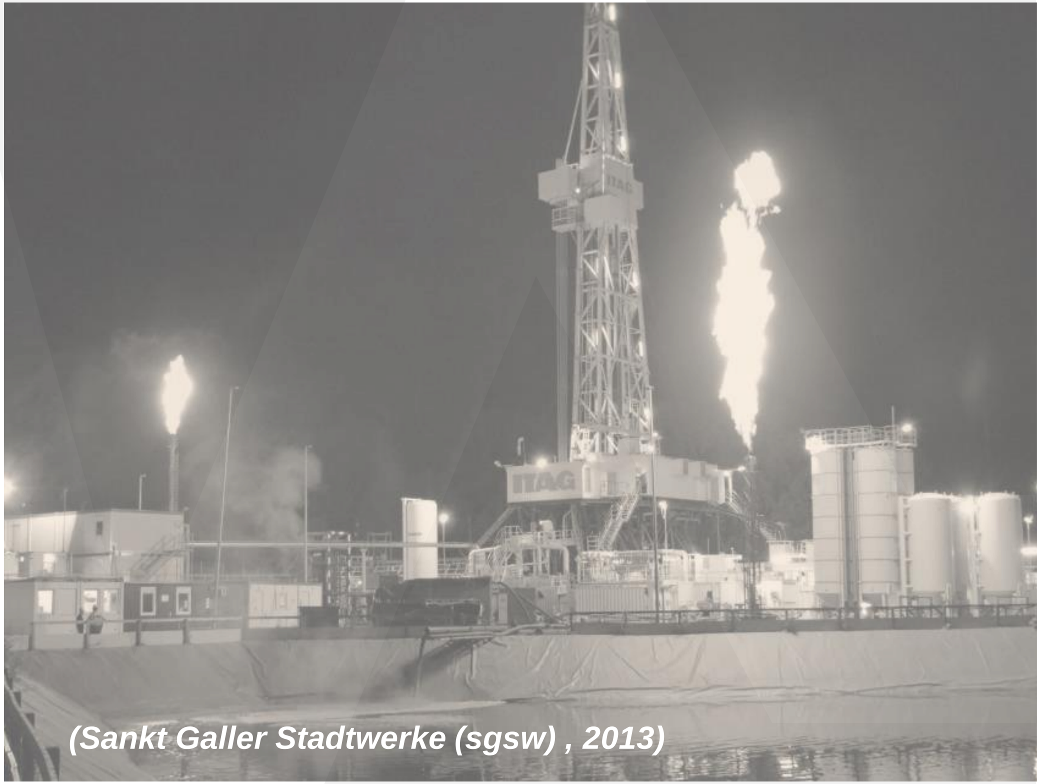
The induced earthquake sequence of St. Gallen, Switzerland: Fault reactivation and fluid interactions imaged by microseismicity

T. Diehl[1], T. Kraft[1], E. Kissling[2], S. Wiemer[1]

[1]Swiss Seismological Service,
ETH Zurich, Switzerland

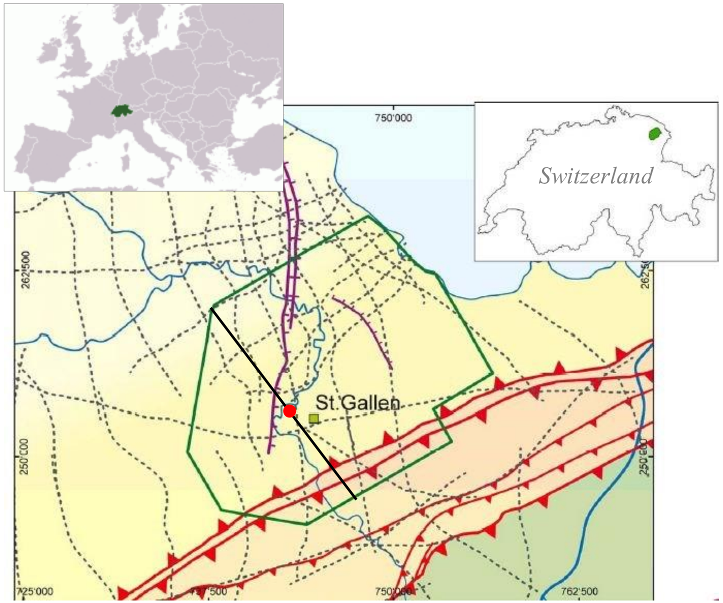
[2]Institute of Geophysics,
ETH Zurich, Switzerland

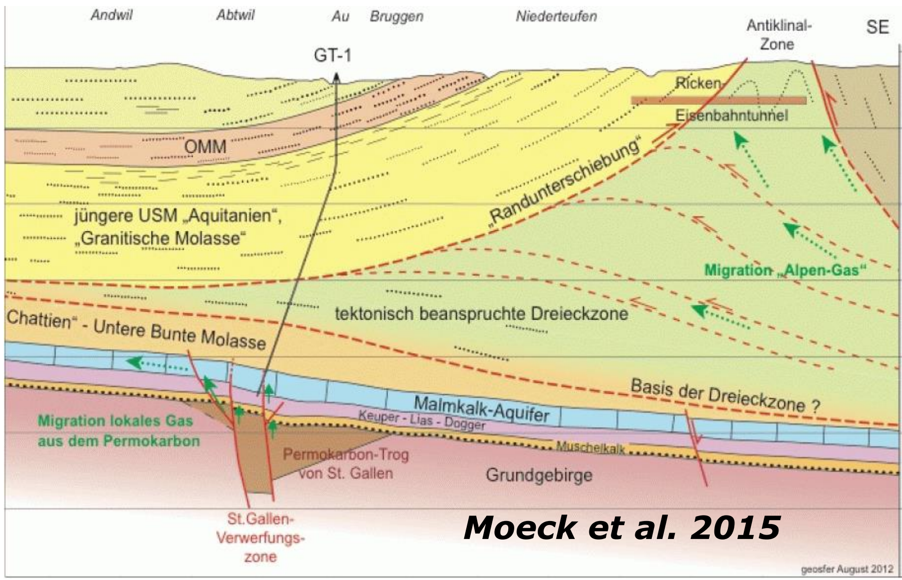


(Sankt Galler Stadtwerke (sgsw) , 2013)

Introduction: The St. Gallen Project and the 2013 Induced Eqk. Sequence

- → Hydrothermal system producing hot water from natural aquifer in the Molasse basin of NE Switzerland. St. Gallen Fault Zone targeted to enhance permeability.
- → 2010: 3D Seismic Campaign (270 km2), e.g. *Heuberger et al. 2016*
- → 2013: In July drilling finished, first hydraulic (120m^3) and acid (170m^3) stimulations (e.g., *Wolfgramm et al. 2015; Obermann et al. 2015*)
  - → Immediate **microseismic activity** in response to reservoir stimulations
  - → Gas kick about 5 days after initial stimulations, well-control procedures
  - → About 15 hours after well-control procedures were initiated: ***M_L3.5 (M_W3.3)*** **strike-slip earthquake** (e.g., *Edwards et al. 2015; Diehl et al. 2014*)
  - → October: Production rate achieved in test (6 l/s) far below targeted value (50 l/s)





Moeck et al. 2015

Objectives of High-Precision Hypocenter Relocation

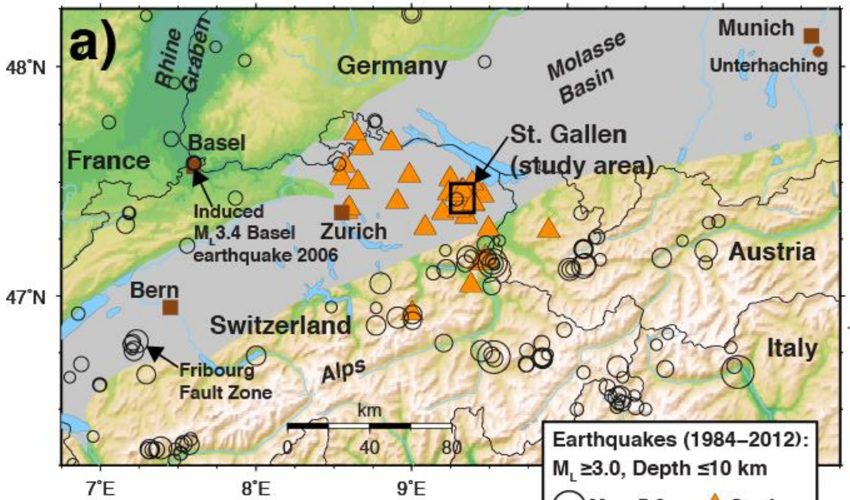
- In total, about 340 earthquakes of the sequence could be located with the dense monitoring network. Routine locations derived with regional 3D P-wave model of Switzerland (Husen et al. 2003). → Not enough resolution, not suitable for S.

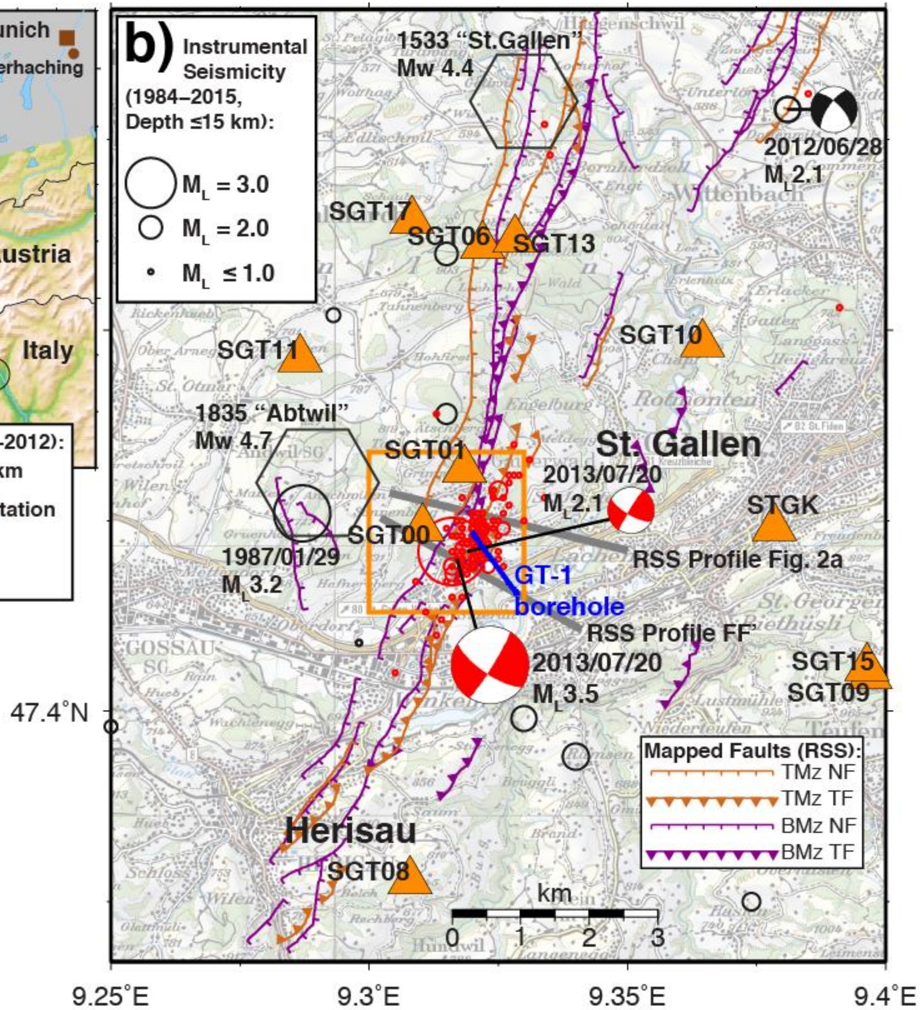
- **Objective 1:** Identify the host rock formation of the fault reactivated by fluid injections (e.g., within Molasse sediments, Mesozoic sediments, pre-Mesozoic basement) and its distance to the open-hole section of the well. Problem: Coupled hypocenter velocity-structure problem needs to be solved at high resolution.

- **Objective 2:** Resolve the precise geometry of the activated fault and compare it to faults imaged by the 3D reflection seismic survey. Can it be associated to an imaged fault segment? Is it limited to the imaged segment?

- **Objective 3:** Analysis of the spatio-temporal evolution of the earthquake sequence to study fluid interactions and hydraulic properties of the targeted fault zone.

Objective 1: Absolute Hypocenter Locations
Host Rock Formation

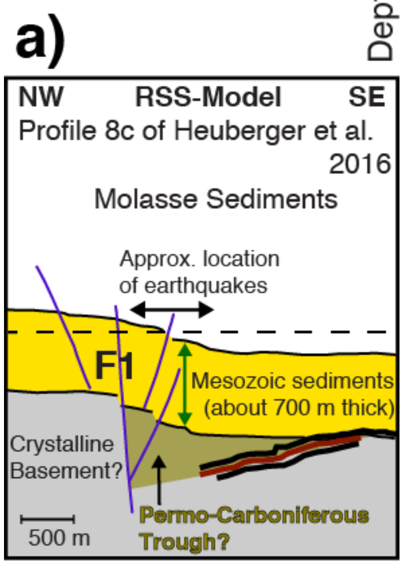


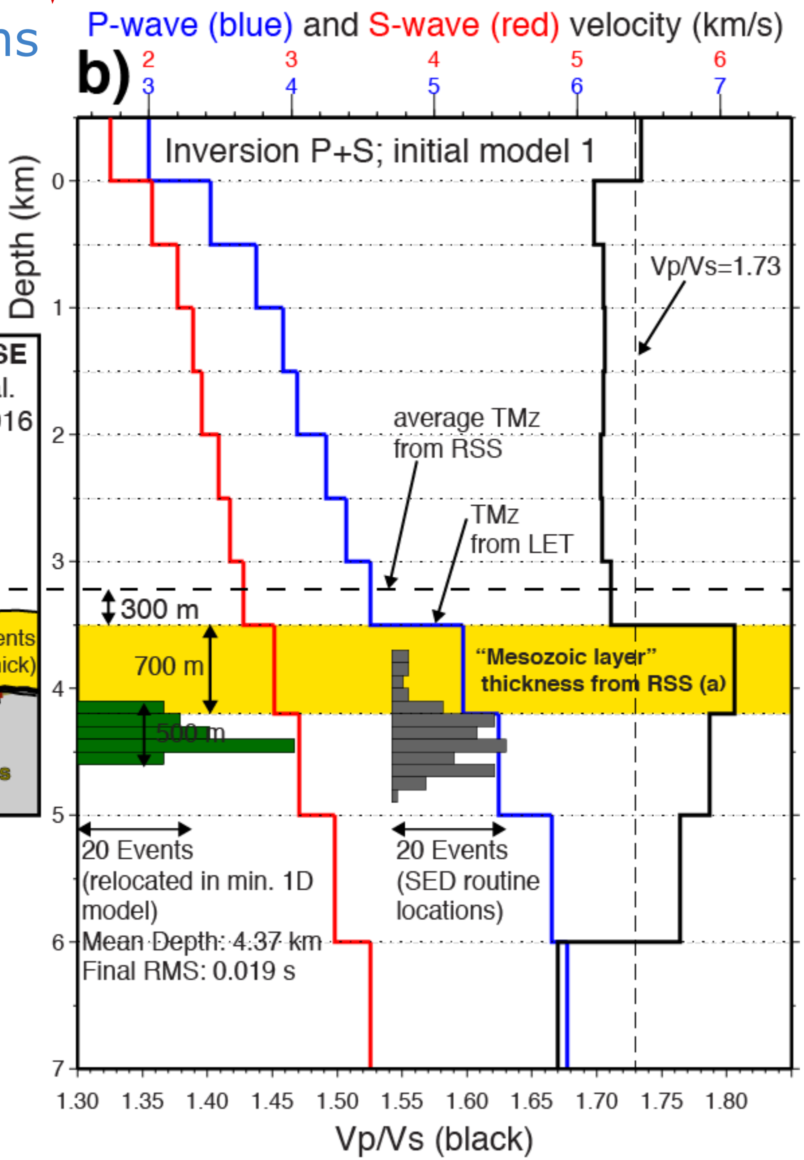


- No check-shots from source region to monitoring stations. VSP only covered area of borehole, no V_S.
- To improve absolute locations, simultaneous inversion of subset of earthquake P- and S-phase arrivals was performed to solve the coupled problem (VELEST). About 130 events, 1300 P-phases, 1400 S-phases.
- ➔ **Minimum 1D Model:** 1D V_P, V_S velocity profiles, station corrections (account for 3D effects), and hypocenters

Objective 1: Absolute Hypocenter Locations
Host Rock Formation

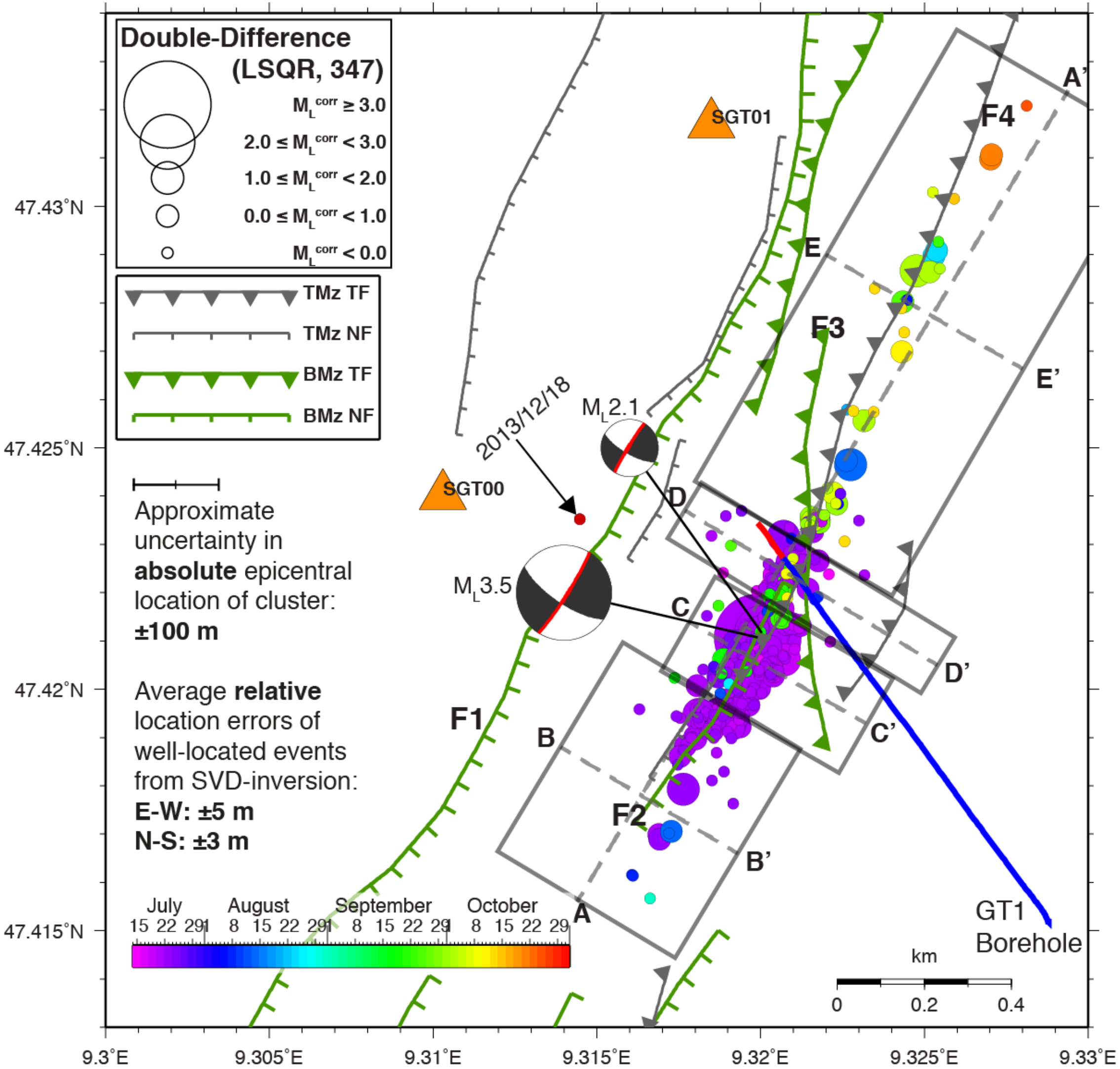
- Prominent velocity contrast in P (and S) velocities at 3.5 km depth → Top of Mesozoic Layer
- Majority of seismicity locates below Mesozoic Layer
- By using varying initial parameters (velocities & hypocenters) and data (P, S, P+S) in simultaneous inversion, uncertainties of absolute locations were estimated: **vertical ±150 m** **horizontal ±100 m**
- Absolute depths aligned with average Top Mesozoic reflector by subtracting difference of 300 m between Tomo and RSS.





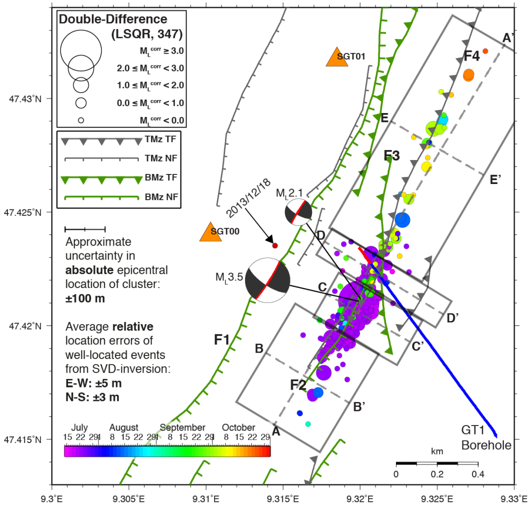
Objective 2: Relative Hypocenter Locations
Fault Geometry

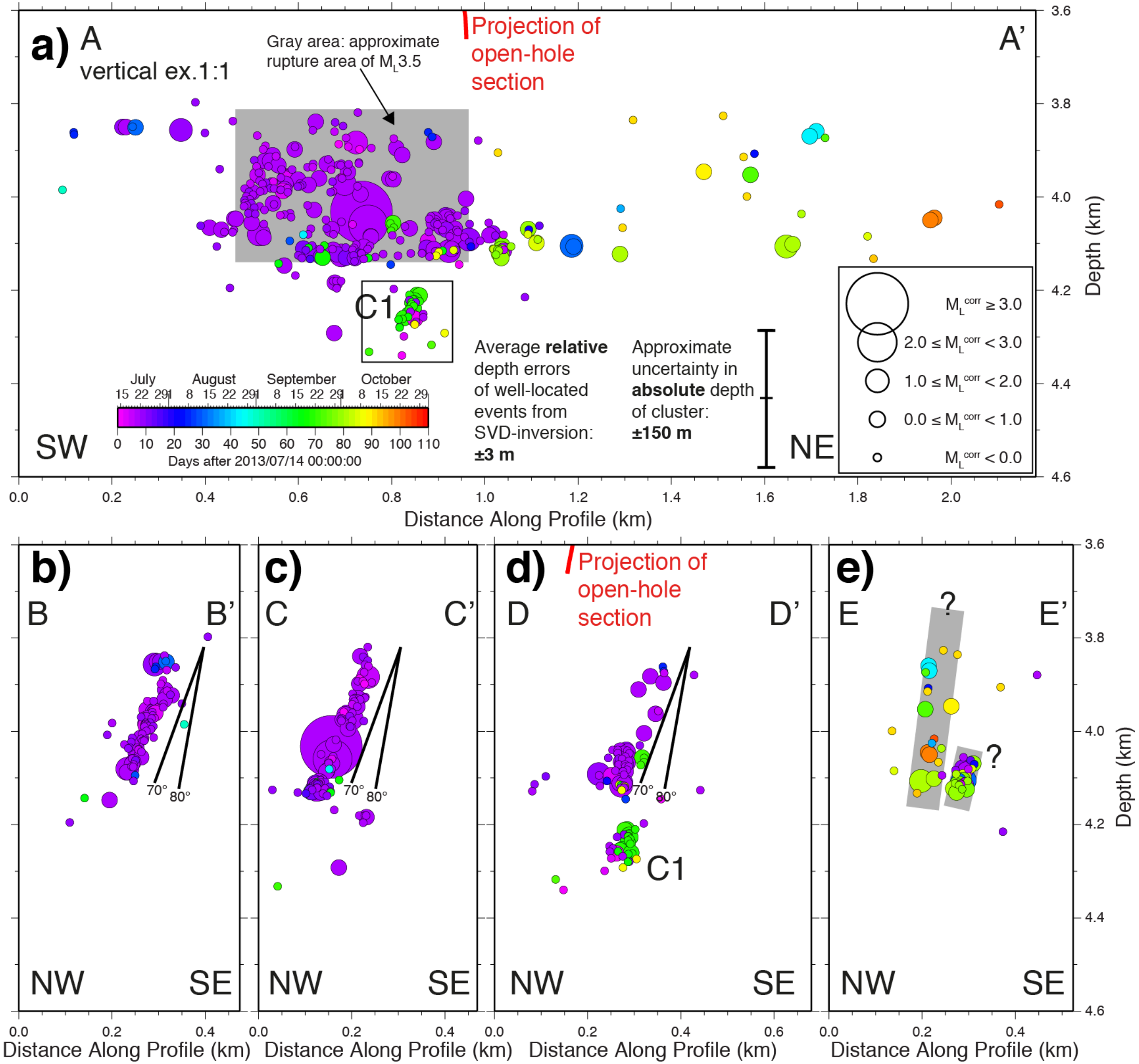
- Min. 1D model and relocations of previous step used as initial values for double-difference relative relocation (hypoDD, Waldhauser & Ellsworth 2000)
- Differential times from **catalog picks** (approx. av. resolution 20 ms) and time-domain **waveform cross-correlation** (resolution 1 ms) including quality check.
  CC-DT-P: 84,000
  CC-DT-S: 91,000
- Seismicity strikes SW-NE consistent with FM and trend of faults.



Objective 2: Relative Hypocenter Locations
Fault Geometry

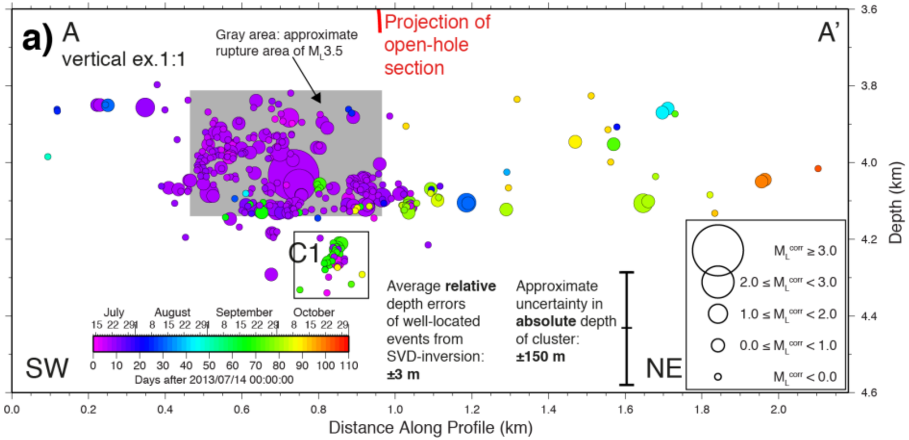
- Fore- and aftershocks precisely outline geometry of $M_L 3.5$ rupture. Dip towards NW.
- Cluster C1 vertically offset from main band.

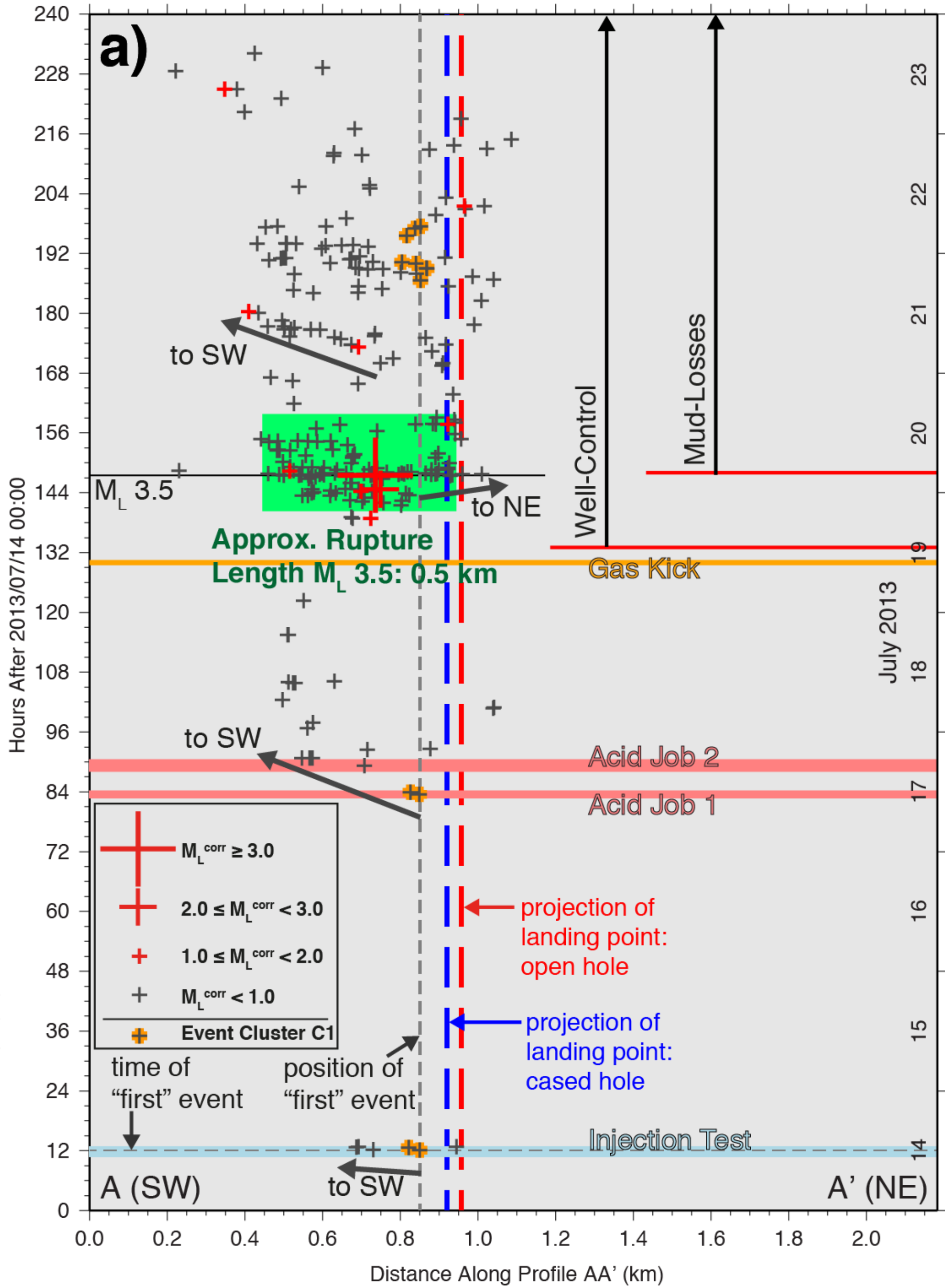




Objective 3: Spatio-Temporal Evolution **Fluids & Hydraulic Properties**

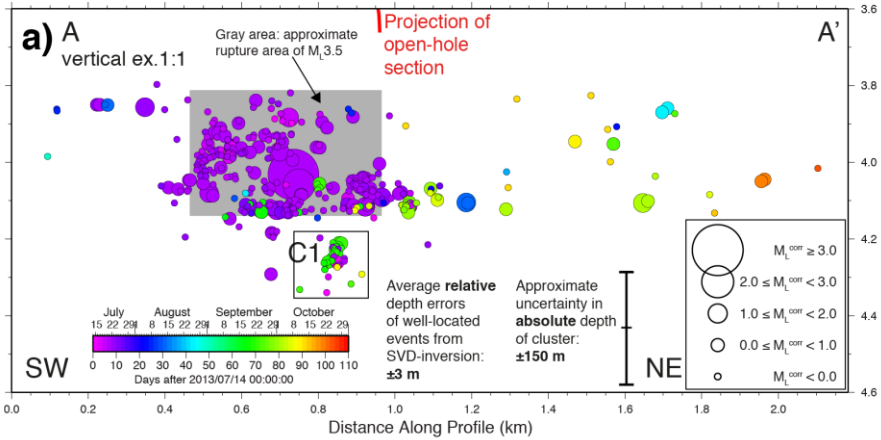
- Seismicity migrates unilaterally towards the SW prior to $M_L 3.5$ rupture.
- Seismicity also migrates towards the NE following the $M_L 3.5$ rupture (but at lower propagation velocities).
- Stimulation and clean-out operations correlate with seismic activity in **cluster C1**.

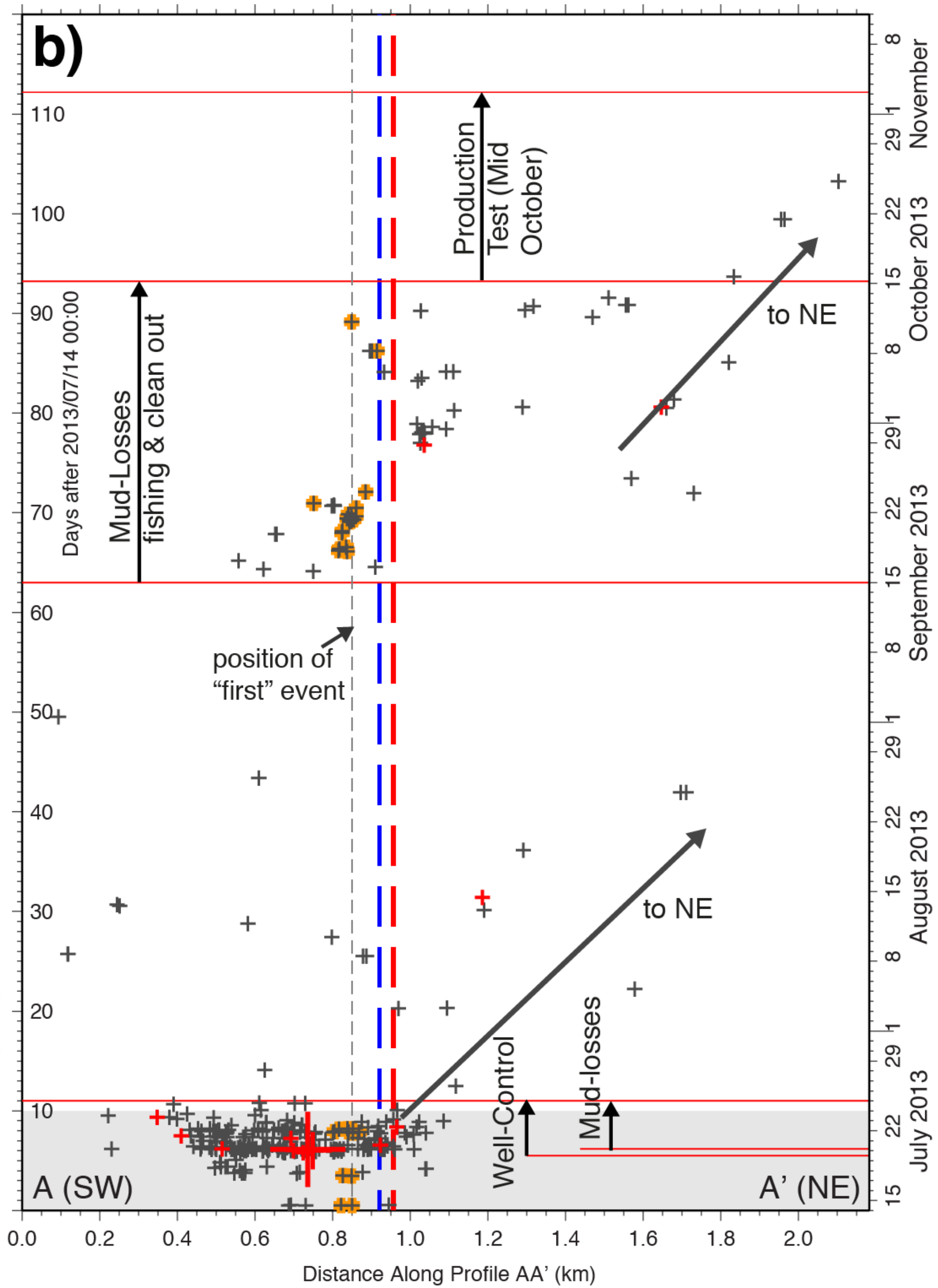




Objective 3: Spatio-Temporal Evolution
Fluids & Hydraulic Properties

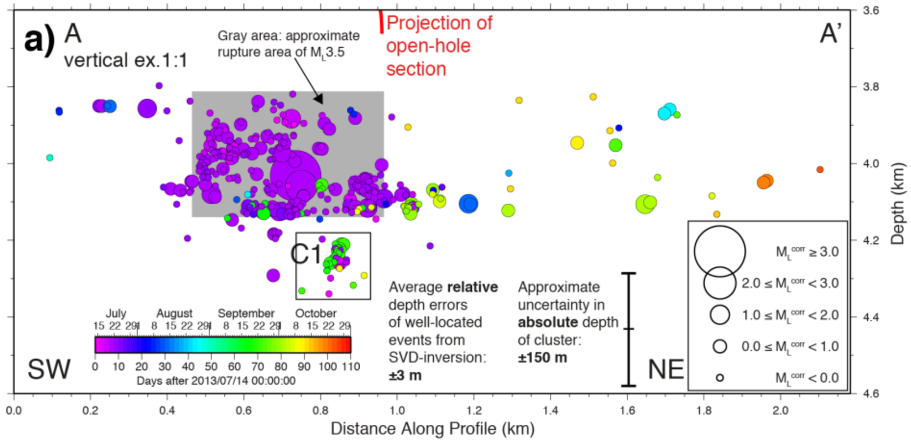
- Seismicity migrates unilaterally towards the SW prior to $M_L 3.5$ rupture.
- Seismicity also migrates towards the NE following the $M_L 3.5$ rupture (but at lower propagation velocities).
- Stimulation and clean-out operations correlate with seismic activity in **cluster C1**.

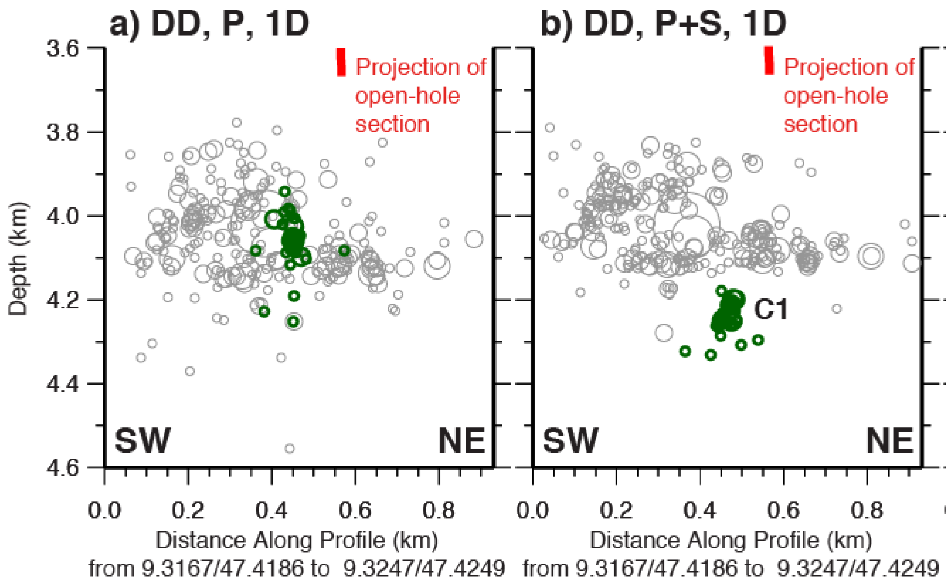




Discussion: Depth of Cluster C1

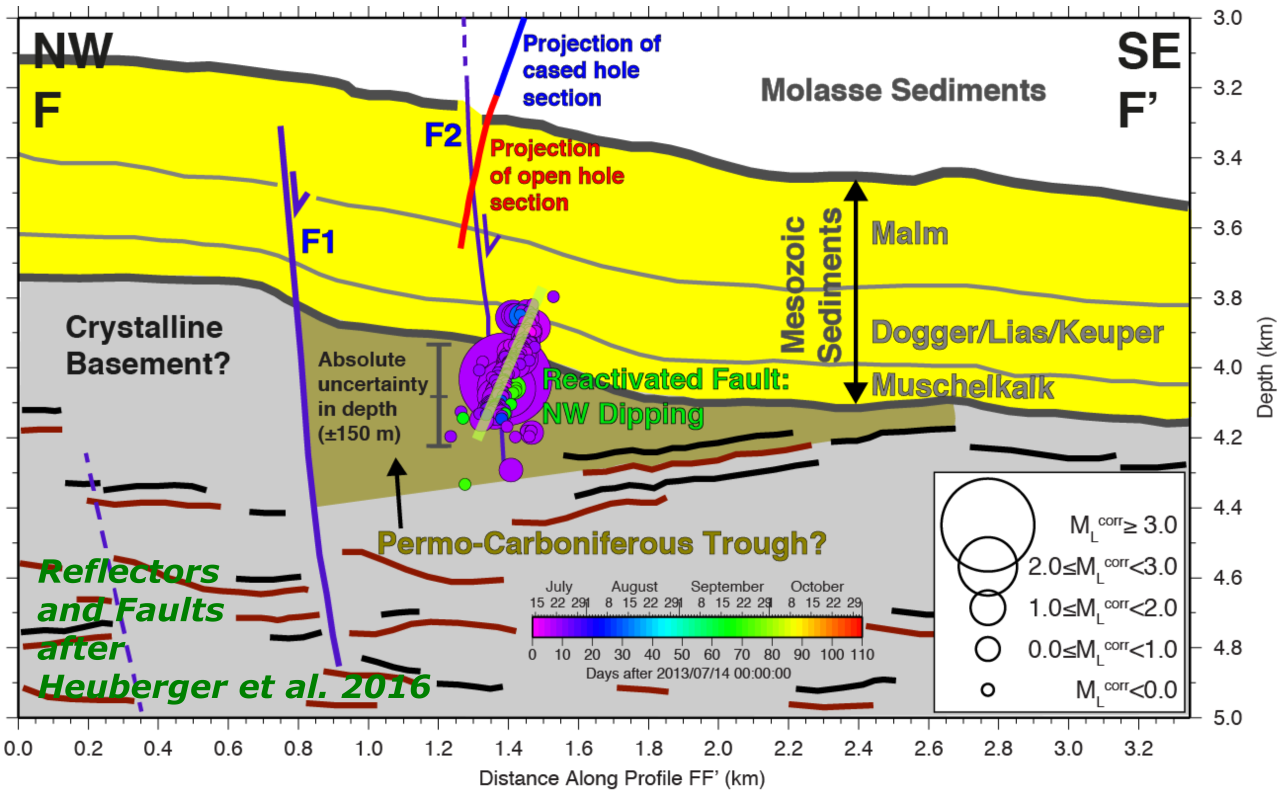
- Offset between main seismicity band and C1 only when using P+S CC-data.
- 3D forward modeling shows that offset might be related to locally increased V_P/V_S ratio. Possible interpretation in discussion.





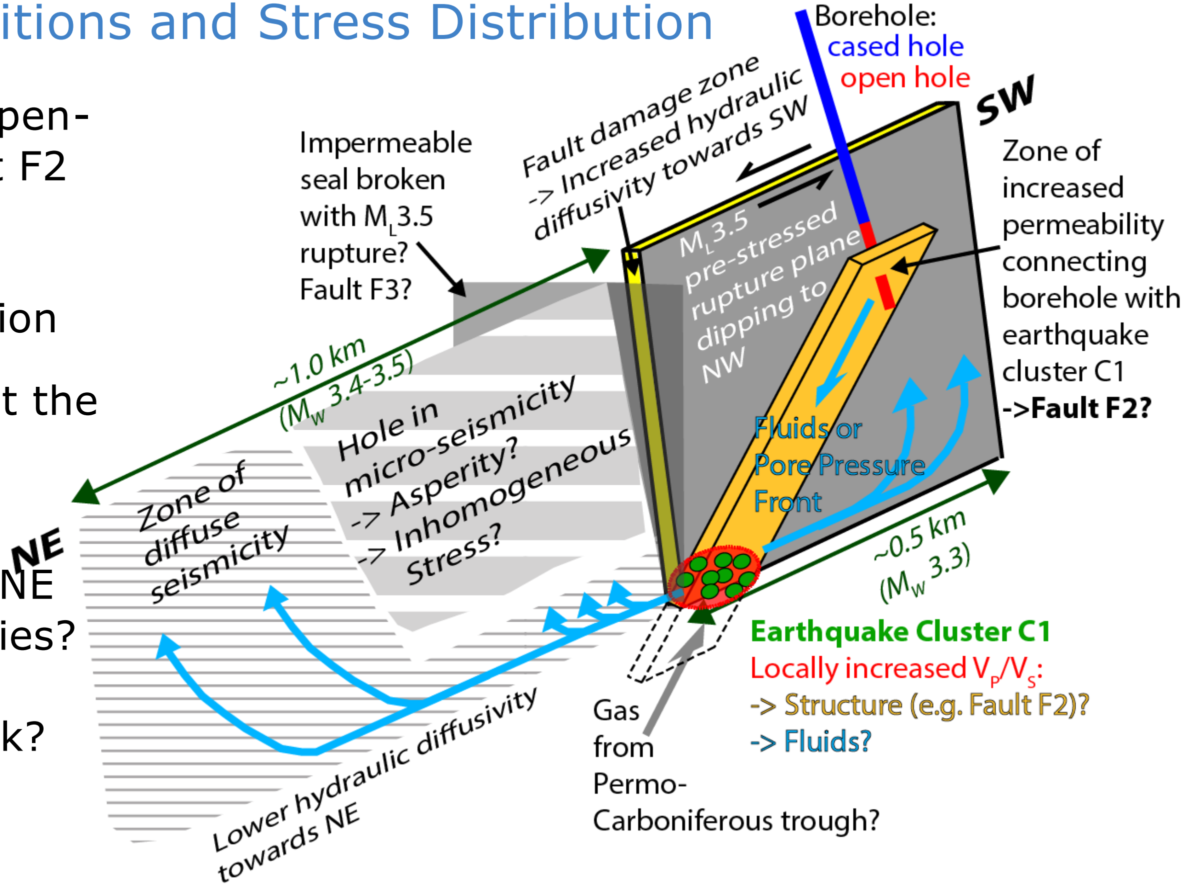
Discussion: Host Rock Formation and Fault Geometry

- Majority of fault in pre-Mesozoic basement (likely in Permo-Carboniferous Trough). Gas composition indicative for PC sediments (*Wolfgramm et al. 2015*).
- Activated fault dips to NW, not mapped by 3D reflection seismics.
- Hydraulic connectivity between open-hole section and activated fault (F2?). Evidence for intersection with well from well logging data (*Wolfgramm et al. 2015*).



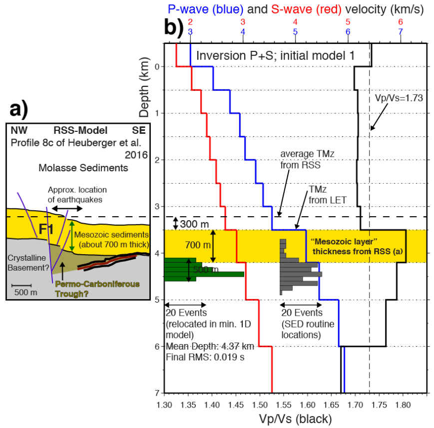
Discussion: Hydraulic Conditions and Stress Distribution

- Hydraulic connectivity between open-hole section and cluster C1. Fault F2 not activated, though directly stimulated.
  → heterogeneous stress distribution
- High migration velocities to SW at the edge of future $M_L 3.5$ rupture.
  → Critically stressed segment
- Delayed and slower migration to NE
  → Difference in hydraulic properties?
  → Segments separated by seal?
  → Role of gas released in gas-kick?
- NE-segment not ruptured (potential M_W 3.4-3.5)
  → heterogeneous stress distribution?
  → difference in mechanical properties?

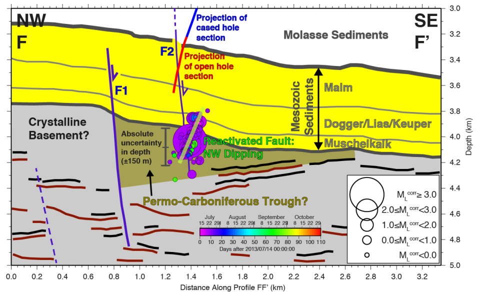


Conclusions

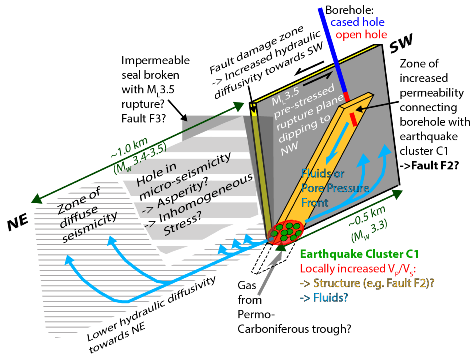
- By solving the coupled hypocenter – velocity problem and the joint interpretation with reflection seismic data, the absolute location and depth could be precisely constrained.
  → Host rock formation and geometry of the activated fault



- The spatio-temporal evolution reveals correlations between borehole operations and seismicity and provides insights into the hydraulic conditions of the targeted fault system.

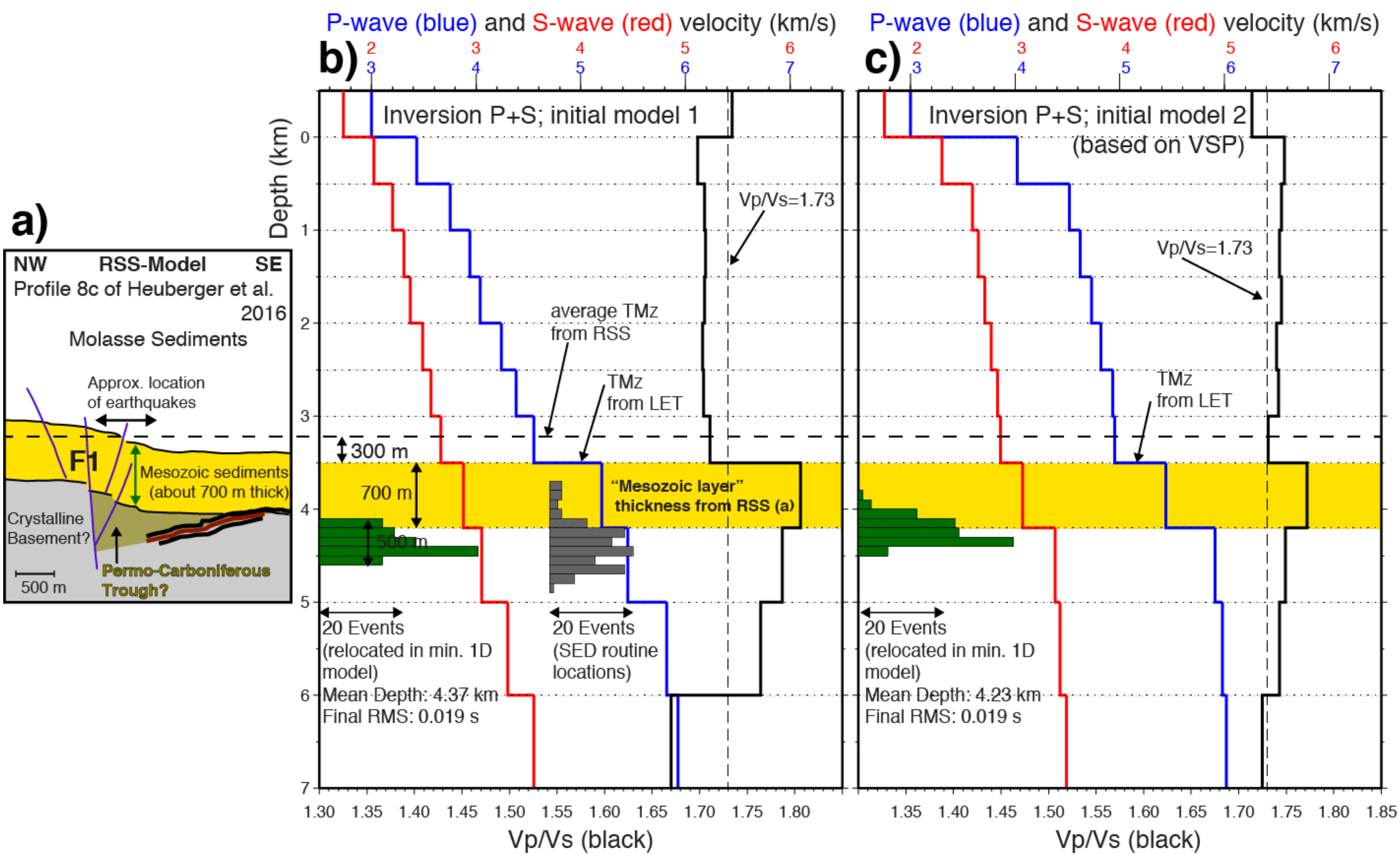


- **Our results document the complexities of crustal faults zones in terms of structure, hydraulic condition, and state of stress that geotechnical projects have to be prepared for when targeting such systems.**

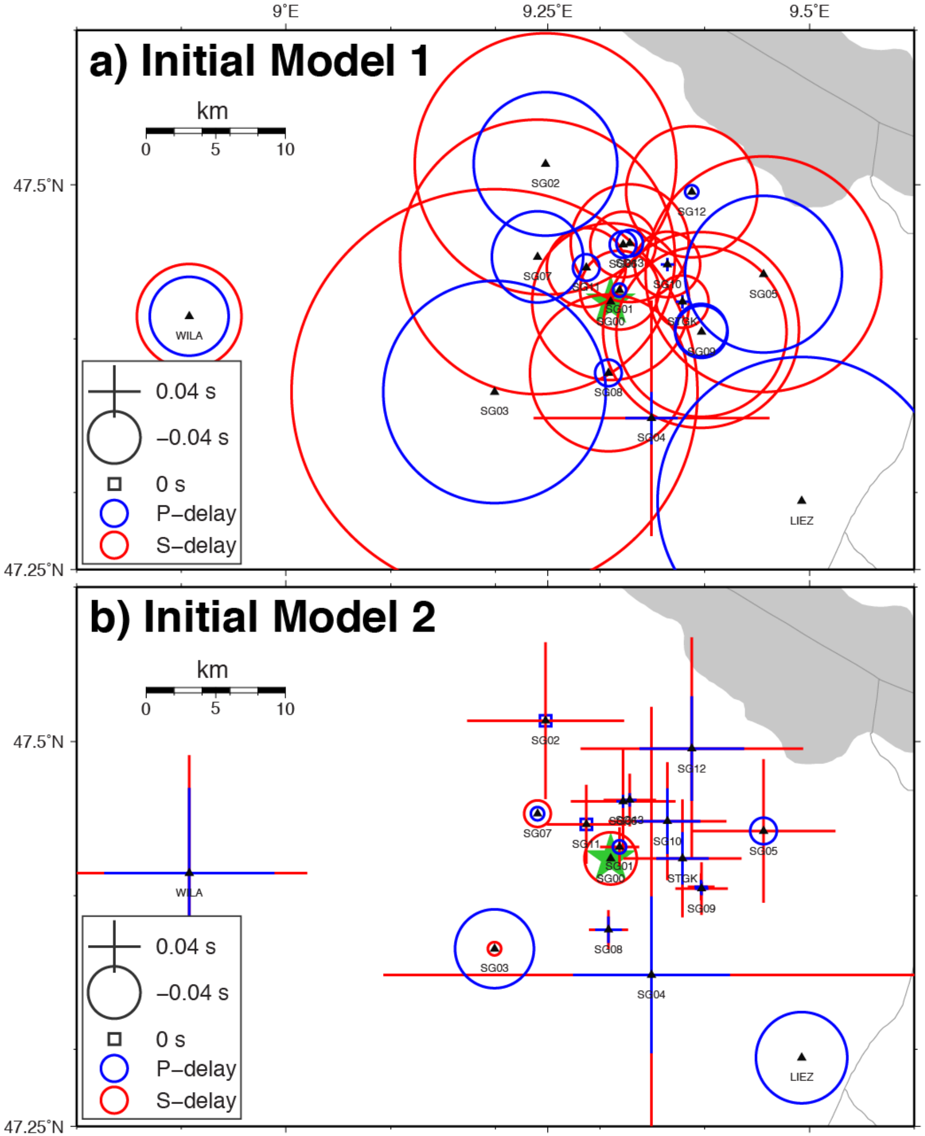


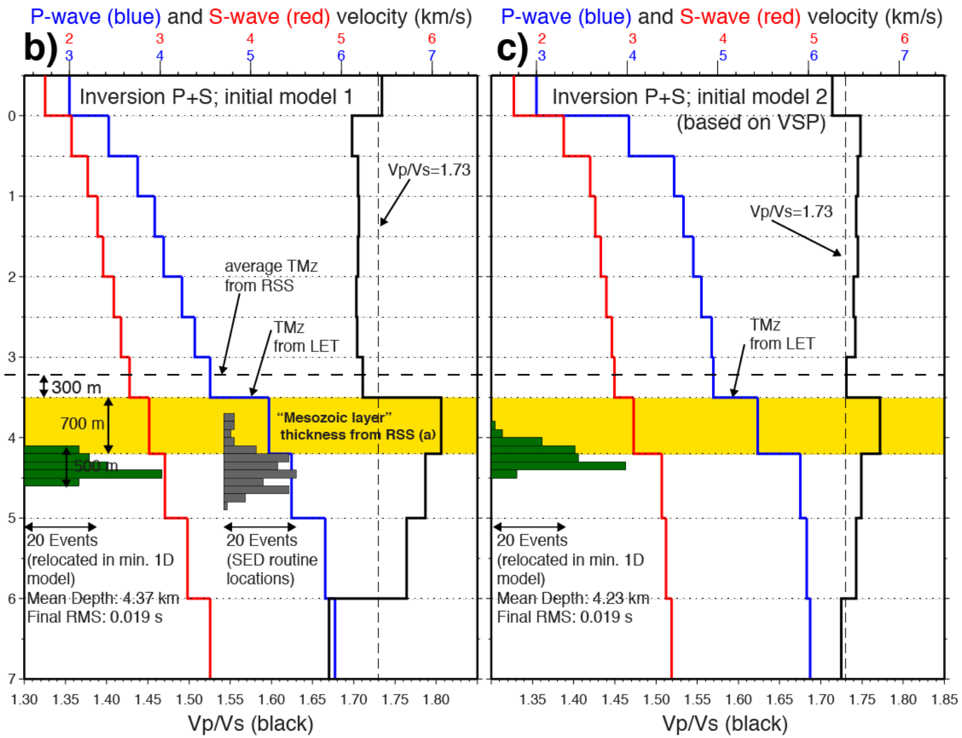
THANK YOU!

Goal 1: Absolute Hypocenter Locations and Host Formation

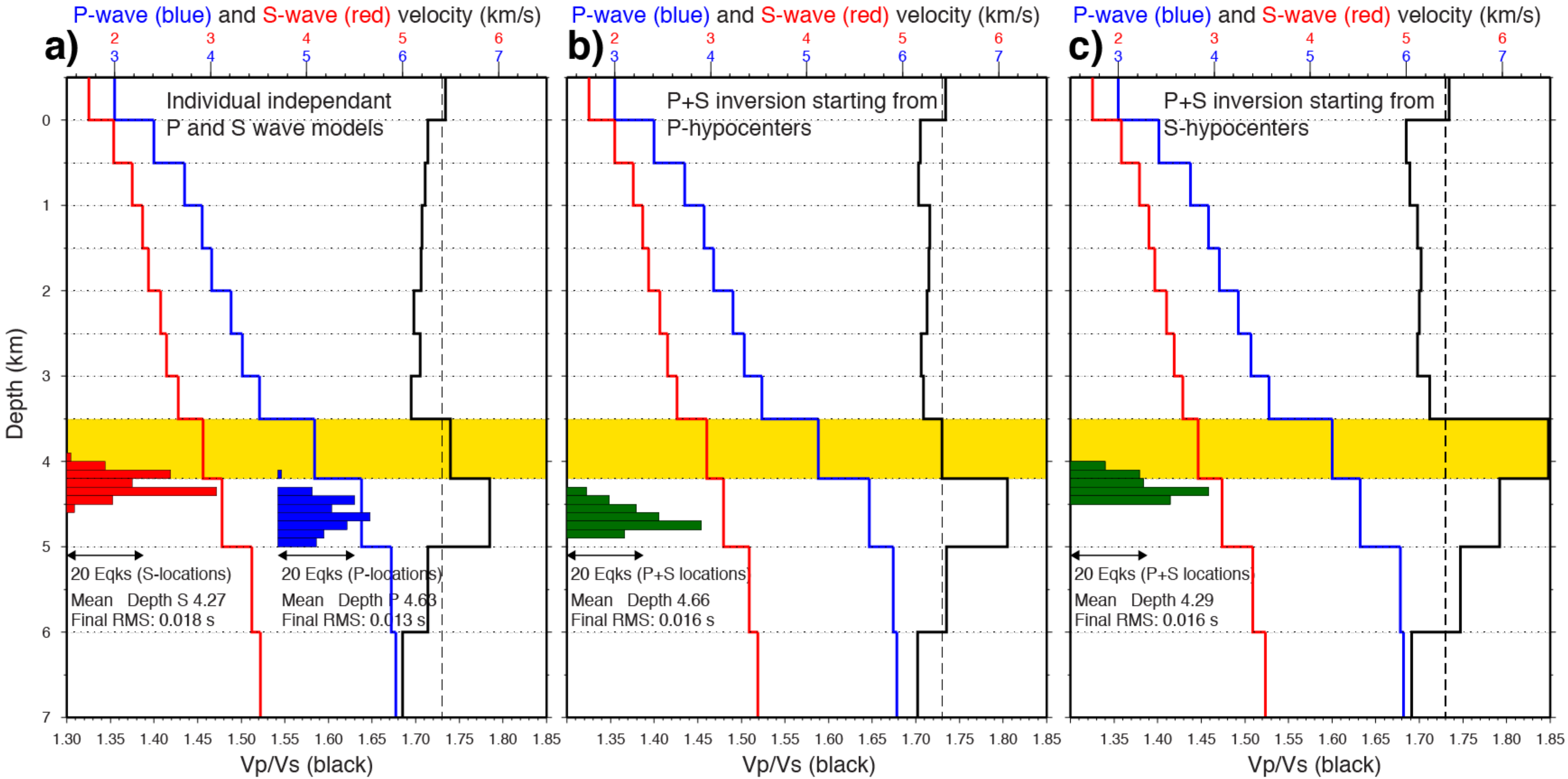


Goal 1: Absolute Hypocenter Locations and Host Formation



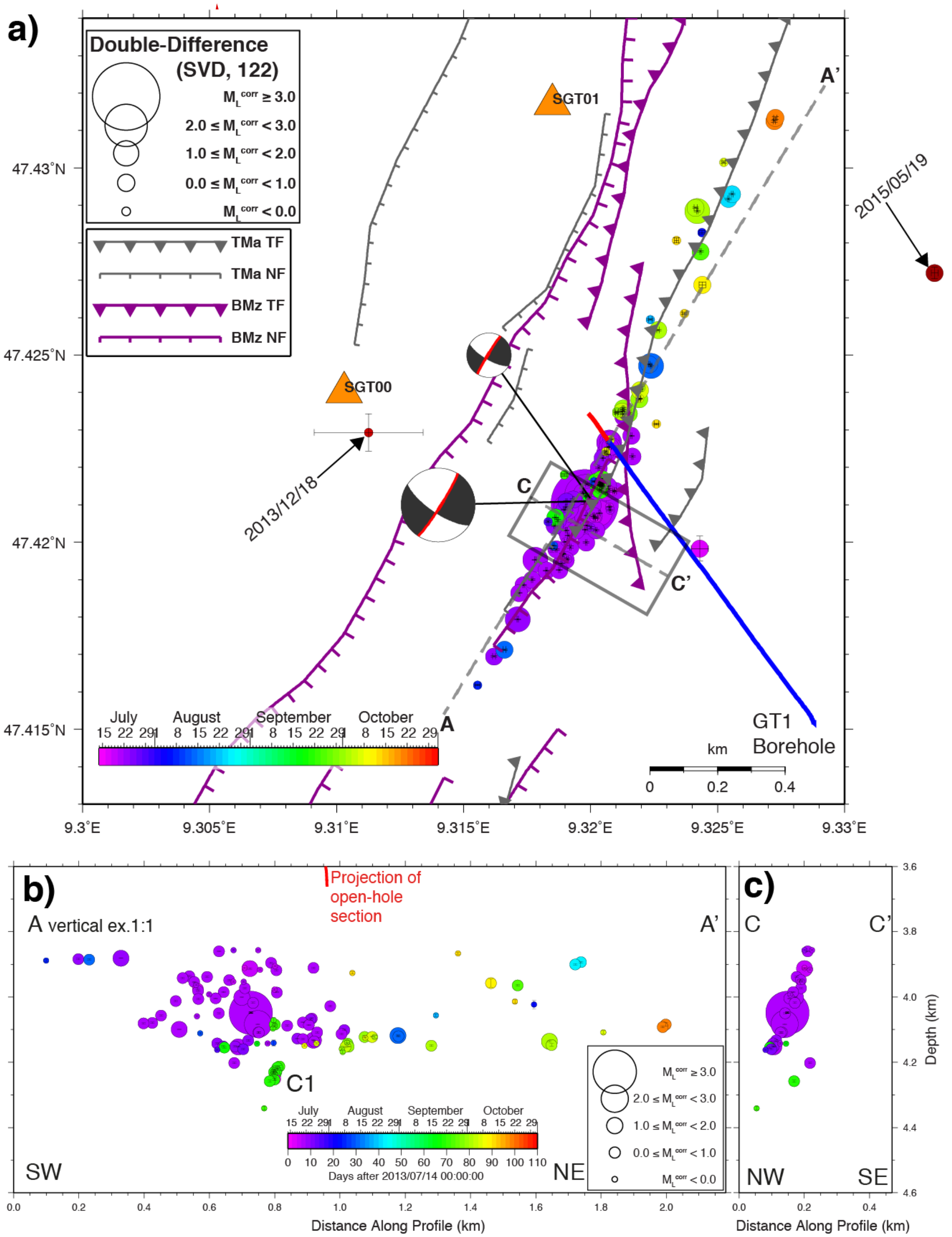


Goal 1: Absolute Hypocenter Locations and Host Formation

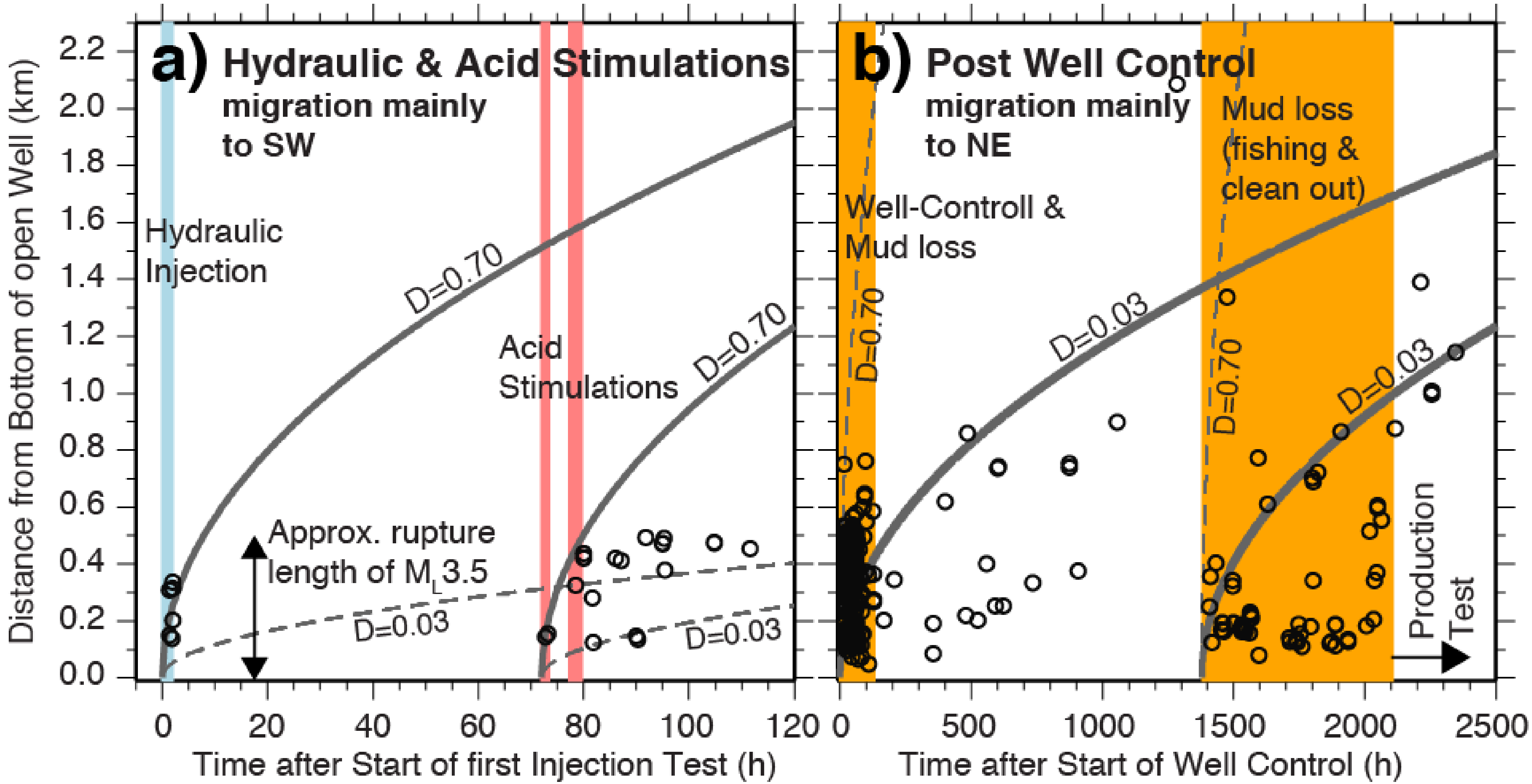


Goal 2: Relative Hypocenter Locations
Fault Geometry

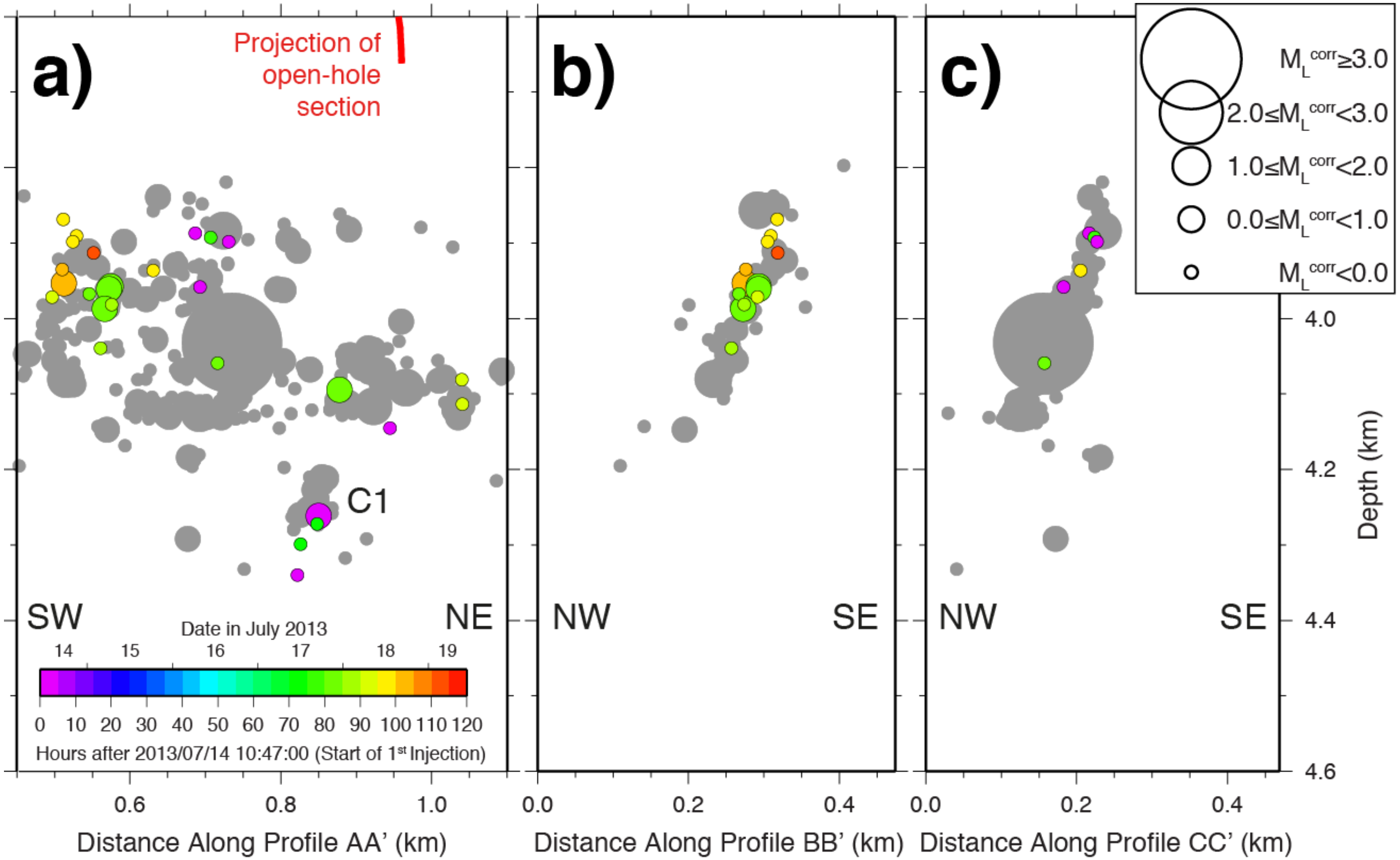
- Entire seismicity relocated in min. 1D model to improve absolute locations.
- Minimum 1D model used for ray-tracing in double-difference relative relocation (hypoDD, Waldhauser & Ellsworth 2000)
- Differential times from **catalog picks** (approx. av. resolution 20 ms) and time-domain **waveform cross-correlation** (resolution 1 ms) including quality check.
  CC-DT-P: 84,000
  CC-DT-S: 91,000
- Seismicity strikes SW-NE consistent with FM and trend of faults. Bilateral migration of seismicity



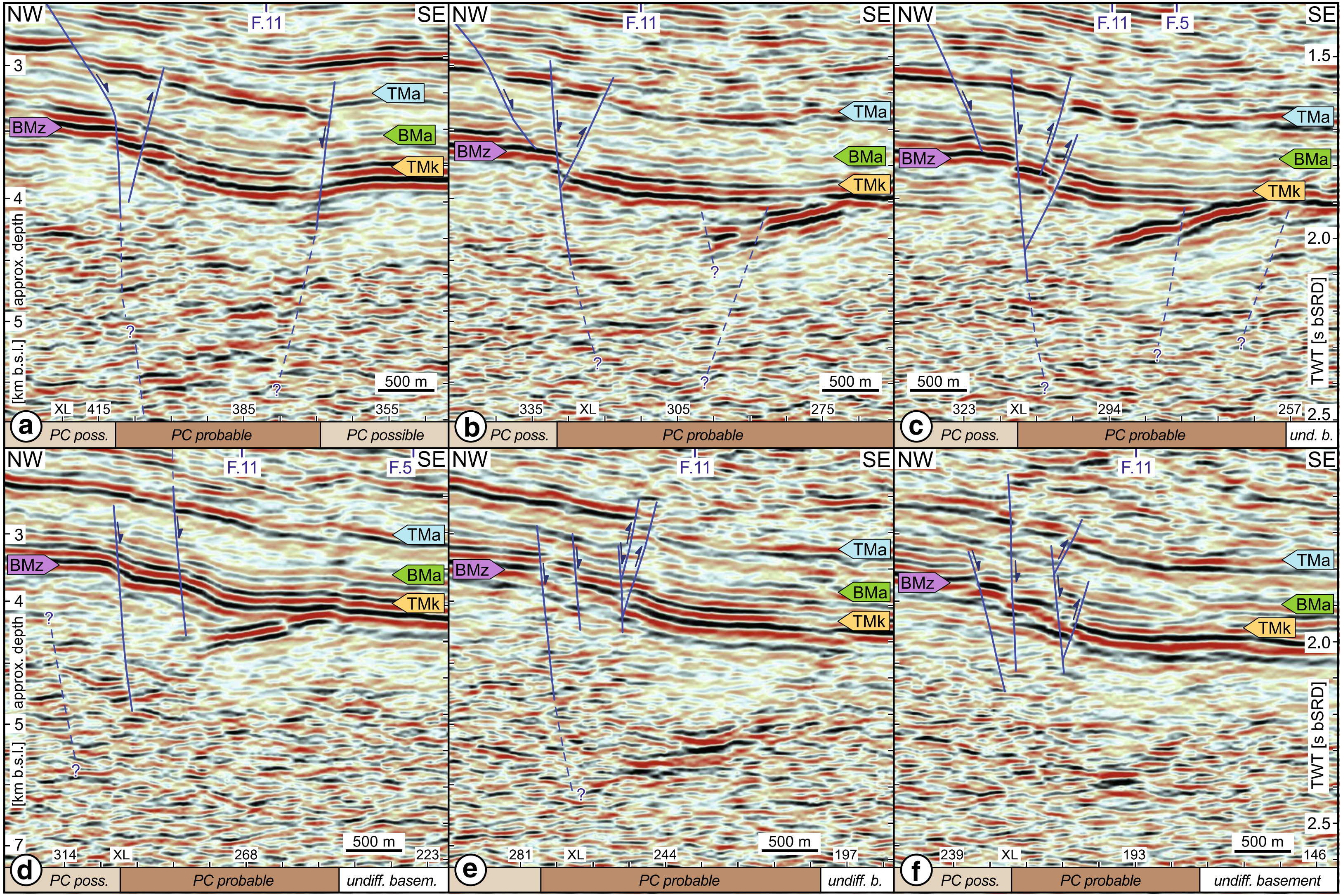
Discussion: Hydraulic Conditions and Stress Distribution



Discussion: Hydraulic Conditions and Stress Distribution

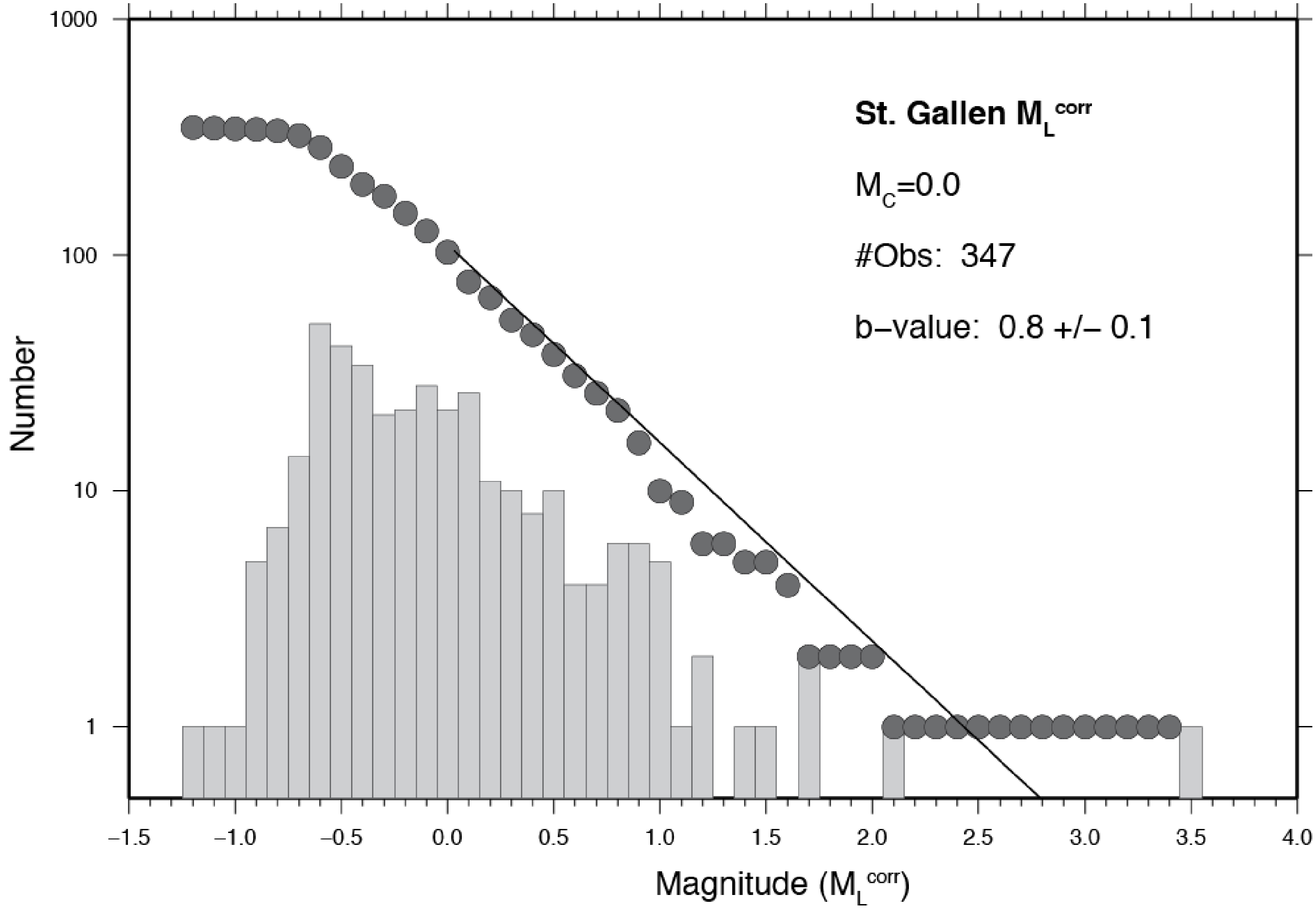


Discussion: Host Rock Formation and Fault Geometry



Heuberger et al. 2016

Data:


St. Gallen M_L^{corr}
M_C=0.0
#Obs: 347
b–value: 0.8 +/– 0.1
Number
1000
100
10
1
–1.5
–1.0
–0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Magnitude (M_L^{corr})

Goals of High-Precision Hypocenter Relocation

- In total, about 340 earthquakes of the sequence could be located with the dense monitoring network. Routine locations derived with regional 3D P-wave model of Switzerland (Husen et al. 2003). → Not enough resolution, not suitable for S.
- **Goal 1:** Identify the host rock formation of the fault reactivated by fluid injections (e.g., within Molasse sediments, Mesozoic sediments, pre-Mesozoic basement) and its distance to the open-hole section of the well. Problem: Coupled hypocenter velocity-structure problem needs to be solved at high resolution.
- **Goal 2:** Resolve the precise geometry of the activated fault and compare it to faults imaged by the 3D reflection seismic survey. Can it be associated to an imaged fault segment? Is it limited to the imaged segment?
- **Goal 3:** Analysis of the spatio-temporal evolution of the earthquake sequence to study fluid interactions and hydraulic properties of the targeted fault zone

Presented results document complexities in terms of:

→ Fault structure and incompleteness of mapped faults

→ Limited knowledge of hydraulic conditions

→ Limited knowledge of stress distribution in targeted fault system