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Seismological monitoring of the GRT1 hydraulic stimulation (Rittershoffen, Alsace, France)

Mohamed Boubacar[1], Olivier Lenglinė[2]

1. University of Quebec, INRS

2. University of Strasbourg, EOST

Summary

The deep geothermal project ECOGI at Rittershoffen, 6 km south-east of Soultz-sous-Forêts, in Northern Alsace was initiated at the end of 2012. A first well GRT1 has been drilled up to 2580 m. Water injection has been carried out in June 2013 to enhance the connections between the well and the reservoir by inducing hydro-shearing along the pre-existing fracture network. The operation resulted in significant induced microseismicity that was recorded by a surface seismic network made of a permanent and a temporary surface seismic network composed of 18 surface stations in total (Stations sampling frequency ranging between 100 to 300 Hz). We computed a detection function based on the ratio of the signal averaged over long and short period and reviewed all manually detections to isolate only those corresponding to seismic events with clear arrival times visible at least at 6 stations. With this procedure we identified a total of 682 seismic events. Two periods of activity can be observed: a main swarm of two days (27 and 28 June) during the injection and a second swarm that occurred on 2 July, three days after water injection ended. The first swarm includes 82% of the events in the catalog. Interestingly, we also noticed that when the second phase of the injection took place between 11:00 and 17:00 PM on the 28th of June, no seismic event was observed. The absence of seismicity during this second injection was at a lower rate than the preceding one the day before is characteristic of a Kaiser effect. The second noticeable feature of the seismicity is the complete absence of seismic events between the two swarms with no earthquake recorded during the 3 days time interval. We then performed a manual picking on compressive and shear phases (P and S) for all events. Location of seismic events shows that the second swarm is located around 500m away from the first one and relative relocation using the HypoDD software was performed in order to improve the resolution of the earthquake location. Earthquakes relative relocations enhanced the clustering of the seismicity observed previously and confirmed the spatial gap between the two swarms. Local magnitudes for all events of the sequence range between -0.9 and 1.3 and the estimated magnitude of completness is 0.1. We clearly observed larger magnitudes for events of the second swarm.

Introduction

The enhancement of the permeability in geothermal resevoirs by water injection at high pressures induces seismicity. Though, in some cases seismicity has been observed after the fluid injection ended. In June 2013, during the stimulation of Rittershofen, Alsace, geothermal well, two crisis have been observed. The first crisis occured during the water injection but the second crisis occured three days after water injection ended. This seismicity observed after injection periods remains poorly understood. Here, we proceed to the analysis of the seismicity observed within a period of nine days including the two crisis. We interactively used automatic detection along with manual picking of phases resulting in the validation of 682 microseismic events. The sources location of the events has been improved by double difference relocations with HypoDD software. Uncertainties evaluated with Monte Carlo simulations helped to validate relocations. It clearly appears that events are splitted into two crisis positioned in two distinct areas of the reservoir. The mechanism that lead to second swarm is attributed either to the slip of an active structure or to aseismic slip. Local magnitudes for all events of the sequence range between -0.9 and 1.3, with larger magnitudes for events of the second swarm.

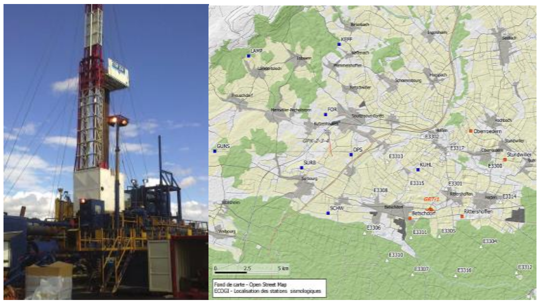

Figure 1: Left-GRT1 borehole deeping at 2580m, with the openhole at 1922m during the hydraulique stimulations of April 2013 and June 2013 (5000 m3 injected). Right-The surface seismic networks including 18 sensors (Red, blue and white squares) sampling at 100,

1. Detection and picking

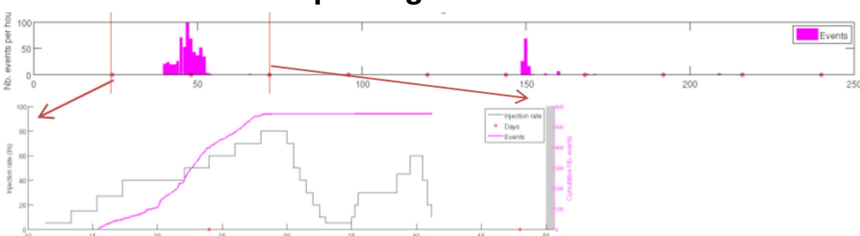

Figure 2: Top-Hourly distribution of events. The vertical red bars demarcates the injection time period. Bottom-Zoom in the first swarm. The averaged injection rate (Stairs) and the cumulative number of events (Magenta curve) indicate a kaiser effect.

From 1586 candidates reviewed, we formed a catalog of 682 seismic events (Magenta in top of Figure 2). Two periods of activity can be observed: the main crisis of 27 and 28 June (82% of the catalog) and a second crisis that occured on 2 July, three days after water injection ended. The absence of seismicity when the injection rate started to be lowered in the first part of the injection and during the entire second part are characteristic of a Kaiser effect (Figure 2-Bottom).

2. Double difference relocation (DD)

The DD considers that the travel time differences or time delays between the events is due to their spatial offset and the difference of their origin times. If we consider two earthquakes i and j, their travel time differences determined at station k is given by :

$$\left(\delta t_k^{ij}\right)^{cal} = \frac{1}{c}\left[\delta x_k^{ij} sin\theta sin\varphi + \delta y_k^{ij} cos\theta sin\varphi + \delta z_k^{ij} cos\varphi\right] + \delta t_{0k}^{\ ij}$$

The equation above is solved by least square inversion untill the residual between $\left(\delta t_k^{ij}\right)^{cal}$ and $\left(\delta t_k^{ij}\right)^{obs}$ (Computed by cross correlating arrival times) is minimized.

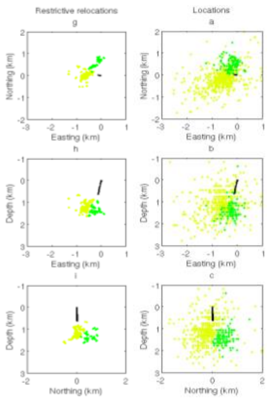

Figure 3: Relocation of 682 events (catalog). Left panels (a,b,c)-Absolute locations (99% of the catalog). Right panels (g,h,i)-Relocations (46%). Events are represented relatively to their distance to the openhole (Black line). First and second swarm events are plotted in yellow and green respectively.

Figure 3 shows absolute and relative locations of the catalog events. Relocations provide better horizontal and vertical resolutions. We can see that the two swarms took place in different areas and events are located on either side of the injection well

3. Relocations uncertainty

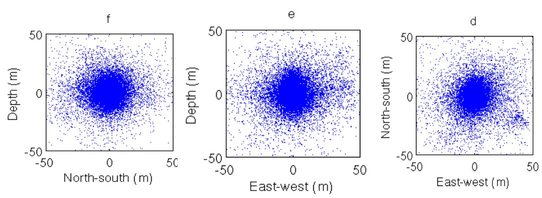

Figure 4: Monte-Carlo analysis of the relocation errors. Samples represent the changes in location that have been computed between initial relocations and their 100 disturbed relocations leading to 227 × 100 samples.

To analyse the effects of unertainties on the relocations we introduced disturbances in the initial set of cross delays and each event was relocated 100 times to get the standard deviations in the three spatial directions. Using the spatial differences, the error in distance that corresponds to 95 % of the distribution is 53 m.

4. Local magnitudes estimation

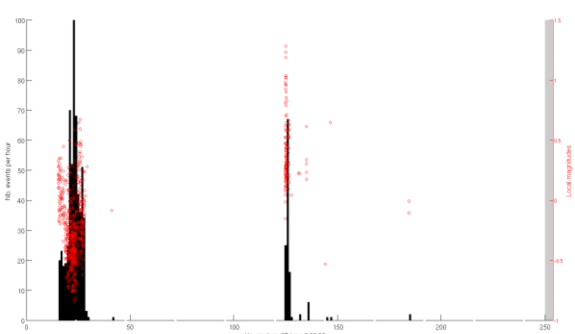

Figure 5: Events distribution (Black) superimposed on local magnitudes (Red circles) ranging from -0.9 to 1.3.

Here we consider the local magnitude, therefore each trace was deconvolved to get the original signal which was applied a sensor response of type wood-anderson. The resulting events were corrected from the medium attenuation by searching for the distance correction that minimizes the magnitude residuals between close sensors. In Figure 5 we observe that the second swarm events are of higher magnitude than the first swarm by at least 0.5.

5. Interpretation

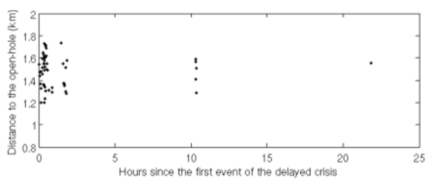

Figure 6: Occurrence time of events as a function of their distance to the openhole section during the second swarm

The alignement and continuity in space of events observed in Figure 6 suggests the slip of an active structure on a whole as a consequence of a stress load that started with the water injection and continued after the shut-in of GRT1, this thesis is supported by the higher magnitudes for the second swarm events. Another explanation can be a slow aseismic slip on faults that may have been progressively set up by pore pressure diffusion in the medium during the three days of inactivity after the first swarm.

6. Conclusion

The analysis of the seismic data collected during the hydraulic stimulation of GRT1 shows that the later swarm events occured almost simultaneously and the reason for their relocations in a different area from the first swarm is likely that a stronger active area slipped after suffcient stress load. Even so, analysis of multiplets (Similar events) could help to rule out the thesis of aseismic slips.

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