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SEISMIC SOURCE PARAMETER EVALUATION AND ITS IMPORTANCE IN THE DEVELOPMENT OF AN HDR/EGS SYSTEM

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ABSTRACT

In 2000 and 2003, massive hydraulic stimulations were carried out at the European Geothermal Hot Dry Rock (or EGS) site at Soultz-sous-Forêts, France. These stimulations were performed in the 5000 m deep wells in the crystalline basement. The objective was to create a dense network of enhanced permeability fractures, which would form the heat exchanger. The injection of water in the fractured rock generated a high level of microseismic activity. Around 30,000 and 90,000 micro-earthquakes were triggered during the injection of 2000 and 2003 respectively. From this around 14,000 and 9,000 events were then located and processed. Source parameters for these events were calculated using Brune's model on acceleration traces. An automatic process based on a genetic algorithm was developed to calculate source parameters such as seismic moments, moment magnitudes, stress drops. Large events were induced during the shut-in period and the spatial distribution of stress drops suggests that a redistribution of stresses may be occurring in the reservoir. Some of these big events may be caused by the release of locked up stress on specific fractures. Events in the range of up to 2.9 Ml have been generated during these periods and it is felt that the detailed understanding of the source parameters may be a way forward for reducing these larger events by revaluating the stimulation strategy.

INTRODUCTION

In 2000 and 2003, massive hydraulic stimulations were carried out at the European Geothermal Hot Dry Rock (or EGS) site at Soultz-sous-Forêts, France. These stimulations were performed in the 5000 m deep wells in the crystalline basement. The objective was to create a dense network of enhanced permeability fractures, which would form the heat exchanger. The injection of water in the fractured rock generated a high level of microseismic activity. Around 30,000 and 90,000 micro-earthquakes were triggered during the injection of 2000 and 2003 respectively. From this around 14,000 and 9,000 events were then located respectively and processed. Source parameters for these events were calculated using Brune's model (1970) on acceleration traces.

MICROSEISMIC NETWORK

A comprehensive seismic monitoring system was set up and operated during operations in 2003 (see figure 1). Seismometers were deployed in wells GPK-1, 4616, EPS1 (depths 3500m, 1480m and 2017m respectively) and 4-axis accelerometer tools in wells 4550, OPS4, 4601 (depths 1482m, 1484m and 1539m respectively) as shown in figure 1. The frequency band of the acquisition system was from 10Hz to 1 kHz. The sampling rate was 0.5 ms and the total duration of the recorded signal was 5 seconds. P and S arrivals on the triggered events were picked automatically. The hypocenter locations shown here were calculated by **Semore Seismic** [http://www.seismics.net/].

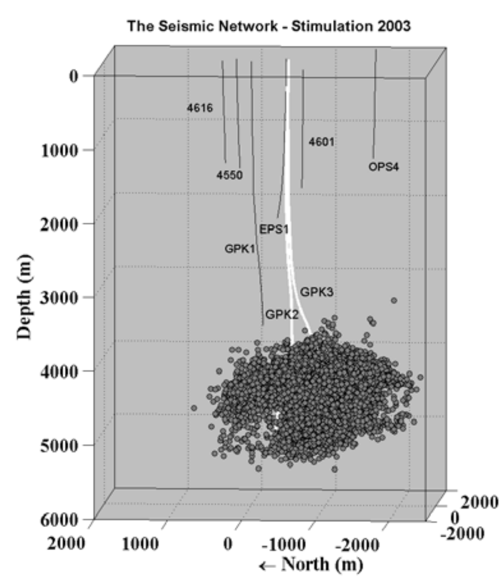


Figure 1: the seismic network – stimulation 2003

Monitoring the reservoir creation

Between 30th June and 6th July 2000, a total volume of 23,400 m^3 of water was injected into the openhole section of the well GPK-2 (See figure 2). The initial flow rate was 31 l/s, this one was increased up to 41 and then 51 l/s. After the stimulation, a test of injectivity was also done from 13th July to 15th July 2000 with 4,500 m^3 of water injected. During the monitoring period, 31,511 triggers were recorded on the down-hole network from which 13,954 events were located. The seismic activity was high throughout the entire experiment: roughly 150 events per hour. After shut-in, it decayed rapidly but a significant event rate persisted (more than 20 events/h). We observed that the seismic cloud was trended North West of the well GPK2 (figure 3) and that events occurred between the casing-shoe (4430m) and a depth of 5500m. The moment magnitudes of events were ranging between –2 and 2.6. The greatest, 2.6 occurred the 16th July 2000 i.e. one day after the end of the operations.

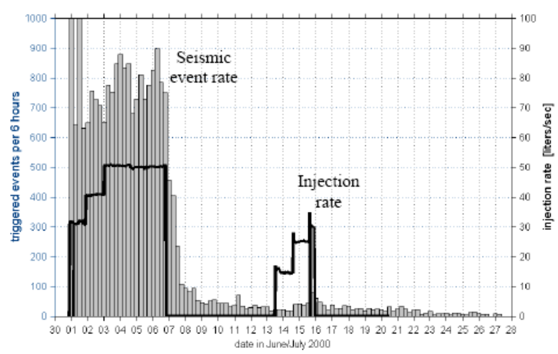


Figure 2: Distribution of events per 6 hours and injection rate (l/s) in 2000 at Soultz (Weidler et al., 2002)

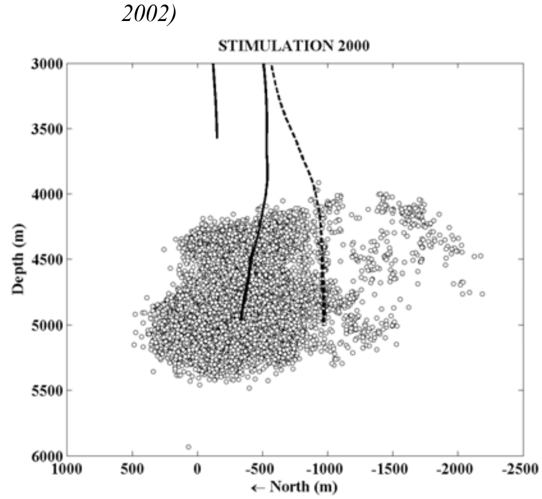


Figure 3: The seismic cloud viewed from the West – stimulation 2000

The most recent stimulation test at the site was carried out in the summer of 2003. Between 27th May and 7th June a total volume of 34,000 m^3 of water was injected into the open-hole section of GPK-3 and between 2nd June and 4th June, 3,300 m3 of water was injected into the open-hole section of GPK-2. Moreover, between 11th June and 17th June, a venting test in the GPK-2 well was performed.
The injection in GPK-3 started the 27th May; different steps of rate followed as can be seen on figure 4. In the middle of the experiment, a dual injection between the GPK2 and GPK3 wells was undertaken. The shut-in in GPK-3 was performed the 6th June: the flow rate was decreased progressively in three steps in order to avoid large seismic activity caused by rapid pressure drops. After this, the GPK-2 well was put in production on the 11th June. This test was stopped on the 17th June.

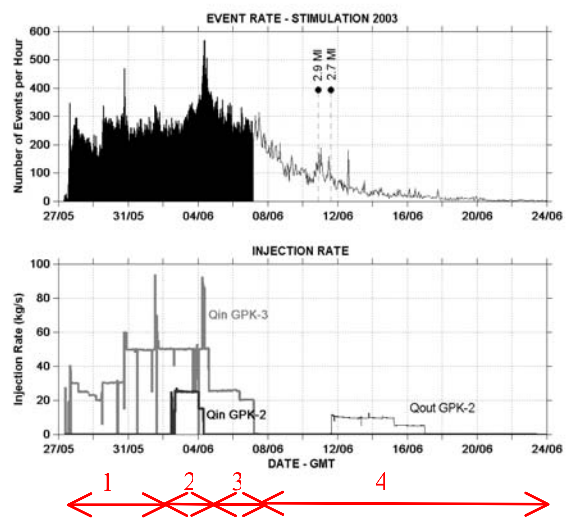


Figure 4: the seismic activity & the injection rate – stimulation 2003

During the stimulation test, 90,648 triggers were recorded on the down-hole network from which 8,354 events were auto-located (See figures 5 & 6). The seismic activity was high throughout the entire experiment i.e. an average of 300 events per hour and a maximum rate of 580 events per hour just after the flow rate of 93 l/s. The seismic rate during the 2000 stimulation was not that high because the threshold trigger was higher than in 2003. During this test, the seismic activity was very well correlated to changes in flow rates: each time the flow rate is increased the number of events per hour increased. After the shut-in of the well GPK-3 (the 6th June 2003), the number of events per hour decreased but the seismic activity was still high (more than 100 events per hour). The 10th June and the 11th June, two microseismic events of local magnitude 2.9 and 2.7 respectively occurred just before the venting test in the GPK-2 well. An increase in the seismic activity is observed just before each of these two large microearthquakes. This behavior can be seen as a pre-shock crisis in reference to aftershock sequences following an earthquake. The venting test was held in response to this high seismic activity in order to decrease the over-pressure within the stimulated zone.

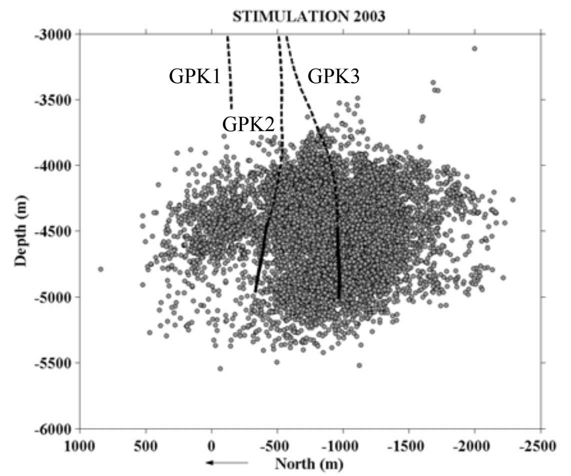


Figure 5: the seismic cloud viewed from the West – stimulation 2003

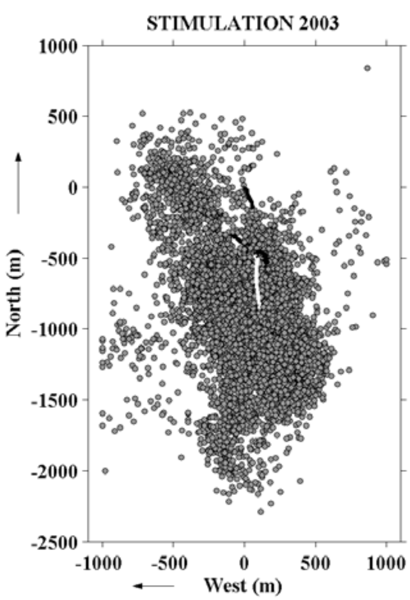


Figure 6: top view of the seismic cloud – stimulation 2003

The seismic cloud has an approximate volume of 3 km^3, striking N30W which is in accordance with orientation of the acting major horizontal stress (Hettkamp, 1998).

We also looked at the distribution of the depth with the time (Figure 7). A migration upward of the microseismic events is observed starting with the dual injection (2nd June 2003). At the same time, instead of having a change of pressure in the GPK-3 well, stabilization is seen. This stabilization of the pressure and its independence to the flow rate indicate that at least some portion of the fractures was completely mechanically opened (Cornet F.H. and Berard Th., 2003).

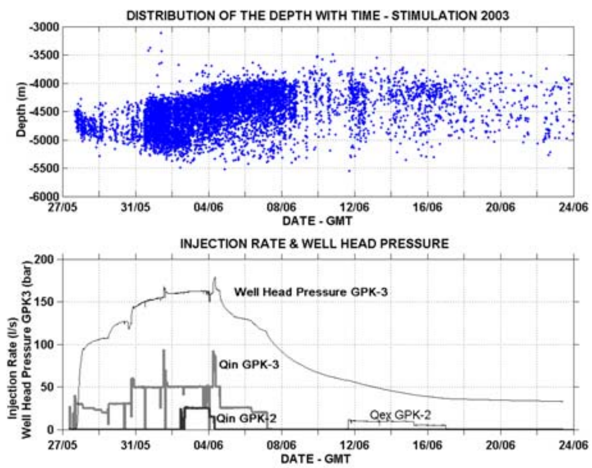


Figure 7: Distribution of the microseismic event depth with time (top part of the figure) and injection rate and wellhead pressure in GPK3 with time

Source parameter calculation: method

We only processed the records of the sensor in the well 4550 because the system used an amplitude threshold trigger on the accelerometer sensor in this well to detect and acquire potential microseismic events. We only worked on the P arrivals on the vertical sensor traces because we assume that the P-wave has vertical angle of incidence (the sources are at 5 km depth and the sensor at 1.5 km above). We didn't process the S arrivals on the sub-horizontal sensor traces at present. The vertical trace from each station was then windowed with a window of 300ms containing the P pulse and beginning at the picked P-wave arrival time and then Fourier transformed to give the corresponding acceleration spectrum. We worked in the Fourier domain in order to characterize the mechanism of the seismic source. We have first corrected the spectrum from attenuation. To do so, we used a least squared method and calculated the attenuation factor Q value that gives a zero-slope for the corrected data A_0 for frequencies between 140 and 260 Hz:

$$A\_0 = data \times \exp(\pi \times \mathrm{K} \times f)$$

Where K=R/(Q.α) is in second (Anderson, 1991), R is the distance between the source and the sensor (m), Q is the attenuation factor and α is the P-wave velocity (m/s).

Then, we used a genetic algorithm (Gordy, 1996) applied to the Brune's model (1970) to find the best combination of {corner frequency, seismic moment} that fit the spectrum at *low frequencies* (16 to 120 Hz) with:

$$S_1 = \Omega_0 \times (2 \times \pi \times f)^2$$

and at *high frequencies* (120 to 260 Hz) with (see figure 8):

$$S_2 = \Omega_0 \frac{(2 \times \pi \times f)^2}{\left(\frac{f}{f_c}\right)^2}$$

where f_c is the corner frequency (Hz), Ω_0 is the low frequency limit (N.m).

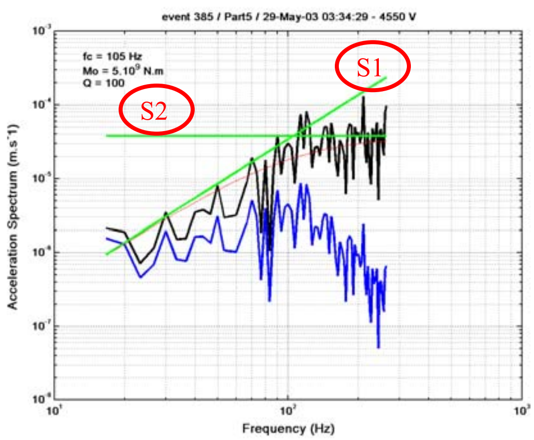


Figure 8: Fitting of the inversion for a typical event

From these parameters, it is possible to deduce the seismic moment M_0, related to the low-frequency limit of the acceleration spectrum Ω_0 by the following expression:

$$M_o = \frac{4\pi \times \rho \times \alpha^3 \times R}{0.39} \times \Omega_0$$

Where ρ is the density (2640 kg/m^3), α is the P wave velocity (5950 m/s), R is the source to sensor distance (m).

The estimates of source radius r assumed Madariaga's (1976) quasi-dynamic circular model:

$$r = \frac{1.97 \times \beta}{2 \times \pi \times f_0}$$

Where β is the S wave velocity (3400 m/s).

Estimates of stress drop Δσ and average slip Δu can be derived from the moment using relations appropriate for a circular crack with uniform stress drop:

$$\Delta\sigma = \frac{7 \times M_0}{16 \times r^3} \quad \text{and} \quad \Delta u = \frac{M_0}{\mu \times \pi \times r^2}$$

where μ is the shear modulus (1.2.10^{10} Pa).

In this study, seismic moment was converted to moment magnitude M using the following relation from Pearson (1982):

$$M = (\log_{10}(M_0) - 10.2) \times 1.298$$

Where M_o is in N.m.

<u>Source parameter: results & discussions</u>

On figure 9 is shown the histogram of moment magnitudes for the 2003 data. Most magnitude values lie in the range between -2 and 2.1 but the largest event was 2.9Ml, unfortunately not located by our network because the signal is saturated on downhole sensors for microearthquakes greater than 2.

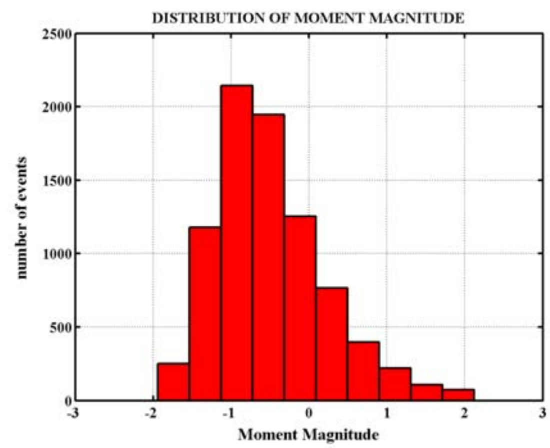


Figure 9: distribution of moment magnitude values

We will now focus on the source parameters that we computed for the 2000 and 2003 data. The first important parameter is the seismic moment because it allows quantifying the intensity of the earthquake. We decided to study the after shut-in events (figure 10) because during this period, the two largest microseismic events occurred. We observed that the seismic activity is confined to two zones: the first one is around the GPK-3 well at 4000 m depth; the second zone is in the northward part of the cloud at 4400 m depth. In 2000, large after shut-in seismic moments were also observed in this second zone (this zone is indicated by a red circle in figure 11). It seems therefore that this zone is seismically very active and that the fractures are there close to rupture. Besides, stress accumulations seem to be considerable in this area as the 2.6Ml event occurred here in 2000.

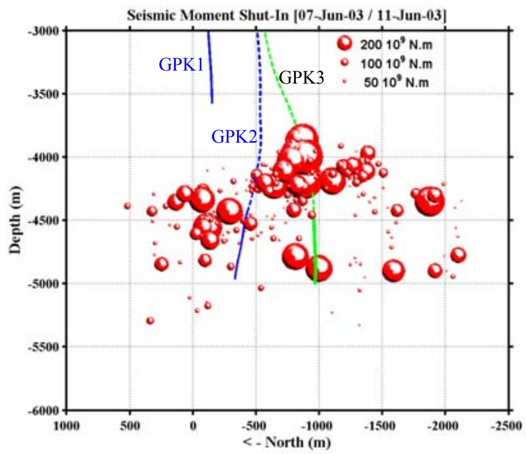


Figure 10: spatial distribution of the seismic moment after the shut-in – East view – stimulation 2003

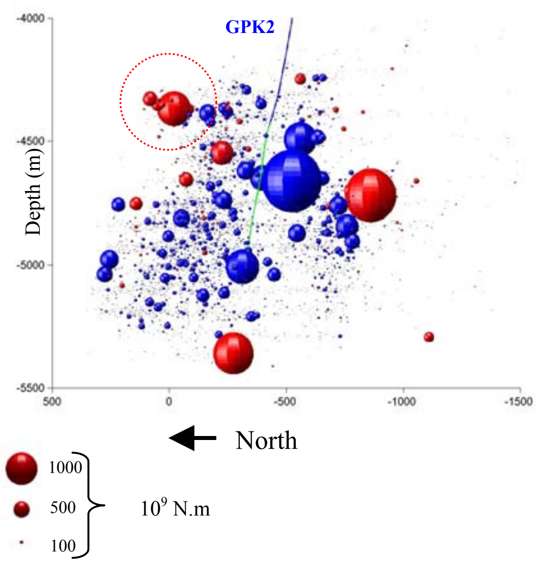
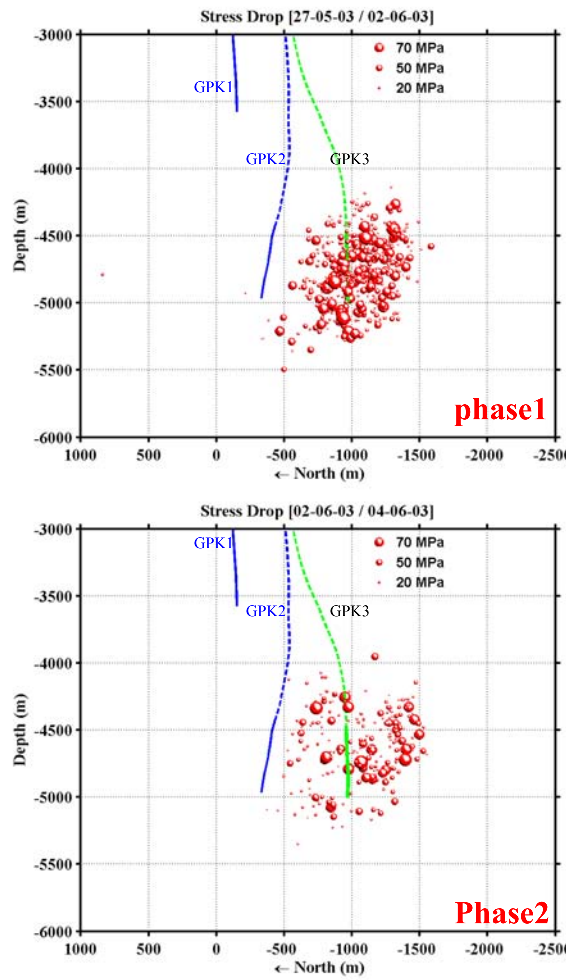


Figure 11: spatial distribution of the seismic moment - blue = during stimulation; red = after the shut-in – East view – stimulation 2000

The second key parameter is the stress drop because it depends on the stress field and the geometry of the fracture. For the 2003 stimulation, we have represented on vertical section the distribution of stress drops (see figure 12) for four periods of time indicated on figure 4: (1) injection only in the GPK-3 well, (2) dual injection in the GPK-2 and GPK-3 wells, (3) injection only in GPK-3 well with the shut-in in the GPK-2 well and at last, (4) shut-in in GPK-3 well and venting in the well GPK-2. During the first phase (1), the events with large stress drops are located all around the GPK-3 well but during the following phase (2), (3) and (4), these events are migrating to the boundaries of the seismic cloud. Thus, at the end of the stimulation, large stress drops happen in the upper part of the stimulated reservoir and around one kilometer away from GPK-2 and GPK-3. The same observation was done in 2000, especially for the after shut-in events (figure 13). These observations suggest that a stress front is propagating from the well out into the reservoir. Fehler and Phillips (1991) also found that events with the largest stress drops occurred near the edges of the seismically active zone where newly activated faults may be expected rather than in the interior of the seismic zone, which has already been fractured.



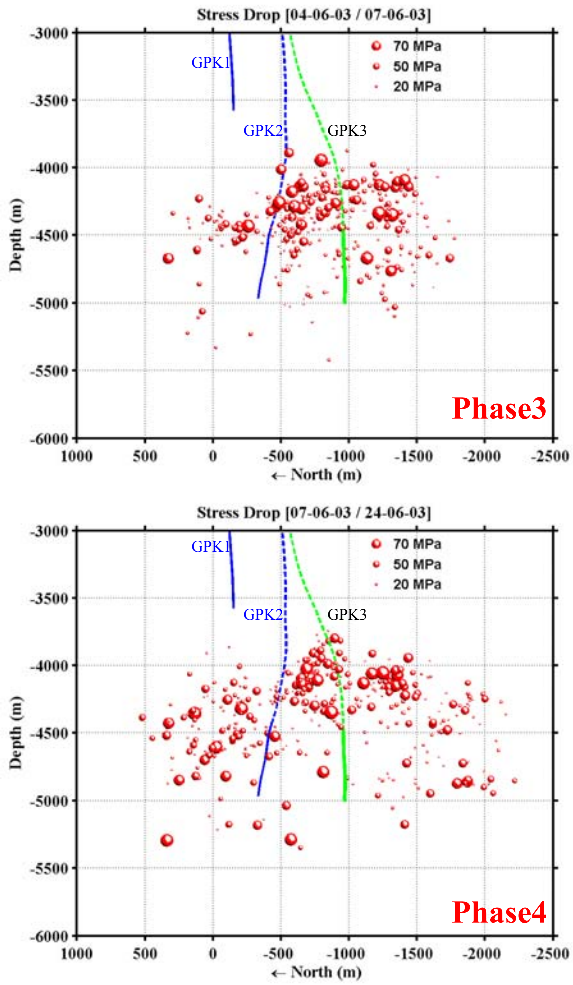


Figure 12: time evolution of stress drop during the stimulation 2003

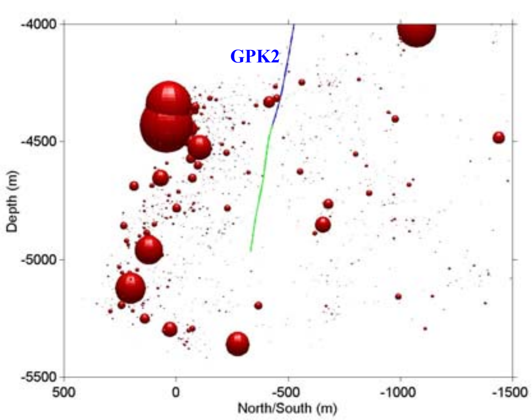


Figure 13: spatial distribution of the seismic moment after the shut-in – East view – stimulation 2000

We also observed that after shut-in, these zones with large stress drops (figure 13 and 12 (4)) coincides with the location of the largest events (magnitude > 2.5). The migration of large stress drop events may therefore indicate when zones of high seismic risk are situated.

CONCLUSION

In 2000 and 2003, two stimulations took place at the Hot Dry Rock site in Soultz-sous-Forêts (France). We triggered more than 30,000 and 90,000 microearthquakes respectively each time. From these, 14,000 and 9,000 microseismic events were located and processed in order to characterize the geometry of the reservoir. We then computed automatically the source parameters of these events, especially their seismic moment and stress drops. We found that the events with the largest seismic moments occur predominantly where the M > 2.5 events occur. It seems therefore possible to use this information to delineate the zones of seismic risk. Besides, we found that events with large stress drops are migrating to the boundaries of the stimulated zone and where the M > 2.5 events occur. This suggests that the monitoring of stress drops during stimulation operations may allow the determination of zones of high seismic risk.

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