Active seismic monitoring of CO_2-saturated brine injection into a fault (CS-D experiment in the Mont Terri Rock Laboratory)

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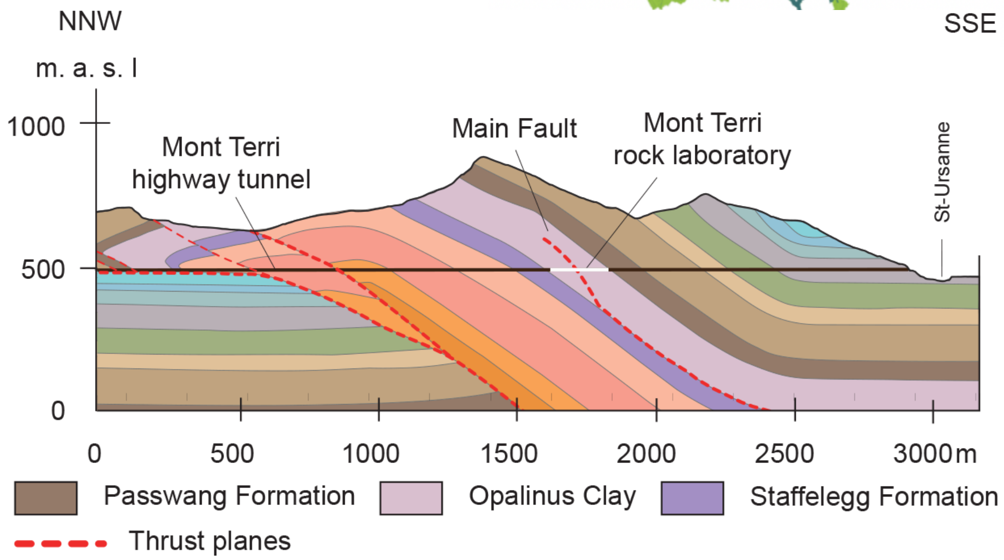
Introduction:
CS-D experiment in the Mont Terri Laboratory

Mont Terri Project



After Nussbaum et al. (2017): Tectonic evolution around the Mont Terri rock laboratory, northwestern Swiss Jura: constraints from kinematic forward modelling. Swiss Journal of Geosc., 110, DOI 10.1007/s00015-016-0248-x.

 Grab et al. (https://doi.org/10.5194/egusphere-egu2020-21588)

Flow through faults, potential leaks through a cap rock:

Simulating CO_2 (dissolved in formation water) leaking trough a fault in a caprock

Objectives of the CS-D experiment:

- investigating how the exposure to CO_2-rich brine affects sealing integrity of a caprock, hosting a fault system (permeability changes, induced seismicity).
- observing directly the fluid migration along a fault and its interaction with the surrounding environment.
- testing instrumentation and methods for monitoring and imaging fluid transport.

More about the CS-D experiment:

Wenning et al., “Fault hydromechanical characterization and CO_2-saturated water injection at the CS-D experiment, Mont Terri Rock Laboratory” (EGU2020-19243)

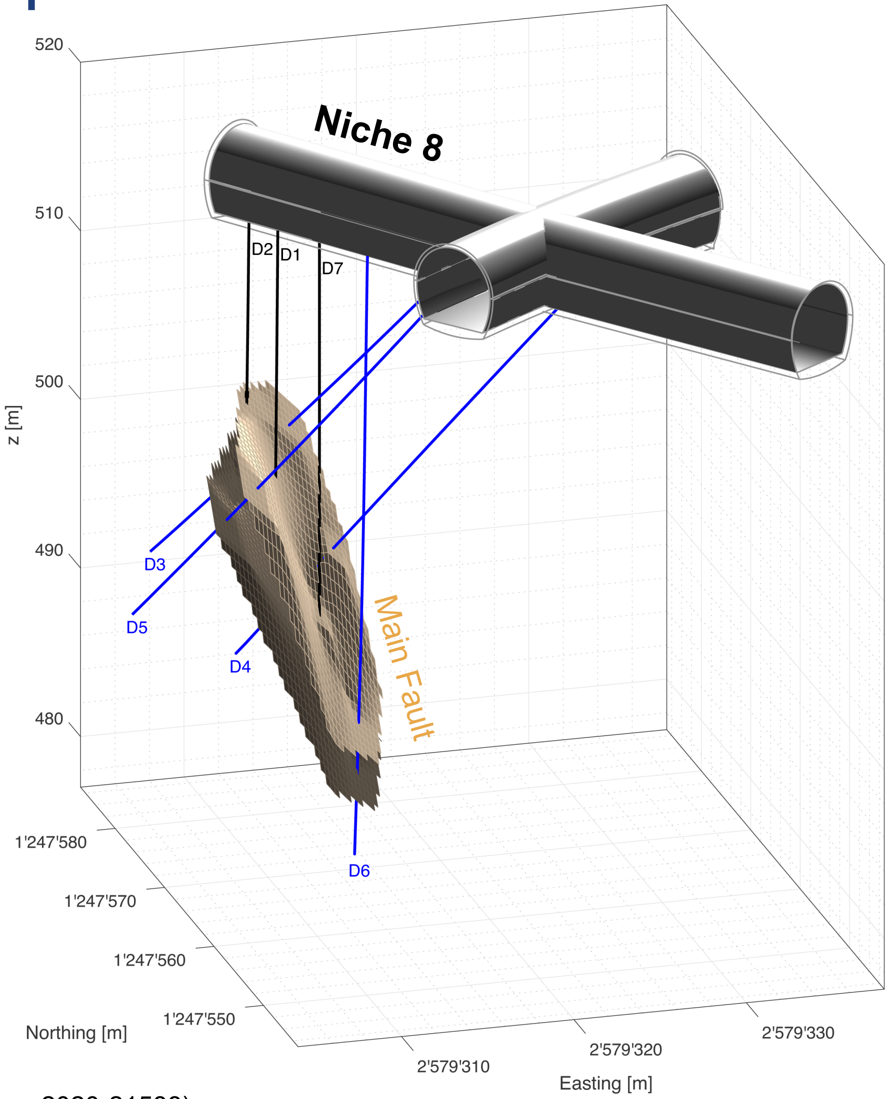
Zappone et al. "CO2 Sequestration: Studying Caprock And Fault Sealing Integrity, The CS-D Experiment In Mont Terri." *Fifth CO2 Geological Storage Workshop*. Vol. 2018. No. 1. European Association of Geoscientists & Engineers, 2018.

Introduction:
Layout of the CS-D experiment

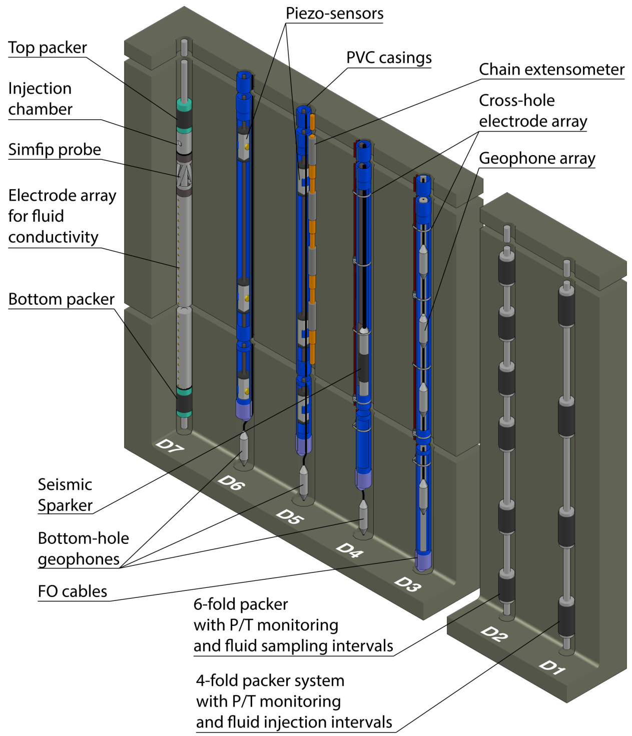
CO_2-Injection:
Injection of CO_2-saturated formation water into the main fault in Mont Terri

Borehole D1:
4 intervals for fluid injection within the core of main fault and in its close vicinity.

Borehole D2
6 intervals for fluid sampling and hydraulic/geochemical monitoring.



Geophysical monitoring:
Various equipment in boreholes and in the gallery for active and passive seismic monitoring and DC-resistivity monitoring. Here, the active seismic monitoring is presented.



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Methods:
Data acquisition

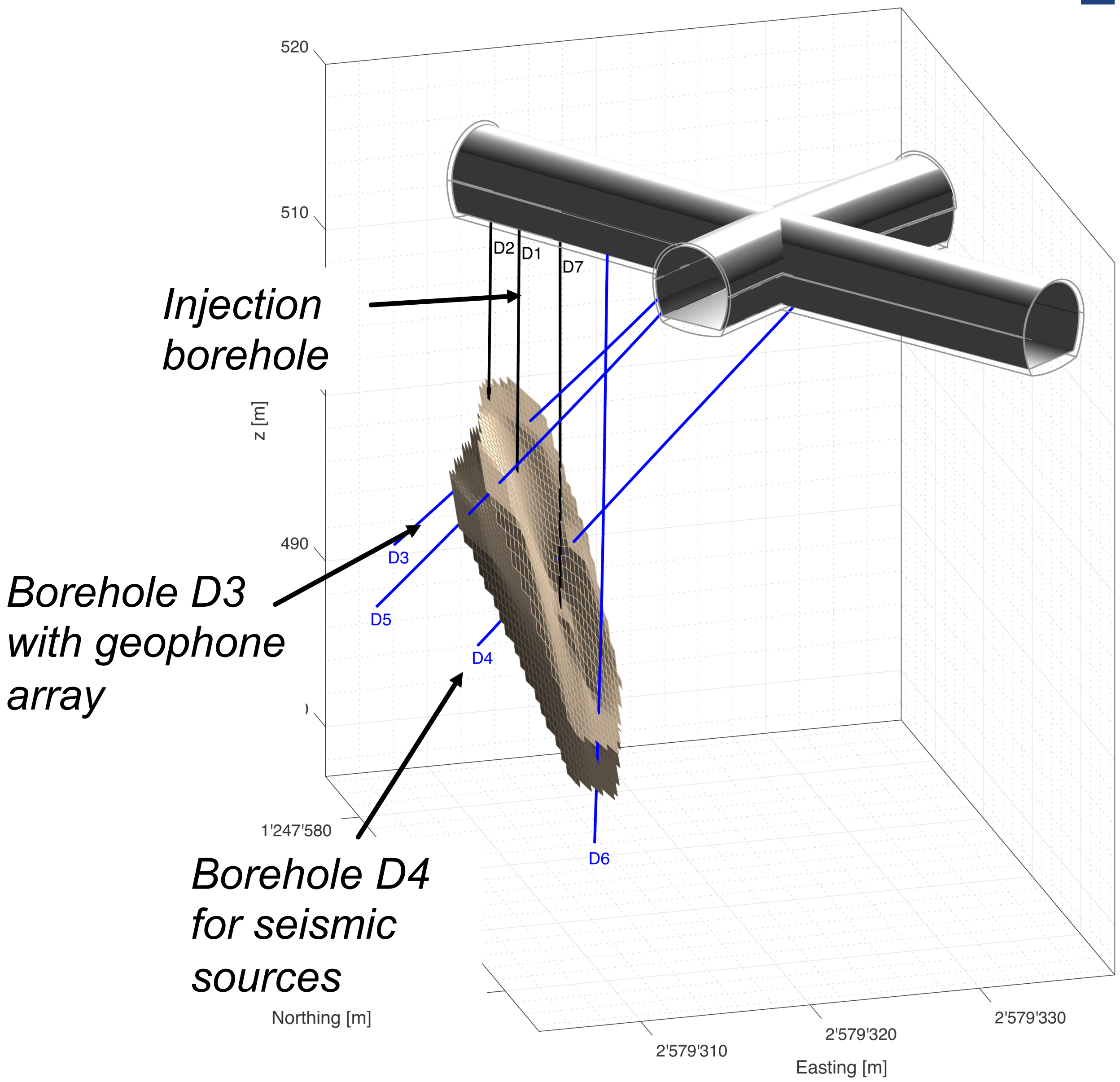
The active seismic monitoring experiment presented here was conducted with seismic sources in borehole D4 and a geophone array cemented in D5.

Sources:

- P-Wave sparker source
- For tomographic imaging: source fired every 25 cm
- For time-lapse monitoring during step-up injection: source fired from constant location for better repeatability.

Geophone array:

- 24 three-component geophones
- 50 cm spacing
- Cemented, for optimum coupling and repeatability over long times



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Methods:
Data processing and seismic tomographic imaging

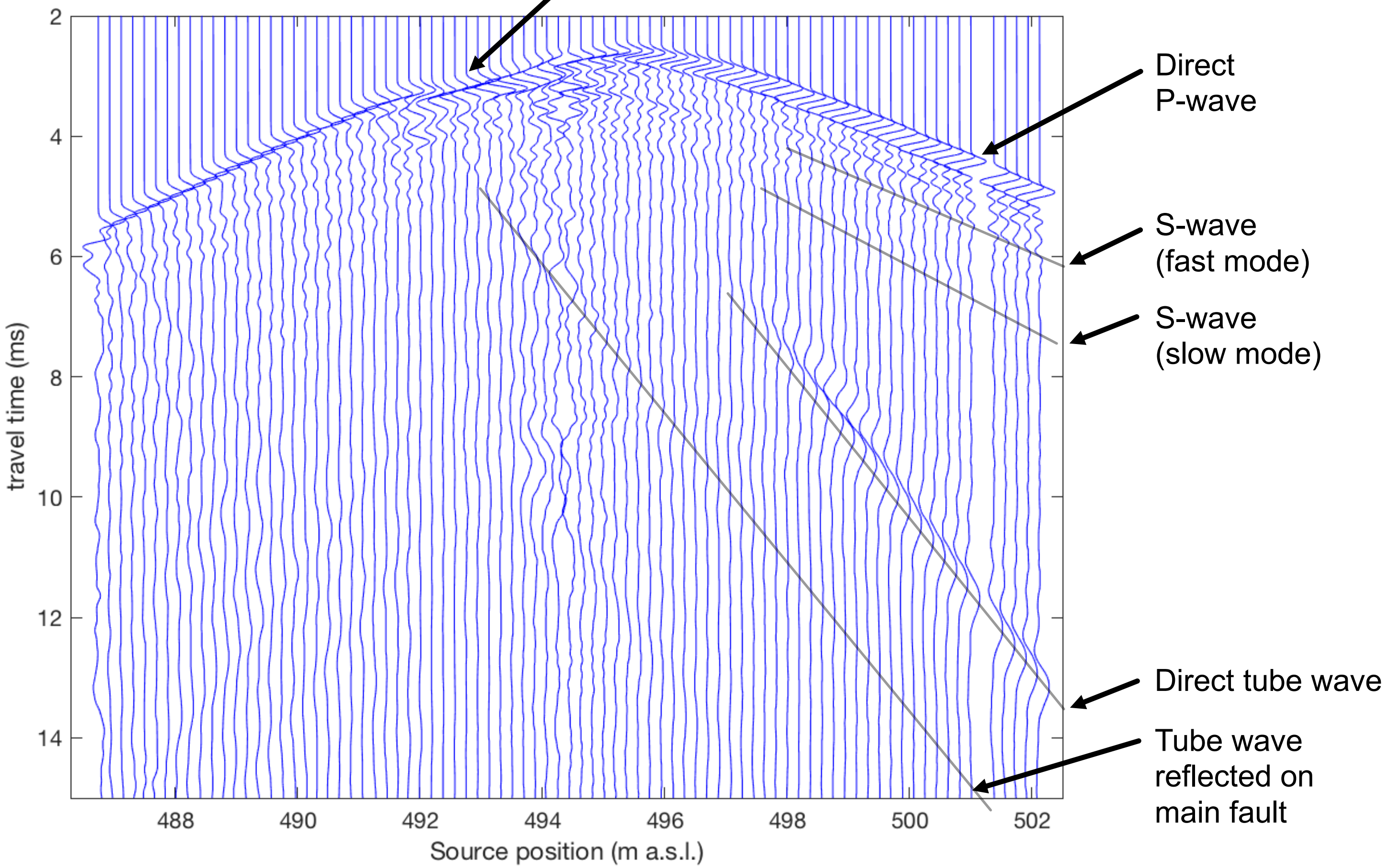
Processing Workflow:
1. Bandpass / Dewow filtering
2. T_0 correction by cross-correlating trigger-signals
3. Stacking of 5-10 shots
4. Automatic picking of first arrival times
5. Picking refinement with cross-correlation

Tomographic imaging:

6. Anisotropy correction
7. Iterative travel time inversion for V_P-imaging (after Lanz et al. 1998)

Lanz, E., H. Maurer and A. G. Green (1998). "Refraction tomography over a buried waste disposal site." Geophysics 63(4): 1414-1433.

Example receiver gather:

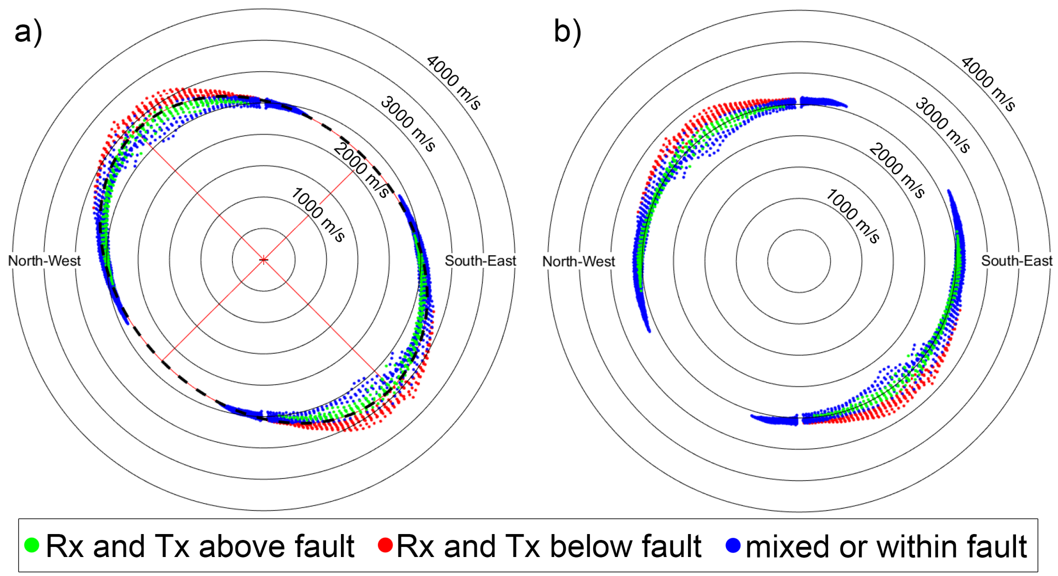


Receiver in borehole D3, sources in borehole D4

Results: P-wave velocity tomogram (baseline measurements)

Anisotropy of P-wave velocities V_P (Figure a):

- Average V_P parallel to bedding: 2870 m/s
- Average V_P normal to bedding: 2280 m/s
- Anisotropy slightly stronger in the foot wall compared to hanging wall
- Velocity corrected for anisotropy prior to travel-time inversion (Fig b),
- Clay bedding normal to tomographic plane (no off-plane effects due to anisotropy)



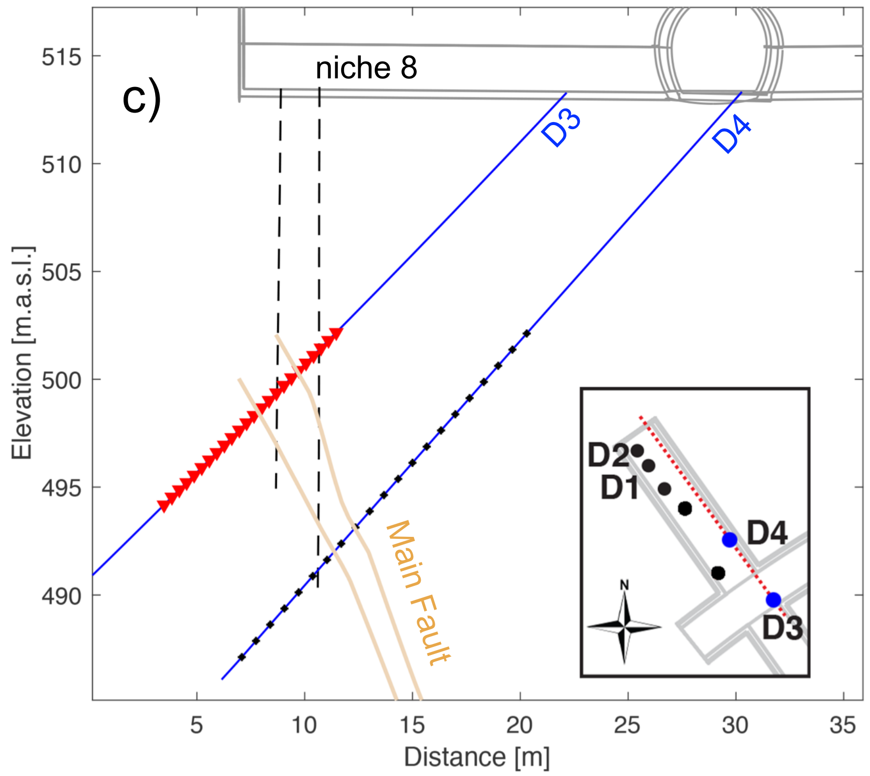


Figure a: Anisotropic P-wave velocities within tomographic plane (shown in Figure c).

Figure b: P-wave velocities corrected for their anisotropy.

Figure c: Tomographic plane with geophone locations (red triangles) and source locations (black dots).

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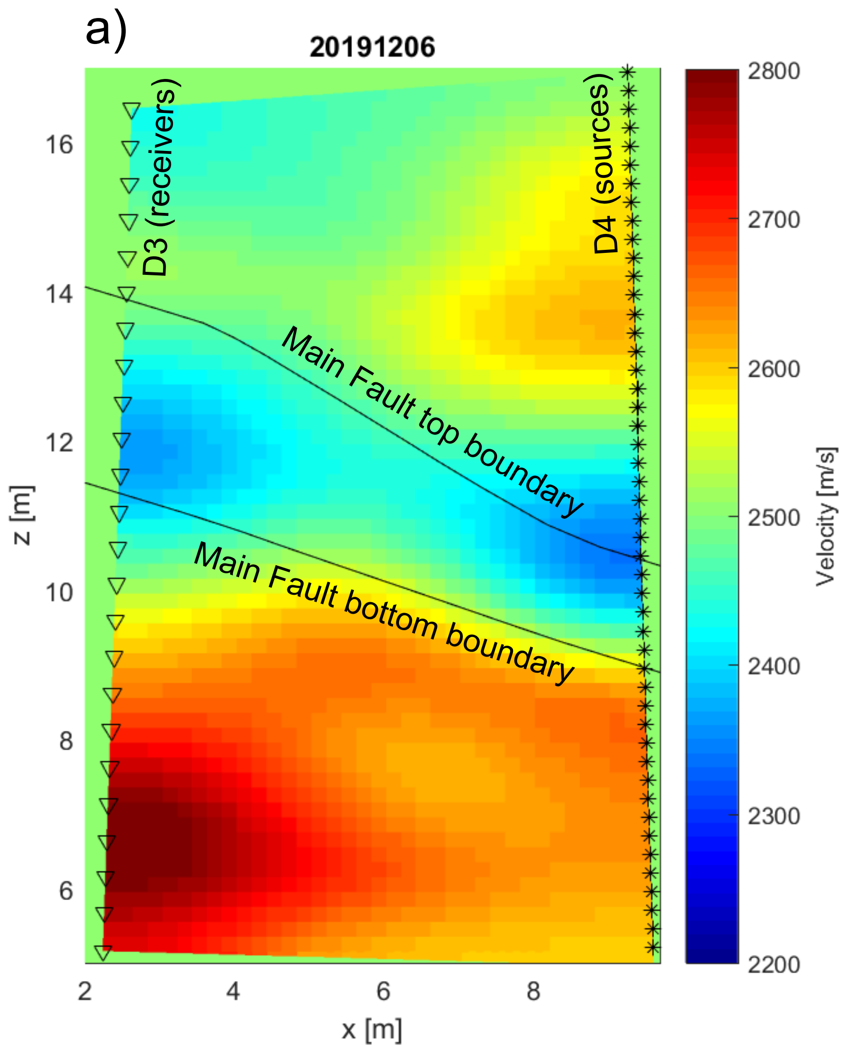
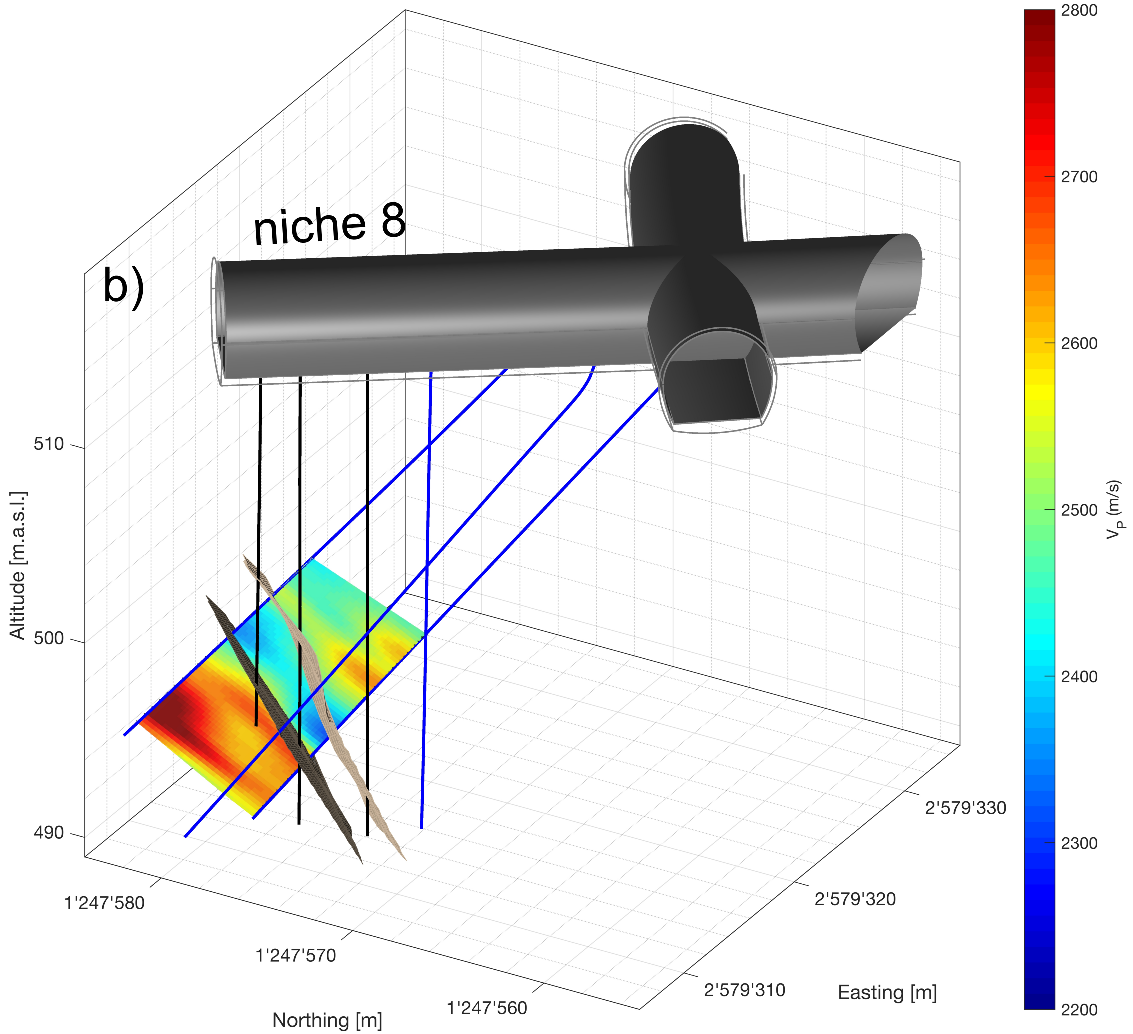
Results: P-wave velocity tomogram (baseline measurements)

Figure a:
Tomogram with P-wave velocities (anisotropy-normalized) with Main-Fault boundaries interpolated from borehole observations.

Figure b:
P-wave tomogram projected to its locations below niche 8 in the Mont Terri rock laboratory





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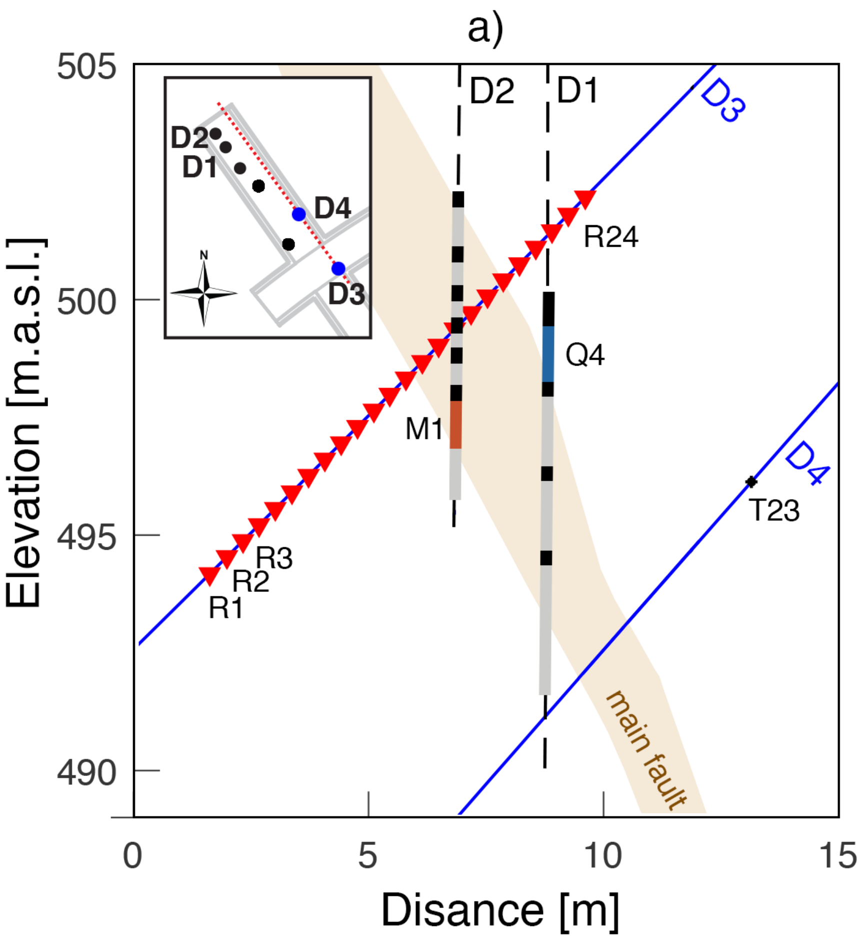
Results: V_P-monitoring during step-up injection test

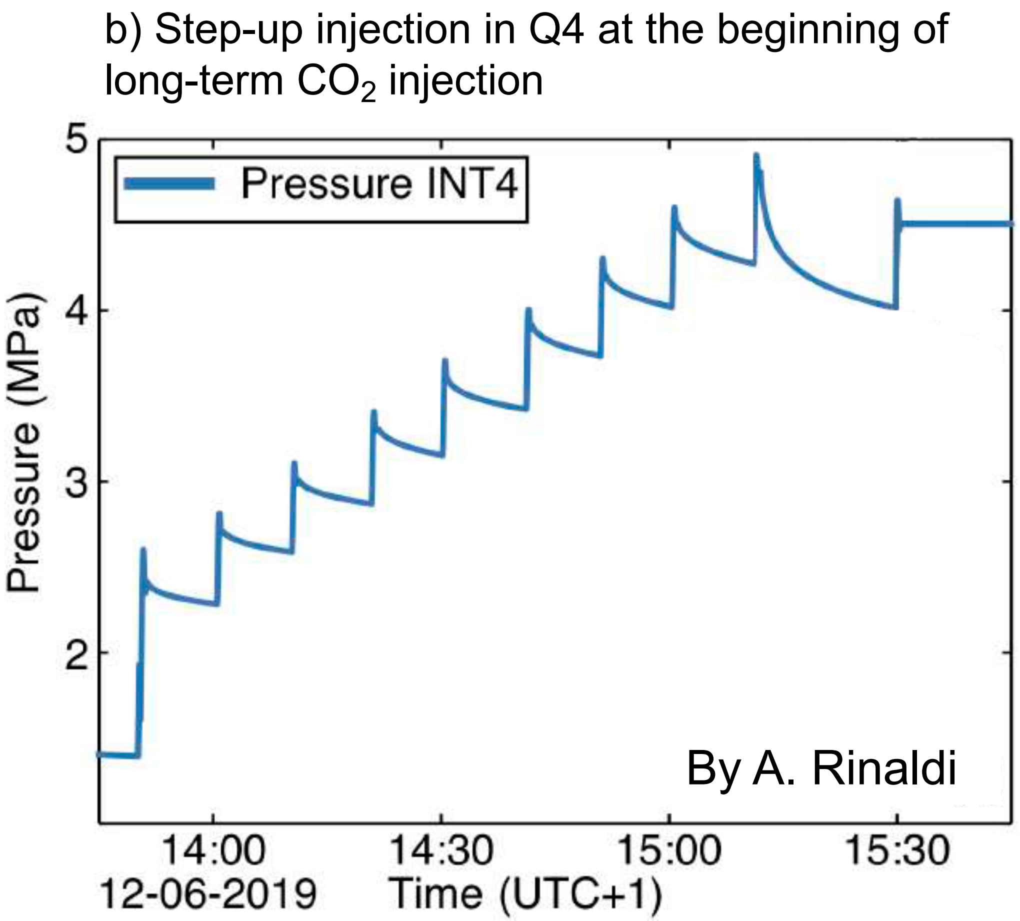
Injection location (a)

- Injection of CO_2-saturated formation water in interval Q4 (figure a)
- Interval Q4 is 2 m off-plane relative to seismic tomographic plan
- Geophone locations (▼), and source location (✦ T23)

Injection protocol (b)

- Increase of injection pressure in 0.3 MPa steps every 10 min (figure b)





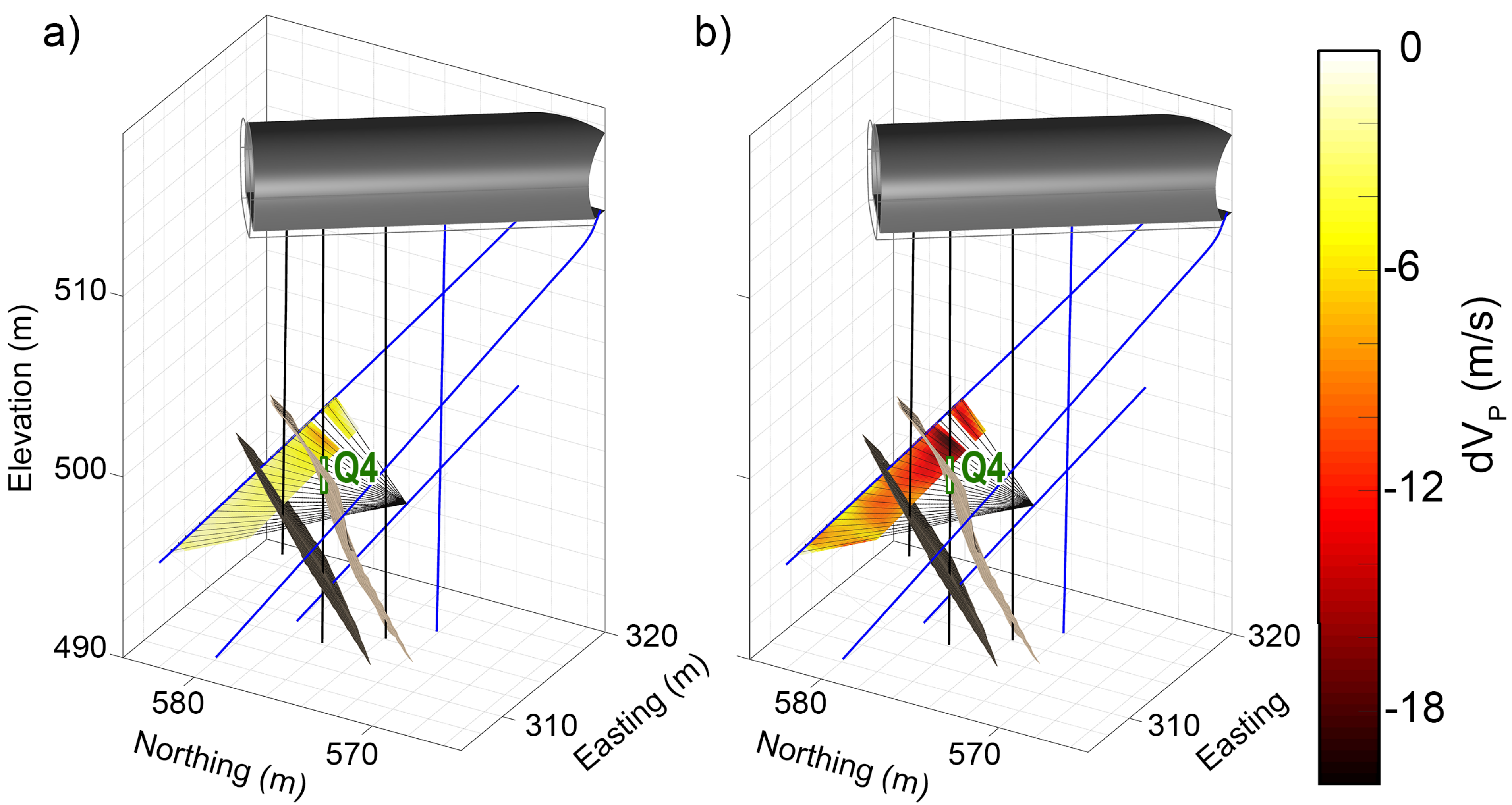
More information about this injection test:
Wenning et al. (EGU2020-19243), slide about "Testing for Fault Opening Pressure"

Grab et al. (https://doi.org/10.5194/egusphere-egu2020-21588)

Results: V_P-monitoring during step-up injection test

Active Seismic monitoring

- P-wave sparker shots repeated after each injection step-up
- Change in P-wave velocity (dV_P), relative to V_P from baseline tomogram
- Figure a: dV_P at injection pressure of 2.4 MPa (first step)
- Figure b: dV_P at injection pressure of 4.5 MPa (last step)
- Reduction of V_P by around 1% in the vicinity of the injection interval



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Discussion and Conclusion:

Baseline measurements for site characterization:

- Geology (Main Fault) resolved with P-wave travel-time tomography
- Anisotropy not uniform in hanging/foot wall (critical for V_P-tomography but less critical for dV_P tomography)

Time-lapse seismic during injection

- Travel time tomography sensitive to pressure induced effects (step-up test)
- During injection test, pressure in injection interval was increased from 2.4 MPa to 4.5 MPa. This resulted in a decrease of V_P by around 1%, which we were able to monitor and locate with active seismic monitoring.
- We interpret this as a poro-elastic effect, induced by pressure disturbance. This affects a volume which is much larger, than the volume within which the injected fluids were propagating (only very small fluid volume injected).

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