Data Acquisition and Analysis of Microseismicity from Simulation of Deep Reservoir at Soultz by the MTC/MURPHY International Collaborative Project

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ABSTRACT

Hydraulic stimulation of a HDR/HWR reservoir at a depth around 4500m to 5000m was carried out at Soultz, Alsace, France in 2000. A total amount of 23,000m^3 of heavy brine and water was injected in a 5000m borehole. The induced microseismic events were detected by three downhole 4-component accelerometers and two hydrophones. The authors in the MTC/MURPHY project temporally installed their own digital recording system to collect signals with higher resolution and longer data length. The number of triggered events during the stimulation was approximately 40,000, and we picked approximately 8,000 events with best quality. Results from mapping show that the reservoir extended to the NW and its size is comparable or larger than that of a shallower reservoir created in 1993. It has been also suggested from seismic activity that the reservoir is more hydraulically closed system than the shallower one.

Introduction

A HDR/HWR project for commercial electrical power generation has been on-going at Soultz-sous-Forets, Alsace, France since 1987 mainly supported by EU, the governments of France and Germany, and power companies (Baria *et. al.*, 1995, 1999, 2000). A large-scale hydraulic stimulation was made in 1993 using well GPK-1, and a reservoir was created at a depth interval of 2500m to 3600m. A 3600 m deep well GPK-2 was drilled into the reservoir in 1994-5 and a circulation system was built. Hydraulic characteristics of the reservoir were encouraging, and it was decided to build a scientific test plant using the reservoir, which is at a temperature around 200 degree-C (Jung and Weidler, 2000). A well, GPK-2, was extended to a depth of 5080 m in 1999 with a open-hole section from 4340 m to 5080 m, and a stimulation of GPK-2 was carried out in June-July, 2000. An amount of 1000 m^3 of heavy brine was injected in the initial stage of the stimulation for a deeper reservoir extension, and 22,000 m^3 of water was then injected with a flow rate of 40-50 l/s.

Research teams at Tohoku University and National Institute for Resources and Environment (NIRE) (currently National Institute of Advanced Industrial Science and Technology; AIST) in the MTC/MURPHY international collaborative project for advanced mapping/imaging and understanding of HDR/HWR reservoir (Niitsuma *et. al.*, 2000) decided to collect data from the stimulation in cooperation with a team in Soultz. The MTC team installed their own digital data acquisition system and recorded seismic events independently from a contractor with Soultz project (Semore Seismic). This is because (a) resolution of advanced mapping techniques developed in the MTC/MURPHY project, such as doublet analysis (Moriya *et. al.*, 2000) and clustering method (Phillips *et. al.*, 2000) is restricted by the sampling rate, and (b) the AE reflection method, which uses microseismic events as a source of reflection imaging of deeper structure (Soma *et. al.*, 2000), needs a longer data length. The researchers in the MTC/MURPHY Projects recorded approximately 40,000 events during the experiment.
In this paper, the outline of the data acquisition, signal quality evaluation and results from the conventional mapping are described.

Outline of Data Acquisition

A plan view showing location of the major wells in Soultz site is shown in Figure 1. The whole section of GPK-2 was stimulated in this experiment by injection from the well head. The induced microseisimicity was detected by the 4-component accelerometers in wells 4550, 4601 and OPS-4. Two hydrophones were also deployed in the wells EPS-1 and GPK-1. The depth of sensors are also shown in the Figure 1. The seismic monitoring well OPS-4 was drilled in 2000 to improve the performance of the network; the effectiveness of this station is described in the later section.

The authors used a specially designed digital data acquisition system with a sampling frequency of 10 kHz, amplitude

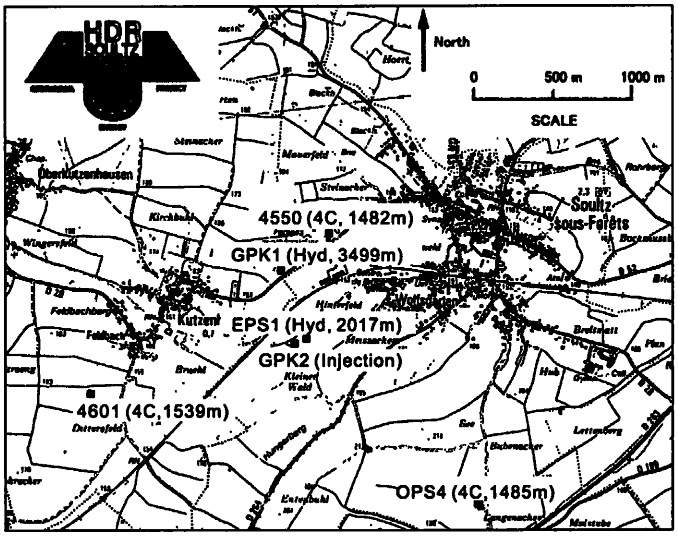


Figure 1. A plan view of the Soultz HDR Field. Four component (4C) accelerometers are deployed in the wells 4550, 4601, and hydrhydrophones in GPK-1 and EPS-1. Depth of sensors are indicated in the figure.

resolution of 16 bit and data length of 55,000 words per trigger. The data was sent to a PC and workstations and used for nearly realtime mapping for daily reports.

Present Results

Data Quality and Picking

The seismic activity during the stimulation was comparable or higher than that in creating the shallower reservoir in 1993. The team of the MTC Project had approximately 40,000 triggers during the stimulation, although the acquisition system ran 11 days from the beginning of the stimulation and missed some of the events after shut-in. An example of the recorded signal is shown in Figure 2. The hydrophone in EPS-1 did not work

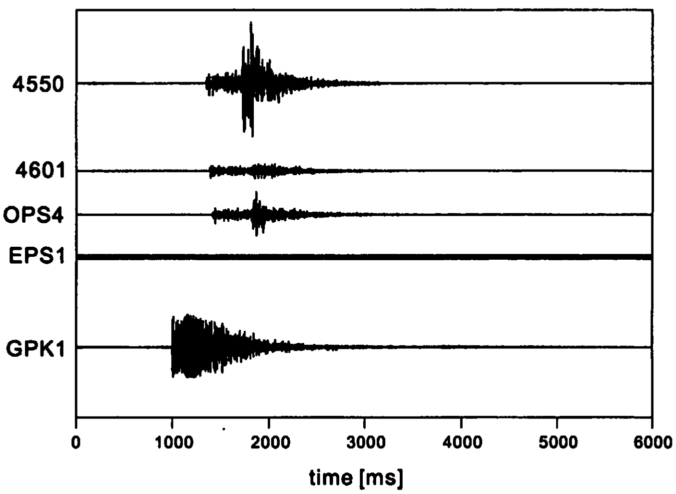


Figure 2. An example of seismic signals recorded by the researchers in the MTC/MURPHY Project. No signal was found on a trace from EPS-1 because of sensor failure.

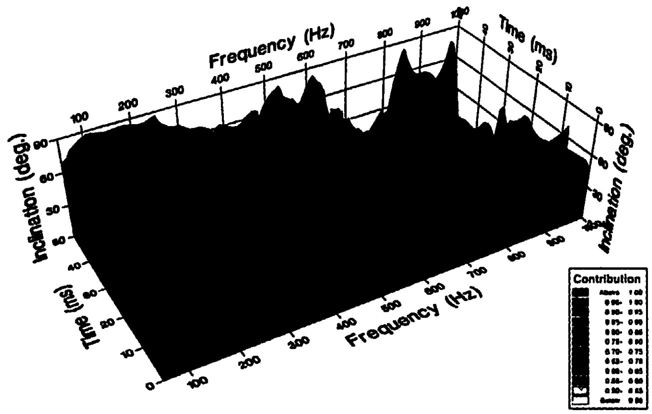


Figure 3. A time-frequency representation of polarization direction and linearity of the hodogram detected by a station in newly drilled well OPS-4.

well during all the experiment. We found that some of the other detectors suffered from electrical noise and signals had lower quality during some parts of the stimulation. Therefore, we manually picked events with higher signal-to-noise ratio for reliable mapping. Total number of picked events was 7,595 which is approximately 18% of all the triggers.

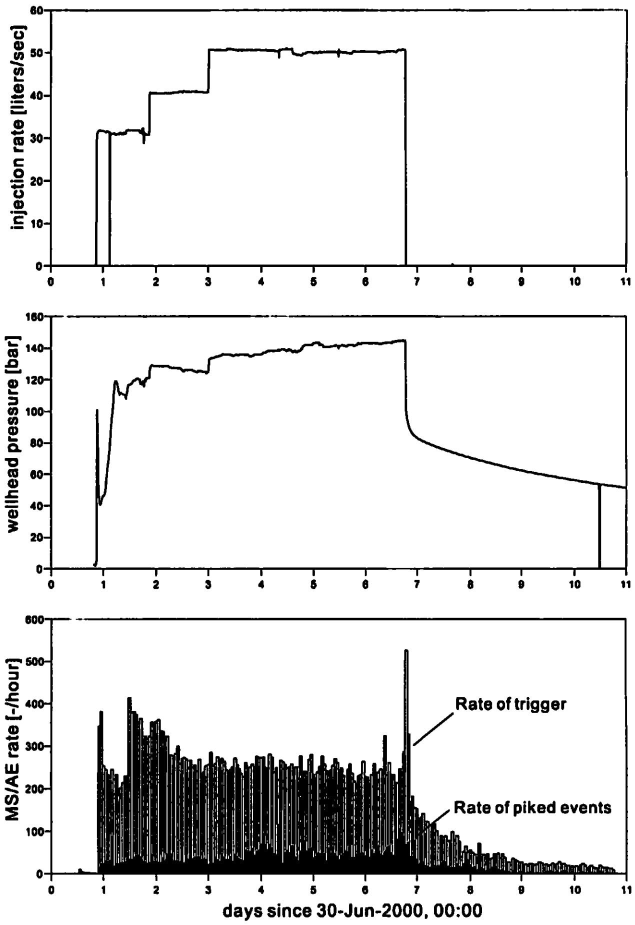
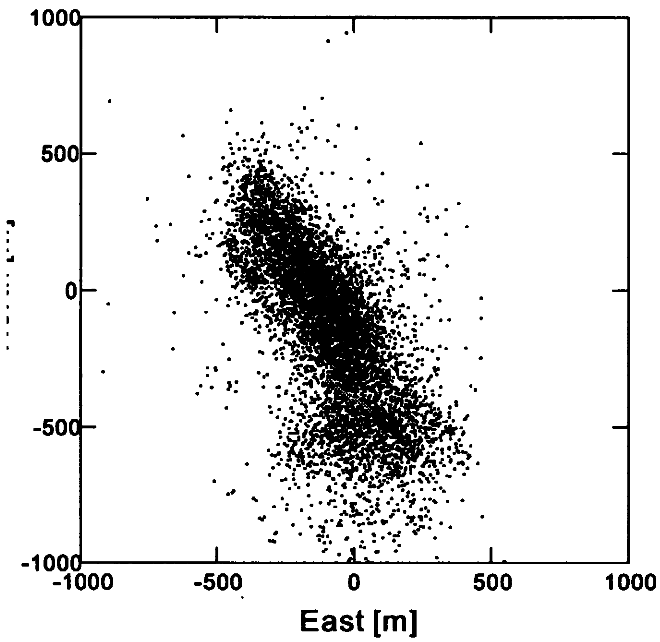


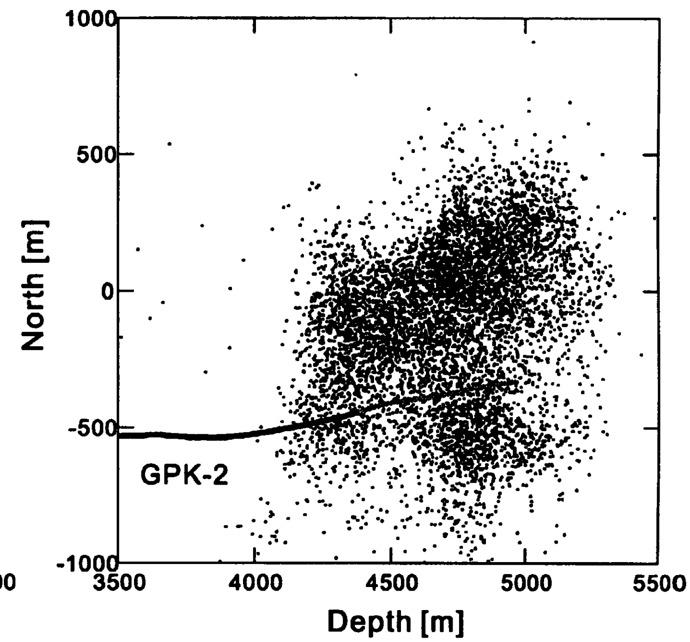
Figure 4. A time history of flow rate, wellhead pressure at GPK-2, trigger rate and rate of picked events.

The authors also evaluated the performance of the 4-component detectors by spectral matrix analysis (Niitsuma *et. al.*, 1995) and by the 4-component coherency technique. We have found that all the 4-C detectors had good detectability of the hodogram up to approximately 300 Hz, excluding those detectors with electrical problems. Figure 3 shows an example of a time-frequency representation of the polarization and linearity of the hodogram by the spectral matrix analysis for an event detected by new station OPS-4. The hodogram is linearly polarized to the direction of the hypocenter by the JHD up to 350 Hz. This result is comparable or better than the other 4-C detectors in granitic basement, although the well OPS-4 did not reach to the basement.

Seismic Activity

Figure 4 is a time record showing injection rate, pressure at the wellhead of GPK-2, number of triggers per hour and number of picked events per hour. The trigger rate is higher in the first day, because of increase of electrical noise. Also the quality of signal from one of the stations was not good until the 3rd day and thus the early number of picked events is lower than during the later days. The following observations are noted from the figure; (a) the seismic activity is roughly constant through all the experiment and there is no clear relationship between flow rate and seismic activity, and (b) the reduction of seismic activity after shut-in was much smaller than in 1993. These two points are the major differences compared to the seismic monitoring in 1993 (Baria *et. al.*, 1995), suggesting that the reservoir creation process is the same (i.e. shearing on natural joints) but its hydraulic characteristics are different from those of shallower reservoir.





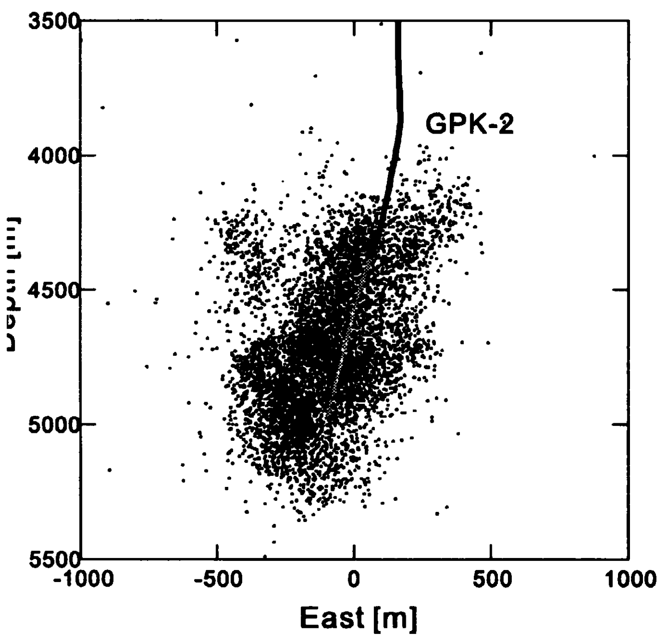


Figure 5. A JHD locations of the microseismicity.

Location by the Joint Hypocenter Determination

After picking of the timing of the events with reasonably good quality, the events were located using the Joint Hypocentre Determination method (JHD; Frohlich, 1979). Because there is no calibration shot data available for a seismic wave velocity model in this experiment, we used velocity and station corrections to minimize distance between GPK-2 and location of initial 100 events. The optimum velocity was 5674.0 m/s for the compressional, P wave and 3239.8 m/s for the shear, S wave, they are same as those used in the mapping of seismicity from shallow reservoir created in 1993. The station correction had variety of -4.8 ms to 8 ms, and it is reasonable comparing with previously used station corrections.

A three dimensional view of the locations by the JHD is shown in Figure 5. It is seen that the general extension of the

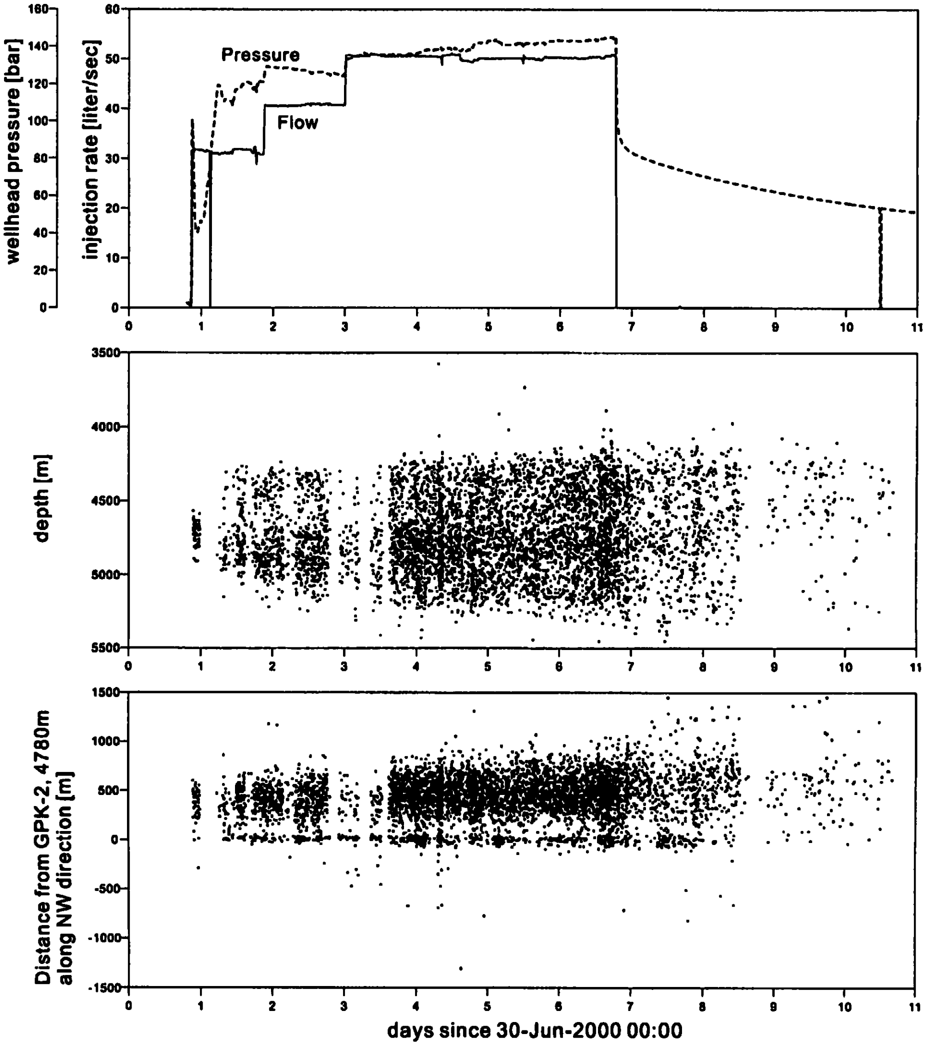


Figure 6. Horizontal and vertical distance of the JHD location from one of the most possible injection points at 4780m in GPK-2.

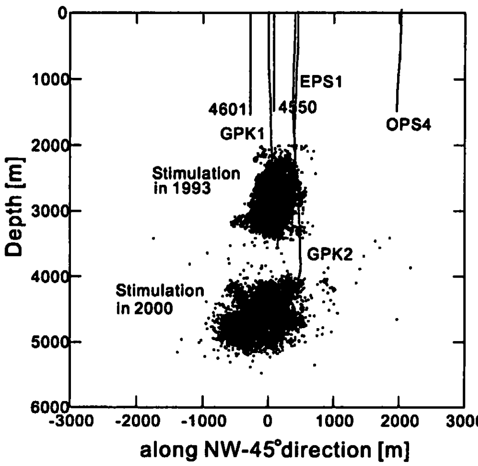


Figure 7. Vertical distributions of seismic events in 1993 and 2000. A view from NW is shown.

reservoir is NW, which is consistent with the distribution of seismicity in 1993. The depth of the hypocenter of microseismic events corresponds to the open-hole section of GPK-2, suggesting the injection of heavy brine in the initial stage of the stimulation effectively suppressed the growth of reservoir to a shallower region.

The time variation of the distance between seismic locations and one of the most likely injection points, at 4780 m, is shown in Figure 6. The growth of the reservoir to the NW is seen in this figure.

The locations and the sizes of seismic clouds for the two stimulations, first in 1993 and then in 2000, are compared in Figure 7, where a vertical view from SW45 degree is plotted. The size of the cloud for the 2000 stimulation is slightly larger than that of 1993. Very few events are located between the two clouds, suggesting little hydraulic communication with the earlier, shallower reservoir during the 2000 stimulation.

Effect of a New Station

The horizontal distributions of locations by JHD with/without including observations from the new measurement well, OPS-4, are compared in Figure 8. It is clear that locations without using OPS-4 observations are approximately 500m NW to the GPK-2. Some aligned locations to a NE-SW line near GPK-2 are also seen. Currently we understand that this is because all the other stations used in this experiment are roughly on a NE-SW line and therefore the location in NW-SE directions are mainly determined by the pick from OPS-4. We can conclude that the new seismic well OPS-4 greatly contributed to better locations and quality of signals, even though it did not extend deep enough to penetrate the granitic basement.

Conclusions

The international collaborative MTC/MURPHY Project, collected roughly 40,000 triggers of seismic events during a stimulation at the Soultz HDR site in 2000. Approximately 8,000 events were manually picked and located by one of the conventional mapping techniques after estimation of velocity and station corrections. The extension of the reservoir to the NW at depths between 4300 m to 5300 m was estimated by the mapping. It has been also revealed that the recently drilled seismic monitoring well, OPS-4, effectively contributed to better locations.

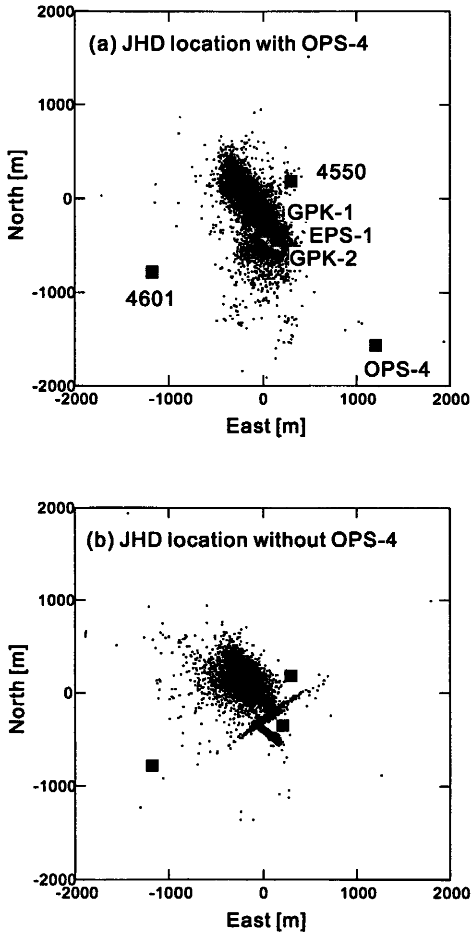


Figure 8. Results of the JHD mapping with (upper) and without picking from OPS-4 (lower). Solid rectangles show location of stations.

Now that fundamental analysis/evaluation of the data has been completed, the authors will relocate events using advanced MTC mapping techniques, including variations of the collapsing method, doublet analysis and clustering method, and will try to understand behaviour of the reservoir during the stimulation. Approach to identifying reflectors inside/outside the reservoir using the idea of the AE reflection method is one of the other areas of further research.

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