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Multiplet Analysis for Estimation of Critical Pore-Pressure of Fractures Inside Geothermal Reservoirs

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ABSTRACT

Microseismic multiplets are introduced to estimate the critical pore-pressure of fractures required for shear slip during hydraulic fracturing of a geothermal reservoir. Because the multiplets can be used to estimate the precise source locations using cross-spectrum analysis, the orientations of hydraulically activated fractures are derived from the source locations of multiplets. The critical pore-pressure required for shear slip of fractures is estimated using the fracture orientations and the stress field that was measured in a borehole. The method and the results of its application to microseismic multiplets at Soultz field, France, are demonstrated. The feasibility of the method for estimation of pressure distribution and fluid flow in a reservoir is also discussed.

1. INTRODUCTION

The enhancement of geothermal reservoirs is important, and hydraulic fracturing is often conducted at geothermal fields in order to extract more geothermal energy from reservoirs. The monitoring of fluid flow in a reservoir is indispensable for the effective stimulation of pre-existing fractures. The locations of seismically and possibly hydraulically activated fractures can be estimated using the induced seismic events associated with the shear slip of pre-existing fractures.

The method of precise mapping of induced microseismic events has succeeded in revealing the structures that may indicate fluid flow zones in a reservoir (e.g., Fréchet, 1989; Niitsuma et al., 1999). Multiplet-clustering analysis is a high-resolution mapping technique in which similar microseismic events are analyzed to determine the precise source locations, and then the seismic clusters can be derived from the relative source locations of multiplets (Moriya et al., 2003). Multiplet-clustering analysis can estimate not only fine-scale structures but also larger structures interconnected with the fractures derived from each multiplet. In addition, fracture orientations can also be estimated using the source locations of each multiplet, since similar microseismic events within a multiplet are considered to radiate on the same fracture plane.

In this paper, we suggest a method for the estimation of pore-pressure in fractures during hydraulic stimulation of a geothermal reservoir by using induced microseismic multiplets, for which we also introduce the method of multiplet-clustering analysis. We show the feasibility of the method by applying it to microseismic events at Soultz field..

2. HYDRAULIC FRACTURING AT SOULTZ HDR FIELD

The European Hot Dry Rock (HDR) project site at Soultz-sous-Forêts is located on a local horst structure in the Rhine graben, where Hercynian-age granites are covered by a 1.4-km-thick sedimentary section (Baria et al., 1999). The GPK1 well (Fig. 1) was drilled to a depth of 3590 m (open hole below 2850 m depth), and since 1987 it has been used for a number of detailed experiments.

Major hydraulic fracturing experiments were performed in September and October 1993. In the September test, 25 000 m^3 of fresh water was injected between 2850–3350 m over a 17-day period at progressively higher rates up to 40 L/s and at pressures of up to 10 MPa. Throughout the test, it was demonstrated that the fracture network in the basement rock was well developed, with enhanced permeability and a substantial increase in transmissivity (Baria et al., 1999; Evans, 2000). Three 4-component seismic detectors and a hydrophone were set at depths of 1500, 1420, 1600, and 2850 m, respectively. Using these detectors, source locations for more than 10 182 events were determined. The plots in Figure 2 show the source locations for all of the analyzed events determined by JHD, where the map view and cross section looking N65°E are shown. As shown in this figure, the seismic cloud of shallow events has approximate dimensions of $0.5 \times 1.2 \times 1.5$ km^3, striking N30°W and dipping nearly vertically (Phillips, 2000).

3. MULTIPLET-CLUSTERING ANALYSIS FOR ESTIMATION OF FRACTURES

Multiplet-clustering analysis is a method for estimating the relative positions of multiplet clusters as well as the relative source locations within individual multiplets (Moriya et al., 2003). We applied multiplet-clustering analysis to the induced microseismic events as follows.

In the first step, similar microseismic events were identified using the coherency function, and these were automatically classified into groups. In the case of the hydraulic fracturing in September 1993, a total of 5490 events (58.3%) were identified as multiplets (containing more than 3 similar waveforms) among the located events, with coherency ranging from 0.80 to 0.99. The relative source locations within each multiplet were estimated by using cross-spectrum analysis, where the relative differences of P- and S-wave arrival times were used to determine relative locations among similar events within the multiplet. Source locations, relative to a reference source location, were determined within each multiplet by assuming that the velocity structure was homogeneous along the wave propagation path. The RMS error for the relocation was about 0.1 ms. In order to apply the multiplet-clustering analysis, we selected 142 groups of multiplets.

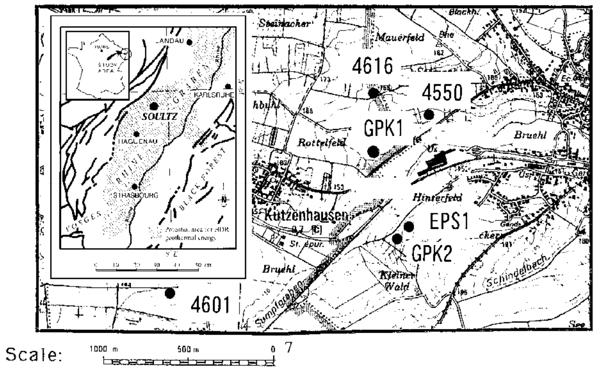


Figure 1: Microseismic monitoring and fracturing wells at the Soultz HDR field, France.

In pre-processing, we applied a low-pass filter with a cut-off frequency of 150 Hz to the raw signals. After checking the similarity of the waveforms, we made stacks of aligned waveforms for each multiplet by a method similar to that of Rowe et al. (2002). Arrival time differences for the stacks were determined relative to the master event. Using the time differences, the relative locations among the multiplet clusters were estimated assuming a homogeneous velocity structure having P- and S-wave velocities of 5850 m/s and 3340 m/s, respectively (Moriya et al., 2003).

Figures 3(a) and (b) show the source locations of multiplet events before and after multiplet-clustering analysis (Moriya et al., 2003). Following multiplet-clustering analysis, small planar clusters corresponding to each multiplet were identified within 3 larger seismic clouds denoted by “A”, “B”, and “C.” Two separate clouds, corresponding to “A” and “B,” were identified at a depth interval of 2750 to 3000 m, as shown in Figure 3(b). The closed boxes denote permeable fracture zones detected by well loggings. The 2 clouds are considered to be permeable fracture zones that intersect the borehole, which is consistent with the well-logging results..

4. CALCULATION OF CRITICAL PORE-PRESSURE OF FRACTURE FOR SHEAR SLIP

We estimated the distribution of the critical pore-pressure of fractures required for shear slip during hydraulic stimulation. We used the fracture planes derived from the source locations of multiplets. The procedure for calculation of the critical pore-pressure is as follows.

The stress directions and magnitudes were measured by the hydraulic fracturing method in a borehole. The stress magnitudes are described by the following equations (Klee and Rummel, 1993)

$$S_h = -5.9 + 0.0149Z$$
$$S_H = -25.3 + 0.0336Z$$
$$S_V = -1.3 + 0.0255Z$$

$$P_h = 0.9 + 0.0098Z\,, \qquad (1)$$

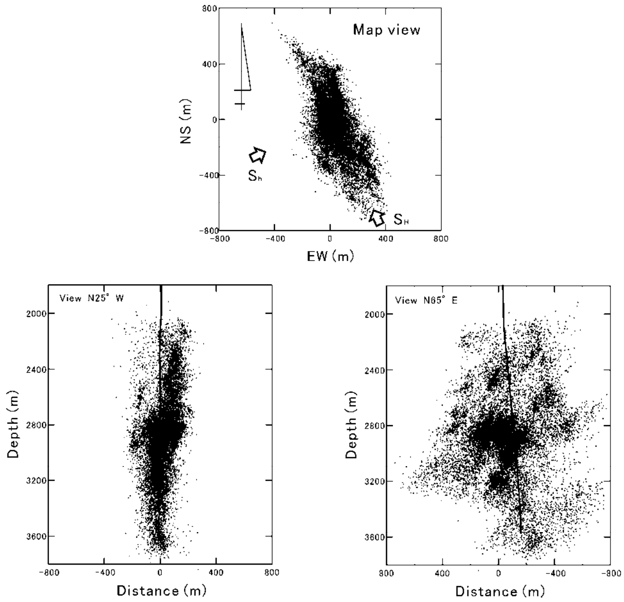


Figure 2: Source locations of induced microseismic events, where the events were determined by the JHD method. The cross section is the view toward N65°E. The thick line denotes the fracturing well GPK1.

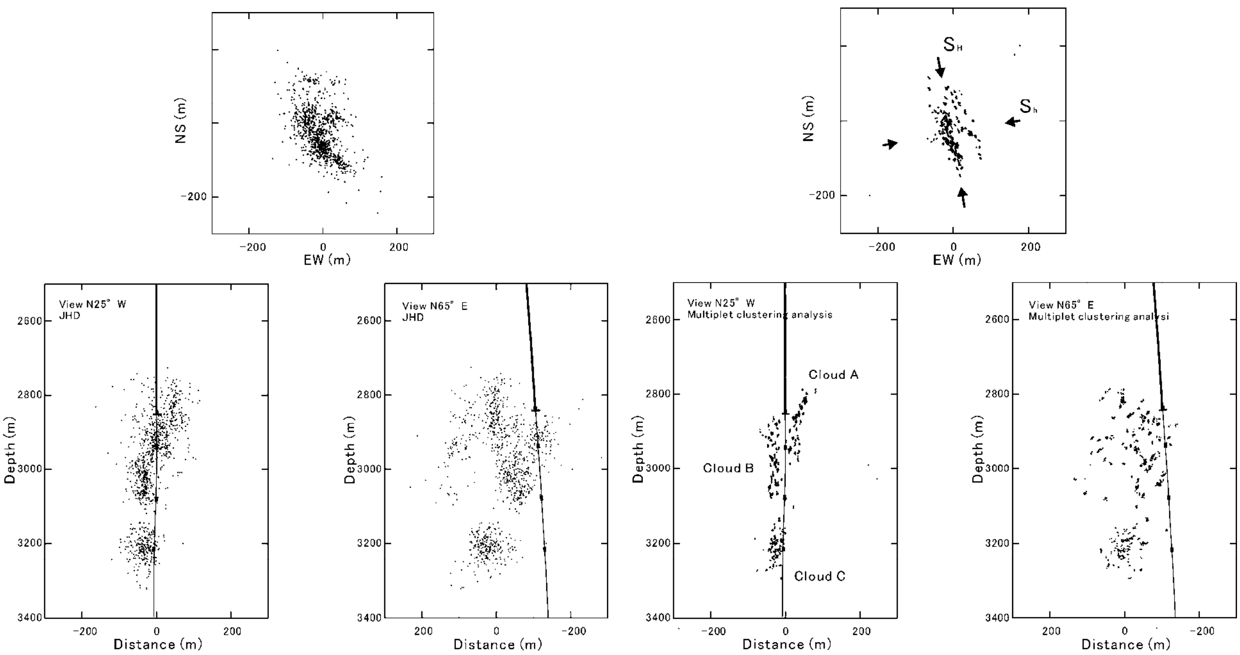
where S_h, S_H, S_V, and P_h denote minimum horizontal stress, maximum horizontal stress, vertical stress, and hydrostatic pressure in MPa, respectively. Z denotes the depth in meters. According to Coulomb’s law of friction, the relationship among shear stress, normal stress, coefficient of friction, and pore-pressure at the moment of shear slip (critical condition) due to an increase of pore-pressure is described as follows:

$$\tau - \mu_S(\sigma_N - P_P) = 0\,, \qquad (2)$$

where τ, σ_N, μ_S, and P_P denote shear stress, normal stress, coefficient of friction, and pore-pressure on a fracture surface, respectively. The cohesion is ignored in the formulation above. The critical pore-pressure for shear slip P_C can be expressed as follows:

$$P_C = P_P - P_h$$
$$= \sigma_N - \frac{\tau}{\mu_S} - P_h\,. \qquad (3)$$

P_C is the increase of fluid pressure required for inducing shear slip at a fracture. When the orientation of a fracture plane is given, the normal and shear stresses acting on the plane can be calculated. The fracture plane can be approximated using the distribution of the source locations within the multiplet: the fracture plane is defined as the plane best fitting the distribution of the source locations within the multiplet distribution (Moriya et al., 2002). The depth of a fracture plane can be estimated from the center of gravity of the source locations of each multiplet. In our case, we estimated the fracture orientations and their depths through multiplet-clustering analysis.



(a) (b)

Figure 3: Source locations of multiplets determined by (a) JHD and (b) multiplet-clustering analysis. Closed boxes along well describe the permeable fracture zones detected by well loggings. The thick line denotes the fracturing well GPK1. The casing shoe is at a depth of 2850 m (Moriya et al., 2003).

Figure 4 shows a stereographic projection of poles of the estimated fracture planes as well as the critical pore-pressure distribution, where the contours represent the increasing pore-fluid pressure P_C necessary for shear slip. The coefficient of friction was assumed to be 0.8. We can see that the poles of the fracture planes are distributed in the area of lower critical pore-pressure. Figure 5 shows the locations of the fracture planes and the calculated P_C, where the cross section looking to N65° E is shown. Zones along the well locus in the figure represent the depth intervals of the permeable fracture zones in fracturing well GPK1. The positions and distribution of permeable fractures were confirmed using FMI and temperature loggings (Evans, 2000). Figure 6 shows the depth of the fracture planes, calculated critical pore-pressure, downhole pressure at 2805 m, and injection flow rate with the date in September 1993.

The estimated critical pore-pressure required for shear slip suggests that the fluid pressure in fractures has a higher value near the fractured zones 1 and 2 around 2900 m, and that it declines as the fractures are further away from the zones. The results in Figure 5 imply that fluid pressure was transmitted into the fractures, and that the pore-pressure around zones 1 and 2 increased up to near the maximum fluid pressure in the fracturing well. It has been reported that the fractures in zones 1 and 2 had flow under low flow rate (Evans, 2000).

On the other hand, the critical pore-pressure is not related to the injection rate and downhole pressure. As shown in Figure 6, we cannot see any systematic change in the critical pore-pressure over time. The critical pore-pressures around a depth of 3200 m are lower than at other depths. This result suggests that the fractures were favorably oriented to the principal stresses around the region, and a small increase of fluid pressure induced shear slip.

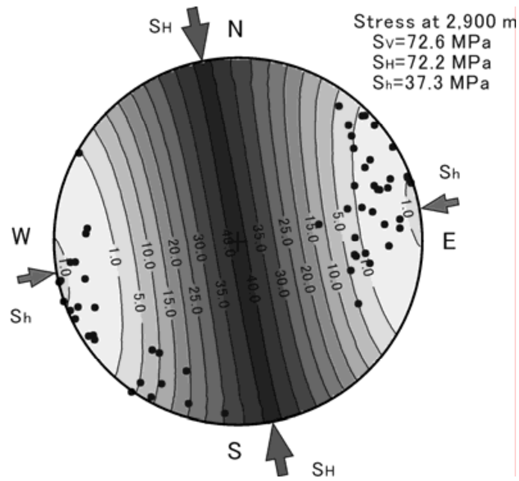


Figure 4: Stereographic projection of poles of the estimated fracture planes and the contour of critical pore-pressure *Pc*, where the poles are projected on the lower hemisphere of a Schmidtnet.

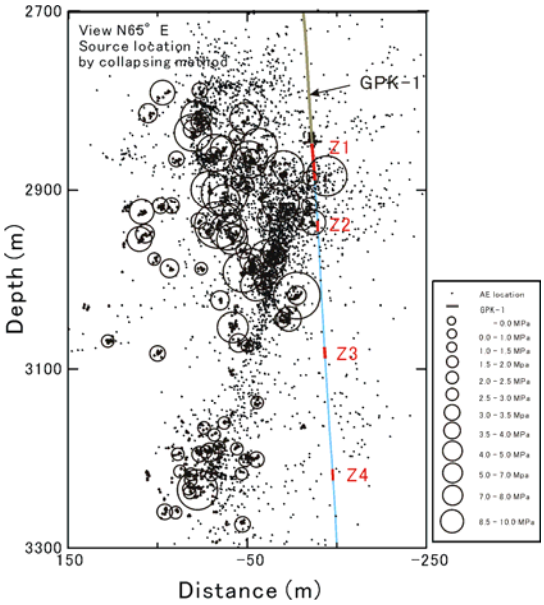


Figure 5: Location of fracture planes and the calculated P_C. The circle size represents the value of the critical pore-pressure.

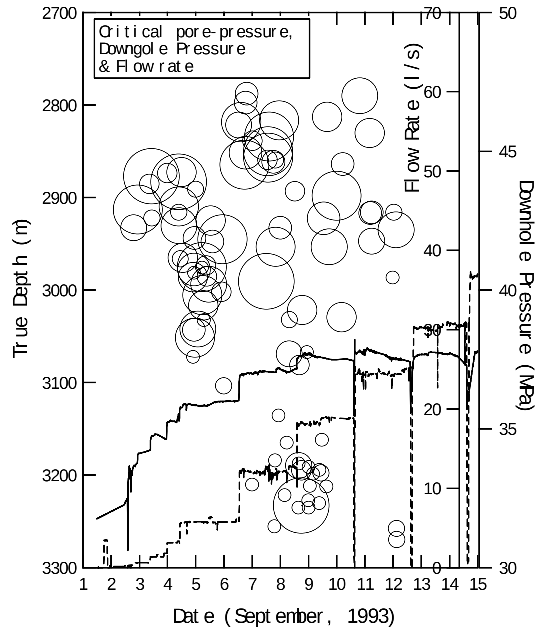


Figure 6: Depth of fracture planes, their calculated critical pore-pressures for shear slip, downhole pressure, and injection flow rate by date in September 1993. The circle size indicates the value of the calculated critical pore-pressure.

5.CONCLUSION

We have presented a method to estimate the critical pore-pressure necessary for shear slip of fractures during the hydraulic stimulation of a geothermal reservoir in which we have introduced multiplet-clustering analysis, which is a precise mapping of induced microseismic events. The distribution of the estimated pore-pressure suggests that the fluid pressure in fractures is larger around hydraulically activated fracture zones, and that it declines as the fractures are distant from the permeable zones. The estimated pore-pressure by the present method is the fluid pressure in a fracture at the moment of shear slip, and it does not represent the maximum pore-pressure in the region. However, the results are useful for the understanding of the fluid flow and pressure propagation through a fracture system in a reservoir away from wells. We can state that this estimation method based on induced microseismic multiplets is effective for the evaluation of fluid pressure of subsurface fractures away from wells.

6. ACKNOWLEDGEMENT

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