The Mzero experiments

Can hydraulic preconditioning of fractures modify induced seismicity characteristics?

Gischig Valentin, Meier Men-Andrin, Aretusini Stefano, Behnen Kathrin, Bröker Kai E.N., Ceccato Alberto, Clasen Repollés Victor, Clinton John, Dal Zilio Luca, Edme Pascal, Gholizadeh Doonechaly Nima, Hertrich Marian, Haag Thomas, Hochreutener Rebecca, Jalali Reza, Jiang Danyang, Lambiase Aurora, Lightfoot Alexandra, Magnabosco Cara, Massin Frédérick, Maurer Hansruedi, Mesimeri Maria, Mizrahi Leila, Mosconi Francesco, Obermann Anne C., Palgunadi Kadek, Pezzulli Edoardo, Pozzi Giacomo, Rinaldi Antonio Pio, Rosskopf Martina, Scarabello Luca, Schultz Ryan, Schwarz Miriam L., Selvadurai Paul A., Shakas Alexis, Spagnuolo Elena, Supino Mariano, Tian Lu, Tinti Elisa, Tuinstra Katinka B., Villiger Linus, Zhe Wang, Zappone Alba S., Zimmermann Eric, Jordan Aaron, Amann Florian, Giardini Domenico, Wiemer Stefan, Massimo Cocco

A joint effort of ETH, INGV, RWTH in the Bedretto underground laboratory

Schatzalp Workshop 2025 on Induced Seismicity

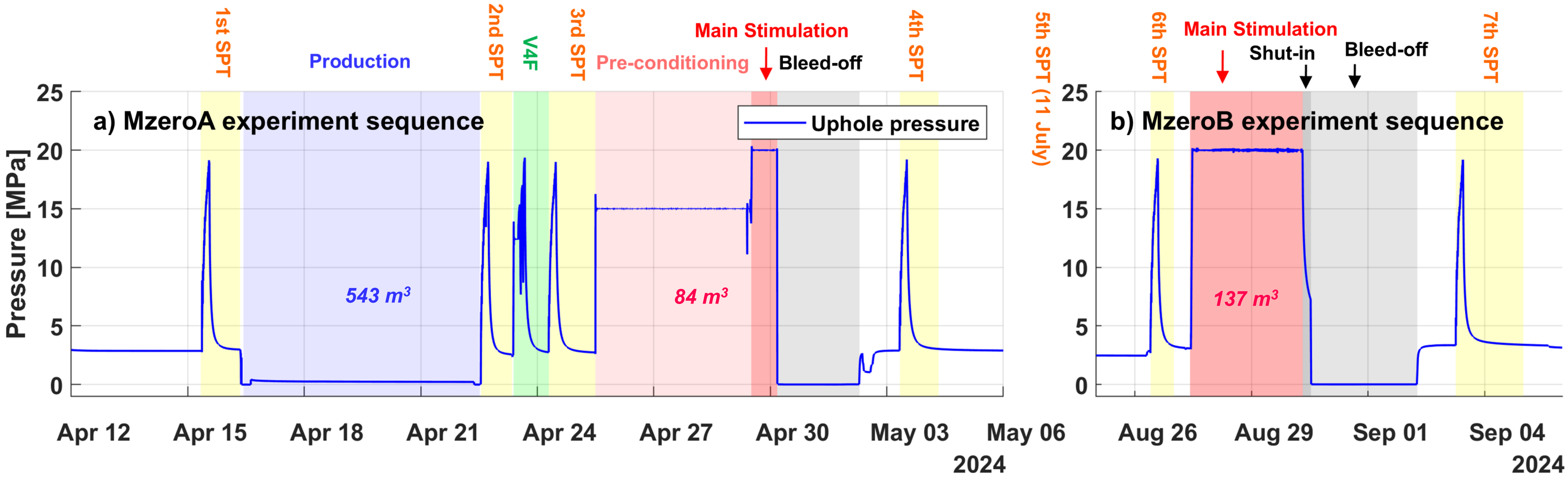
20 March 2025

FEAR

Fault Activation and Earthquake Rupture

Overview of Mzero experiments, injection protocol

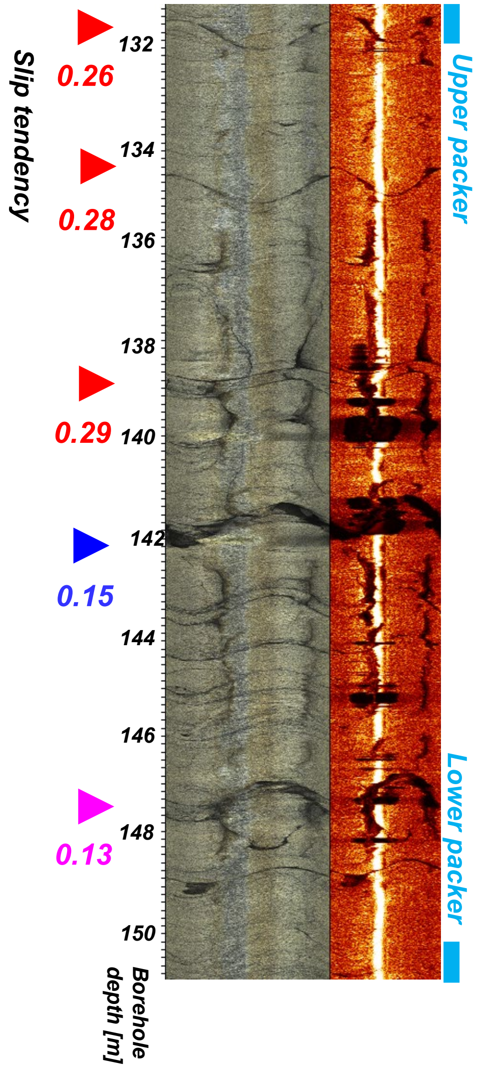
*The goal was to induce a Mw0.0 event. If only volume controls induced seismicity, estimated required volumes would have been 1000 – 10'000 m³. **Can we modify injection such that larger events become more probable?***

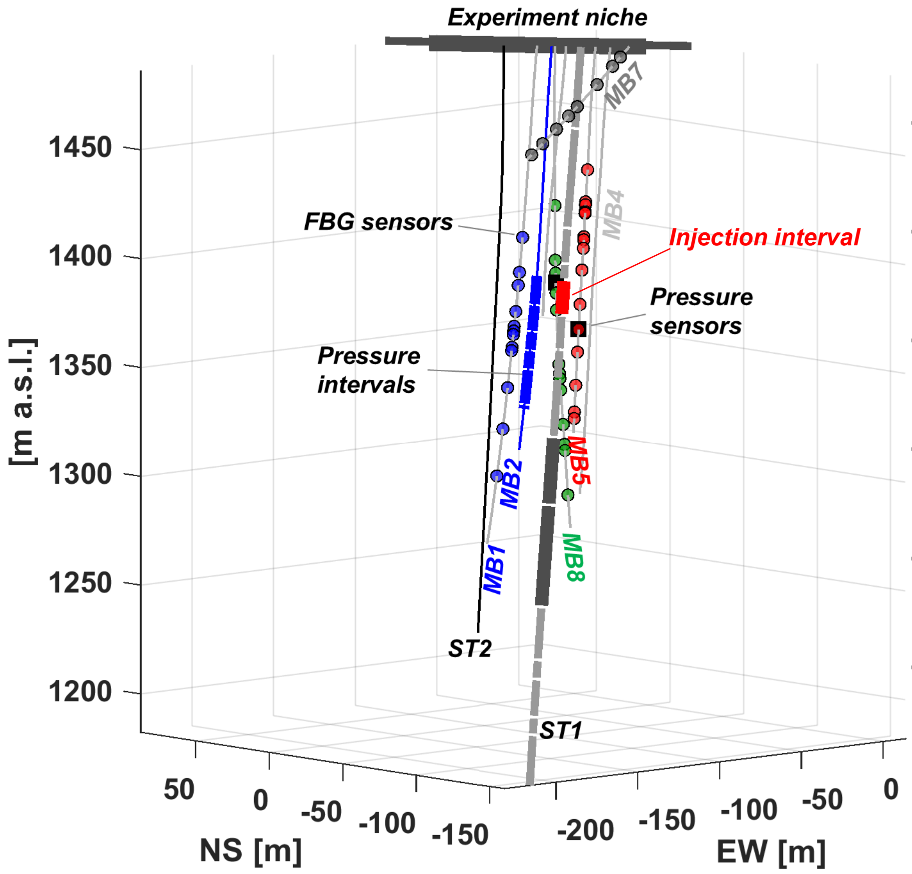


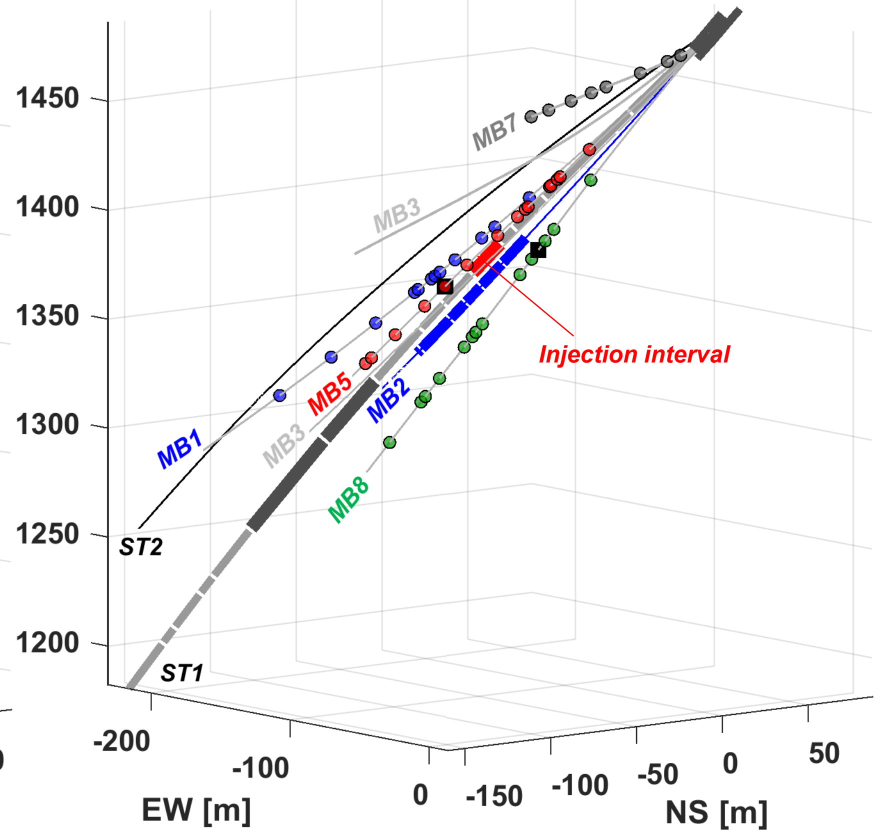
MzeroA: 4 days of preconditioning, i.e. injection close but below jacking / reactivation pressure, then rapid increase to 20 MPa

MzeroB: pressure directly increased to maximum pressure of 20 MPa

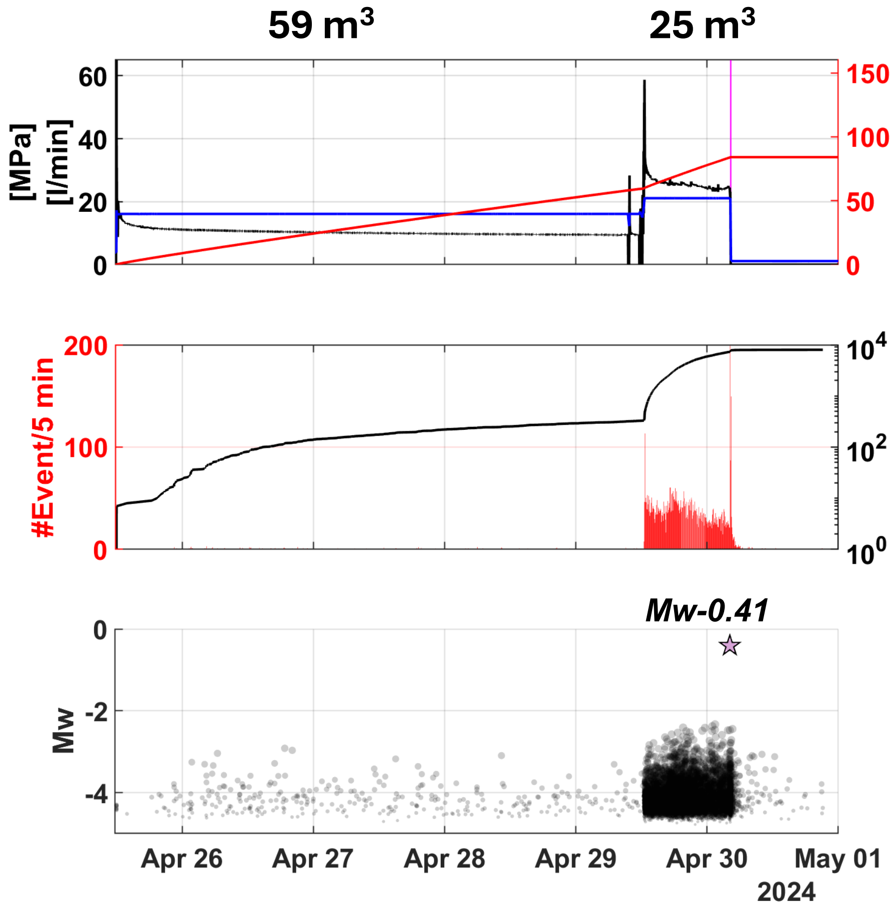
Stimulation interval and monitoring network

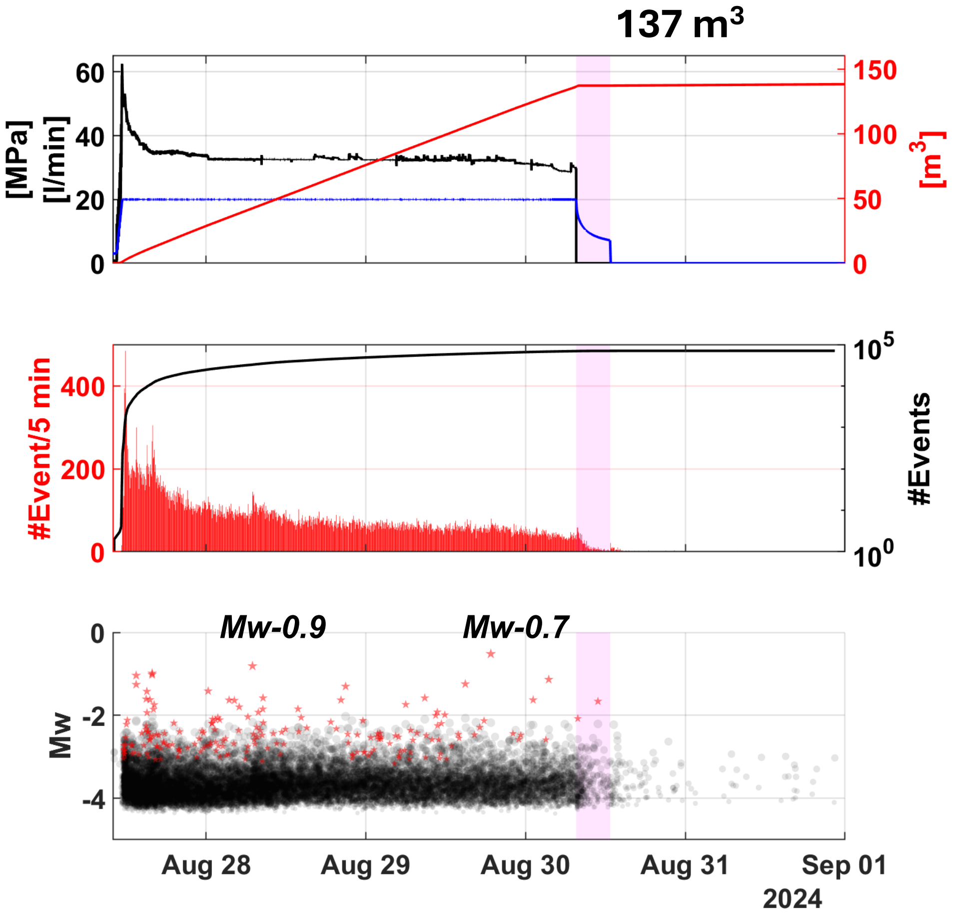






Temporal evolution of seismicity





***Steady state flow rates**:*

MzeroA ~25 l/min

MzeroB ~32 l/min

Seismicity rates:

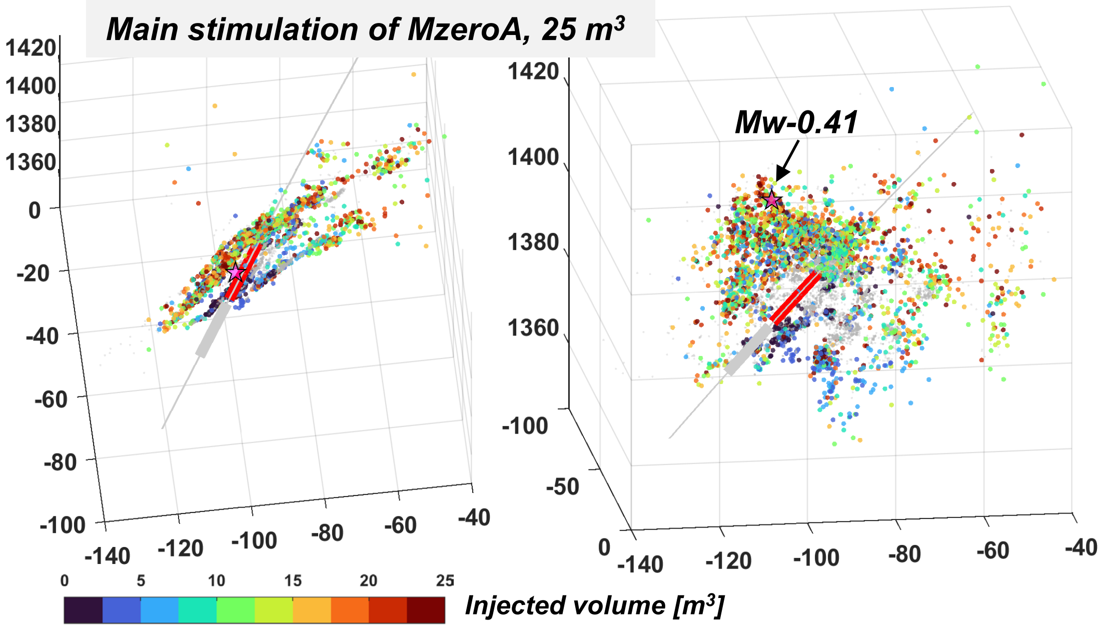
MzeroA >7'000 in 16 hours

MzeroB >70'000 in 70 hours

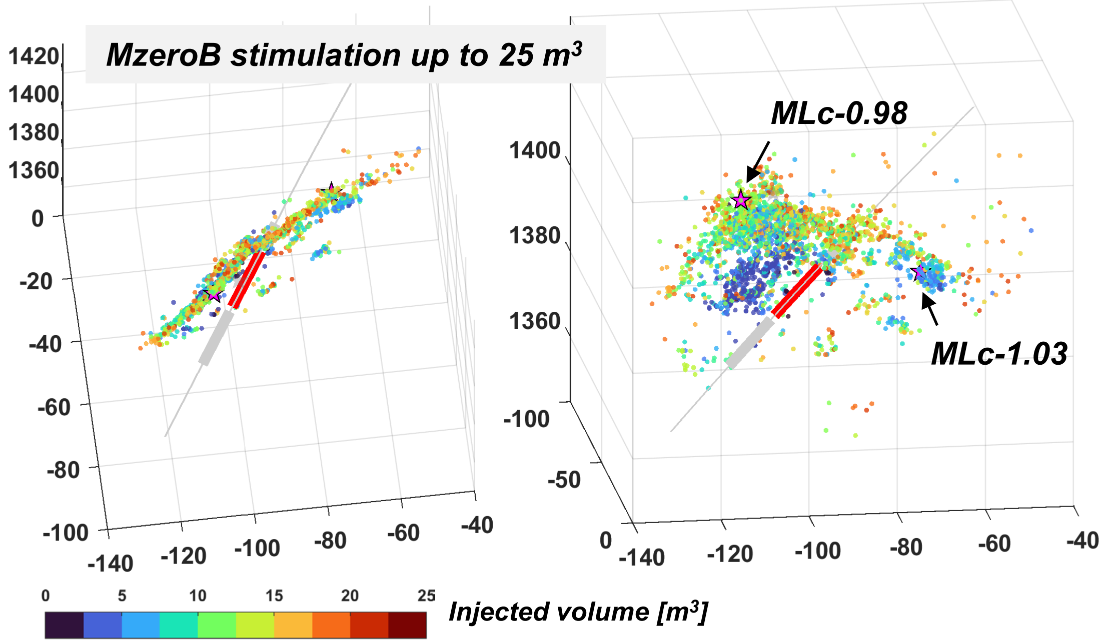
i.e. average seismicity rates more than twice as larger during MzeroB compared to MzeroA.

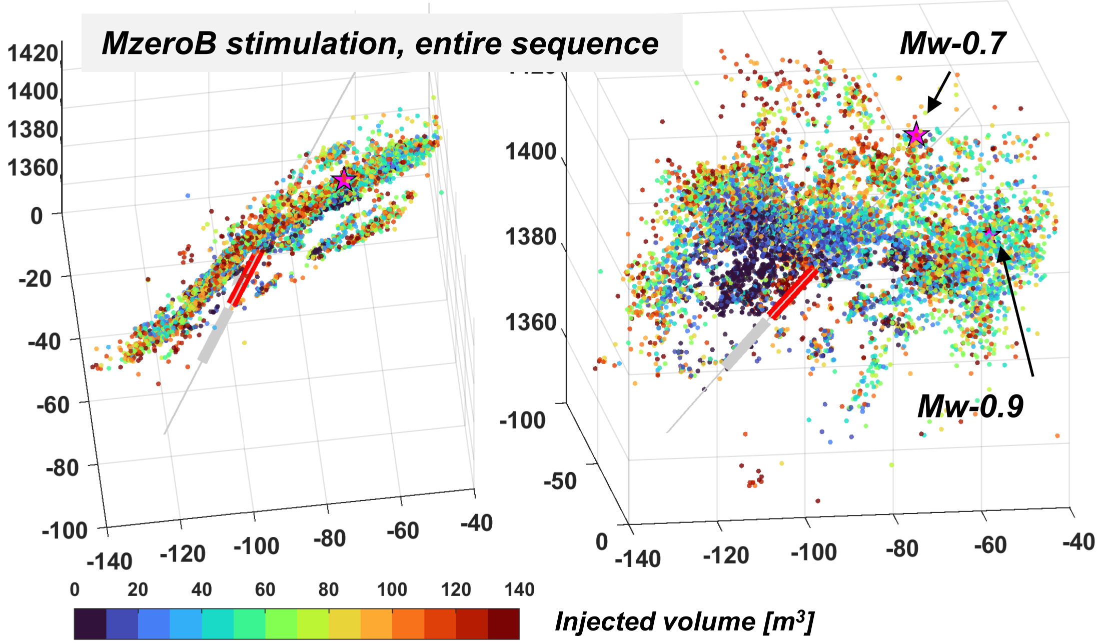
(Also if referenced to volume instead of time)

Spatial evolution of seismicity

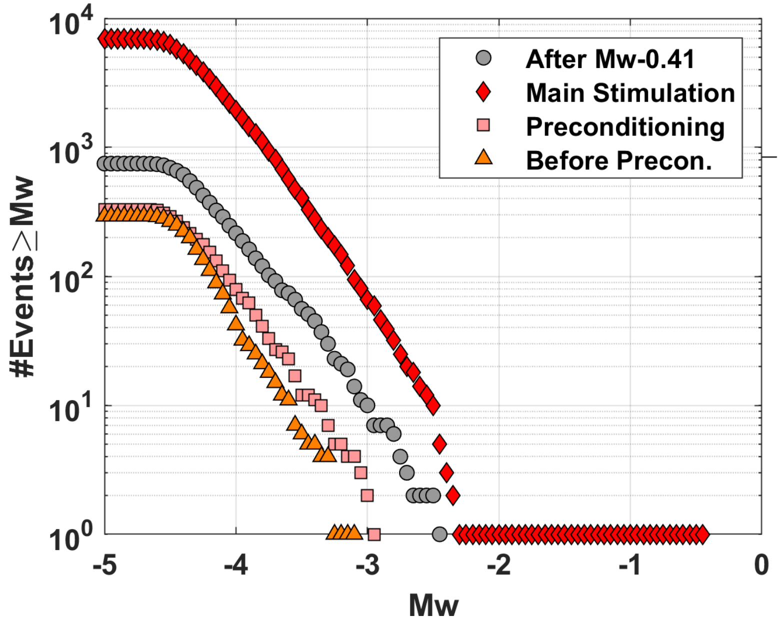


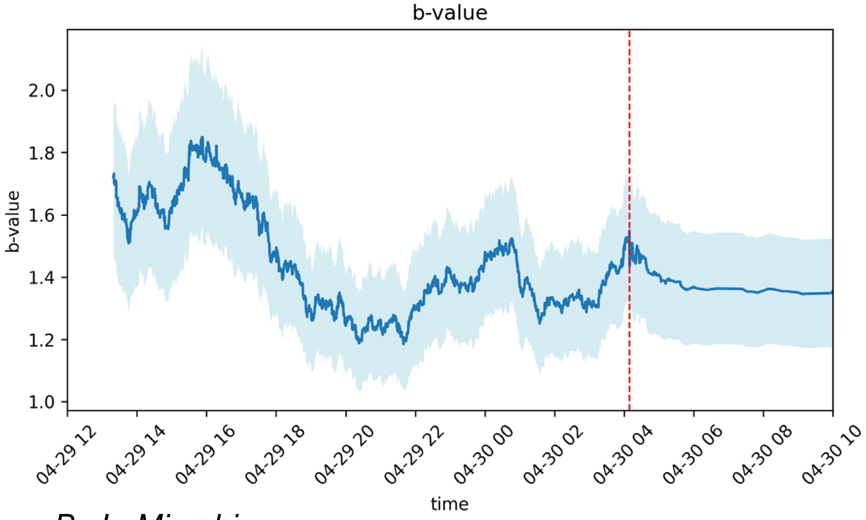
Seismicity pattern: *propagation pattern during MzeroA less clear than during MzeroB (first 25 m*^{3}*). Extend of seismicity cloud much larger during MzeroB.*



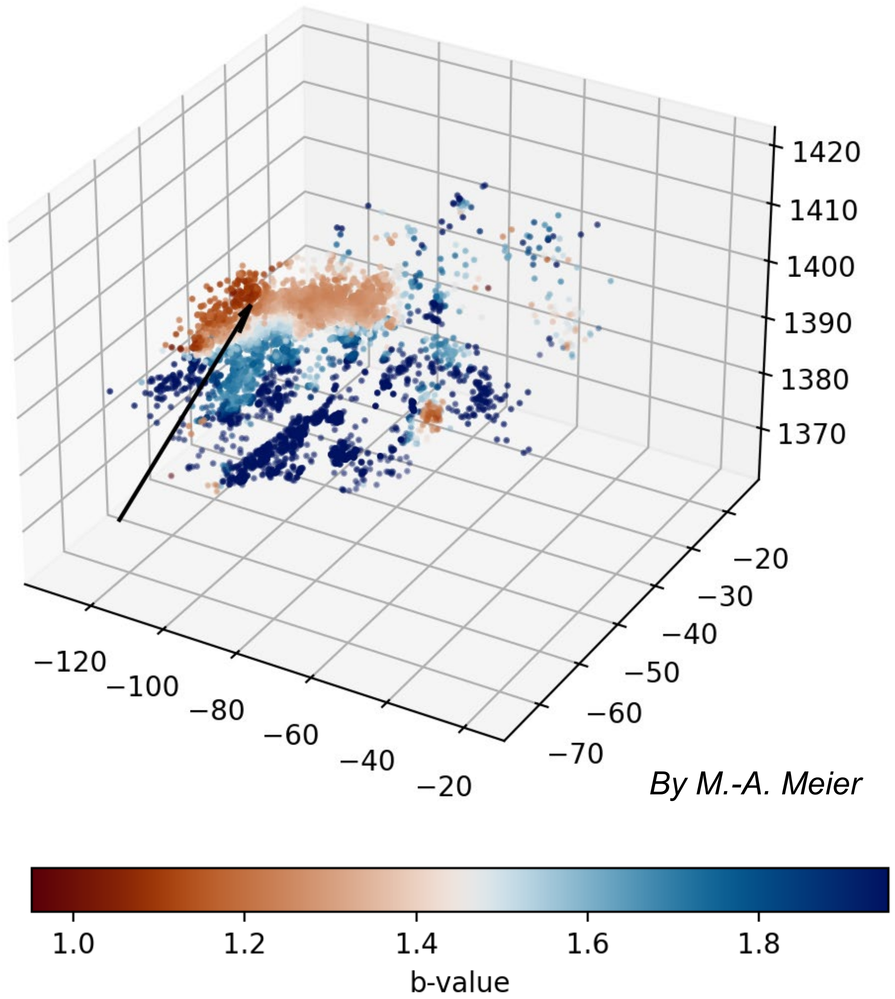


Magnitude statistics of MzeroA





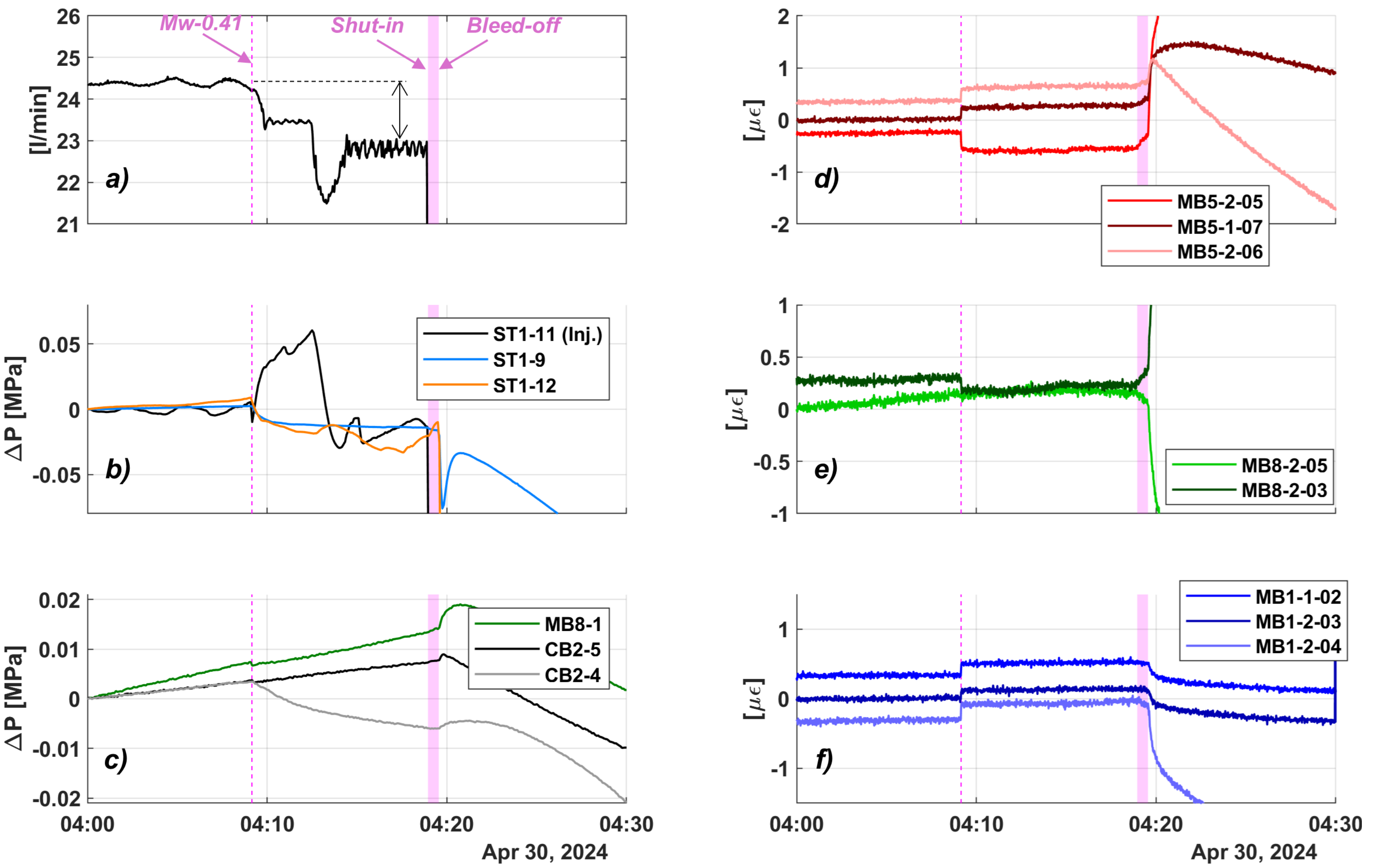
By L. Mizrahi



By M.-A. Meier

Mw-0.41 *event seems to be an* ***«outlier»*** *considering Gutenberg-Richter statistics. However, the temporal evolution and, even more, the spatial evolution of b-values make the event more expected.*

Poroelastic effects of Mw-0.41 event



Injection interval: *Flowrate dropped and interval pressure increased, i.e. resistance to flow increased.*

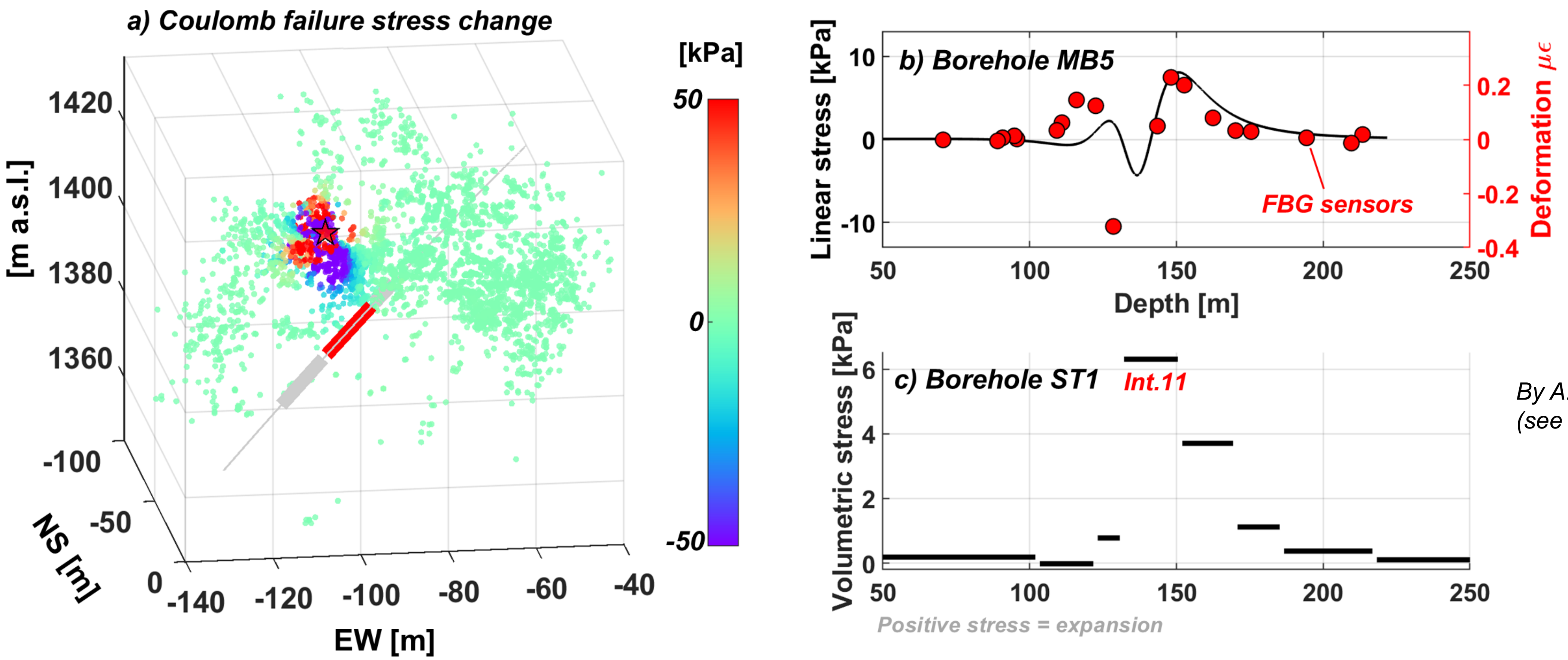
Pressure monitoring: *Several intervals showed a drop in pressure followed by a change in rate.*

Transmissivity: *a slight decrease of transmissivity confirmed these observations.*

Deformation monitoring *(FBG sensors): co-seismic deformation of a few 10th of microstrain was observed.*

>> Can be used to infer stress redistrbution

Stress redistribution by Mw-0.41 event



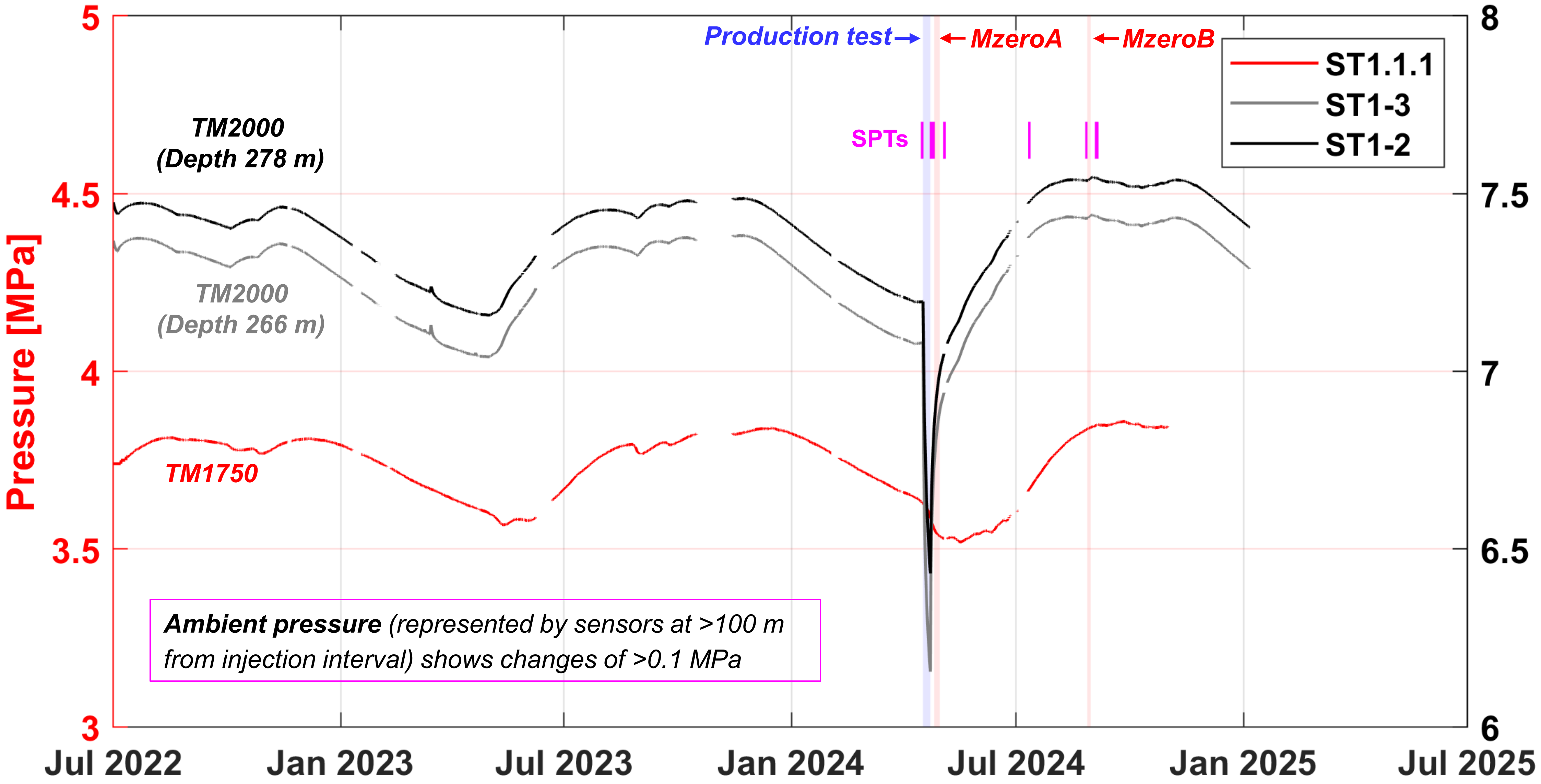
By A. Lambiase (see also her poster)

Stress changes *> 0.05 MPa are mostly focussed 5-10 m around the main shock, most of MzeroB seismicity cloud has seen <0.05 MPa*

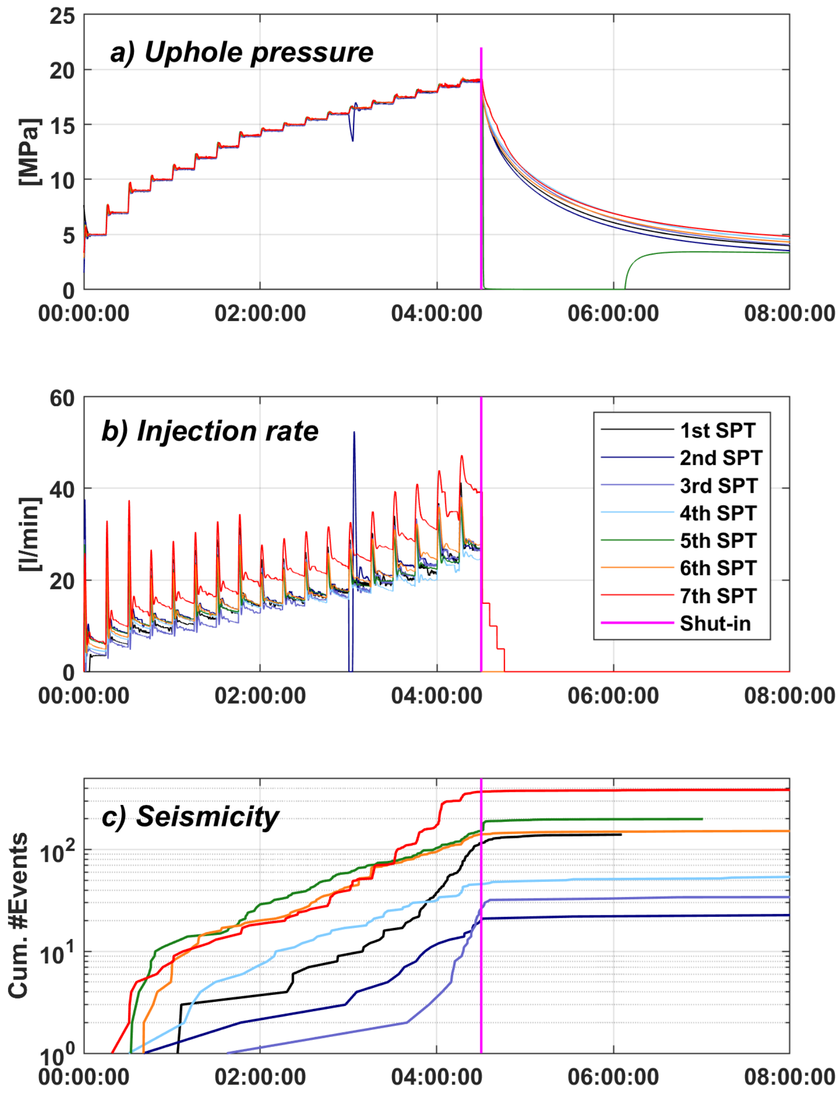
Linear stress and volumetric stress *observed in deformation and pressure monitoring, respectively, are only in the range of <0.01 MPa*

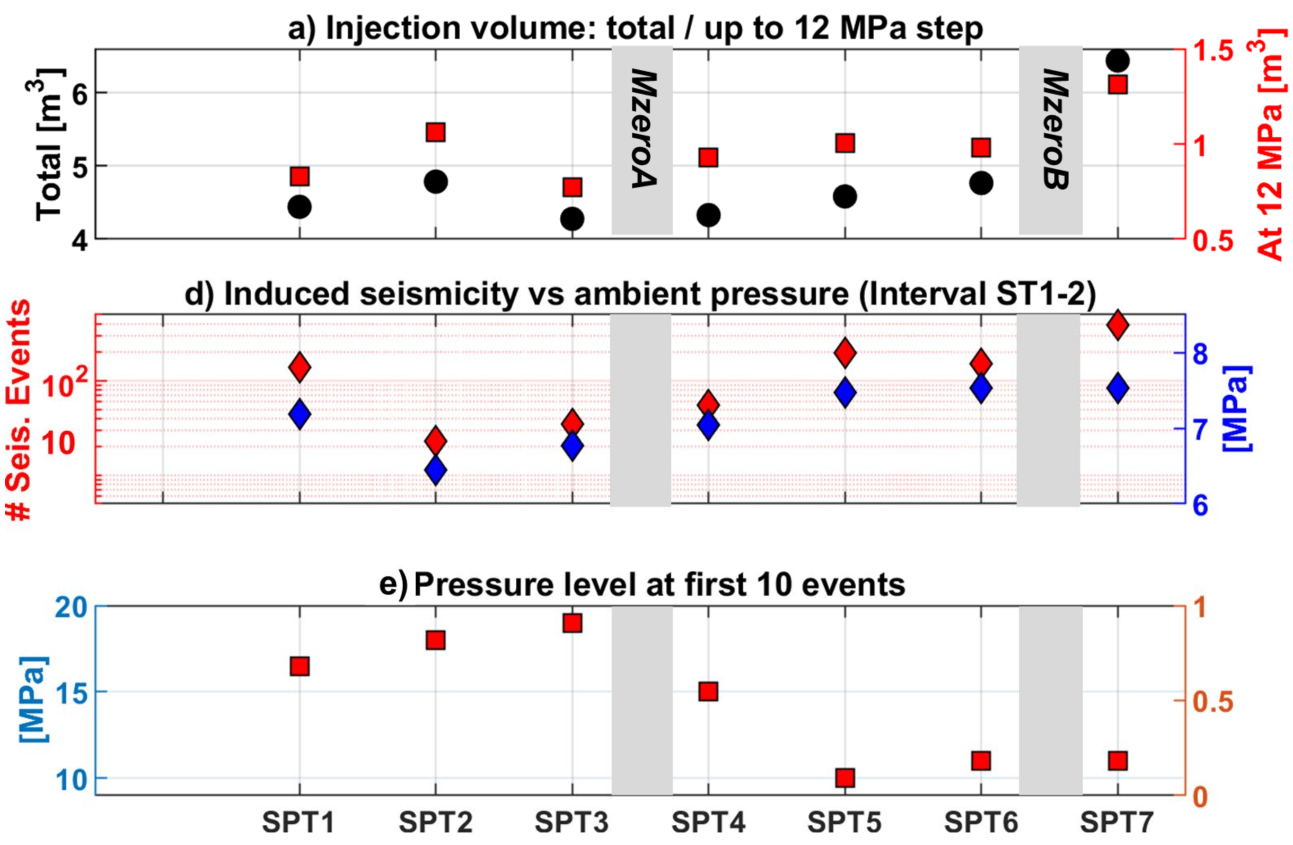
>> May not explain (alone) the different seismogenic responses of MzeroA and MzeroB

Seasonal pressure changes around the Bedretto tunnel



Reservoir changes from SPT tests: seismicity





Number of seismic events *per experiment correlates with ambient pore pressure (ST1-2 as proxy). Onset of seismicity (first 10 events as proxy) occurred at lower pressure levels.*

>>Are the different seismogenic responses of MzeroA and MzeroB driven by ambient conditions?

Conclusion

- Difficult to compare different injection strategies (e.g. success of preconditioning), because subsequent tests may find altered reservoir conditions.
- Mechanisms that may have led to changes in reservoir and thus change in seismogenic response:

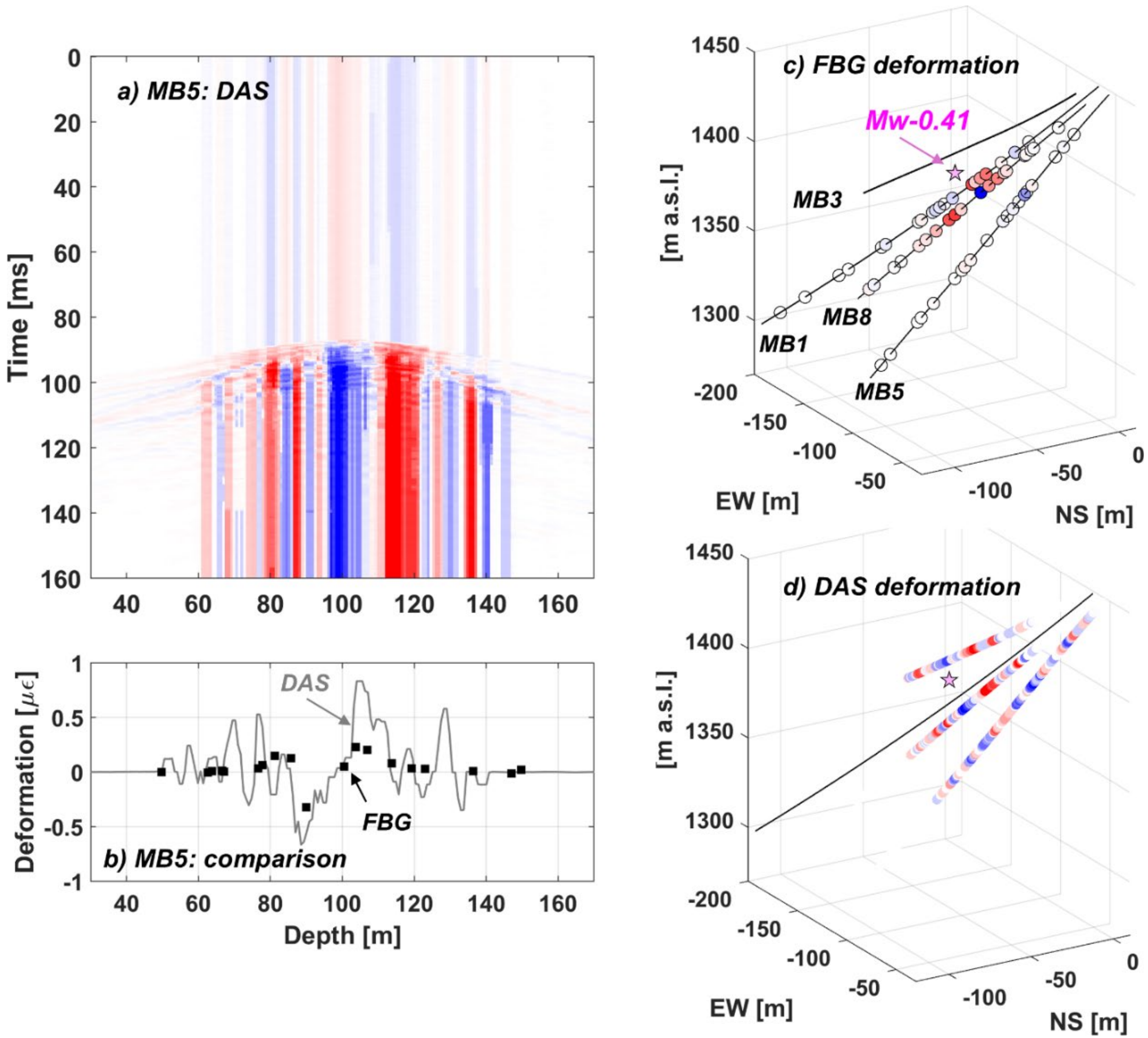
  → Stress redistribution due to main shock (< 0.01 MPa)
  → Ambient pressure change: order of 0.1 MPa
  → Time-dependent stress relaxation / "resetting" through aseismic processes

- **BUT perhaps preconditioning DID do the trick** – after all it is not a minor change in injection strategy.
- Understanding the details of the poroelastic and rupture dynamic effects that may lead to a change in response depending on injection strategy is work in progress .

Key implication for induced seismic hazard: if two subsequent hydraulic stimulations in the same rock mass deviate so strongly from each other, even if partly owed to a different injection protocol, how do we do a priori seismic hazard analyses?

FEAR
Fault Activation and Earthquake Rupture

Stress redistribution of main shock



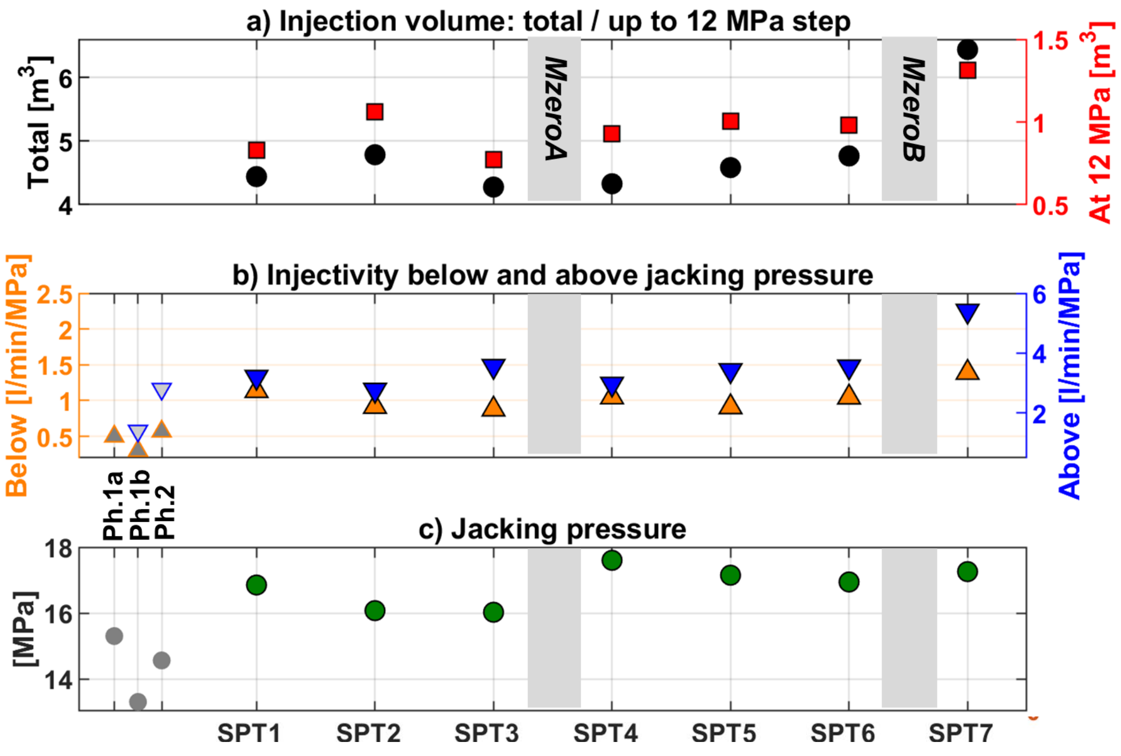
Stress redistribution related to the Mw-0.41 has been observed on from FBG time series, DAS and evidently lead to changes in hydraulic connections.

Have the stress redistribution been responsible for the different response of MzeroB?

What is missing?

Where do the differences between FBG and DAS strain come from?

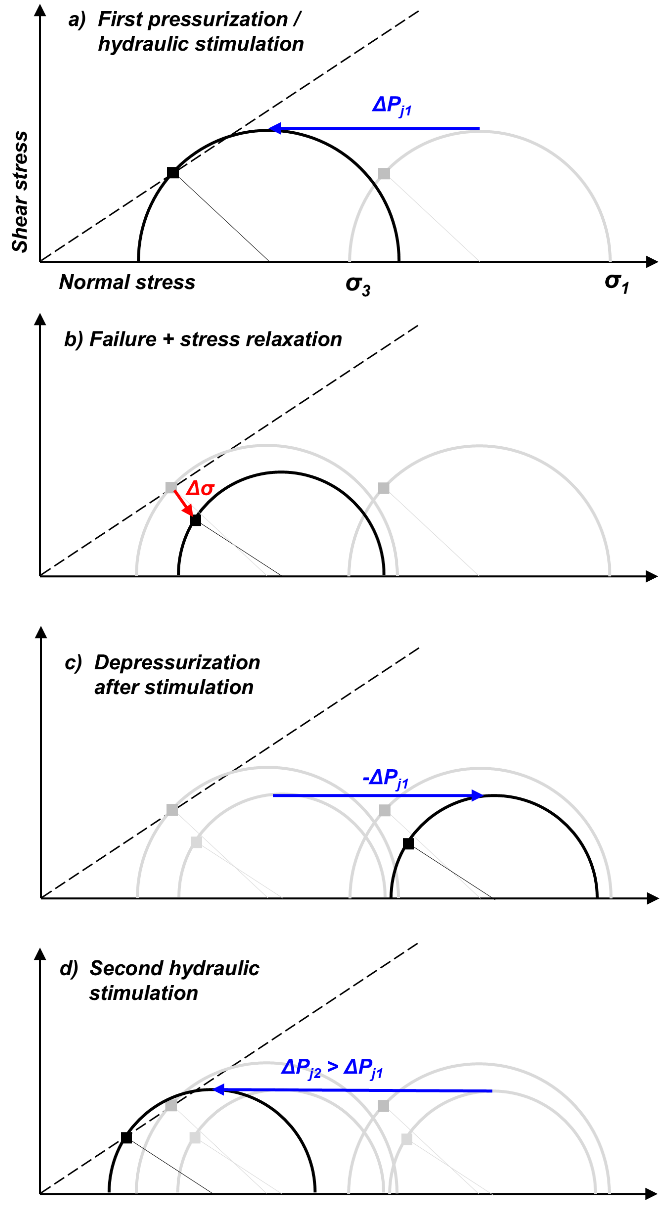
Reservoir changes from SPT tests: Hydromechanical properties



Increase of injectivity after MzeroB.

Drop in transmissivity (from 4e-7 m^2/s. to 1.7-1.8e-7 m^2/s) not reflected in injectivity measurements

Signs of deviatoric stress relaxation after MzeroB?

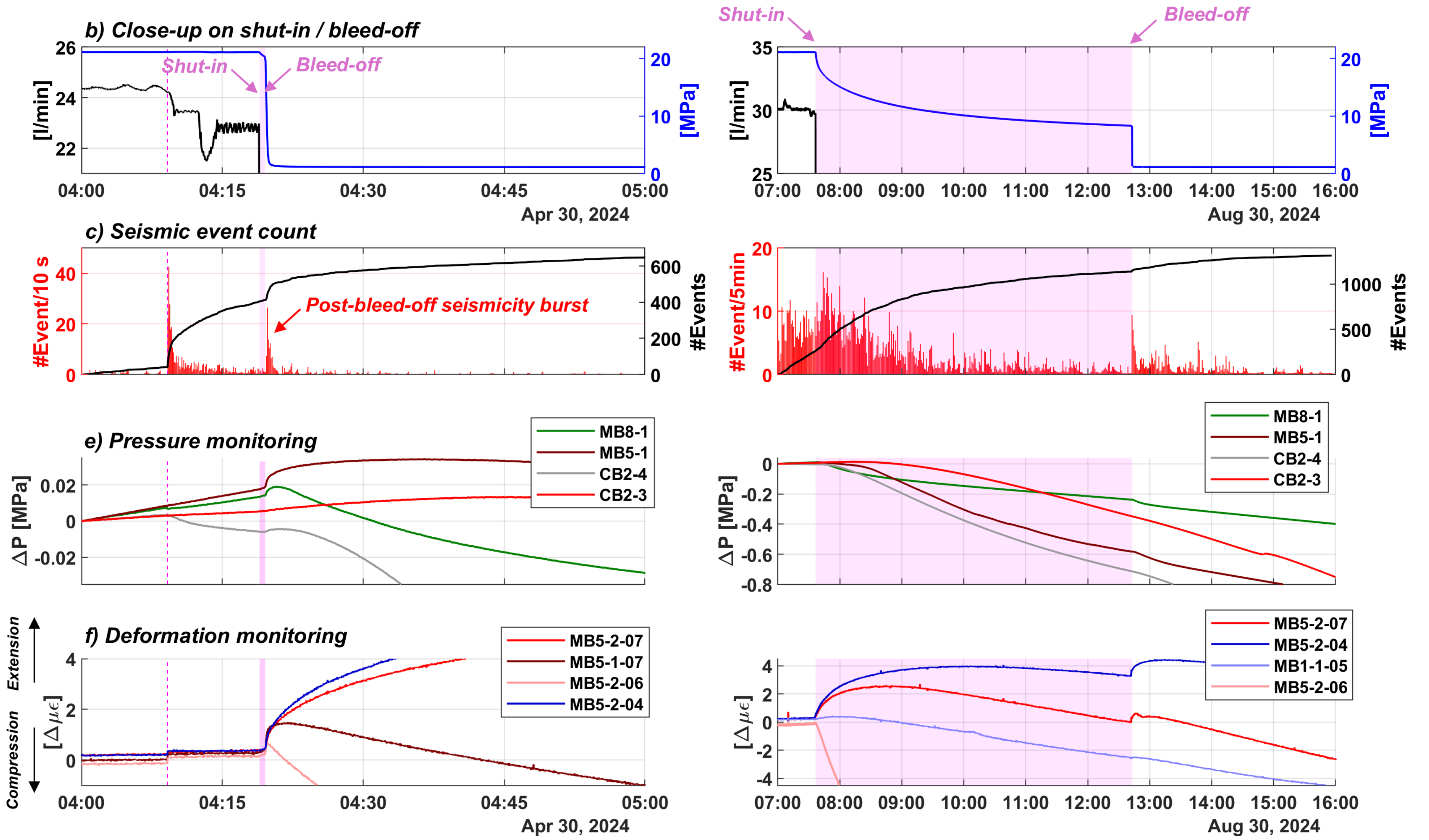


What is missing?

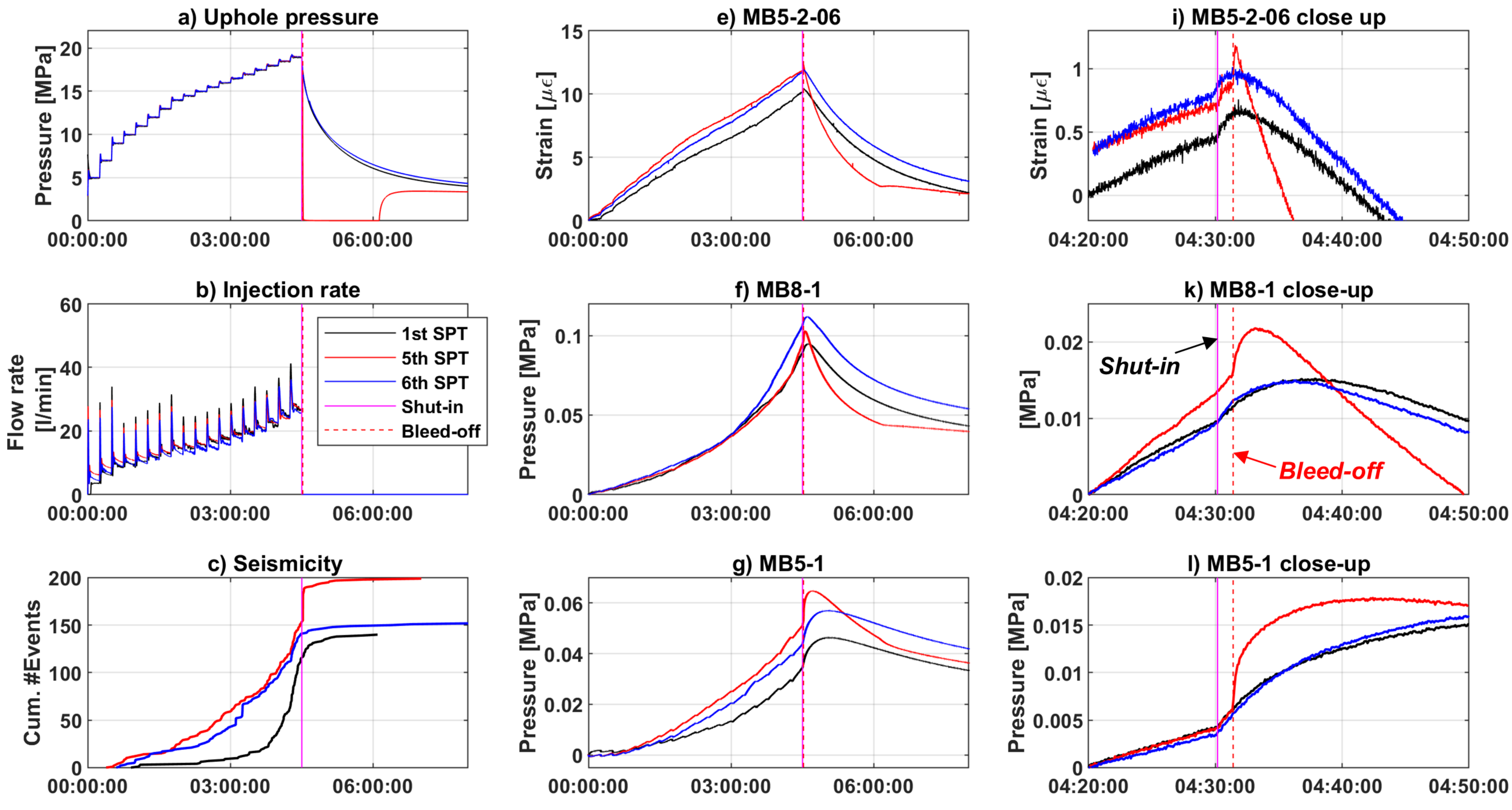
Transmissivity values after MzeroB

Are different hydraulic conditions reflected in noble gas / geochemistry / microbiology monitoring?

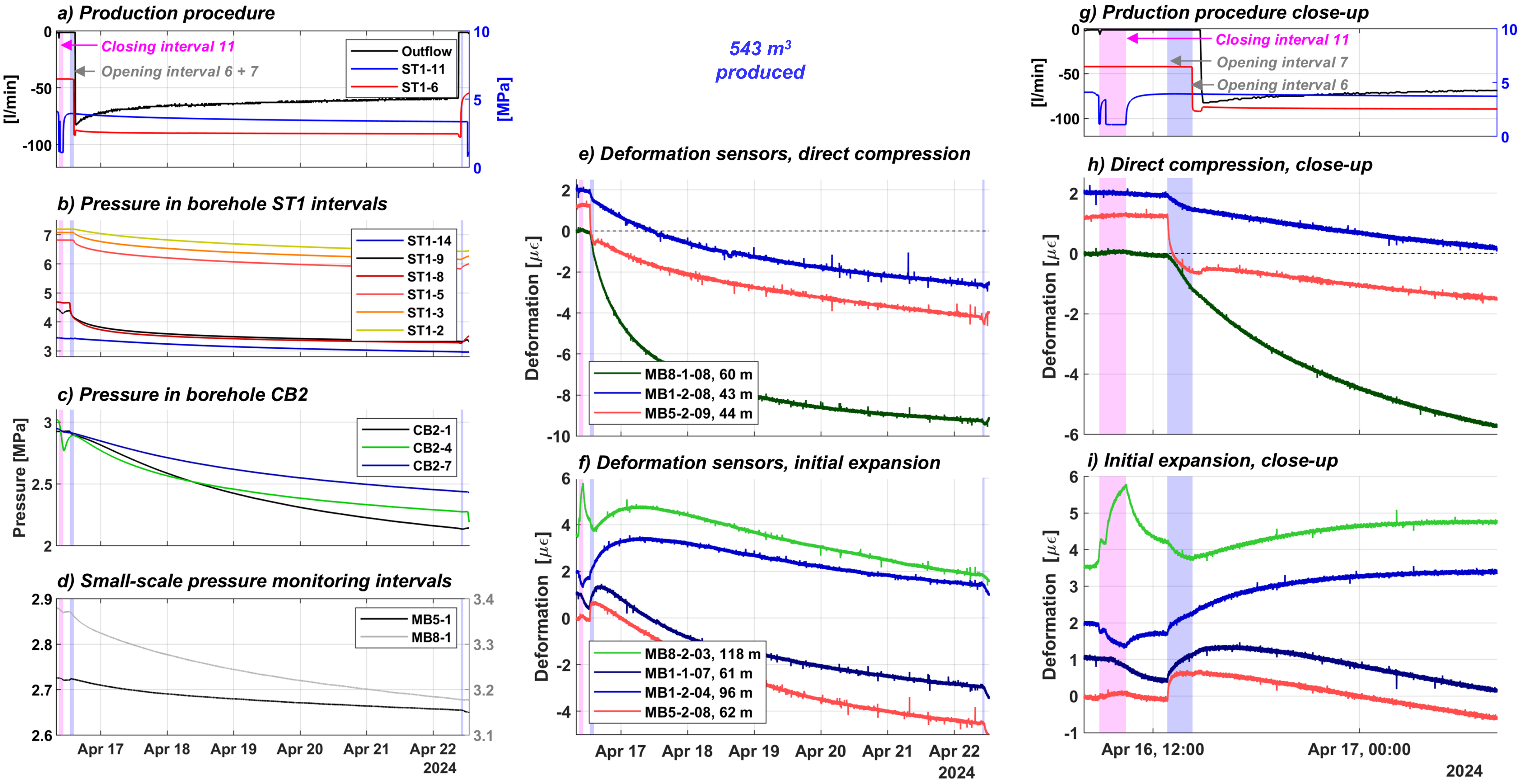
Shut-in and bleed-off related effects (work in progress, another paper?)



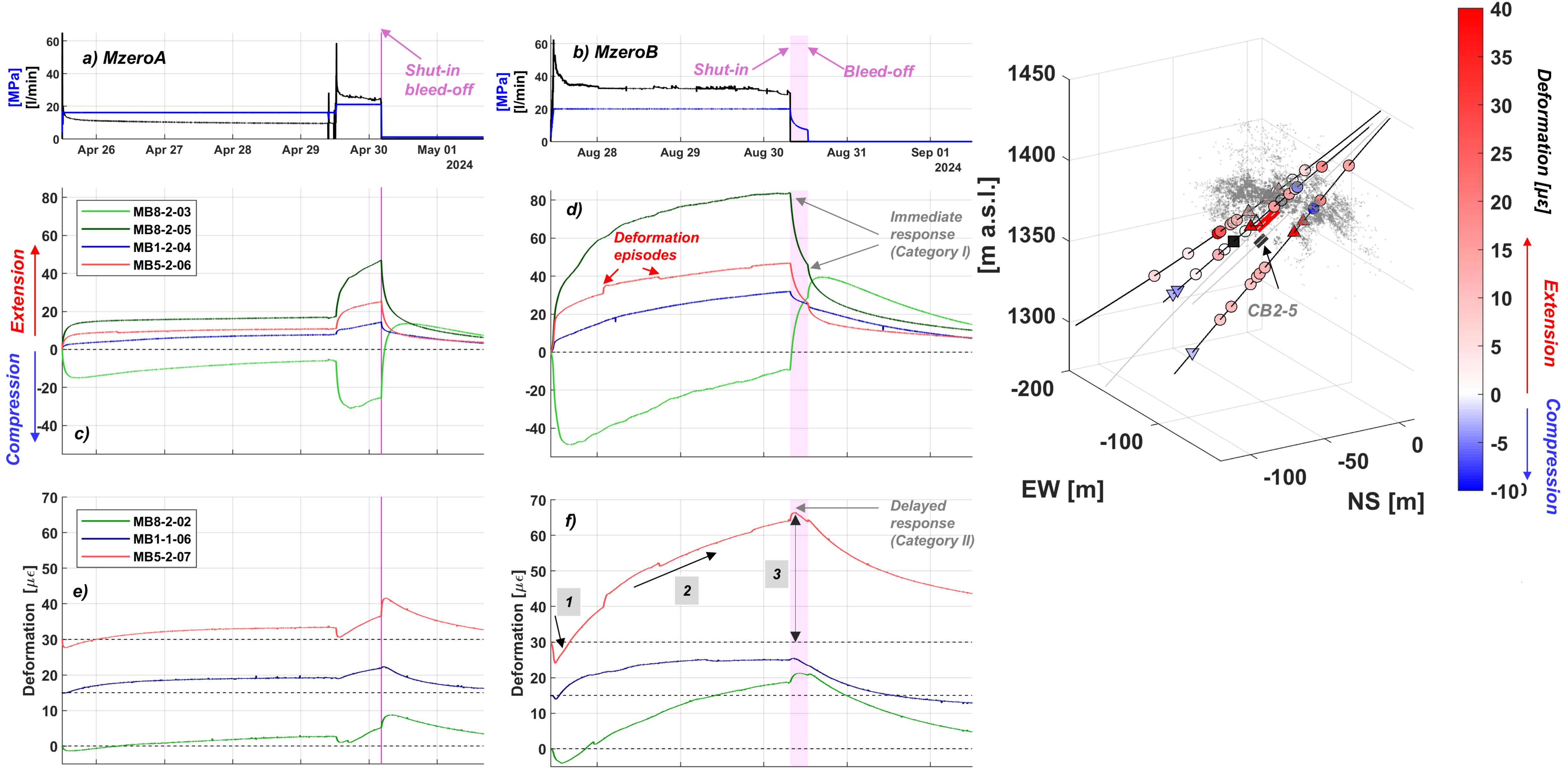
Shut-in and bleed-off related effects (work in progress, another paper?)



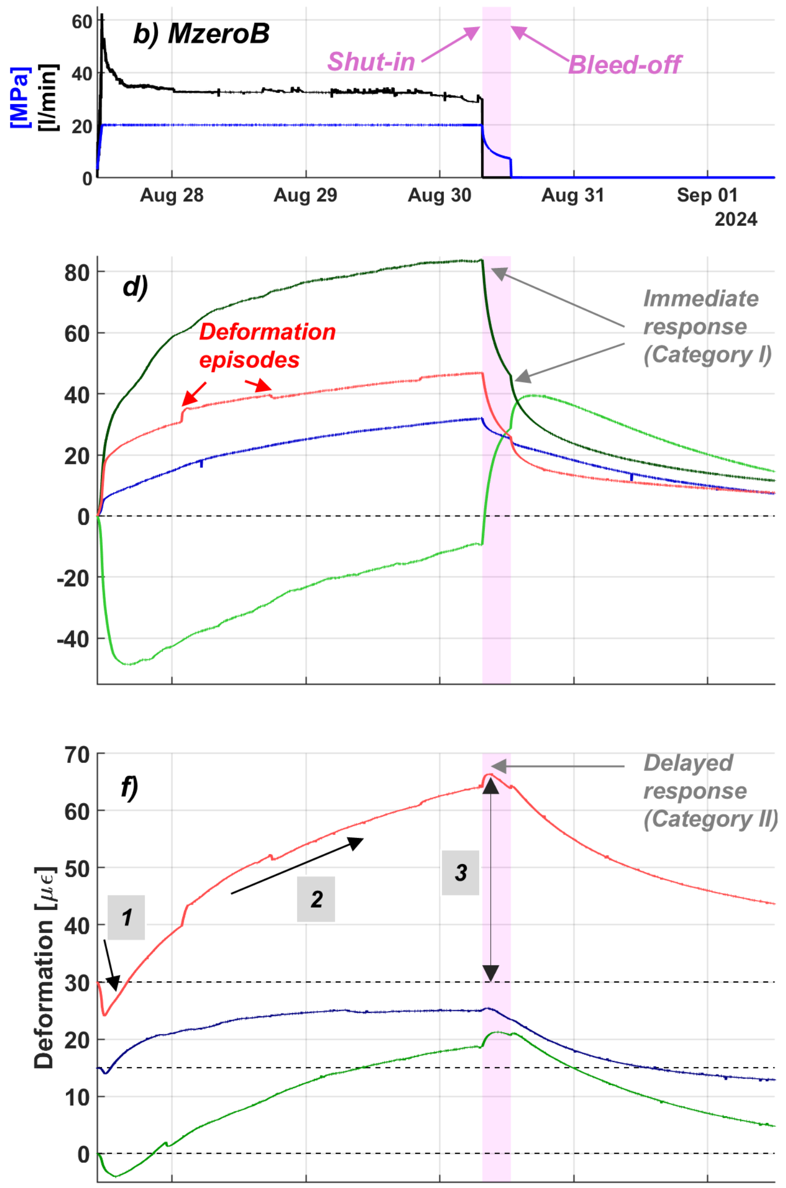
Production related poroelastic effects (work in progress)

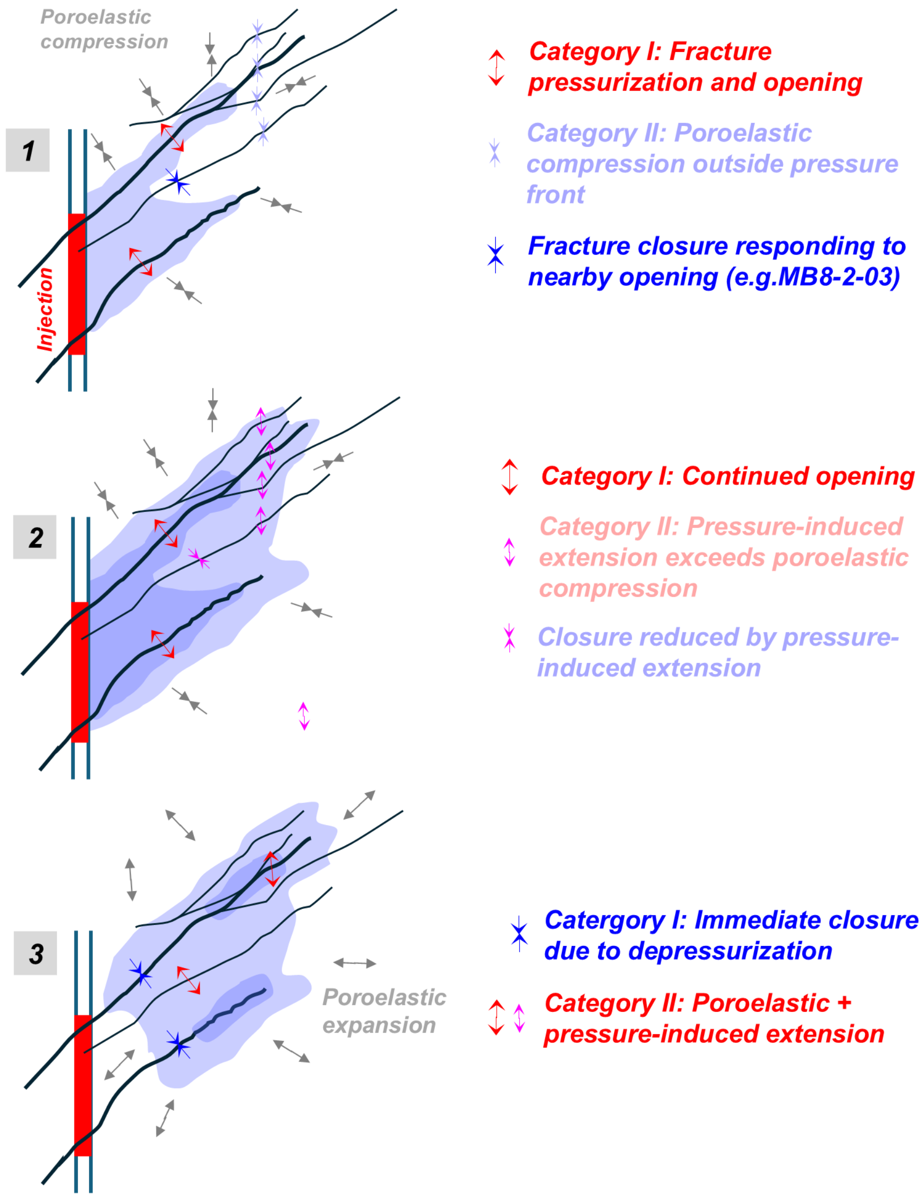


Observations on deformation field



Interpretation of different deformation responses





Is the initial phase of compression defining for the seismogenic response?

Has the initial phase of compression been less prononuced for preconditioning explaining the different seismogenic response?

(What is missing?)

(Numerical models would be better suitable to explain the poroelastic effects)