Seismic Response of the Rittershoffen Geothermal Reservoir to the Series of GRT-1 Stimulations

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SUMMARY

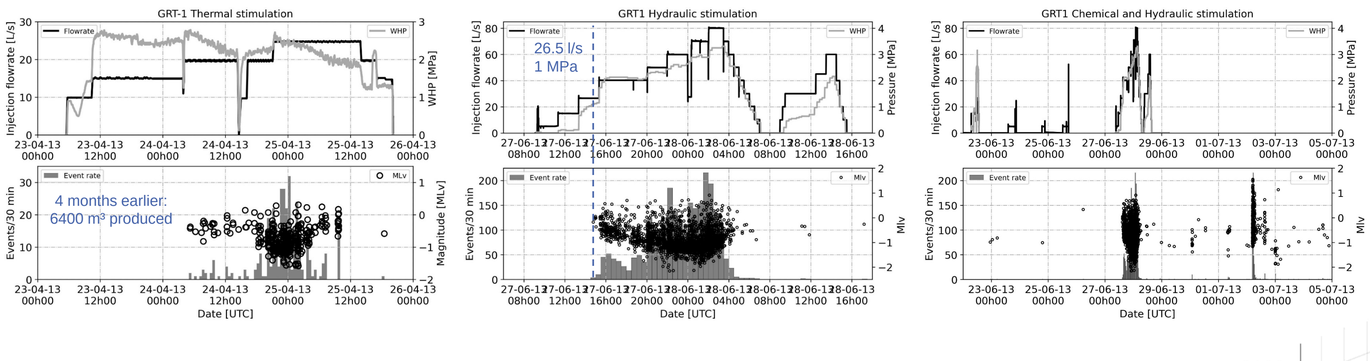
- Between **April and June 2013**, the GRT-1 well, located at the Rittershoffen geothermal site in the **Upper Rhine Graben** (France), was stimulated.
- Three distinct stimulations: 1. **thermal**, 2. **chemical** and 3. **hydraulic**.
- A local surface seismic network continuously monitored these operations, which triggered **thousands of seismic events**.
- The current study extends and refines the work of *Lengliné et al. (2017)*, who were considering the hydraulic stimulation of GRT-1 only, and the work of *Maurer et al. (2020)*, who were limited in the result interpretation due to questionable absolute locations of the seismicity, especially depth.

Phase	Templates	Final	Q_{Max} (l/s)	WHP_{Max} (MPa)	Volume (m^3)	Duration (h)	I_{index} (l/s/bar)
Thermal (23-26 April)	146	328	25	2.8	4230	62.6	0.9
Injection test (22 June)	0	5	27	2.5	357	6.5	
Chemical (23-25 June)			5	n.a.	269	14.2	1.7
Hydraulic (27-28 June)	984	2965					
Co-injection	823	2473	80	3.3	4000	28.2	2.5
Post-injection	161	492					
TOTAL	1130	3298					

METHOD

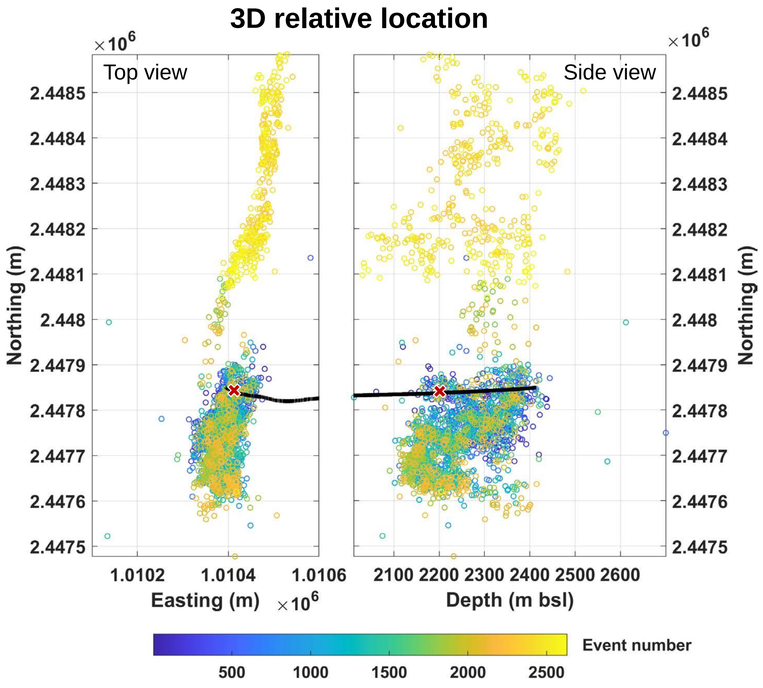
- **Detection and picking**
  - Template: *Maurer et al.* reference catalogue
  - Matching: *Lengliné et al.* method with automatic setting of detection threshold (100 sps, 10-45 Hz, 2.56 s CC window, -0.5 s before P, 1 false detection/10000 days)
- **Relative location method**
  - 3D velocity model, URG scale, *Freymark et al. (2020)*
  - Cross-correlation to propagate arrival times (CC > 0.5)
  - GrowClust3D
  - 1st event of thermal stimulation on fault crossed by GRT-1 (2201 m bsl)
- **Magnitude**: Template Mlv corrected from amplitude and distance

History of operations and seismicity

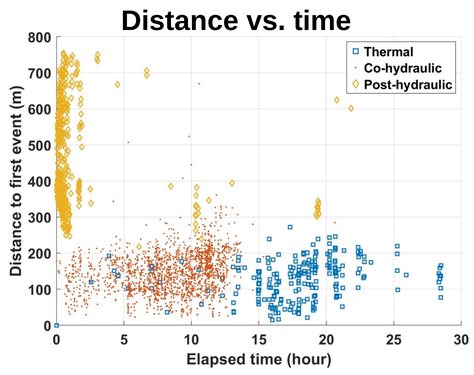


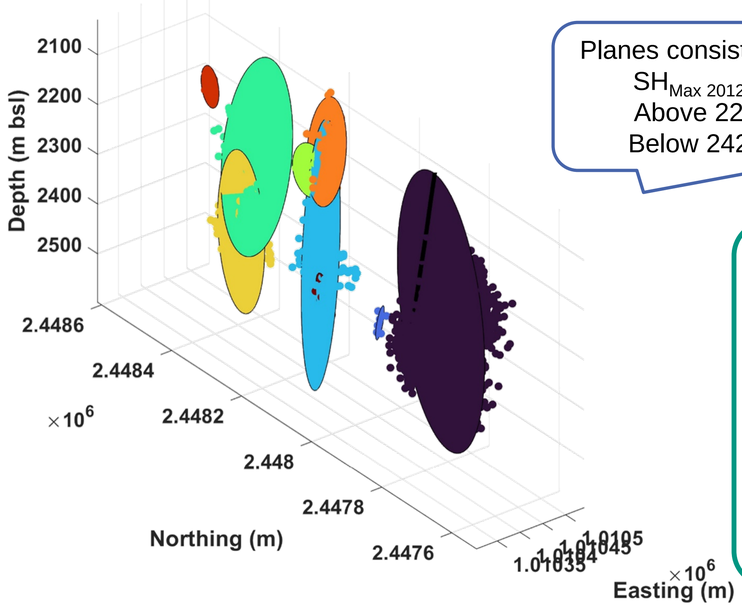
b-values	Thermal	Co-hydraulic	Post-hydraulic
Aki in *Maurer et al.* (*Wiemer-Wyss*)	1.53 ± 0.15	1.16 ± 0.05	0.92 ± 0.08
Aki (*Wiemer-Wyss*)	1.90 ± 0.18 (41)	1.30 ± 0.05 (109)	0.82 ± 0.04 (122)
b-positive (*van der Elst*)	1.42 ± 0.14 (111)	1.15 ± 0.04 (885)	0.80 ± 0.06 (176)
b-more-positive (*Lippiello & Petrillo*)	1.58 ± 0.11 (221)	1.20 ± 0.03 (1936)	0.88 ± 0.04 (382)

3D relative location



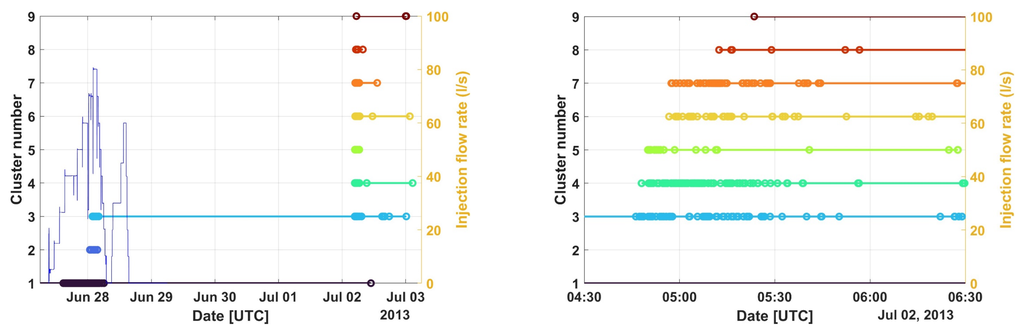
77% of the volume activated during thermal stim. is reactivated during hydraulic stim.
(cells: 30 m × 30 m × 30 m, more than 1 event)





Planes consistent with local stress field $SH_{Max\ 2012}$ (*Azzola et al. 2019*)
Above 2270 m bsl.: 15°N±19°
Below 2420 m bsl.: 165°N±14°

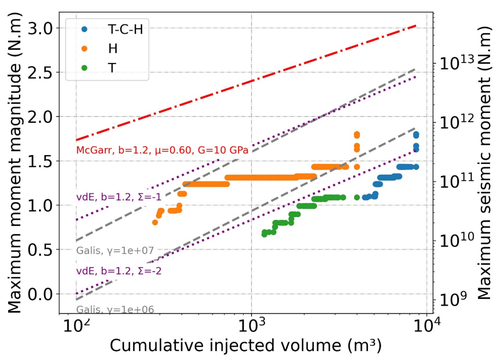
Occurrence time of clusters



CLUSTERING

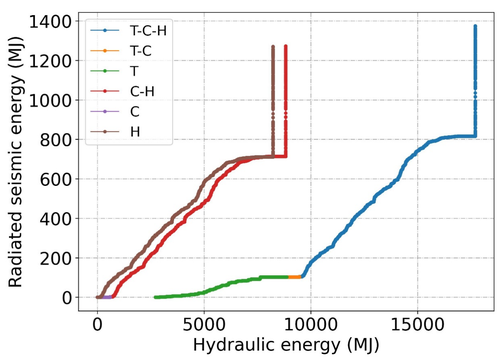
- **Pre-processing:** Remove hypocenters with uncertainties > UIF in space and residuals
- **DBscan**
  - Density-based clustering
  - Minimum 5 points
  - "Radius": UIF location errors

M_{Max} vs. Cumulative injected volume

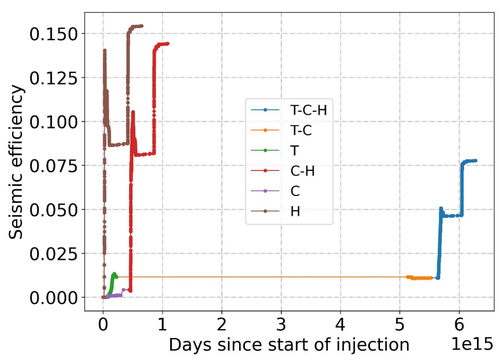


Shall we consider the thermal, chemical and hydraulic stimulations independently?

Seismic energy vs. Hydraulic energy



Seismic efficiency vs. Time



The seismogenic behavior during the thermal and the hydraulic stimulations are different.

CONCLUSIONS

- Comprehensive catalog: 3 stimulations, > 3000 events
- Similar active zones between thermal and hydraulic stimulation ⇒ effect of the chemical stimulation?
- Aseismic chemical stimulation
- Part of the post-stimulation active zone was active at the end of the hydraulic stimulation
- Confirm change of b-value between co-hydraulic stimulation and post-stimulation seismicity
- Mw_{Max} vs. Cum. Vol., Radiated seismic energy vs. Hydraulic energy and Seismic efficiency vs. Time behave differently between the stimulations

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