the French Ministry of Research and Higher Education. Research presented in this poster is supported by the Agence Nationale de la Recherche through the "HYDROSEIS" project under the contract No. ANR-13-JS06-0004-01 (PI: F. Cappa).

Abstract

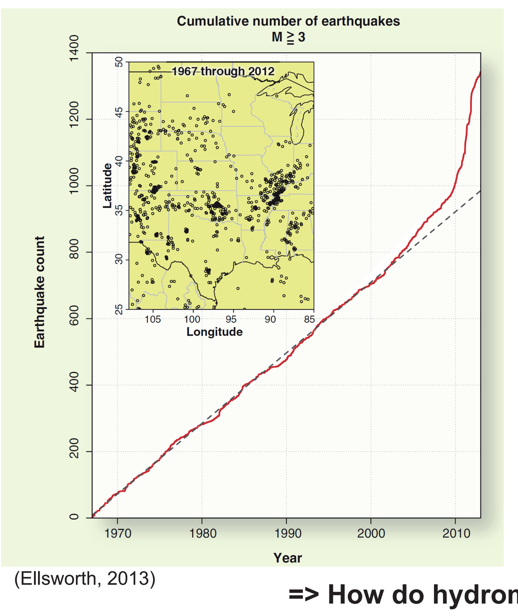
Understanding the triggering mechanisms of injection-induced seismicity is fundamental to effective seismic hazard assessment and mitigation. Various mechanisms have been proposed. Fluid injections into reservoir formations can sometimes produce earthquakes on faults, by increasing the pore pressure or by perturbating the elastic stresses around the injection. Earthquakes can also be triggered far from the injection by driving forces that involve aseismic deformation on the fault. The relationship between seismic and aseismic fault slip during injection is particularly complex due to the coupling between fluid pressure diffusion, evolving stress and hydromechanical properties.

In this study, we aim to investigate, through 3D hydromechanical modeling, the main fault parameters that govern the aseismic and seismic deformations on a slip-weakening fault that is subjected to a local injection of fluid. We simulate a constant injection rate and vary the fault permeability, frictional properties and the initial state of stress. A synthetic seismic catalog is calculated during each simulation to determine the seismic source parameters.

Through our investigations, we observe that deformation is mainly aseismic, even within a fault with a high stress criticality. Another interesting finding is that events are mainly driven by shear stress transfer from the aseismic deformation and other events : only the first detected events are caused by pressure. Moreover, in addition to the injected volume, 4 hydromechanical and frictional fault parameters strongly affect the seismic/aseismic partitioning and the released seismicity : these are the stress criticality, the friction drop, the initial permeability and the critical slip distance, by order of influence. Excepting the critical slip distance, these parameters also impact the volume needed to rupture a fixed sized patch. These numerical experiments represent a promising attempt to understand the interplay of seismic and aseismic deformations during complex interaction among hydromechanical and frictional properties in the fault zone.

The subsequent step is to compare with geophysical observations from in-situ experiments and large-scale operational injection sites to better constrain the range of fluid perturbations favoring aseismic slip or seismic rupture.

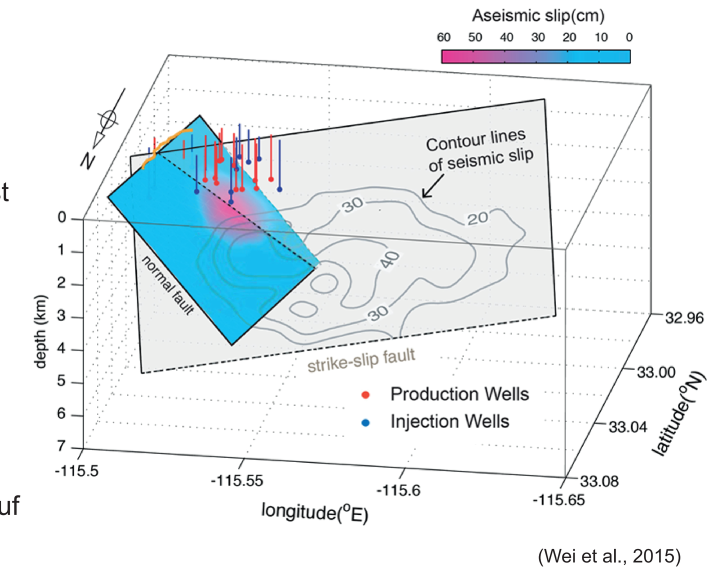
Fluids can trigger aseismic and seismic slip



(Ellsworth, 2013)

Numerous examples of injection- or extraction-induced seismicity across the world support the existence of a link between fluid pressure and seismic slip, such as in Oklahoma (Ellsworth, 2013). Moreover, the released seismic moment is firstly linked to the injected volume (Galis et al., 2017 ; McGarr & Barbour, 2018 ; van Der Elst et al., 2016) but it is sensitive to other injection and reservoir parameters (De Barros et al., 2019).

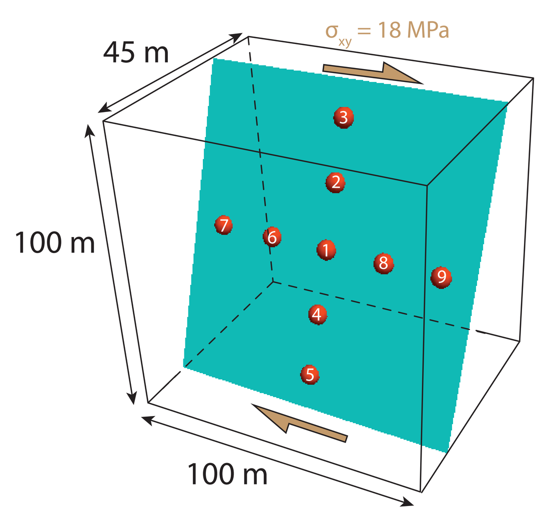
However, fluids also induce aseismic slip around the injection : an aseismic zone can be observed around injection point, and can trigger seismicity by stress transfer, which can be poroelastic (Wei et al., 2015) or caused by accelerating creep (Cappa et al., 2019). Moreover, experiments show that more than 95% of the deformation induced by fluid injection is aseismic (Duboeuf et al., 2017).

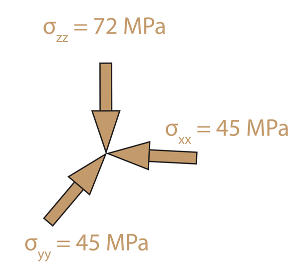


(Wei et al., 2015)

=> How do hydromechanical and frictional parameters influence the spatial and temporal repartition of seismic and aseismic slip into a fault and their consequences of the seismic moment to injected volume ?

Model setup

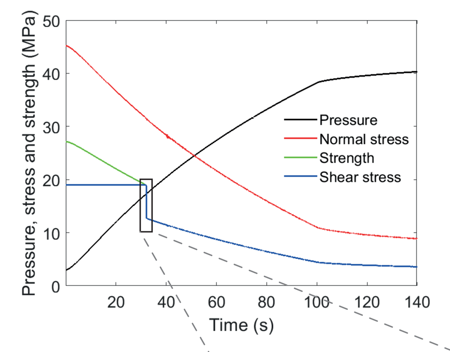


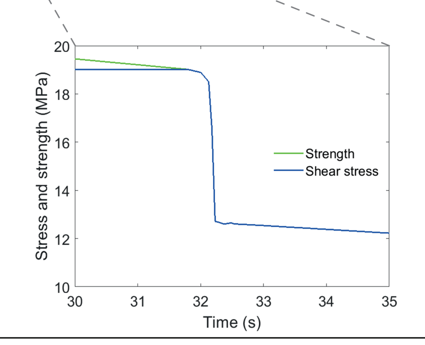


Geometry of the model and stress state on the fault.
A fluid injection is simulated in a 70°-dip fault located inside a homogeneous 100*45*100 m rock block near 3 km depth, using a hydromechanical code based on the distinct element method (3DEC).

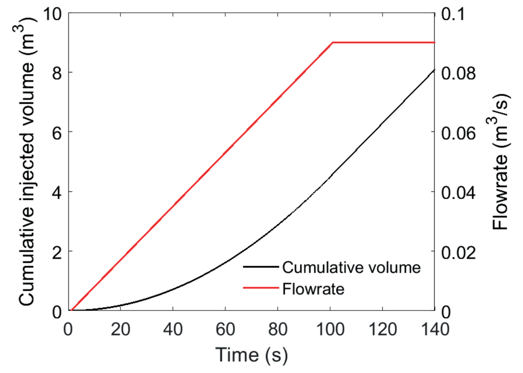
Initial stress state	Initial normal stress σ_{N0}	48 MPa
	Initial shear stress τ_0	19 MPa
	Criticality $\tau_0/(\sigma_{N0}-P_0)$	42.2 %
	Initial pressure P_0	3 MPa
Rock mechanical properties	Shear modulus G	15 GPa
	Bulk modulus K	25 GPa
	Density ρ	2500 kg/m³
Slip-weakening frictional properties of the fault	Static friction μ_S	0.6
	Dynamic friction μ_D	0.4
	Critical slip distance D_c	10 µm
Hydromechanical properties of the fault	Initial permeability k_0	3.3×10^{-8} m²
	Dilation angle ψ	0°

Initial parameters for the reference case simulation.



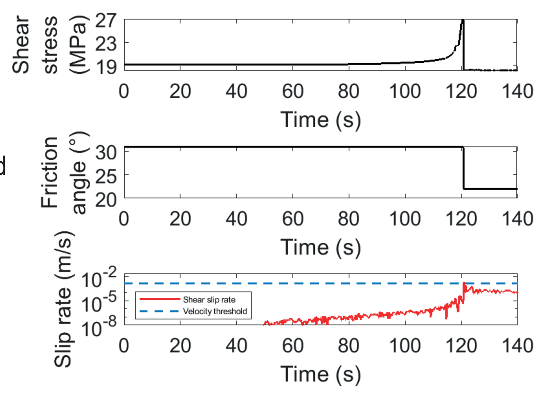


Stress, strength and fluid pressure evolution during the simulation at injection point.
A zoom is made when the strength becomes equal to the shear stress, that is when Mohr-Coulomb rupture condition is reached ($\tau=\mu(\sigma_N-P)$).
A linear slip-weakening friction law is used to simulate rupture.



Injection scenario during the 140 s-simulation.
The flowrate is imposed at control point 1, located at the center of the fault.

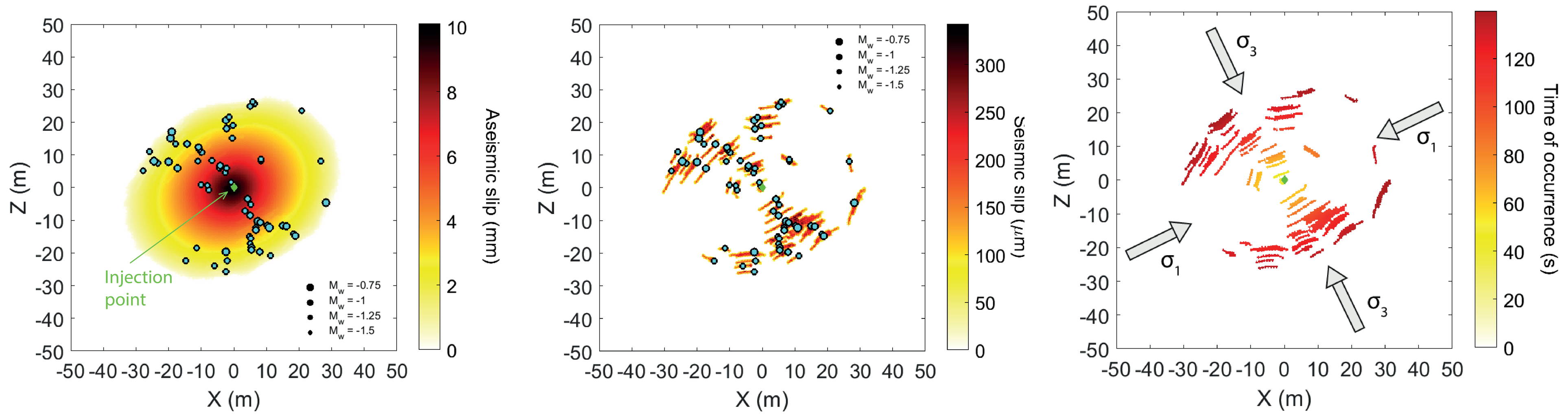
How is a seismic event defined ?
When rupture is reached, an event is detected if the slip rate exceeds a velocity threshold (defined here as 1.25×10^{-3} m/s, according to Day et al., 2005). This event is considered seismic if the slip rate threshold is exceeded on a large enough zone (>1 m²) in a short time lapse.



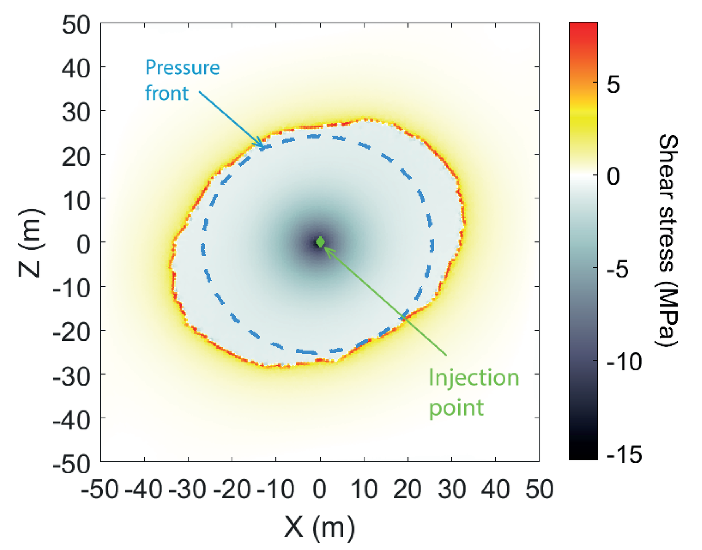
Reference case : spatio-temporal distribution of the aseismic and seismic slip on the fault

The detected events appear to be small : their magnitude are lower than M_w = -0.75.
The aseismic slip is continuous in space, whereas seismic slip has a more discrete distribution along elongated patches. The total slip (and therefore, the rupture) propagates elliptically, being guided by the stress field.
The seismicity propagates away from the injection point over time, in the orientation of the smallest principal stress σ_3 in both directions.

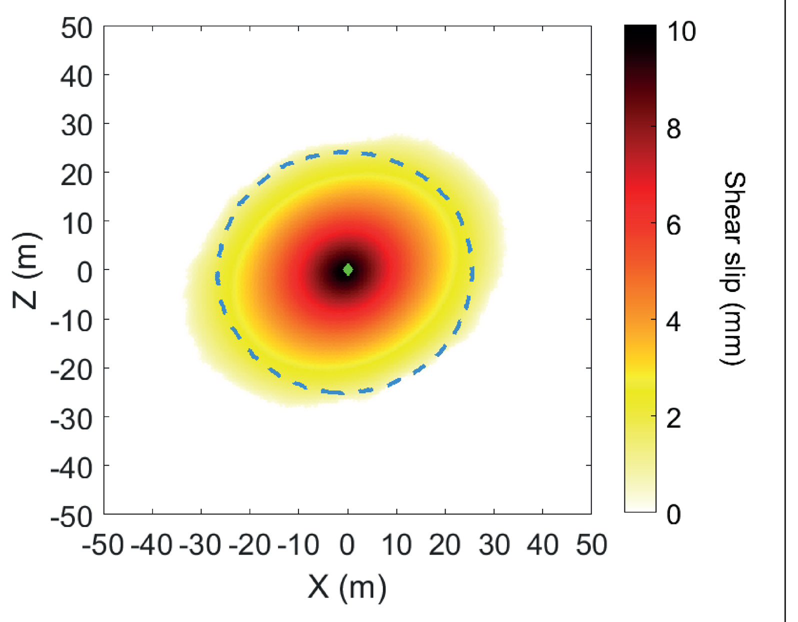
The majority of the deformation and of the moment released during the injection is aseismic.
The seismic slip is far smaller than the aseismic slip : its maximum value is 30 times smaller than the maximum value of the aseismic slip. It means the deformation is mostly aseismic. Moreover, the sum of the seismic areas is far smaller than the aseismic area ; consequently, the released moment is mostly aseismic (only 0.7% of the moment is seismic).



The spatio-temporal distribution of seismicity is driven by stress transfer



Events are mainly driven by shear stress transfer.
At the end of the simulation, the transition from negative to positive shear stress variations are located beyond the pressure front. Moreover, shear slip outpaces the pressure front : so the last seismic events are triggered entirely by shear stress transfer.



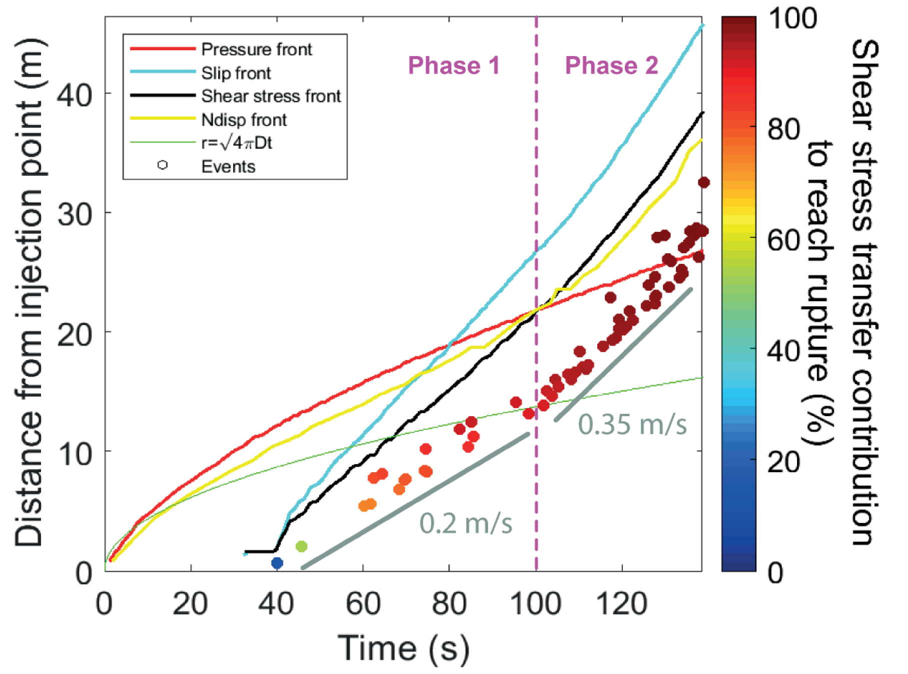
Furthermore, we want to quantify the contribution of the shear stress transfer for each seismic event. To this aim, the variation of stress ΔCFF needed to reach Mohr-Coulomb rupture from the initial stress state is defined as the sum of the stress and pressure variations when rupture state is reached :

$$\Delta CFF = \Delta\tau_{rupt} + \mu\Delta P_{rupt} - \mu\Delta\sigma_{N\,rupt}$$

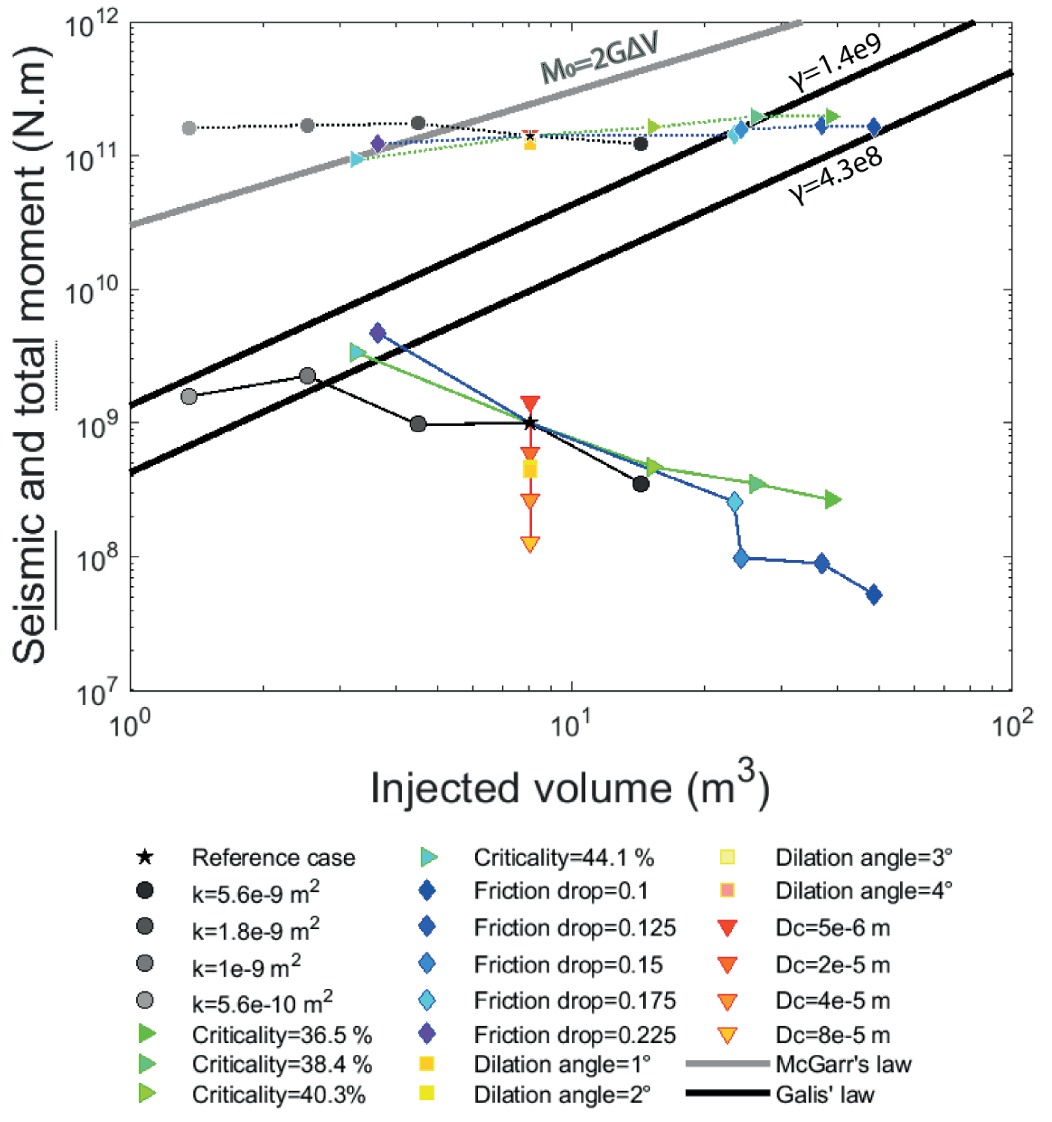
The shear stress transfer contribution ($\Delta\tau_{rupt}$ / ΔCFF) allows us to quantify the contribution of shear stress variations to reach rupture. Normal stress variations are neglected to measure ΔCFF. It appears that pressure variations dominate the rupture process only for the first 2 events ; as a consequence, shear stress transfer is the predominant mechanism to trigger events in this injection.

The permeability front evolves after 100 s as the shear stress front.
The stress and pressure fronts are defined as the farthest distance from injection to have an actual value superior as 105% of its initial value ; for displacement fronts, the threshold to be reached is 1 µm.
The normal displacement front initially follows the pressure front. After 100 s, it follows the shear stress front, ahead from the fluid. That is due to small variations of normal displacement that occur at the same time as the rupture. Thus, aseismic or seismic shear slip induces variations of permeability.

An evolution of seismicity in 2 phases :
- before 100 s, the event propagation (velocity of 0.2 m/s) follows the pressure front : even if shear stress transfer contribution is very high, the pressure diffusion seems to have a role in the spatial distribution of the seismic events.
- after 100 s, the event propagation increases its velocity (0.35 m/s), and follows the shear stress front, with a shear stress transfer contribution larger than 90%.



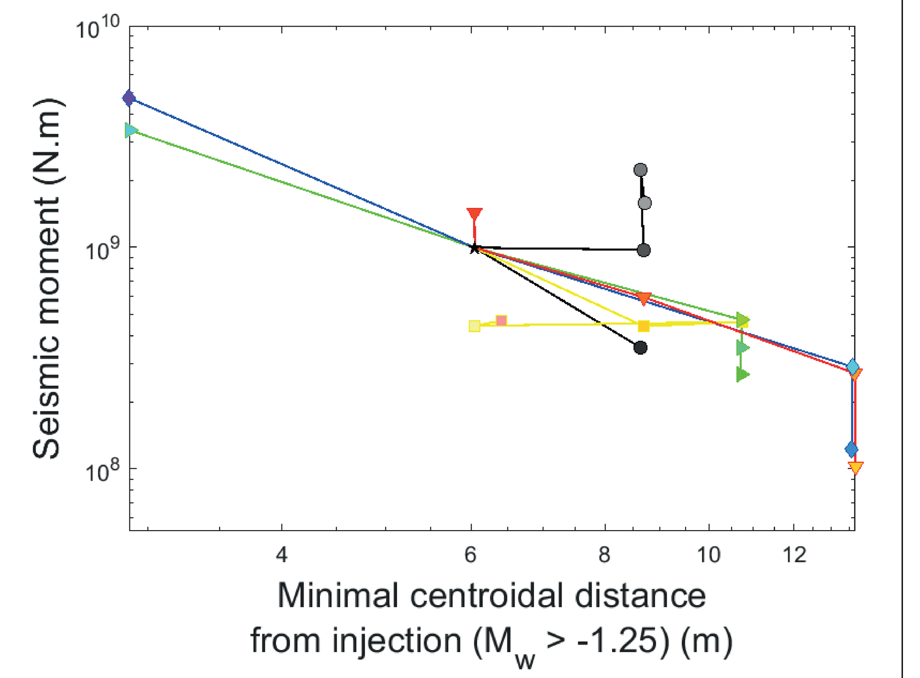
Influence of fault hydromechanical and frictional parameters on the seismic and aseismic behavior



A parametric study is performed to determine the predominant hydro-mechanical and frictional fault parameters influencing the seismic and aseismic moments. 22 injections are simulated, where 5 parameters (criticality of the stress state, initial permeability, dilation angle, friction drop, critical slip distance) are studied. In each test, the value of a single parameter is changed from the reference case. The simulations are stopped when the rupture front reaches a same fixed value (32 m from the injection source) : thus, the total moment is quasi-constant.

Stress criticality, friction drop, initial permeability and critical slip distance have an influence on the seismic moment.
A small increase of the criticality of the stress state (21%) involves an increase of the seismic moment of 900% (1 order of magnitude) ; to obtain a same variation of the seismic moment, a larger increase of the friction drop (60%), of the initial permeability (460%) or of the critical slip distance (700%) is needed.
Some parameters (criticality, friction drop, initial permeability) influence Mohr-Coulomb rupture criterion, by affecting the stress needed to reach rupture, the intensity of the stress transfer or of the pressure diffusion ; as a consequence, the volume needed to reach rupture changes for these parameters.

Hydromechanical and frictional parameters influence the seismic/aseismic partitioning.
Since the total moment is quasi-constant, the decrease of seismic moment with a fault hydromechanical parameter implies a decrease of the seismic/aseismic partitioning. Moreover, apart from permeability, a linear trend is highlighted between the seismic moment and the distance from injection of the first event that overcomes a fixed magnitude, for other seismic moment influencers. The location of the first detectable events could then be used to approximate the seismic/aseismic partitioning during the injection and the released seismic moment (De Barros et al., 2019).



Conclusion

- We have presented an investigation on the spatio-temporal evolution of seismicity during a fluid injection simulation. We have tested the sensitivity of the hydromechanical and frictional fault parameters on the released seismic moment and the injected volume.
- The majority of the rupture is aseismic. Rupture is predominantly driven by shear stress transfer.
- The spatio-temporal distribution of seismicity can be separated in 2 phases :
  - before 100 s, the event propagation (slow velocity : 0.2 m/s) follows the pressure front ;
  - after 100 s, the event propagation (faster velocity : 0.35 m/s) follows the shear stress front and the permeability front.
- 4 fault parameters (criticality, friction drop, initial permeability, critical slip distance, by order of importance) exert a high influence on the seismic moment released during the injection and on the seismic/aseismic partitioning.
  The first 3 parameters also influence the volume needed to rupture a same sized-patch, thus they are interdependent with the injected volume.
- Future directions :
  - Evaluate the interdependences between the injected volume and the fault permeability, the criticality and the friction drop.
  - Compare synthetic moments presented here with geophysical observations from in-situ experiments involving similar injected volumes.

References

Cappa, F., Scuderi, M.M., Collettini, C., Guglielmi, Y., Avouac, J.-P., 2019. Stabilization of fault slip by fluid injection in the laboratory and in situ. Sci. Adv. 5, eaau4065. https://doi.org/10.1126/sciadv.aau4065

Day, S.M., Dalguer, L.A., Lapusta, N., Liu, Y., 2005. Comparison of finite difference and boundary integral solutions to three-dimensional spontaneous rupture. J. Geophys. Res. 110. https://doi.org/10.1029/2005JB003813

De Barros, L., Cappa, F., Guglielmi, Y., Duboeuf, L., Grasso, J.-R., 2019. Energy of injection-induced seismicity predicted from in-situ experiments. Sci. Rep. 9. https://doi.org/10.1038/s41598-019-41306-x

Duboeuf, L., De Barros, L., Cappa, F., Guglielmi, Y., Deschamps, A., Seguy, S., 2017. Aseismic Motions Drive a Sparse Seismicity During Fluid Injections Into a Fractured Zone in a Carbonate Reservoir: Injection-Induced (A)Seismic Motions. J. Geophys. Res. Solid Earth 122, 8285–8304. https://doi.org/10.1002/2017JB014535

Ellsworth, W.L., 2013. Injection-Induced Earthquakes. Science 341, 1225942–1225942. https://doi.org/10.1126/science.1225942

Galis, M., Ampuero, J.P., Mai, P.M., Cappa, F., 2017. Induced seismicity provides insight into why earthquake ruptures stop. Sci. Adv. 3, eaap7528. https://doi.org/10.1126/sciadv.aap7528

McGarr, A., Barbour, A.J., 2018. Injection-Induced Moment Release Can Also Be Aseismic. Geophys. Res. Lett. 45, 5344–5351. https://doi.org/10.1029/2018GL078422

van der Elst, N.J., Page, M.T., Weiser, D.A., Goebel, T.H.W., Hosseini, S.M., 2016. Induced earthquake magnitudes are as large as (statistically) expected: INDUCED EARTHQUAKE MAXIMUM MAGNITUDES. J. Geophys. Res. Solid Earth 121, 4575–4590. https://doi.org/10.1002/2016JB012818

Wei, S., Avouac, J.-P., Hudnut, K.W., Donnellan, A., Parker, J.W., Graves, R.W., Helmberger, D., Fielding, E., Liu, Z., Cappa, F., Eneva, M., 2015. The 2012 Brawley swarm triggered by injection-induced aseismic slip. Earth Planet. Sci. Lett. 422, 115–125. https://doi.org/10.1016/j.epsl.2015.03.054