Characterisation of microseismic sequences induced by the Rittershoffen deep geothermal project (Alsace, France)

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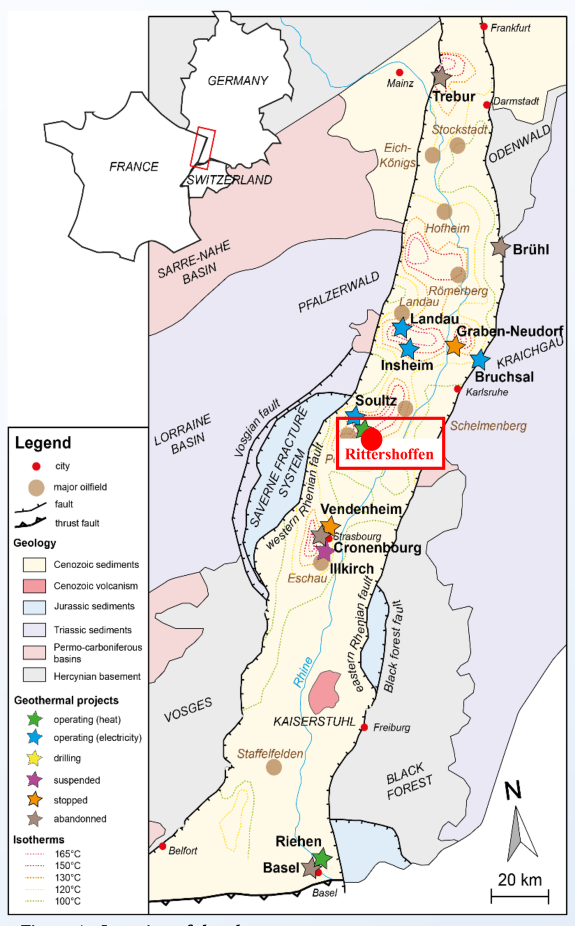

Figure 1 : Location of the plant

The plant :

- **Location** :

Rittershoffen, Northern Alsace (France)

- **Geothermal reservoir** :

Naturally fractured at 2 500m depth

- **Enhancements** :

Thermal, chemical and hydraulic stimulations

- **Wells** :

2 deep wells drilled between 2012 and 2014

Designed to produce 24 MWth

Seismic catalogue and problematic :

- Microseismicity monitoring : Monitored by a network of twelve permanent seismological stations
- Between 2012 and 2024 : over 10,000 events recorded with magnitudes less that 2.3

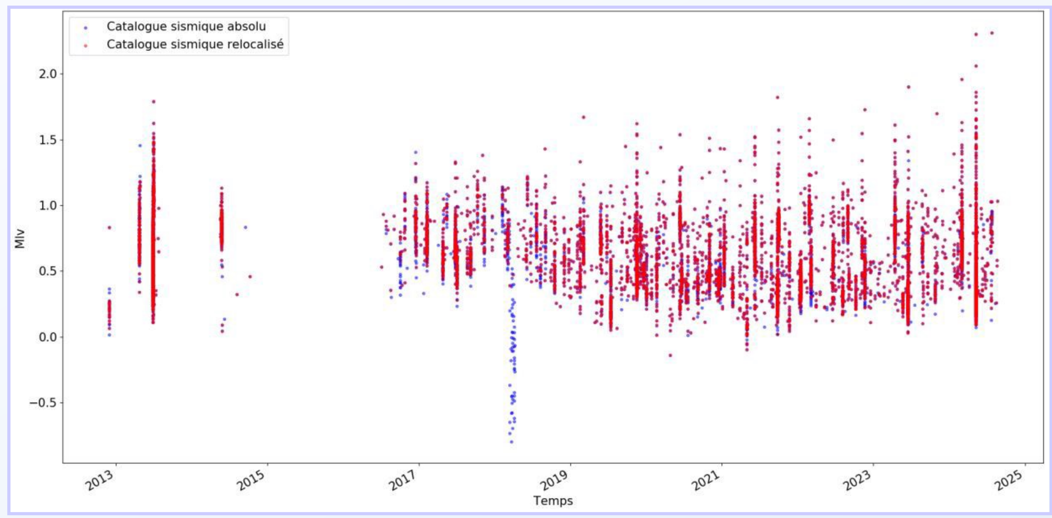

Figure 2 : seismic catalogue

- **Seismic activity pattern** : Alternating phases of high seismic activity and quieter period (Fig 2)

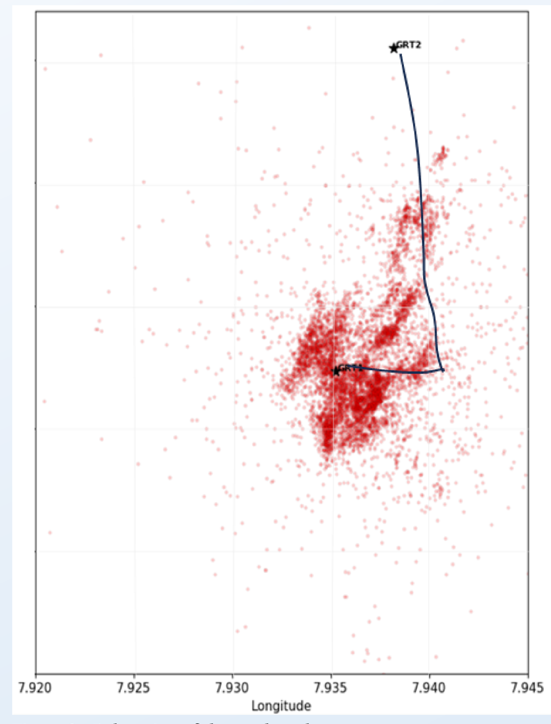

Figure 3 : Relocation of the earthquakes

- **Relative relocation of seismicity** : There appear to be structures in the subsurface (Fig 3)

Aim of the study : Characterise seismic sequences (A) and better understand subsurface structures (B)

A. Temporal sequences :

- **First step : identify periods of intense activity sequences and quieter intervals based on inter-event time**

Method : Temporal dispersion of seismicity analysed using the ISIn threshold (Bakkum et al., 2014)

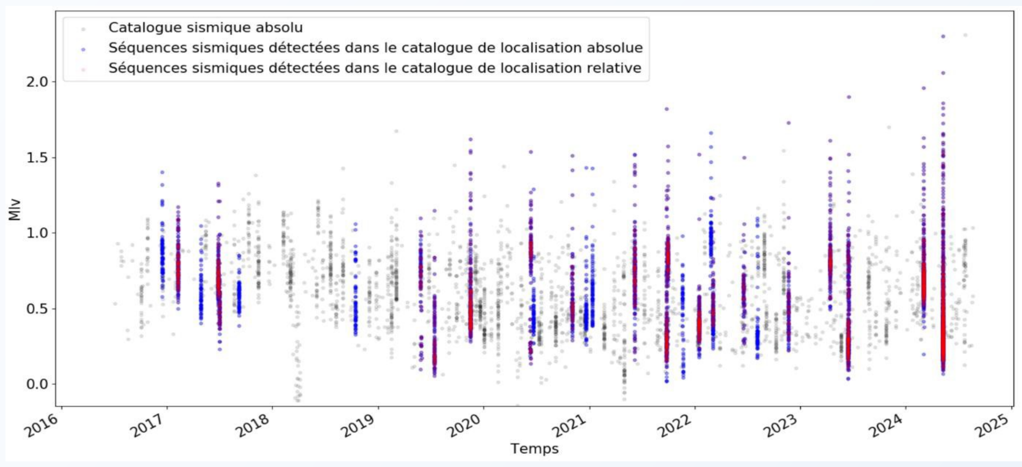

Figure 4 : temporal sequences since the beginning of the production

⇒ 1 sequence : over 60 events with a maximum inter-event time of 28 hours

⇒ 29 sequences between 2016 and 2024

- **Second step : analyse the characteristics of theses sequences**

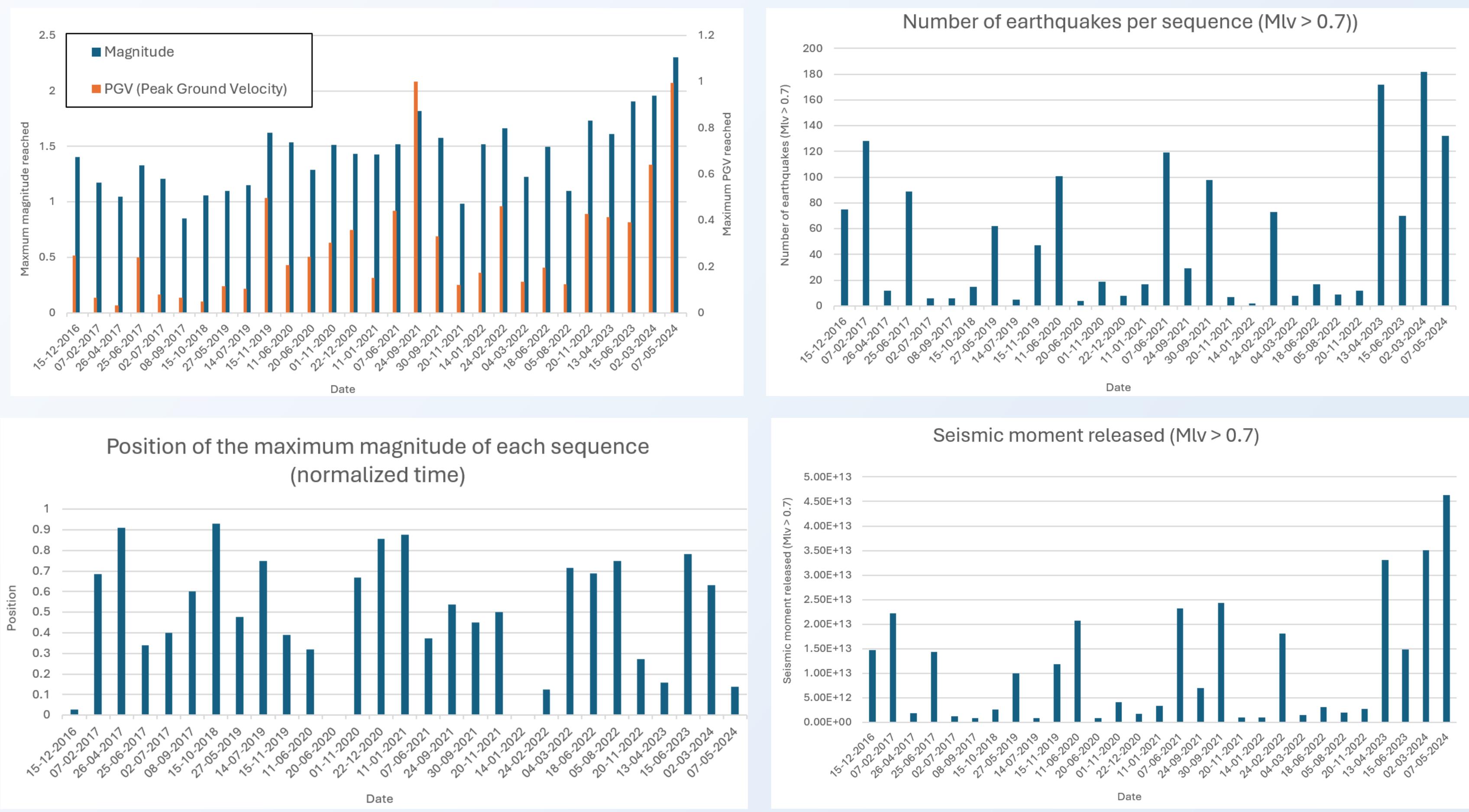

Figure 5 : Histograms of different characteristics of the sequences

⇒ Maximum magnitude, maximum PGV and seismic moment released vary across sequences

⇒ Timing of maximum magnitude event show no consistent pattern

The sequences are heterogeneous across all studied characteristics, making their occurrence and evolution difficult to predict.

B. Waveform analysis :

- **First step : Waveform cross-correlation**

Method : Events with a waveform correlation above 0.7 (for N,E, V components) were grouped into the same clusters.

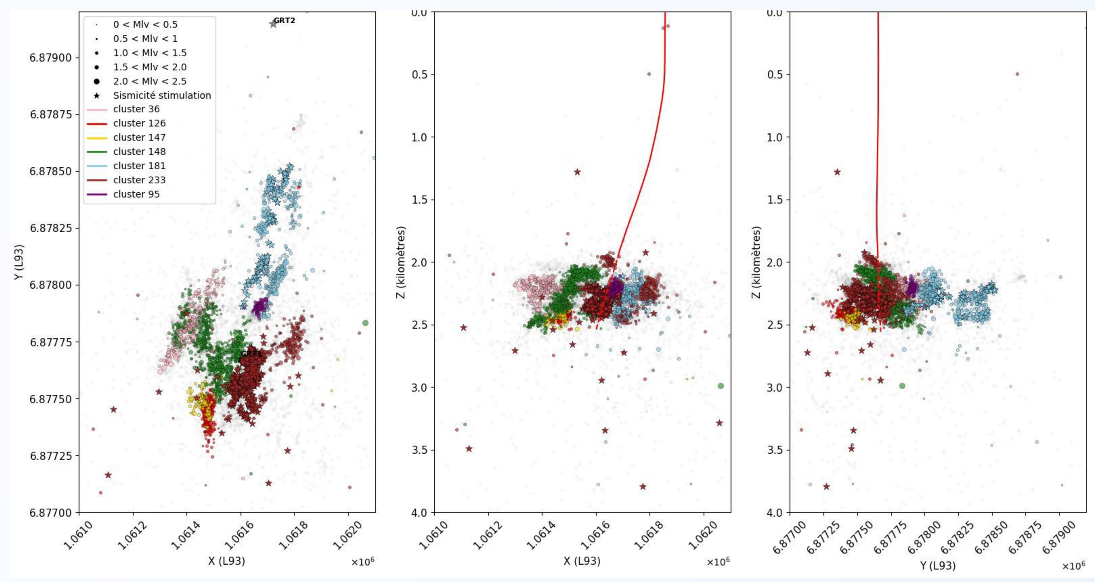

Figure 6 : Localisation of the different clusters

⇒ 7 major clusters containing more than 50 events, representing recurrent seismic structures over time

⇒ The spatial distribution of clusters divides the area into distinct zones.

- **Second step : occurrence over time**

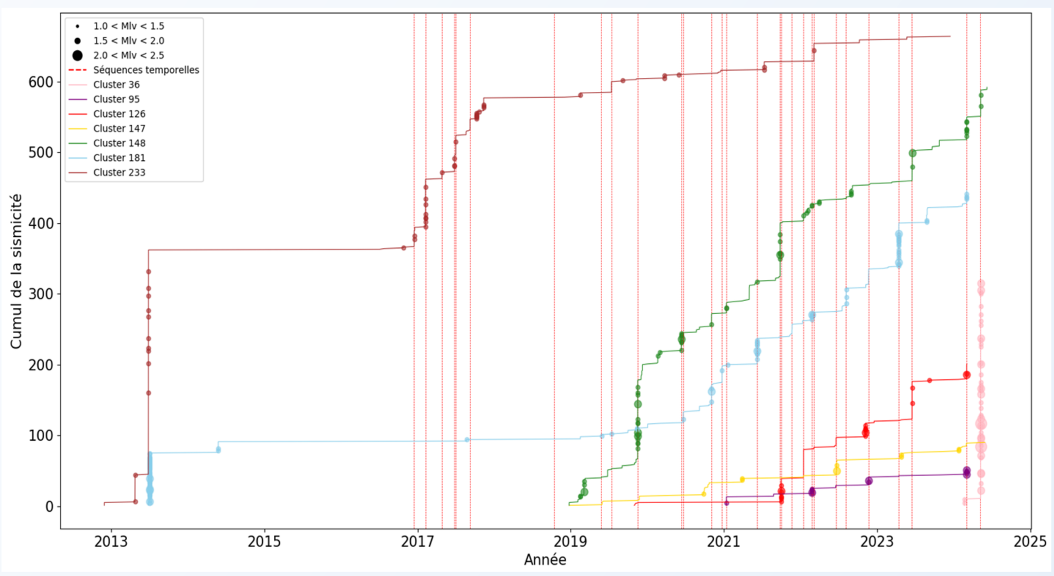

Figure 7 : Cumulative seismicity over time

⇒ Hydraulic & thermal stimulation (P~30bars): Cluster 181 and cluster 233 stimulation, near the injection well GRT-1

⇒ 2017-2019 :
Cluster 233 reactivated

⇒ Since 2019 : 5 new clusters
Reactivation of cluster 181
cluster 148 has a sustained activity

- **Third step : analysis of b-value**

B-value determined by applying a linear regression to the entire Gutenberg-Richter distribution starting from the completeness magnitude

Year	Cluster Nr.	b-value	Number of events
2012	233	3.11	700
2013	181	2.2	486
2019	148	1.86	611
2019	147	1.42	93
2019	126	1.34	202
2021	95	1.24	56
2024	36	1.06	312

⇒ Cluster 233 and 181 : high average b-value

⇒ Since 2019 : Decrease in the b-value of clusters.

The seismicity of cluster 181 and 233 is mainly driven by injection pressure and fracture reactivation near the wells, enhancing reservoir productivity. Recent seismicity in distant structures seems linked to long-term processes like thermoelastic deformations from the cold front.

Focus on a active seismic structure

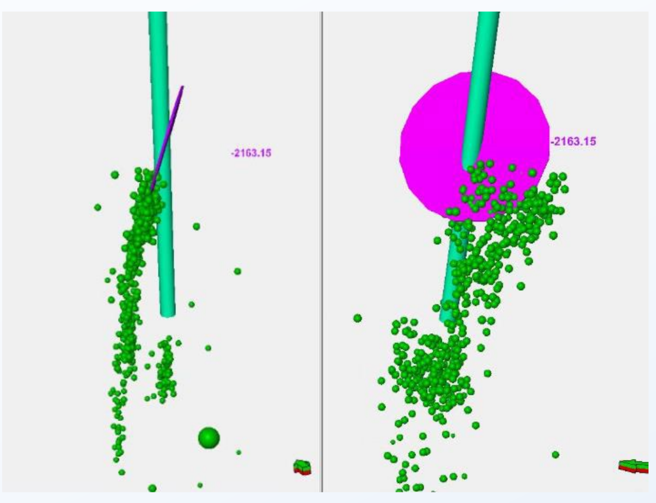

Figure 8 : Localisation of the seismicity from the cluster 148 (green). The GRT-1 well is in blue. The fracture seen on acoustic imaging is in pink

⇒ N231E, 47°NW, correlated with a fracture observed in the acoustic imaging

⇒ Fracture not initially considered as the main flow zone….

But ! Seismic activity : a new fluid flow pathway ?

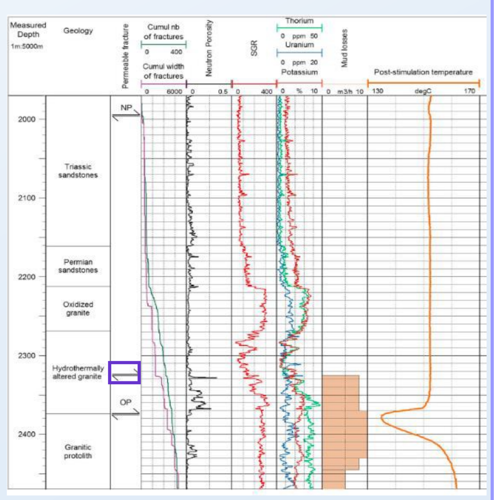

Figure 9 : Log in the open hole of GRT-1. OP = Originally permeable, NP = Newly permeable. The fracture in question is shown in purple. Adapted from (Vidal et al., 2017)

⇒ Previous characterisation : (Vidal et al., 2017) identified as the start of a highly fractured, originally permeable zone

⇒ Mineralogical evidence : The presence of hexagonal quartz (Glaas et al., 2017) in fracture interstices indicates past reopening

Conclusion

⇒ Heterogeneity : analysis of the microseismic catalog reveals unpredictable induced seismicity, with unique temporal evolution in each sequence

⇒ Seismogenic zones & migration : cross correlation of waveforms identifies distinct seismogenic zones that reactivate over time and migrate away from the injection well.

⇒ B-value decline : a decreasing b-value suggests changes in the underlying physical processes driving seismicity.

⇒ The intermittent behavior of the clusters suggests an aseismic behavior of the structures.

Aknowledgement :

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References :

- Bakkum, D. J., Radivojevic, M., Frey, U., Franke, F., Hierlemann, A., Takahashi, H. (2014). Parameters for burst detection. *Frontiers in Computational Neuroscience, 7*, 193. https://doi.org/10.3389/fncom.2013.00193
- Baujard, C., Genter, A., Dalmais, E., Maurer, V., Hehn, R., Rosillette, R., Vidal, J., & Schmittbuhl, J. (2017). Hydrothermal characterization of wells GRT-1 and GRT-2 in Rittershoffen, France: Implications on the understanding of natural flow systems in the Rhine graben. *Geothermics, 65*, 255–268. https://doi.org/10.1016/j.geothermics.2016.11.001
- Glaas, C., Genter, A., Girard, J.F. et al. (2018), How do the geological and geophysical signatures of permeable fractures in granitic basement evolve after long periods of natural circulation? Insights from the Rittershoffen geothermal wells (France), *Geotherm Energy*, 6, 14, https://doi.org/10.1186/s40517-018-0100-9.
- Vidal, J., A. Genter, and F. Chopin (2017), Permeable fracture zones in the hardrocks of the geothermal reservoir at Rittershoffen, France, *J. Geophys. Res.Solid Earth*, 122, 4864–4887. doi:10.1002/2017JB014331