Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Estimation of Radiational Mechanism of AE Multiplets Observed While Hydraulic Fracturing in HDR Reservoir

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Keywords: Induced AE multiplet, Waveform similarity, Streaks of source distribution on multiplet plane, Direction of shearing stress, Asperity

ABSTRACT

Multiplet is a group that consists of seismic events with similar waveforms, and observed in a variety fields, e.g. oil or geothermal reservoir or natural seismicity. In this paper we deal with induced microseismic (AE) multiplets observed during hydraulic fracturing at Soultz-sous-Forêts HDR field, France in 1993.

The multiplet analysis has been one of mapping techniques, using cross- spectrum analysis. We noticed the similarity of the microseismic waveform and observed waveforms of microseismic events in detail. During observations we found that the similarity was not related to the amplitude of microseismicity, and the similarity of waveforms varied with matching of events. All the events included in one multiplet group showed similar waveforms at P-wave arrival. Waveforms of some events included in one multiplet group fit together almost perfectly, as well as those of coda wave and P-wave arrival part.

It is reported in conventional multiplet analysis that source locations of microseismic multiplet events revealed the structural plane (multiplet plane). On a multiplet plane we divided the multiplet events by similarity of waveforms. Then we found streaks consisting of multiplet events with especially similar waveforms, on the multiplet plane. The directions of streaks were uniform in one multiplet plane and not consistent with the calculated maximum shearing stress direction on the plane, indicating that the microseismic multiplet streaks were not related to the slip direction of the fracture.

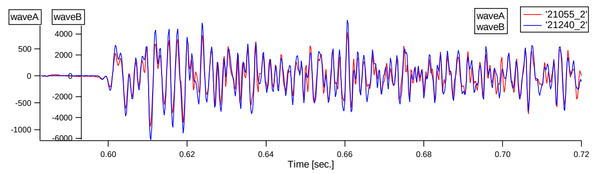
1. INTRODUCTION

A microseismic multiplet is a group of microseismic events with similar waveforms. The relative source locations of events involved in a multiplet group can be found by cross-spectrum analysis. The source distribution of events involved in a group shapes a structural plane. In case of the hydraulic fracturing, the plane is considered to be an expression of stress release on the same fracture plane. Therefore we can image internal structural planes existing in a hydraulic stimulated fracture zone.

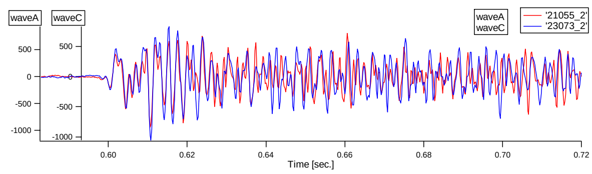
In the Soultz field, a hydraulic fracturing was carried out in borehole GPK-1, which was drilled to 3590 m depth (open hole below 2850 m depth). In September 1993, 25000 m^3 of fresh water was injected between 2850 and 3350 m depth at progressively higher rates up to 40 l/s and at pressures of up to 10 MPa over a 17-day period. The first event was observed when the downhole pressure at the 2850 depth reached 5.6 MPa. Similar events were searched for from among these 10,812 located events by calculating coherence of every observed wave trace, and 5940 events were identified as multiplets.

2. OBSERVATION OF WAVEFORMS

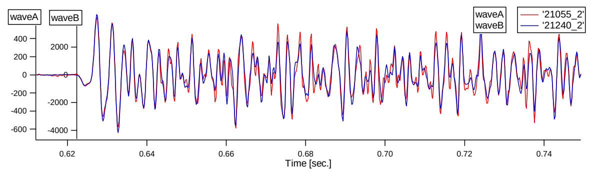
Through the observation of waveforms of multiplet events in detail, we found that the similarity of waveforms varied with the matching of events. And some of the events included in one multiplet group show waveforms that look similar. But there is not a relationship between the similarity of waveforms and the amplitude. (Figure 1 a and c). Even if the waveforms don't look similar, they fit well at the P-wave arrival section (Figure1 b and d).



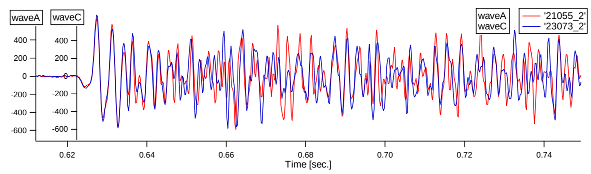
(a)



(b)



(c)



(d)

Figure 1: Example of waveforms of multiplet events. There are waveforms of 3 events, wave A, wave B and wave C in this figure. (a) and (b)are waveforms detected at the same station, (c) and (d) is at another station. Wave A and wave B fit well with each other at both station, although their amplitude is different. Wave A and Wave C don't fit well, but their P-wave arrival part looks similar.

3. STREAKS OF SOURCE DISTRIBUTION ON A MULTIPLET PLANE

Figure 2 shows the source distribution in each of the 2 multiplet planes viewed from a normal direction of the plane. The source locations were calculated by the relative location technique using cross spectrum analysis, and the rms error is less than 0.1 ms, i.e. the location error was evaluated as less than 2 m. The orientation of the plane was calculated by a principal component analysis using the coordinates of the source locations. We reclassified multiplet events into some groups by manual identification of waveform similarity. The source locations connected by a thick line in this figure represent that these events are classified into the same group, because of their high similarity of waveforms including the coda waves. These source distributions of events classified by manual identification show a uniform trend.

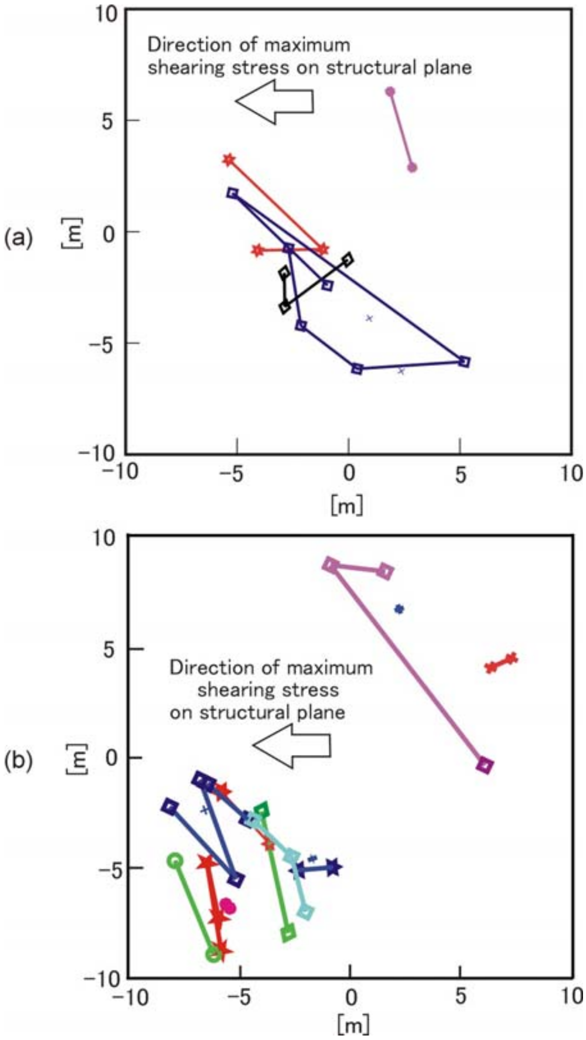


Figure 2: Source distribution in a multiplet group. Source locations connected by thin line each other represent their waveforms fit well each other including coda wave. An arrow expresses the direction of maximum shearing stress acting on the multiplet structural plane.

We tried to relate the source distribution of a multiplet to stress conditions of multiplet structural planes. The stress direction and magnitude were measured in boreholes by the hydraulic fracturing method in the Soultz HDR field [Baria et al., 1999]. Then we calculated the direction of maximum shearing stress acting on a multiplet plane by using the stress field and orientation of the multiplet plane. Arrows in Figure 2 represent the direction of maximum shearing stress acting on each of the multiplet planes. In this Figure, the direction of maximum shearing stress and the trend of source distribution don't indicate the relationship to each other. Figure3 is a stereographic of projections of the multiplet structural plans indicated by the source location shown in Figure2. The arc and open circle on the multiplet structural plane and the direction of maximum stress acting on that and the directions of the streaks are plotted using various symbols. Figure 4 shows the projection of the 24 different multiplet structural planes and the directions of streaks that have been rotated in order to make the structural planes lie along the EW axis. These resulst indicate that the trend of streaks of source distribution are not consistent with the direction of maximum shearing stress at least in the case of induced microseismic events.

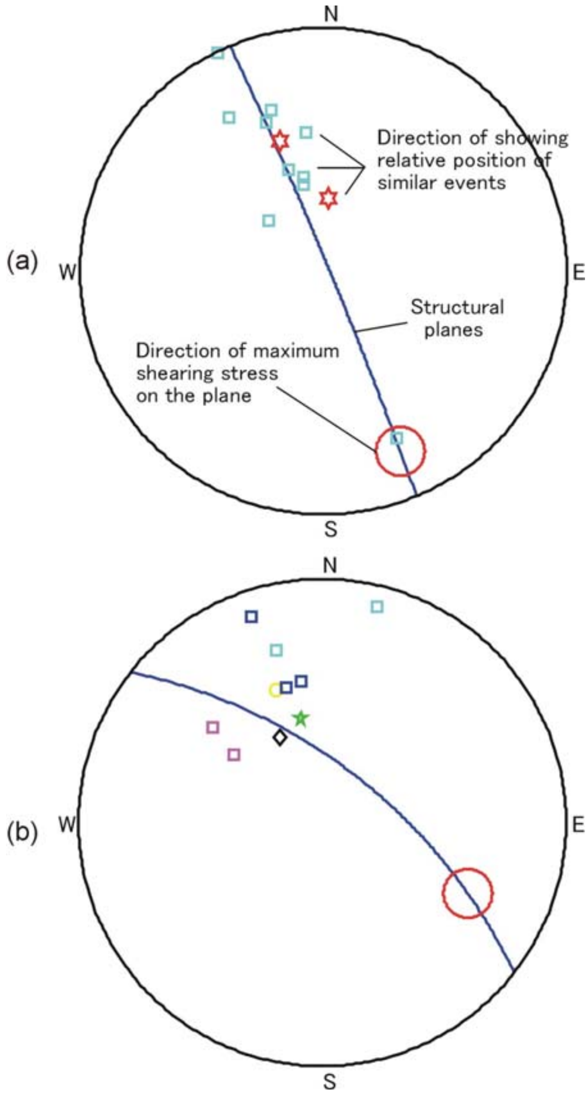


Figure 3: Stereographics of each multiplet planes. The blue arc stands for the orientation of the multiplet plane. The red open circle means the direction of maximum shearing stress on the plane. The varied symbols represent the direction of streaks indicated by source locations of events that shows similar waveform including the coda wave. Each of the symbols and the line are projected on under hemisphere of Wulff's net.

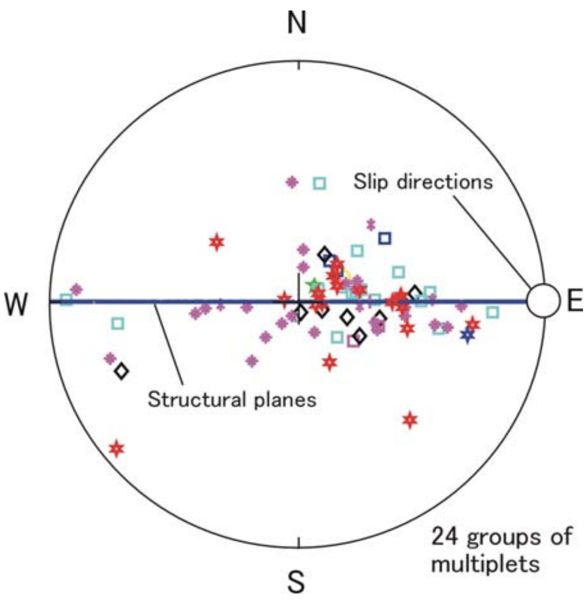


Figure 4: Stereographic of 24 multiplet planes. Each plane is rotated in order to make lie along the EW axis.

4. DISCUSSION

There are many candidate mechanisms for generating streaks on a structural plane. For instance, when fractures are continuously loaded by creep of the surrounding rock, such as in the case of the San Andreas fault, it is known that repeated earthquakes and streaks of microseismic events are aligned with the slip direction [Rubin et al., 1999].

On the other hand, induced microseismic events as well as the shear slips are triggered by increasing pore-fluid pressure. Then the direction of shear slips would be controlled by the shearing stress on the fracture. However, in the case of the microseismic multiplet observed during hydraulic fracturing in Soultz field, the streaks indicated by source distribution of microseismic multiplet events are not consistent with the calculated shear slip direction.

In the Soultz field, pre-existing fractures have an orientation in the direction of stress as they can easily cause shear slip [Genter and Dezayes, 1993; Philips, 2000]. Therefore, we infer that the induced microseismic events in the adjacent area were generated by shear slip along pre-existing fractures, and that similar seismic events in the adjacent area were generated by asperities on the same fracture plane experiencing shear slip when the effective normal stress decreased as a result of increasing pore- fluid pressure.

We could explain the reason for the multiple streaks as follows. First, a microseismic multiplet can be interpreted as a group of microseismic events generated at different asperities distributed on the same fracture plane. When the pore-fluid pressure reaches the critical pressure for shear slip along a fracture surface, the fracture surface wants to start sliding. At this point, asperities on the surface cause it to “catch”, thus preventing if from sliding. If an asperity is destroyed by increasing shear force because of an increase in pore-fluid pressure, the shear slip initiates around that asperity, where a part of the accumulated strain energy is released as elastic waves. The slip direction is controlled by the shearing stress on the fracture surface. However, the seismic source migrates in the direction of fluid flow and pressure propagation, because the injected fresh fluid intrudes into any permeable fractures in principle and flows through channels on the fracture surface. This fluid flow or pressure propagation triggers the shear slips at the asperities. Therefore, in the case of induced microseismic events, streaks originate from fluid migration along the fracture surface and are not related to slip direction.

5. CONCLUSION

The structural details inferred from the source locations of induced microseismic multiplets were examined as well as the similarity of waveforms. We found that the similarity of waveforms was not related to the amplitude of the microseismic events, and that the waveforms of some pairs or groups of events fit well with one another. We also showed that the source locations of multiplets reflect structural planes, and that streaks of source locations can be identified on the planes. The origin of the similar seismic events were considered the asperities on the same fracture plane, and the release of accumulated strain energy at each asperities due to increasing pore-fluid pressure around the asperity. Comparison of these streaks with the stress field shows that there is not related to the slip direction but to the direction of fluid migration which was estimated from well-logging data and source migration data for all microseismic events. This result shows that the streaks of source locations are not related to the direction of shear stress on the fracture and the streaks are related to the direction of pore-fluid flow and pressure propagation. The knowledge obtained through the analysis of induced multiplet gives us a hint to reveal the formation mechanism of permeable fracture system in geothermal reservoir.

ACKNOWLEDGEMENT

We thank Dr. K. F. Evans (ETH, Switzerland) and R. H. Jones (ABB-OS, UK) for providing us the data of source parameters and for detailed technical discussions. This work is carried out as a part of the MTC International Collaborative Project.

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