DETECTING HYDRAULICALLY CREATED PERMEABLE STRUCTURES IN THE SOULTZ HDR SITE BY HIGH RESOLUTION SEISMIC MAPPING TECHNIQUES

H.NIITSUMA[1], H. MORIYA[1], H. ASANUMA[1], K. EVANS[2], R. JONES[3], R. JUNG[4] & R. BARIA[5]

[1]Graduate School of Engineering, Tohoku University, Sendai, Japan
[2]Institute of Geology, ETH, Zurich, Switzerland
[3]ABB OS, UK
[4]BGR, Hannover, Germany
[5]GEIE , Soultz-Sous Forets, France

SUMMARY – The collapsing, the multiplet analysis, and the multiplet-clustering analyses have been applied to the microseismic data recorded during the hydraulic stimulation at Soultz-sous-Forêts HDR field, France, in 1993. A seismic structure, which was growing linearly at the early stage of the stimulation, has been analysed. It is estimated that this structure represents enhanced permeable paths and consists of sub parallel microstructures, which are oriented to the directions most easy to slip by the stimulation.

1. INTRODUCTION

A comprehensive understanding of the -fracture distribution and hydro-geomechanical processes occurring during hydraulic stimulation is essential in the developments of both conventional and Hot Dry Rock (HDR) / Hot Wet Rock (HWR) geothermal systems. Some of this information can be obtained from well logging data such as flow, temperature, pressure, BHTV, FMI, etc. However, they only provide restricted information near the well.

Microseismic monitoring is currently the best available method for obtaining three-dimensional information about reservoirs and fracture systems at locations remote fiom boreholes. The primary problem of the method is its location accuracy. When located with conventional location algorithms, the events are frequently seen to be distributed as a cloud with little macro- or micro-structures. It is difficult to meaningfully correlate such images with logging data of existing wells. Therefore, information on detailed reservoir structure, fracture orientation, and hydraulic behavior cannot be obtained from the application of conventional microseismic location techniques.

There have been considerable improvements in microseismic mapping technology during the last ten years (Niitsuma et al., 1999; Fehler et al., 2001). Various techniques to reduce location error have been developed which include collapsing method (Jones and Stewart, 1997), doublet/multiplet analysis (Poupinet et al., 1984; Moriya et al., 1994, 2002), the double-difference method (Waldhauser and Ellsworth, 2000), clustering analysis (Phillips et al., 1997; Rowe et al., **2002)**, and multiplet-clustering analysis (Moriya et al., **2002)**. These high resolution mapping techniques have demonstrated that the diffuse clouds obtained using conventional techniques are largely artefacts of location error. They also and revealed macro- and micro-structures within the cloud that can be correlated with geological and hydraulic structures identified fiom well logs.

The collapsing method, the multiplet analysis, and the multiplet-clustering analysis have been applied to the microseismic data recorded during the hydraulic stimulation at Soultz-sous-Forêts HDR field, France, in 1993. This paper discusses a microseismic structure which was formed at the early stage of the stimulation and revealed by the high-resolution mapping techniques.

2. HYDRAULIC FRACTURING IN 1993 AT THE SOULTZ FIELD

The European HDR project at Soultz-sous-Forêts was founded by France, Germany and the European Commission (EC) in 198. The site is located on a local horst structure in the Rhine Graben (Figure 1), where Hercynian age granites are covered by a 1.4 km thick sedimentary sequence (Baria et al., 1999).

Well GPK-1 was drilled to 3,590 m depth (open hole below 2,850 m depth), and since 1987 it has been used for a number of detailed experiments. A major hydraulic fracturing experiment was performed in September and October 1993. In the September test, **25,000** m^3 of fresh water were injected between 2850-3350 m at progressively higher rates up to 40 l/s and pressures of up to 10 MPa over a 17 day period. In October, a further 20,000 m^3 of water were injected at rates up to 50 l/s into the entire open hole section. Throughout the test, it was demonstrated that the fracture network in the basement rock was well developed, wich enhanced permeability and caused a substantial increase in transmissivity (Baria et al., 1999; Evans, 2000).

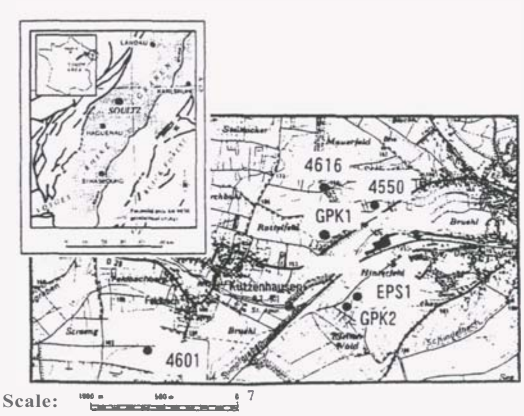

Fig. 1: Location of Soultz field.

The second deep well, GPK-2, was drilled in 1995 to a depth of 3,876 m. At reservoir depth, this well lies -450 m south of GPK-1, and has a bottom hole temperature of 168°C. In 1995, GPK-2 was stimulated using brine followed by fresh water, and circulation tests were performed to confirm the hydraulic connectivity between the two wells. In 1996, the open hole section of GPK-2 was again stimulated, with a total of **28,000** m^3 of fluid injected at a maximum wellhead pressure of 13 MPa, and flow rates of up to 78 l/s (Gerard et al., 1997), to improve its injectivity. After these experiments, well GPK-2 was extended to about 5,000 m depth, and a hydraulic fracturing test was carried out in 2000.

Induced microseismic activity was detected using three downhole 4-component detectors and one hydrophone, installed in wells #4550, #4616, #4601 and EPSI in the I993 experiment. The 4-componet detector consists of accelerometers mounted in a housing and set in sand at the bottom of the borehole. The three 4-component seismic detectors and hydrophone were set at depths of 1,500 m, 1,420 m, 1,600 m and 2,850 m, respectively. The downhole seismic detectors were installed in the same basement rock, and high quality signals were readily detected, since the influence of surface waves could be ignored and the transfer function from source to detectors is simple. The frequency band of the acquisition system was from 10 Hz to 1 kHz, and the signals were digitized by 5 kHz sampling frequency (Baria et al., 1999).

Using these detectors, source locations for more than 10,000 events have been determined (Baria et al., 1999). Figures 2 show source locations for all of the analysed events, with the location of 10,182 events having been plotted. As shown in this figure, the seismic cloud has approximate dimensions of 0.5 by 1.2 by 1.5 km, striking N30° W and dipping nearly vertically (Phillips, 2000).

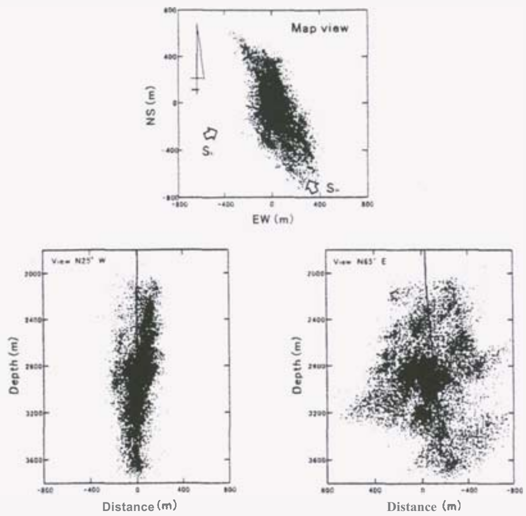

Fig.2: Seismic cloud associated with the **'93** stimulation.

3. SEISMIC LINE REVEALED BY COLLAPSING METHOD

The collapsing method (Jones and Stewart, 1997) is based on the observation that a seismic cluster of points occupies more volume when each point is perturbed by random errors than it does if no errors are present. Collapsing iteratively shifts each microseismic location within its confidence ellipsoid toward the center of mass of events located within its confidence interval. This method provides an enhanced map of seismic structure which is inherent in seismic cloud.

By examining collapsed images of the microseismic cloud developed during the September 1993 stimulation (Jones et al., 1995), Evans et al. (1999) found a major linear structure, which developed early in the injection. This structure, shown in Figure 3, initiated at 2950 m depth near the well and extended to 3300 m prior to the evolution of the other principal structures.

Figure 4 shows the growth of this structure in time. It initiated at a depth where significant flow left the well, and it then grew downwards in a stepwise manner, the steps corresponding to step-increases in injection pressure and flow with a delay of about two hours. Analysis of flow and temperature logs during and following the stimulations indicated that the seismic structure is also a high-permeability, hydraulically-significant structure created/enhanced by the hydraulic stimulation (Evans, 2000; Evans et al. 2001).

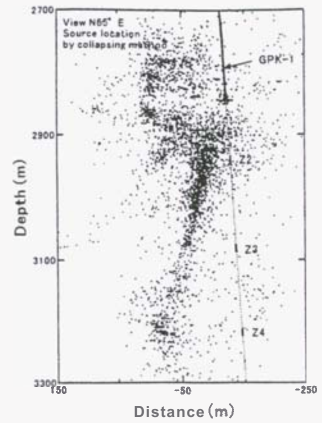

Fig. 3: Seismic line revealed by collapsing method.

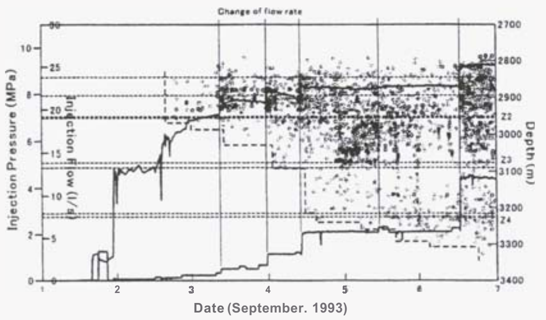

Fig. 4: Growth of the seismic line during the stimulation.

4. ESTIMATION OF MICROSTRUCTURE BY MULTIPLET ANALYSIS

Multiplets are groups of seismic events with very similar waveforms, but different origin times, and are probably the expression of stress release on the same structure. The relative source locations of events within a multiplet cluster can be determined with high resolution using cross-spectrum analysis (Moriya et al., 1994,2001).

In the '93 experiment, about 60% of located events belong to some of the multiplet groups. Figure 5 shows the result of precise relative mapping of a multiplet group (Moriya et al., 2002). The relative location error is estimated to be less than 1 m. The multiplet groups usually define planar structures with diameters of **2** - 12 m. Thus, the multiplet analysis sheds light on the micro-structure of the total seismic cloud.

97 multiplet groups, which consist of 713 events in the seismic line, have been analysed (Moriya et al., 2001). Figure 6 (a) shows the distribution of orientations of individual multiplet planes plotted in lower hemisphere of Schmidt net. Critical pore pressure for frictional slip based on Coulomb's law, using a representative stress field at the depth of 2900 m, is also shown in this figure, where friction coefficient was assumed to be 0.8. Figure *6* (b) shows a fracture distribution detected by **FMI** log at 2000 – 3800 m in **GPK-1** (Genter and Dezayes, 1993).

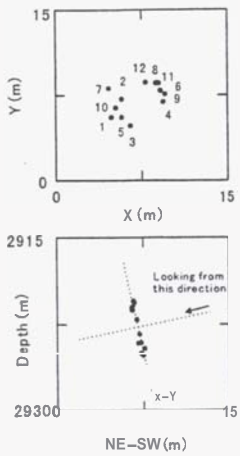

Fig.5: Planer structure of a seismic multiplet group.

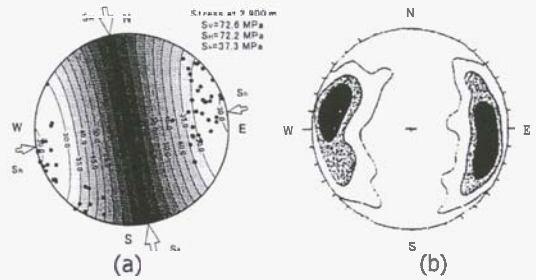

Fig. 6: Orientation of multiplet structure and pre-existing joints. (a) Orientation of multiplet structure and critical pore pressure calculated from stress data. (b) Orientation of natural joints before the stimulation detected by FMI in GPK-1.

As shown in Fig. *6* (a), multiplet planes are almost vertical and their strikes are approximately NNW-SSE. Similar distribution is observed for the pre-existing fractures (Fig. 6 (b)). The direction of the multiplet planes mostly distributes in the area where the critical pore pressure is less than **30** MPa. Because the seismicity started when the wellhead pressure exceeded 5 MPa, the pore pressure would exceed the critical pressure during the growth of the seismic line for most of the plane (Moriya et al., 2001).

5. STRUCTURE OF THE SEISMIC LINE ESTIMATED BY MULTIPLET-CLUSTERING ANALYSIS

The multiplet analysis provides information on the microstructures in the seismic cloud. However, it does not give knowledge of absolute locations of individual multiplet clusters with the same order of precision to the relative location of events in a multiplet cluster.

Moriya et al. (2001) proposed the "multiplet-clustering method" to reduce the location error of multiplet clusters using the technique of "clustering analysis" (Phillips et al., **1997).** In this method, the waveforms of events in a multiplet group are stacked, and similar phases of the stacked waveforms are compared in time domain. Then, relative arrival time differences **(i.e.** relative locations between the stacked events) are determined.

Figure **7** shows a result of the multiplet-clustering method applied to the multiplet groups in the microseismic structure shown in Fig. 2. The **97** multiplet clusters are plotted in this figure. Relative locations between clusters are determined with error less than **6** m, while the location error for the JHD (Joint Hypocenter Determination) mapping shown in Fig. 2 is about 15 m.

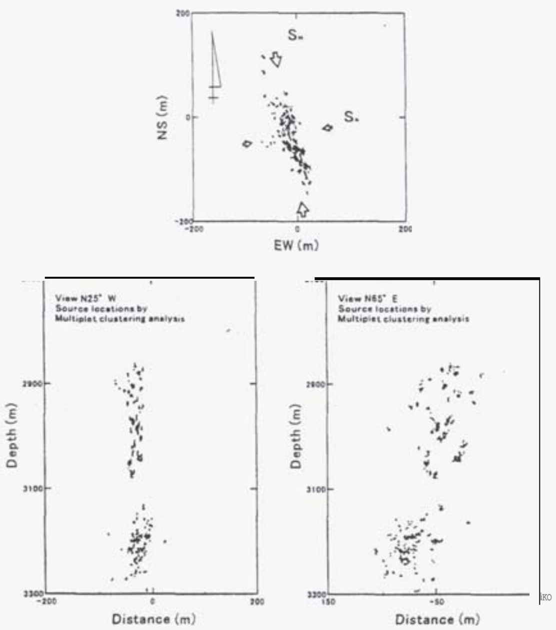

Fig. 7: Detailed structure **of** the seismic line estimated by multiplet-clustering analysis.

As shown in this figure, the structure of the seismic line has a thin volume by 20 **x** 80 **x** 400 m, which consists of the sub parallel multiplet clusters shown in Fig. 6 (a). The cluster found by Phillips (2000) is included in this volume at the depth around **3200** m.

6. DISCUSSION

The multiplet and multiplet-clustering analysis methods have been used to resolve the detailed microstructure of the seismic line which appeared at the early stage of the stimulation. The microstructure consists of the sub parallel multiplet planes. This result suggests that natural joints which are oriented to the directions most easy to slip, were stimulated by the injection. Because the structure developed stepwise corresponding to the step of injection pressure and **flow** with delay, some permeable paths were created aseismically by the seismic events, which were observed as the multiplet clusters, and the structure developed iteratively. The fact that the structure is restricted within the thin layer suggests the existence of a fkactured layer in the region.

7. CONCLUSION

High-resolution seismic mapping techniques have been applied to the microseismic data set recorded during the hydraulic stimulation at Soultz-sous-Forêts HDR field, France, in **1993.** Detailed seismic structure of a seismic line, which was growing linearly at the early stage of the stimulation, has been analysed by the multiplet and the multiplet-clustering analysis. It is estimated that this structure shows enhanced permeable paths and consist of sub parallel microstructures, which are oriented to the directions most easy to slip by the stimulation.

8. ACKNOWLEDGEMENT

This **work** was carried out **as** a part of the MTC/MURPHY International Collaborative Project (International Joint Research Grant) supported by NEDO and MESSC, and by a grant **from** the Industrial Technology Research Grant Program in 2000, supported by NEDO. We would also like to thank SOCOMINE for providing the data from the European HDR site at Soultz-sous-For&, which is supported mainly by the European Commission, BMBF (Germany), and ADEME (France).

9. REFERENCES

Baria, R., Baumgärdner, J., Gerard, **A.,** Jung, R. and Garnish, J. **(1999).** European HDR research programme at Soultz-sous- **Forêts** (France) **1987-** 1996. ***Geothermics,*** Vol. 28,655-669.

Evans, K. F., Jones, R., Soma, N. and Baria, R. **(1999).** ***Correlation of near-borehole microseismic structures defined** by the **'collapsed cloud' of events induced by the 1993** GPKl **stimulation with flowing fractures.*** Internal Report of MURPHY Project **1999,** NEDO.

Evans, K. F. (2000). The effect of the **1993** stimulations of well GPK1 at Soultz on the surrounding rock mass: Evidence for the existence of a connected network of permeable fkactures. ***Proc. World Geothermal Congress 2000***, Vol. **6, 3695-3670**.

Evans, K. F. (2001). ***Determining the effect of stimulation injections on the rock mass around the well GPK-1 from borehole data: Analysis of the 1993 injections.*** Report of BBW Project **no.98.0008-1, 6-74.**

Fehler, M., Jupe, A. and Asanuma, H. **(2001).** More Than Cloud: New techniques for characterizing reservoir structure using induced seismicity, ***The Leading Edge,* 324-328.**

Genter, **A.** and Dezayes, C. **(1993).** ***Fracture evaluation in GPKl borehole by using FMl data.*** Field Report, BRGM Orleans.

Gerard, A., Baumgärdner, J. and Baria, R. (1**997).** *An* attempt towards a conceptual model derived from **1993-1996** hydraulic operations at Soultz. ***Proc.*** *NEDO* ***International Symposium,*** Vol. **2,** 329-341.

Jones, R. H., Beauce, A., Jupe, A., Fabriol, H. and Dyer, B. C. **(1995).** Imaging induced microseismicity during the **1993** injection tests at Soultz-sous-Forêts, France. ***Proc. World Geothermal Congress 1995,*** Vol. **4,2665-2669.**

Jones, R. H. and Stewart, R. (1**997).** A method for determining significant structures in a cloud of earthquakes. *J.* ***Geophys.*** *Res.,* Vol. **102, 8245-8254.**

Moriya, H., Nagano, K. and Niitsuma, H. **(1994).** Precise source location of AE doublets by spectral matrix analysis of triaxial hodogram. *Geophysics,* Vol. **59,3645.**

Moriya, H., Nakazato, **K.,** Evans, K. **F.,** Niitsuma, H., Jones, **R.H.**and Baria, R. **(2001).** Evaluation of the Soultz HDR system by precise mapping techniques of induced microseismic event. ***Trans. Geothermal Resources Council 2000,*** Vol. **25, 187-190.**

Moriya, H., Nakazato, **K.,** Niitsuma, H. and Baria, R. **(2002).** Detailed fracture system of the Soultz-sous-Forêts HDR field evaluated using microseismic multiplet analysis. ***Pure appl. Geophys.,*** Vol. **159,** 517-541.

Niitsuma, H. et al. **(1999).** Current status of seismic and borehole measurements for HDR/HWR development, ***Geothermics,*** Vol. **28, 475-490.**

Phillips, W. **S. (2000).** Precise microearthquake locations and fluid flow in the geothermal reservoir at Soultz-sous-Forêts, France, ***Bull. Seism.*** *Soc. Am.,* Vol. **90(1), 212-228.**

Poupinet, G., Ellsworth, W. L. and 'Frechet, J. **(1984).** Monitoring velocity variations in crust using earthquake doublets: An application to the Calaveras fault, California, *J.* ***Geophys, Res.,*** Vol.89, **5719-5731.**

Rowe, C. **A.,** Aster, R. C., Phillips, W. S., Jones, R. H., Borchers, B. and Fehler, M. C. **(2002).** Using Automated high-precision repicking to improve delineation of microseismic structures at the Soultz geothermal reservoir, ***Pure Appl. Geoph,*** Vol. 159, **563-596.**

Waldhauser, F. and Ellsworth, W. L. **(2000).** A double-difference earthquake location algorithm: Method and application to North Hayward Fault, California, ***Bull.*** *Seism. Soc. Am.,* Vol.90, 1353-**1368.**