MEASUREMENT OF HYDRAULICALLY ACTIVATED SUBSURFACE FRACTURE SYSTEM IN GEOTHERMAL RESERVOIR BY USING ACOUSTIC EMISSION MULTIPLET-CLUSTERING ANALYSIS

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Abstract

AE/Micro-seismic events can be induced by pressurizing a subsurface formation and then used to identify hydraulically activated fracture and fluid flow direction in subsurface reservoir. Recently, with the development of advanced mapping techniques using similar AE events, faulting dynamics in the Earth’s crust have been studied based on such events, and internal structures in the fault zone have been estimated from the precise source locations of those events. In this paper, the pore-pressure of seismically activated fractures during hydraulic stimulation of geothermal reservoir at Soultz HDR field, France is estimated based on the high-resolution mapping method of induced AE events. The AE events with similar waveforms are analyzed, and the seismically activated fracture planes are estimated using the precise source locations determined by the multiplet-clustering analysis. The tectonic stress measured by hydraulic fracturing method in borehole is introduced into the calculation of critical pore-pressure for frictional shear slip of fractures according to Coulomb’s law. The estimated critical pore-pressure suggests that the fluid pressure in pre-existing fractures are higher near the permeable fracture zones in the well, and declines as the fractures are away from the intersecting portions.

Keywords: AE multiplet, Fracture, Pore-pressure, Geothermal

1. Introduction

The measurement of permeable fracture is important in engineering fields, such as the extraction of geothermal energy through subsurface fractures. The Acoustic Emission (AE) method is useful in estimating the location of subsurface fractures and their orientations. Advanced mapping techniques for induced AE events are progressing in order to estimate the fracture system in the reservoir, where the clustering analysis, collapsing method, multiplet-clustering analysis, etc. had been developed [1-4]. The multiplet-clustering analysis is a method to determine the relative locations of AE clusters consisted of multiplets and within the AE events with similar waveforms [5]. A multiplet, which is a group of similar AE events, is considered to be the expression of stress release on the same subsurface fracture, and their source locations of induced AE multiplet reflect the fracture plane behaving as a shear slip plane due to an increase of pore-pressure in the fracture. The multiplet-clustering analysis makes it possible to estimate the fracture planes, which would cause shear slip, and the method has been applied to induced AE events in geothermal reservoirs.

On the other hand, the measurement of pore-pressure distribution is important to understand the fluid flow and the effect of hydraulic fracturing for enhancing the permeability in subsurface fracture system. However, the direct measurement of pore-pressure is impossible for fractures
away from wells, although the spatial distribution and the gradient of pore-pressure are an indispensable indication of fluid flow around the well.

The orientation of subsurface fracture derived from the source locations of multiplet provides us an estimate of stress condition on the fracture plane, if the principal stress directions and the magnitudes are known. According to Coulomb’s law, the shear slip associated with fluid injection is caused by the decrease of normal stress on fracture surface due to an increase of pore-pressure during fluid injection. If the shear slip is controlled by the Coulomb’s law, we can calculate the critical pore-pressure for shear slip by using the orientations of fractures, the directions and magnitudes of principal stresses, which controls the dynamics of the fractures.

In this paper, we describe the method for estimating the critical pore-pressure distribution by using the orientations of subsurface fractures derived from AE multiplets and the regional stress field. The result of application to Soultz geothermal field is shown and the feasibility of the present method is discussed.

2. Induced AE Events at Soultz Field

The European HDR project at Soultz-sous-Forêts was founded by France, Germany and the European Commission (EC) in 1987. Well GPK-1 is located at the Soultz HDR field site. The well 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 undertaken at GPK-1 in September 1993. For twenty days, about 45,000 m$^3$ of fresh water was injected into granite ‘reservoir rock’ with 10 MPa maximum wellhead pressure, whilst the flow rate was increased to 50 l/s. Through 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 [6]. An inspection was undertaken of the borehole wall by BHTV (Borehole Televiewer) and FMI (Formation Micro Imager) after completion of the hydraulic fracturing experiment, and stress measurements related to hydraulic fracturing were also performed [7].

Induced AE events were detected using three downhole 4-component detectors and one hydrophone, installed in wells #4550, #4616, #4601 and EPS1. 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 [6].

Using these detectors, source locations for more than 10,000 events have been determined [6]. Figure 1 shows source locations for all of the analyzed 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 [2].

Multiplet-clustering analysis is a method for precise determination of AE event locations and is used to identify subsurface fractures and fracture networks. A multiplet is a group of microseismic events with very similar waveforms, despite different origin times, and is likely the expression of stress release on the same structure. The relative source locations of similar events
Fig. 1 Source locations of induced AE events, where the events determined by JHD method. The cross section is the view toward N65°E. Thick line denotes fracturing well GPK1.

Fig. 2 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. Thick line denotes fracturing well GPK1. The casing shoe is at the depth of 2,850 m.

can be determined with high resolution and accuracy by using the moving-window cross-spectrum analysis technique. Deduced seismic clusters, called multiplet clusters, are indicative of seismically activated structures, and the orientations of these structures can be estimated using the seismic clusters even though the absolute locations of the multiplet clusters cannot
themselves be determined. We have determined the relative locations of multiplet clusters as well as the relative locations of similar events by using the multiplet-clustering analysis. Figure 2 shows the source locations of AE events before and after the multiplet-clustering analysis, where about 1000 events identified as multiplets are analyzed.

3. Method for Calculation of Critical Pore-Pressure for Shear Slip

In principle, the pore-pressure for shear slip of a plane can be calculated if the orientation of the plane and the stress field are known. In our case, the estimates of fracture orientations are obtained from AE multiplets detected during fluid injection into subsurface reservoir. Then, we calculate the critical pore-pressure of fractures by using the orientations of fractures and the regional stress field in the corresponding field. The procedures for the calculation of the critical pore-pressure are described as follows.

In the Soultz field, the stress directions and magnitudes had been measured by hydraulic fracturing method in borehole [8]. According to Coulomb’s law of friction, the relationship among shear stress, $\tau$, normal stress, $\sigma_N$, the coefficient of friction, $f_S$, and pore-pressure, $P_P$, within a fracture surfaces at the moment of shear slip (critical condition) due to an increase in pore-pressure are described as follow,

$$\tau - f_S(\sigma_N - P_P) = 0.$$ (1)

The cohesion is ignored in the above formulation. The critical pore-pressure for shear slip $P_C$ can be found as follow,

$$P_C = P_P - P_h$$

$$= \sigma_N - \frac{\tau}{\mu_S} - P_h.$$ (2)

Fig. 3 Stereographic projection (Schmidt net, lower hemisphere) of fracture planes estimated using multiplet and the calculated critical pore-pressure.
$P_C$ means the increase of fluid pressure to induced shear slip. When the orientation of a plane is given, the normal and shear stresses acting on the plane can be calculated. In our case, we have estimates of fracture orientations and their depths from the source distribution of individual multiplets, and the depth of fracture plane can be estimated from the center of gravity of source locations of each multiplet. Figure 3 shows the stereographic projection of calculated $P_C$ and the poles of fracture planes derived from the multiplets, where the coefficient of friction is 0.8. We can see that the fracture planes are favorably oriented to principal stresses as the shear slip can be easily caused. Figure 4 shows the calculated critical pore-pressure for each fracture plane and the relationship to the depth, where the size of circle represents the value of critical pore-pressure. Zones in Fig. 4 describe the depth intervals of permeable fracture zones in fracturing well GPK1, where the permeable fractures are confirmed using FMI and temperature loggings [9].

![Fig. 4 The calculated critical pore-pressure for each fracture plane and the relationship to the depth, where the size of circle represents the value of critical pore-pressure.](image)

The estimated critical pore-pressure for shear slip suggests that the fluid pressure in fractures is higher near the fractured zones 1 and 2 around 2,900 m, and declines as the fractures are away from the zones. The result in Fig. 4 implies that the fluid pressure was transmitted into fractures, and that the pore-pressure around zones 1 and 2 increased up to near maximum fluid pressure in fracturing well. It is reported that the fractures in zone 1 and 2 are permeable under low flow rate [9]. Then, the fluid pressure easily penetrated to the fractures near the zone 1 and 2, and the fractures with variable orientations caused shear slips. This explanation would support the pore-pressure distribution in Fig. 4. On the other hand, the $P_C$ becomes below zero around 3,200 m. The same result can be also obtained when the critical pore-pressure is calculated using the orientation of fractures detected by well logging. Then, the reason for lower value of $P_C$ would be that the stress magnitudes are estimated lower than the actual values.
4. Conclusion

We have introduced AE multiplet to estimate the critical pore-pressure for shear slip of fractures during hydraulic stimulation of geothermal reservoir. Because the precise source locations of multiplets can be determined using the similarity of the waveforms, the orientation of subsurface fracture planes can be also estimated from the source distribution. The stress field measured by the hydraulic fracturing method in borehole has been introduced to calculate the stress condition on the estimated fracture planes. The critical pore-pressures for shear slip of fractures have been calculated by using the orientation of fractures and the stress field. The distribution of estimated pore-pressure has suggested that fluid pressure in fractures is larger around hydraulically alternated fracture zones, and declines as the fractures are distant from the permeable zones. The estimation method based on induced micro-seismic multiplets is effective in evaluating the fluid pressure of subsurface fractures away from wells.

References


