

MICROSEISMIC MONITORING OF HYDRAULIC EXPERIMENTS UNDERTAKEN DURING PHASE IIA OF THE SOULTZ HDR PROJECT (ALSACE, FRANCE)

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ABSTRACT

In the framework of the European HDR Project of SOULTZ, co-sponsored by European Community, two 50 hour-hydraulic injections were carried out in the main borehole GPK1. This borehole reached a depth of 2000 m (600 m of granite under a 1400-m-thick sedimentary cover) and a bottom hole temperature of 140°C. Both injections tests were made between a packer sited at 1968 m and bottom hole, with injection flow-rates of 7 l/s and 15 l/s.

3-axis accelerometer probes designed to withstand high temperatures up to at least 135°C were installed at the bottom of three boreholes which reached the granite. This network was supplemented by high temperature hydrophone sensors deployed in a fourth borehole (EPS1) at depth of about 2000 m. Data were transmitted to an on-line computer to perform preliminary interpretations.

During the tests, 135 and 239 induced microseismic events respectively were recorded. Present results show that seismicity starts off very close to the injection point and spreads out to form a cloud with a North-West to South-East elongation.

According to previous interpretations, the direction of the maximum horizontal stress component deduced by BHTV data analysis and hydrofracture in-situ stress measurements led to values of respectively 175°N and 155°N. During the second injection experiment a concentration of seismicity was revealed to the N-W of GPK1. This cloud also shows a trend to grow downwards and no seismicity extends more than 300 m away from the injection interval.

INTRODUCTION

Within the frame of the validation of a new power generation concept, research into the development of "Hot Dry Rock" geothermal energy began in the early 1970's in the US (Los Alamos) and later on, in Europe - Camborne (UK), Urach (Germany), Mayet de Montagne (France) - and in Japan. In all these projects, the monitoring of the microseismicity induced during hydraulic injection tests has proved to be fundamental in the understanding of the growth and size of the stimulated regions (Baria, R. & al., 1989; Matsunaga, I., 1990; Mock, J., 1989).

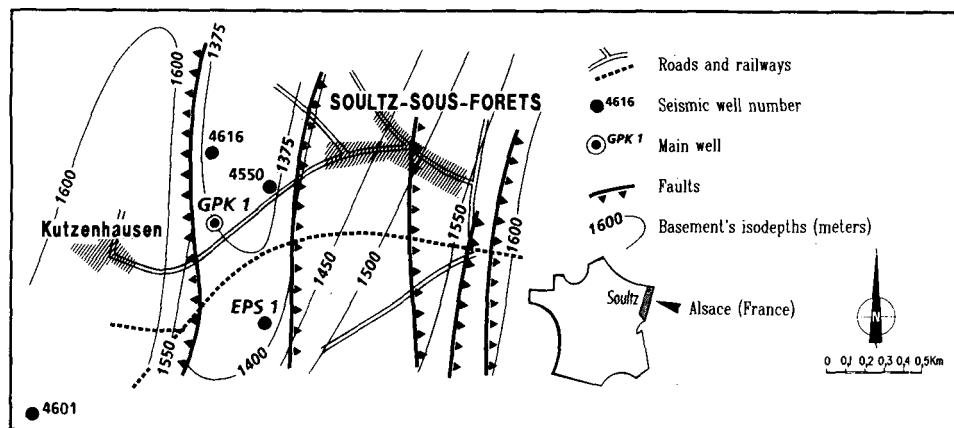


Fig. 1 - Location map of the project

The HDR site of Soultz, situated in the northeastern part of France in Alsace, was chosen in 1986 on top of a very large thermal anomaly which extends over about 4000 km² in the Rhine graben (Figure 1).

Prefeasibility studies (Phase I) began in 1987 after the drilling of the main well GPK1 down to 2000 m (Kappelmeyer & al., 1991). This borehole reached temperatures of 125°C at the top of the granite and 140°C at bottom-hole. A first small scale hydraulic stimulation (at a flowrate of 3 l/s for 3 days) took place in GPK1 at the end of 1988, and the associated seismicity was monitored (Beauce, A. & al., 1991).

In 1990, Phase IIa of the project started with the drilling of a second exploratory borehole (EPS1), sited at about 500 m S-E of GPK1 and planned to reach 3500 m; but, due to technical reasons and a very significant deviation of more than 15°, this well was stopped at about 2000 m. At total depth, final temperature of this borehole was 150°C.

During this phase, two 50-hour hydraulic stimulation experiments were undertaken in GPK1 between a packer set at 1968 m and bottom-hole: one of 7 l/s and one of 15 l/s.

MICROSEISMIC MONITORING NETWORK

To monitor the site during these experiments, three old oil wells (4616, 4550, 4601, see Figure 1) were successfully recovered in the surroundings of GPK1. As deduced from Phase I, and in order to avoid the attenuation effects observed on the seismic signals during their propagation in the sedimentary layers, these boreholes were deepened inside the granite. The coordinates of the sensors are given in Table 1, where the origin of the coordinate system is the wellhead of GPK1.

TABLE 1

| SENSOR | X (m) | Y (m) | Z (m) | MD (m) | Depth in granite (m) |
|---------|----------|---------|---------|--------|----------------------|
| 4516 | -45.03 | 353.61 | 1382.81 | 1387.2 | 7 |
| 4550 | 285.23 | 205.12 | 1492.63 | 1492.0 | 87 |
| 4601 | -1118.05 | -864.35 | 1580.76 | 1599.0 | 26 |
| Hydro 1 | 197.45 | -363.95 | 1917.24 | 1945.0 | -500 |
| Hydro 2 | 210.45 | -353.95 | 1974.82 | 2004.5 | -500 |

Three 3-axis accelerometer probes were especially designed by CSM Associates Ltd to withstand the rough temperature and corrosion conditions, and deployed at the bottom of each of these wells. Various technical problems connected with borehole completion, prevented the correct cementation of these units before the hydraulic stimulations.

Data delivered by the accelerometer and hydrophone units were lowpass filtered

downhole at 1500 Hz and analog transmitted using wires to the computer room in order to be continuously monitored and pre-processed on a micro-VAX. Sampling rate was 5000 cps/channel and a window of 1.6 s (including pre-trigger) of data was stored on disk when an event was detected.

During the hydraulic stimulations either a single hydrophone (during the 7 l/s test), either a pair of hydrophones (during the 15 l/s test) were used. When only the single unit was deployed, then it was placed at the same position as the lower of the pair when that was used.

All the trajectories of these boreholes were measured using a gyroscopic tool.

An additional analog telemetry link seismic network composed of 8 mobile stations was also deployed on surface at about 1 km from the GPK1 wellhead by Institut de Physique du Globe de Strasbourg (IPGS); but no seismicity was recorded during the injection experiments.

VELOCITY MODEL

In order to obtain a velocity field around GPK1, and thus to allow reliable locations, a calibration shot of 300 g of explosives was fired at a depth of 1992 m in GPK1. Clear P-wave onsets were produced on all the sensors of the network; only one S-wave arrival was observed (on probe 4616).

The P-wave calculated velocities are given in Table 2:

TABLE 2

| SENSOR | P-wave velocity (km/s) |
|--------------|------------------------|
| 4616 | 5.715 |
| 4550 | 5.745 |
| 4601 | 5.465 |
| Hydrophone 1 | 5.940 |
| Hydrophone 2 | 5.930 |

The deduced velocities between borehole pairs GPK1-4616 and GPK1-4550 are similar and in agreement with the results obtained in Phase I, i.e. an average velocity of 5.680 km/s.

However, an important discrepancy is observed for the path GPK1-EPS1 that could be due to well survey errors, as borehole EPS1 was highly deviated.

More problematic is the low velocity measured between GPK1 and 4601 and the preceding reason seems to be unlikely as both boreholes are almost vertical. At present, the problem of velocity anisotropy is not completely resolved but it could be

due to the conjunction of two factors: its relative long distance of this probe from the injection interval (around 1470 m) and the presence of an important NE-SW fault affecting the sedimentary layers and the granite which was revealed by a past reflection seismic survey. In order to not perturbate the location results of the microseismic events and to preserve a relative homogeneity in the results, it has been decided not to use the data from this probe at this stage of interpretation.

Bearing in mind these factors, it has been decided to adopt for locations an isotropic average P-wave velocity model of 5.85 km/s and to apply respective calculated time delays to the monitoring stations. As it was not really possible to deduce a good S-wave velocity model from the calibration shot data, no station delays were considered for these waves and a V_p/V_s ratio of 1.73 has been chosen.

INDUCED MICROSEISMICITY DURING THE 7 l/s HYDRAULIC INJECTION TEST

The 7 l/s hydraulic stimulation started on July 11th at 1 p.m., over a 30-m-long vertical section of GPK1 well, between a packer sited at 1968 m and bottom-hole. After eight and a half hours, and an injected volume of about 160 m³, the experiment was stopped as the pressure in the annulus began to increase. The injection restarted at 1:15 p.m. on 12th and carried on from the next 50 hours.

Figure 2 shows a plot of the seismic event rate and down-hole pressure recorded during this period. A total of 135 microseismic events were induced during this test and seismic rate decreased immediately when the injection stopped.

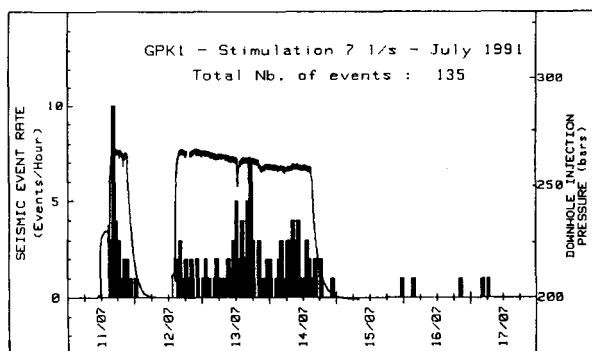


Fig. 2 - Hydraulic and seismic event rate data recorded during the 7 l/s stimulation in GPK1

These events have shown clear P and S wave onsets on the different probes of the network (see figure 3). It must be noted that the probe deployed in the borehole 4601 recorded only about 20% of the whole recorded seismic activity.

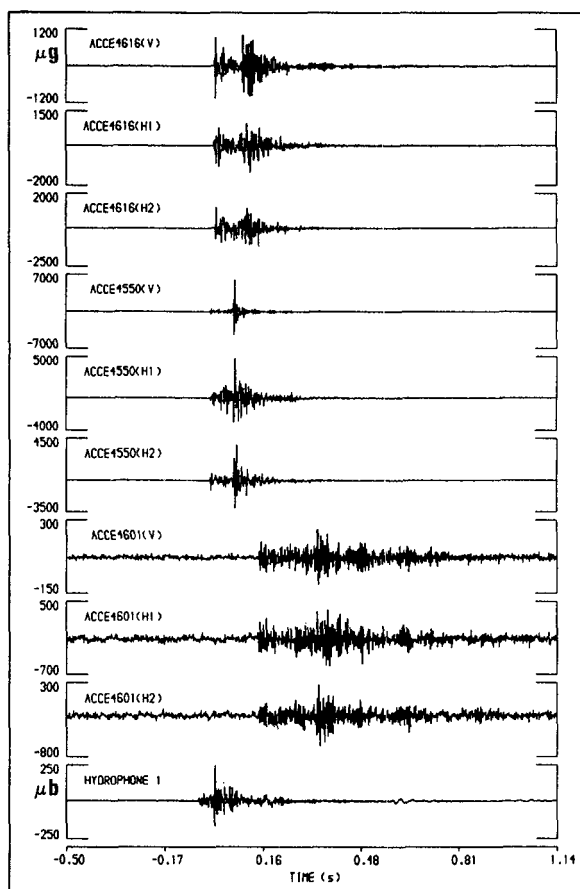


Fig. 3 - Signatures from down-hole accelerometers and hydrophone recorded during the 7 l/s hydraulic injection in GPK1
Event 26 - 11/07/1991 - 17:27:54

Microseismic location results

Of all the seismicity recorded during this test, 60% of the events have been interpreted and located (see figure 4) using the isotropic velocity model presented above. During this test only one hydrophone was deployed in the borehole EPS1. In consequence, as data from 4601 probe was not used for the locations, we only have a coplanar network. So, location results gave dual solutions images which form a mirror image in the plane defined by these sensors: the decision to choose the deepest solutions was based on the results obtained when we have more sensors and a non-coplanar network, i.e. during the 15 l/s injection test.

The plan view of figure 4 shows how the seismicity develops during this test to form an overall cloud with a N-W to S-E elongation, while the vertical plan view from 150°N shows a trend to grow downward.

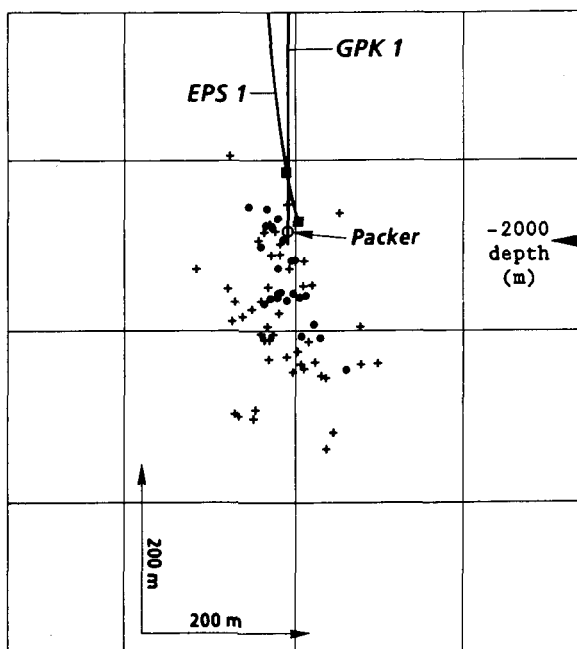
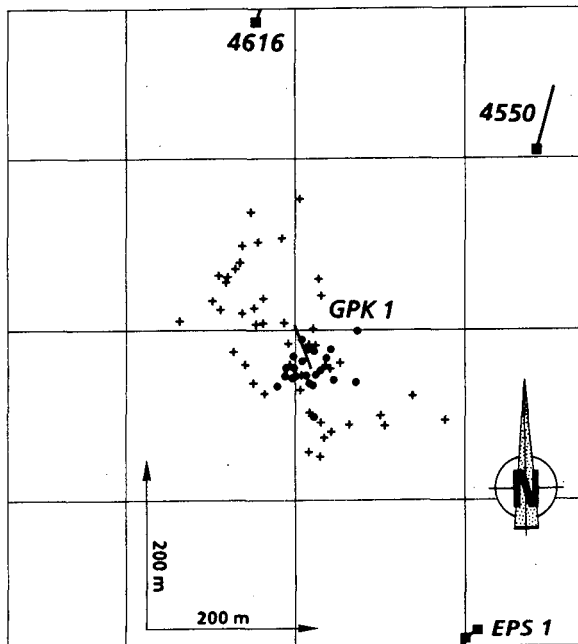


Fig. 4 - Microseismicity during the 7 l/s hydraulic injection in GPK1
Plan view and vertical section view (azimuth 150°N)
● first phase, + second phase
■ seismic probe

More precisely, on the first phase (full circles) the seismicity mainly concentrates near GPK1 and only on the south-southeastern side at depths between 1950 m and 2100 m. These results are in agreement with what was found during Phase I of the project with an hydraulic test with a flowrate of 3 l/s.

During the second phase, the seismicity extends away from GPK1 and at depths down to 2150 m, but in addition and corresponding to the second peak of seismicity observed on figure 2, a new seismic active zone appears on the north-northeastern side of GPK1 during the third day of the injection.

INDUCED MICROSEISMICITY DURING THE 15 L/S HYDRAULIC INJECTION TEST

The 15 l/s injection in GPK1 started on 18th of July at 9 a.m. and lasted about 50 hours in similar conditions to the previous experiment. A total volume of 2300 m³ of fresh water was injected. Figure 5 shows the downhole injection pressure recorded during this test and the associated seismic event rate. The first event occurred after an injected volume of 35 m³ and a total of 239 induced events were recorded. In comparison with the previous test, the average seismic rate (4 events/hour) was double. Moreover, the seismicity still persisted after the end of the stimulation, suggesting the existence of a remanent pressurized zone sited away from the borehole injection interval.

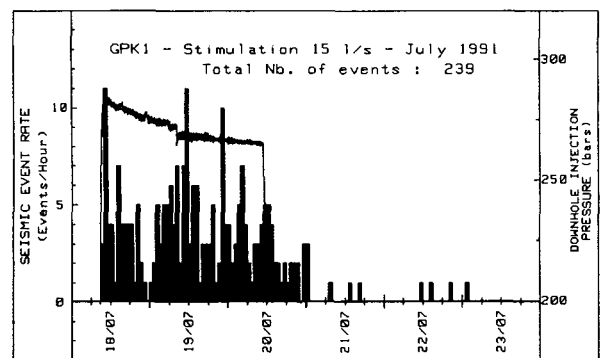


Fig. 5 - Hydraulic and seismic event rate data recorded during the 15 l/s stimulation in GPK1

Microseismic location results

During this injection the string of 2 hydrophones was deployed in EPS1, and again data recorded by the probe sited in borehole 4601 were not used for the locations of the events.

Figure 6 illustrates the chronological migration of the induced microseismicity as a function of days of injection in plan view and associated vertical plane viewed from the azimuth 150°N. During the first day, the seismicity grows downward to a maximum depth of 2150 m but only on the S-SE sector from GPK1 wellhead as it was observed during the beginning of preceding test. On the second day, this seismic zone ceases to be active and a migration of the seismicity towards the N-W of GPK1 clearly appears; this new cloud concentrates at depths between 2150 m and 2250 m and still remains the principal active zone during the last day. When the injection stopped, this zone still also remained active for a few hours.

Once more, the general trend of seismicity is the same as observed during the 7 l/s injection test, that is along a NW-SE axis.

CONCLUSIONS

These preliminary results, both for the 7 l/s and 15 l/s hydraulic stimulations, have shown that the respective seismic clouds seem to organize along a NW-SE axis, and to grow downward from the injection interval. This trend must be associated with the present knowledge of the stress field which indicates an extension regime typical of a graben system with a maximum horizontal stress component of the tensor oriented 155°N to 175°N (Rummel F. & al., 1991).

However, the seismicity did not grow symmetrically along this axis in reference to GPK1 wellhead; in a first stage, the events appeared in the SE sector around the injection interval and deepened as the injection went on. Afterwards, this volume ceased to be seismically active - that was clear in a more obvious way during the second test after an injected volume of about 1000 m³ - and a new zone sited on the NE sector and at depths between 2150 m and 2250 m began to activate.

At this stage of interpretation, it is therefore also necessary to point out that the network configuration will cause difficulties in the forthcoming detailed interpretations of fault plane solutions and source mechanisms.

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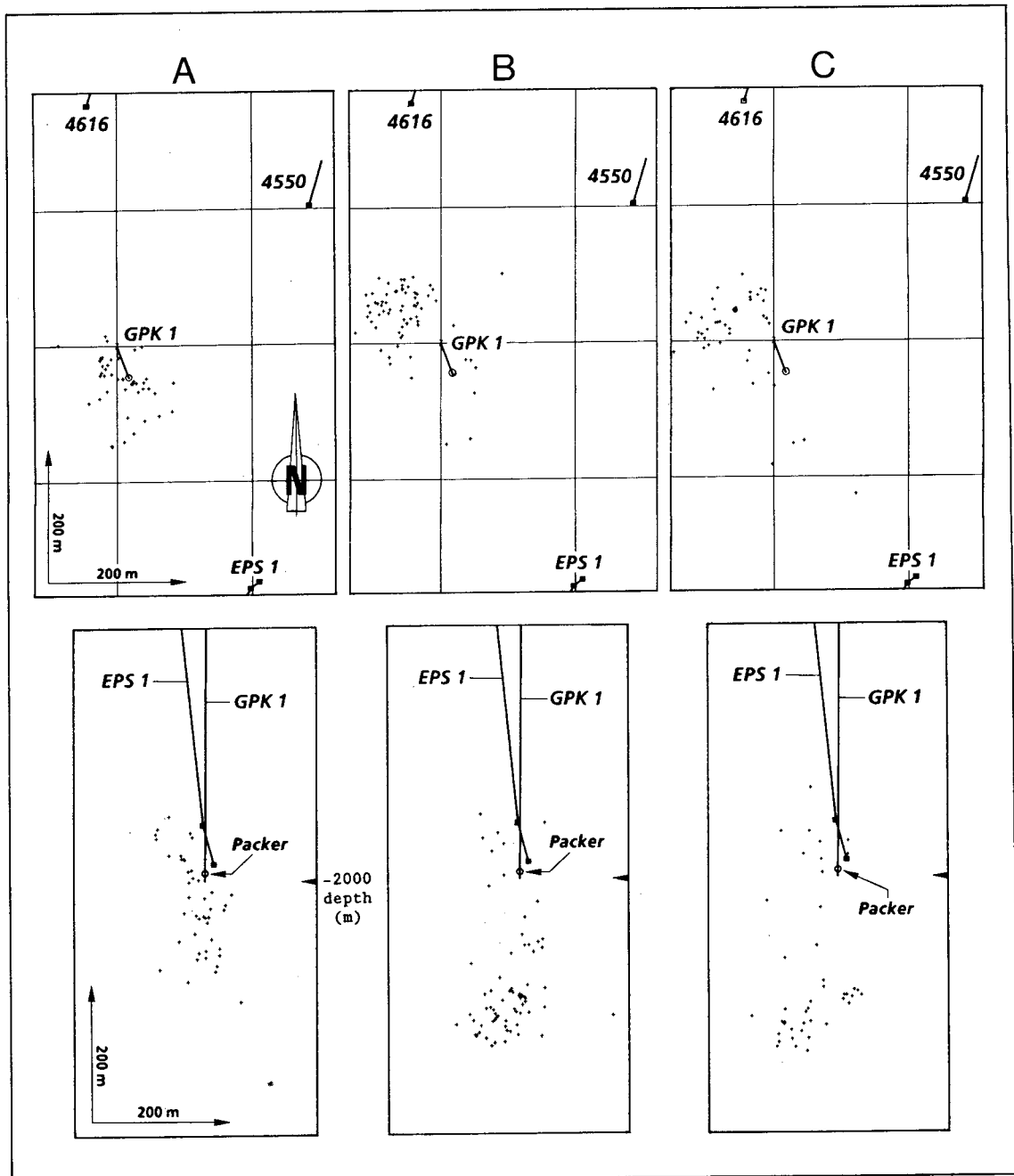


Fig. 6 - Microseismicity during the 15 l/s injection in GPK1
 Plan view and vertical section view (azimuth 150°N)
 A = first day, B = second day, C = third day
 ■ : seismic probe