PROCEEDINGS, Twenty-Eighth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 27-29, 2003
SGP-TR-173

ESTIMATION OF FINE SCALE STRUCTURES IN SOULTZ HDR RESERVOIR BY USING MICROSEISMIC MULTIPLETS

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ABSTRACT

Microseismic multiplet has been used to estimate detailed structures of deep reservoir at Soultz HDR field, France. The multiplet is a group of microseismic events with similar waveforms in spite of different origin times. A hydraulic fracturing experiment was carried out at Soultz in 2000, and the artificial geothermal reservoir was created around the depth of 5,000 m. The induced microseismic events have been observed using downhole detectors, and more than 40,000 events have been triggered in our recording system. Precise source locations of induced microseismic multiplets have been estimated using the multiplet-clustering analysis, and seismically activated structural planes have been estimated as well as their orientations. The principal stress directions were also estimated based on the orientations and the estimated slip directions of structural planes. The results of analyses are demonstrated in this paper, and we discuss the feasibility of utilizing microseismic multiplets for evaluation of enhanced geothermal reservoir.

INTRODUCTION

Evaluation of fracture system is essential to assess performance of geothermal reservoir for energy extraction. The mapping of induced microseismic events is useful for estimating subsurface fractures, because the microseismic events are induced by pressurizing a subsurface formation and they would be an indicator of hydraulically activated fractures behaving as fluid flow path in geothermal reservoir.

In the last few years, major advances have been made in high-resolution microseismic mapping techniques, and the AE(Acoustic Emission) / MS (Microseismic) method is now a powerful tool by which to measure subsurface fractures (Niitsuma *et al.*, 1999). One of the goals of reservoir analysis using induced microseismic events is to understand the formation of fracture systems as a fluid flow path, and to estimate the preferential fluid flow path (Moriya *et al.*, 1994; Jones and Stewart, 1997; Phillips, 2000; Rowe *et al.*, 2002; Moriya *et al.*, 2002; Niitsuma *et al.*, 2002). That is, the high-resolution mapping of induced microseismic events is required to spatially distinguish individual fractures in order to reveal their interconnectivity.

Groups of similar microseismic events are often found among the observed events. These similar events are called “multiplet”, and considered to be an expression of stress release on the same fracture plane and fracture system (Poupinet *et al.*, 1984). This means that the hydraulically activated fracture planes can be estimated from precise source locations of induced multiplets. In addition, since the source locations of each multiplet would represent individual fracture planes, there is a possibility that the spatial distribution of multiplets let us know the distribution and the interconnectivity of individual fracture planes in the reservoir, and which provides us an estimate of fracture network that is important for evaluation of reservoir performance.

We have been working on a high-resolution mapping method using induced microseismic multiplets, and have applied the analysis to induced microseismic events at geothermal fields (Moriya *et al.*, 2002). For example, the induced microseismic multiplets during a hydraulic fracturing test at shallow reservoir in Soultz field, which was conducted in 1993, have been analyzed, and we have succeeded to derive fine scale structures. In this paper, we show the results of the multiplet-clustering analysis applied to induced microseismic events from deep reservoir at Soultz field in 2000, and demonstrate the feasibility of utilizing microseismic multiplet for evaluation of geothermal reservoir.

HYDRAULIC FRACTURING EXPERIMENT AT SOULTZ HDR FIELD

Hydraulic fracturing was performed at the European Hot-Dry-Rock research site at Soultz over the openhole section of GPK2, from 4431 m to 5084 m, and it is reported that a total fluid volume of 23,400 m^3 was injected during 6-day pumping operation. Three downhole 4-component accelerometers (in wells 4550, 4601 and OPS4) and two hydrophones (in wells EPS1 and GPK1) worked for observation of microseismic events. The signals were acquired in our recording system, and more than 40,000 microseismic events were detected (Asanuma *et al.*, 2001). Figure 1 shows source locations for a total of 7557 induced microseismic events, with the source locations determined by JHD (Joint Hypocenter Determination), where the source locations of induced microseismic events at shallow reservoir in 1993 are also described. Source locations are constrained within a depth range extending from approximately 4000 m to 5500 m. The maximum principal axis of the entire seismic cloud is oriented N45 degrees W, with the volume of the seismic cloud similar to that from 1993 hydraulic fracturing experiments (Baria *et al.*, 1999).

ESTIMATION OF STRUCTURES BY USING MULTIPLETS

Figure 2 shows typical waveforms of an induced microseismic multiplet. Multiplet is a group of similar microseismic events in spite of different origin times, and these similar microseismic events are considered to be the events from the same fracture plane and fracture system. The search and classification of multiplets have been automatically performed, and similar microseismic events have been identified using a coherency function, with a total of 990 groups of multiplets corresponding to 2818 events being recorded. We have applied multiplet analysis to estimate relative source locations in order to delineate respective multiplet clusters. After that, we utilized multiplet-clustering analysis (Moriya *et al.*, 2002), to estimate relative positions within the multiplet clusters.

The multiplet-clustering analysis is performed after multiplet analysis, with cross-spectrum analysis determining the relative source locations of similar events, in individual multiplets. As a pre-processing step, we have applied a FIR (Finite Impulse Response) low pass filter, with a cut off frequency of 100 Hz, to the raw signals to emphasize the similarity of waveforms. A stacked waveform has been created after low pass filtering, as a representative waveform for the individual multiplets. We chose an event with high signal to noise ratio as the master waveform, and then detected arrival times of slave events relative to the master event. To estimate the relative location of multiplet clusters, relative arrival time differences have been detected for P- and S-waves in the stacked waveforms. The detection of relative arrival time difference has been determined by relative to a master event. By examining the same portion of a waveform and shifting the slave waveform along time axis (until the master and slave waveforms overlap), we can manually detect the time lag and shift of slave waveform, and make adjustments relative to the master waveform (Phillips, 2000).

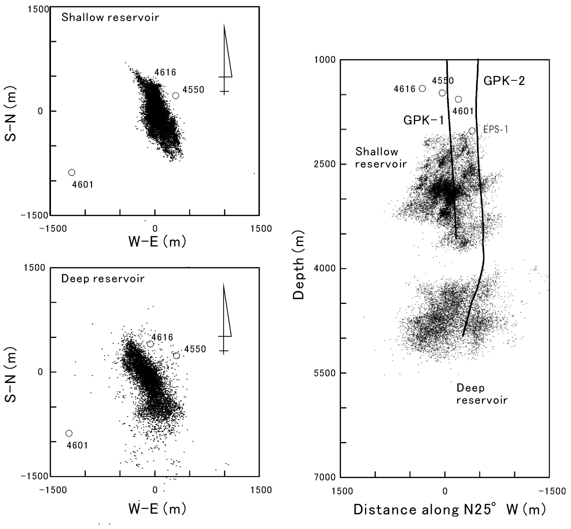


Figure 1: *Source locations of induced microseismic events determined by JHD, and locations of downhole seismic detectors. Well OPS 4 is located at SE of fracturing well (GPK-2) and outside of the figure.*

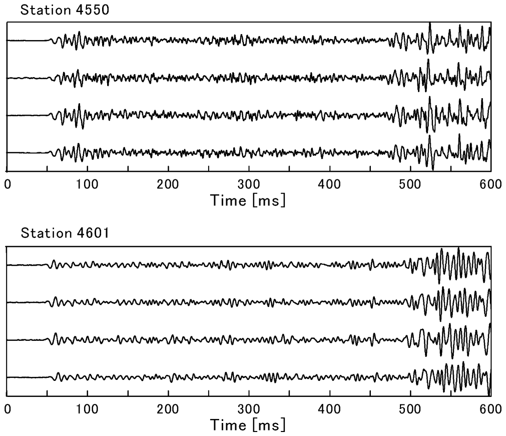


Figure 2: *Typical waveforms of an induced multiplets at well 4550 and 4601.*

A total of 25 groups of multiplets, corresponding to 137 events with high signal to noise ratio and visually clear waveforms, were located. Figure 3(a) and (b) show source locations before and after multiplet-clustering analysis, with the location of multiplet clusters determined relative to the center of gravity of respective multiplet clusters, using detected arrival time differences. After determining the center of gravity of the clusters, individual multiplet events, which the relative locations were determined by the cross-spectrum analysis, have been plotted in order that the center of gravity fit to the clusters its center of gravity.

The residual is an indicator of uncertainty for a source location determined by the least squares. When the P-wave velocity is 5 km/s and we evaluate the location error using one-sigma error magnitude, the location error in JHD is evaluated to be about 35 m from the residuals. On the other hand, the error in relative source locations of multiplet events is around 0.5 m and that in relative location within multiplet clusters (multiplet-clustering analysis) is about 4 m. The principal axis of error ellipsoid, where the size and shape depend on the locations between source and detectors as well as the residuals at observatories, is trending to NE-SW direction. This direction is different from the direction of estimated source distribution shown in figure 3(b), and which means that the estimated source locations are not affected by the location error due to the geometrical relationship between the source and detectors. In figure 3(b), the seismic cloud shrinks for each multiplet and distinct structures are revealed, where the multiplet clusters distribute to N-S direction. This N-S direction is consistent with the dominant direction of pre-existing fractures detected around the shallow reservoir by well logging in well GPK-1 (Genter *et al*., 1993).

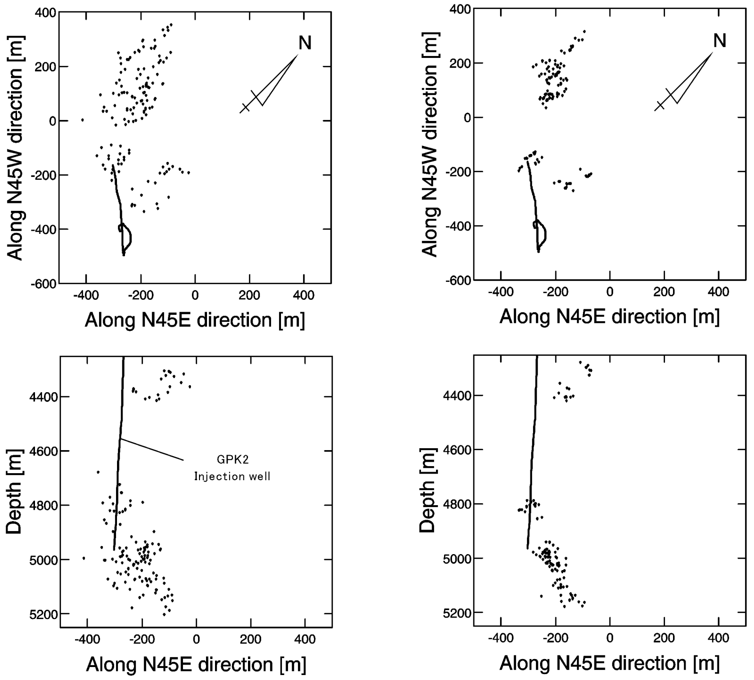
EVALUATION OF STRUCTURAL PLANES BASED ON MULTIPLETS

We have calculated the planes defined by the source distribution of events for each multiplet group or cluster. These planes can be though as the fracture planes which emitted seismic waves due to the increasing of pore-pressure. We have introduced the principal component analysis using the co-ordinates of source locations for objective and quantitative evaluation. In order to confirm whether the source distribution are plane, we have calculated the contribution ratio. Figures 4(a) and (b) show the first contribution ratio and first and second contribution ratio. It is suggested that the source locations show planar structure rather than line structure. When the source distribution is approximated with ellipsoid, the length of the ellipsoid is ranging from 32 m to 189 m if we consider the length in major axis with 99.9 % confidence. The size of planar structures is larger than that in the shallow reservoir. One explanation of the difference is that the equivalent surface areas of shear slip increases due to the larger stress magnitude. Figure 5 shows a stereographic projection of structural planes, where the poles of the planes are projected on lower hemisphere. The orientation of multiplet structural planes is dominantly in a N-S direction. This dominant direction is rotated clockwise from the direction of the structural planes in the shallow reservoir.

In order to understand the formation process of artificial reservoir associated with the fluid injection and shear slip of pre-existing fractures, we have estimated the slip direction of the structural planes. The P-wave polarities are used to estimate the slip directions, where the grid method is employed to find the all possible solutions which are compatible with the observation. Polarities have been detected at four detectors and the slip directions of a structural plane have been examined for every 10 degrees by comparing the observed polarities with the theoretically calculated polarities. Only the compatible slip directions at all detectors are remained as solutions. Figure 6 shows the estimated slip directions of structural planes, where the thick line denotes the planes and the median of the solutions are described with the closed circles. The estimated slip directions can be classified into the normal fault type and lateral strike slip fault type.

ESTIMATION OF STRESS FIELD

The stress regime has not been determined at the deep reservoir in this field. Then we estimated the stress field using the orientation of multiplet structural planes and their slip directions. A grid method has been used to determine principal stress direction and stress ratio (Moriya and Niitsuma, 1995). In the grid method, a stress tensor is assumed as an initial solution. The maximum shearing stress direction on each multiplet structural plane is calculated using the stress tensor. Assuming that the maximum shearing stress direction acting on the multiplet structural plane corresponds to shear slip direction, the observed slip direction has been compared to a calculated slip direction for all multiplet structural planes. If the summation of residuals between calculated and observed slip directions is below a given criterion, then the initial stress tensor is a possible solution. This examination was performed to all stress tensors. Figure 7 describes estimated principal stress directions, with solutions within a 95 % confidence interval being plotted. The estimation is carried out by using the multiplets distributed below 4,700 m, where the multiplets are located within an interval of 600 m in depth.



(a) (b)

Figure 3: *Source locations of multiplets determined by (a) JHD and (b) multiplet-clustering analysis, where the waveforms with high signal to noise ratio and clear waveforms are analyzed.*

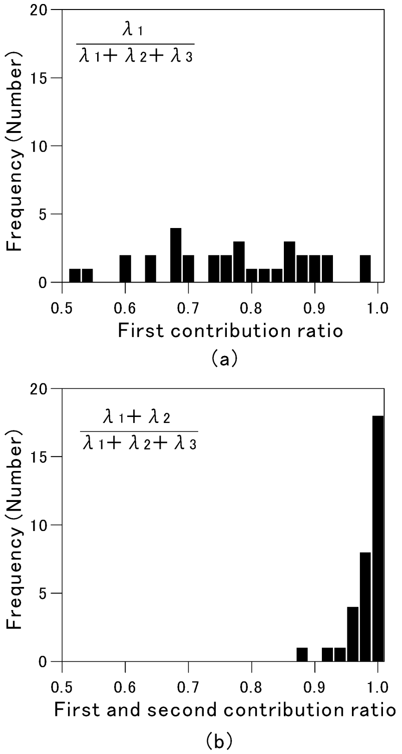


Figure 4: *Histogram of contribution ratio. (a)First contribution ratio and (b) first and second contribution ratio calculated using the co-ordinates of source locations for each multiplet.*

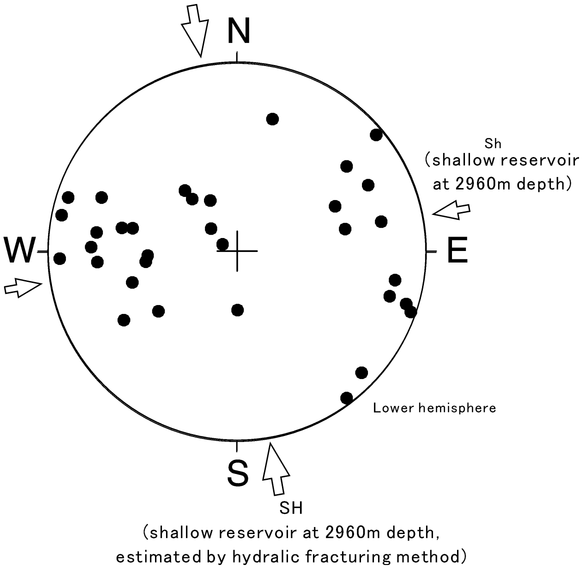


***Figure 5**: Distribution of poles of multiplet planes projected on lower hemisphere (Schmidt net), where the open circle denotes the planes in shallow reservoir and closed circle represents the planes in deep reservoir. The arrows represent the directions of the maximum and minimum horizontal stress direction by the hydraulic fracturing tests at shallow reservoir (Baria et al., 1999).*

The maximum and minimum horizontal stress directions measured by the hydraulic fracturing method at shallow reservoir (Baria *et al.*, 1999) are also described using the arrows. In the analysis, the maximum principal stress direction is inferred to be near vertical. The intermediate principal stress direction ranges from NW to N, with the minimum principal stress direction is almost perpendicular to the seismic cloud.

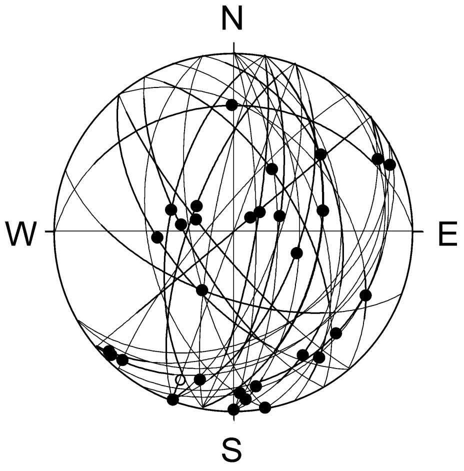


Figure 6: *Stereographic projection (lower hemisphere Wulff's net) of estimated structural planes and possible slip directions. Closed circle denotes median of possible slip direction.*

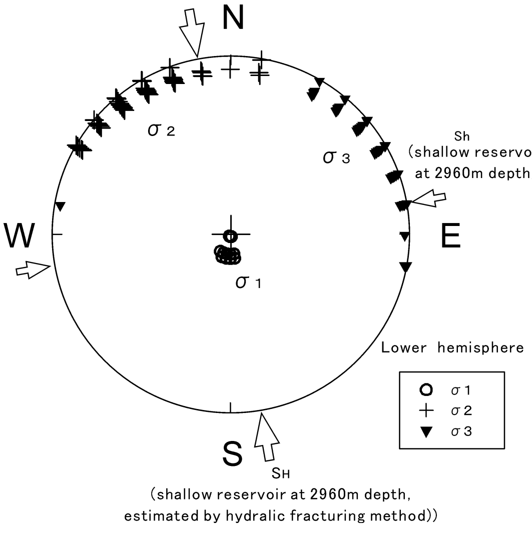


Figure 7: *Principal stress directions estimated using the multiplets. The solutions are projected on lower hemisphere (Schmidt net). The open circle, cross and inverse triangle denote the maximum, intermediate and minimum principal stress directions.*

DISCUSSIONS AND CONCLUSION

The microseismic multiplets have been analyzed to reveal the structures and stress field of Soultz deep reservoir. The improvement of location accuracy by the multiplet-clustering analysis has been confirmed on the basis of error analysis using the residuals.

It has been revealed that the multiplet clusters expand from N-S to NW-SE directions. The orientations of the structural planes, which define the multiplet clusters and are derived from the source locations of each multiplet, are dominated to N-S directions. The estimated slip directions using the distribution of P-wave polarities suggest that the normal and lateral strike slip have been caused associated with fluid injection.

The principal stress directions have been estimated using the orientations of structural planes and its slip directions. The result would show that the axes of three principal stresses are not changed comparing with the stress field at shallow reservoir, and that the maximum principal stress directions are near vertical.

Considering the above mentioned results on induced microseismic events, we would interpret the phenomena in the deep reservoir as follows. The pre-existing fractures, which are oriented to N-S direction and under the critical condition for frictional shear slip, preferentially caused normal and strike slips due to the increasing of pore-pressure, and then the slipped fractures formed tensile fractures at the edge. These tensile fractures are approximately normal to minimum principal stress direction and would be permeable because the normal stress on the fracture surface is relatively low. These tensile fractures interlinked the neighboring slipped fractures. By the repeating of shear slip and interlinking, the permeable zone was formed and extended to the direction normal to the minimum principal stress direction (Hill, 1977). In the induced microseismic events, the slipped fractures would be represented by the structural planes derived from the source locations of each multiplet and the mass of the interlinked fractures are represented by the entire seismic cloud.

ACKNOWLEDGEMENT

We thank Dr. K. F. Evans (ETH, Switzerland) for detailed technical discussions and helpful comments. This work was carried out as a part of the MTC International Collaborative Project, and by a grant from the Industrial Technology Research Grant Program in 2000, supported by NEDO. We would also like to thank SOCOMINE (now EEIG Heat Mining) for providing the data from the European HDR site at Soultz-sous-Forêts, which is supported mainly by the European Commission, BMBF (Germany), and ADEME (France).

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