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STUDY OF MICROSEISMIC DOUBLET/MULTIPLET FOR EVALUATION OF SUBSURFACE FRACTURE SYSTEM IN SOULTZ HDR FIELD

Hirokazu Moriya[1], Katsuhiko Nakazato[1], Hiroaki Niitsuma[1] and Roy Baria[2]
1 Graduate School of Engineering, Tohoku University, Sendai, 980-8579 Japan
2 Socomine, Soultz-sous-Forets, France

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ABSTRACT

Reservoir structure of Soultz HDR field has been studied using doublet/multiplet. In this study, the reservoir structure characteristics are evaluated in detail using precise source location of induced microseismic doublet/multiplet, also the origin of multiplets is discussed. Microseismic events with similar waveforms have been corrected with the microseismic data set obtained during a hydraulic fracturing experiment in 1993, and the relative source locations have been determined by doublet analysis based on the cross spectrum analysis. The orientation of structural planes derived from hypocenter distributions of multiplets suggested that the dip angles of structural planes are changing with depth. The migration of seismic sources with time suggests that the doublet/multiplet tends to be located at the edge of the microseismic cloud.

INTRODUCTION

For several years, the reservoir structure of Soultz HDR field has been evaluated using microseismic source locations, which were determined using precise mapping methods i.e. collapsing method, clustering method and Joint Hypocentral Determination method (Phillips et al., 1997; Jones 1997). Currently, it is understood, from induced seismicity locations, that the fractures expand to the north-west and that the predominant direction of the reservoir structures varies with depth and location. The collapsing method has been applied to microseismic events in the whole area, while the other precise mapping methods have been applied only to some portions of microseismic swarms. A detailed evaluation of the reservoir structure has not been carried out.

Precise mapping methods using microseismic multiplets allow evaluating orientations of detailed structures because the orientation of individual fractures with similar sources can be estimated (Moriya et al., 1994; Tezuka and Niitsuma, 1996, 1997; Gaucher, et al., 1998). For instance in the Soultz field, Gaucher et al. (1998) analyzed the multiplets at a region near a well, and confirmed the consistency between the estimated structural planes and the intersected fractures in the wells. In this study, the reservoir structure in extensive regions of Soultz HDR field is evaluated by using multiplets, and the origin of multiplets is also investigated.

DETECTION OF DOUBLET/MULTIPLET

Microseismic activity was observed using three downhole 4-component detectors and one hydrophone. Figure 1 shows the source distribution of induced microseismicities. More than 10000 events (Fig. 1) have been analyzed to identify doublet/multiplets. Figure 2 shows an example of waveforms of a multiplet. The coherence function of all combinations of events has been calculated, the cross spectrum is calculated at P- and S-wave regions within the frequency range from 100 Hz to 150 Hz. Groups of events with coherency function above 0.8 are regarded as multiplets. As a result, a total of 550 groups, which include more than 4 similar events, are identified as multiplets.

DOUBLET/MULTIPLET RELOCATION AND ESTIMATION OF DETAILED RESERVOIR STRUCTURE

In order to relocate the multiplets, the moving window cross spectrum analysis has been applied to waveforms. The relative traveltime delays of P- and S-waves have been detected at 4 stations, and the relative source locations have been determined for each multiplet. Figures 3 and 4 show the source distribution of 44 multiplets before and after relocation. Figure 5 shows a small section from figure 4.

The re-picking of wave arrival times on cross spectrum analysis results in decreasing of residuals from 0.75 ms to 0.1 ms. A residual of 0.1 ms corresponds to an location uncertainty of less than 1 m. The principal direction of the error ellipsoid source distribution has not been consistent with the source distribution direction, and this result suggests that we can define the structures by using source distribution and migration. If the principal direction of error ellipsoid were the same as the direction of source distribution, the structure delineated from the source distribution would be unreliable.

The source distribution area decreases accordingly to the improvement of location error. The source locations at a depth of 2900 m are distributed in the 30 degrees dip direction (Figs. 4 and 5), and nearly vertically around 3000 m. In figure 5, small swarms are the sources of each multiplet, and the source distribution direction tends to be near vertical.

Considering that the location error in each event among the multiplet is not overlapped, we have calculated the planes derived from the source locations in order to estimate the orientation of structural planes. Figure 6 represents the pole of planes derived from the hypocenter distribution of each multiplet. The strike of the structural planes is oriented to northwest.

Figure 7 shows the relationship between strike and dip of structural planes with depth. The structural plane strike is oriented north-west as shown in previous mapping results, and dip is nearly vertical. It is clear that the dip of structural planes varies with depth. The structural planes for various dip values are estimated around 2900 m, which corresponds to the depth of fracturing point. The reason would be that the fractures with different orientation satisfied Coulomb's criteria due to the relatively high pore-pressure in fractures, and caused shear dislocation along these fracture surfaces. On the other hand, the increase of pore-pressure is small in fractures far from the feed point; therefore, only selected fractures with favorable orientation can satisfy the Coulomb's criteria for shear slip, and this would be a reason that only near vertical structures are detected far from the feed point.

ORIGIN OF DOUBLET/MULTIPLET

In Soultz, a large number of doublet/multiplets were observed. The incident of similar waveforms has been investigated the incidence of doublet/multiplet within each cubic region with side 200 m long, and we could find a tendency that many doublet/multiplets are observed near the edge of seismic swarm.

Figure 8 shows the source locations of a multiplet and other events observed before the initial times of the multiplet events, where the closed circle denotes source locations of a multiplet and dots represent the locations of other events that occurred before the multiplet. It can be seen in Fig. 8, that the multiplets are located at the borders of seismic swarms. This tendency has been observed for the other multiplets also. The tendency suggests that doublet/multiplet occurred under an initial condition before the disturbance of the stress field due to the fracture extension.

Events with similar waveforms would not be generated if background stress state and slip direction along the fault plane were different. Therefore, we can currently consider a hypothesis that doublet/multiplet is an expression of the stress release on the same fracture planes under the same stress state. This hypothesis seems to be correct according with the observation at several fields; then, it is possible to define not only structural planes but also stress fields.

CONCLUSIONS

The detailed structure of the Soultz HDR field has been defined using the study of doublet/multiplets in extensive regions of the reservoir. It has been suggested that the strike azimuth of the structural planes are NW-SE directions, and that the dip depends on the depths even though the nearly vertical planes predominate. Especially, at the fracturing point the dip varies from 45～90 degrees. Observation of source migration shows that doublet/multiplets occur at the edge of the seismic cloud.

The research on doublet/multiplet would allow evaluating the accurate distribution of fracture planes, and also the characteristics within and around the fractures such as regional stress field and fluid flow. It is necessary to clarify the origin of similar waveforms in order to interpret the physical properties of structural planes.

ACKNOWLEDGEMENTS

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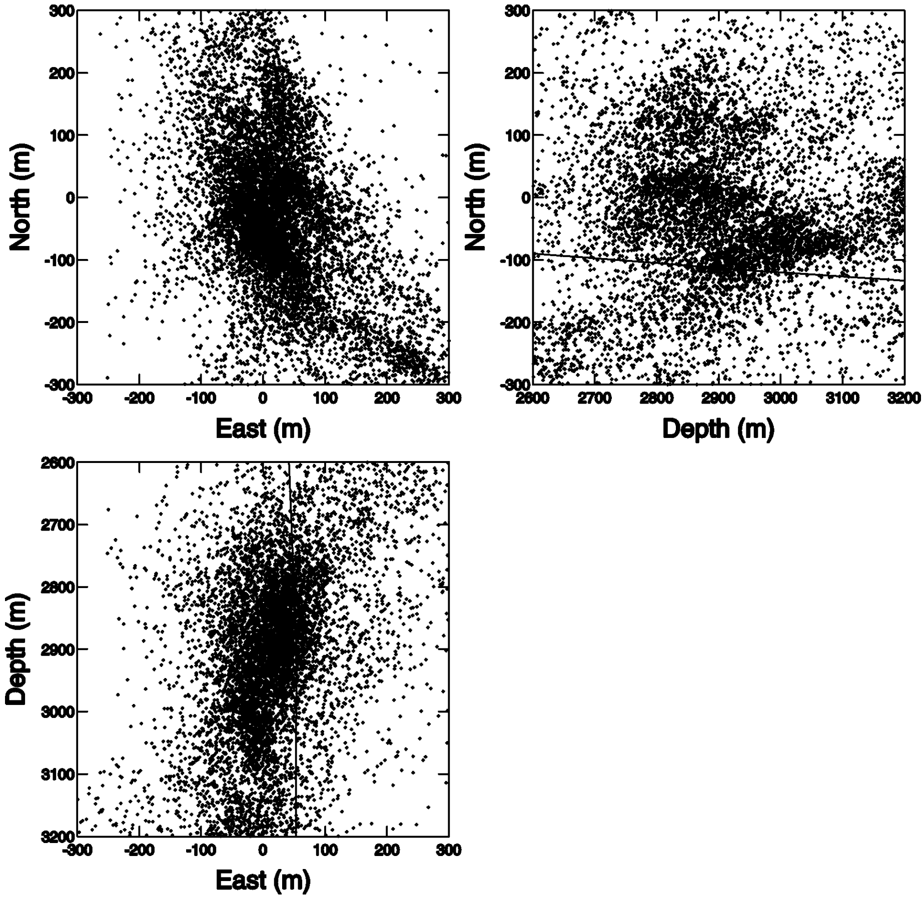


Figure 1. Source location of induced microseismicity by CSMA. P- and S-wave arrival time is determined manually. The line denotes well GPK-1.

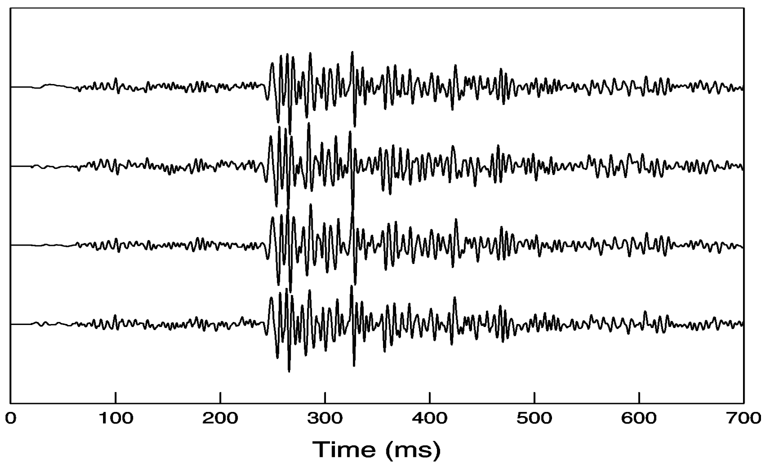


Figure 2. Example of multiplet waveforms. Their initial times are different.

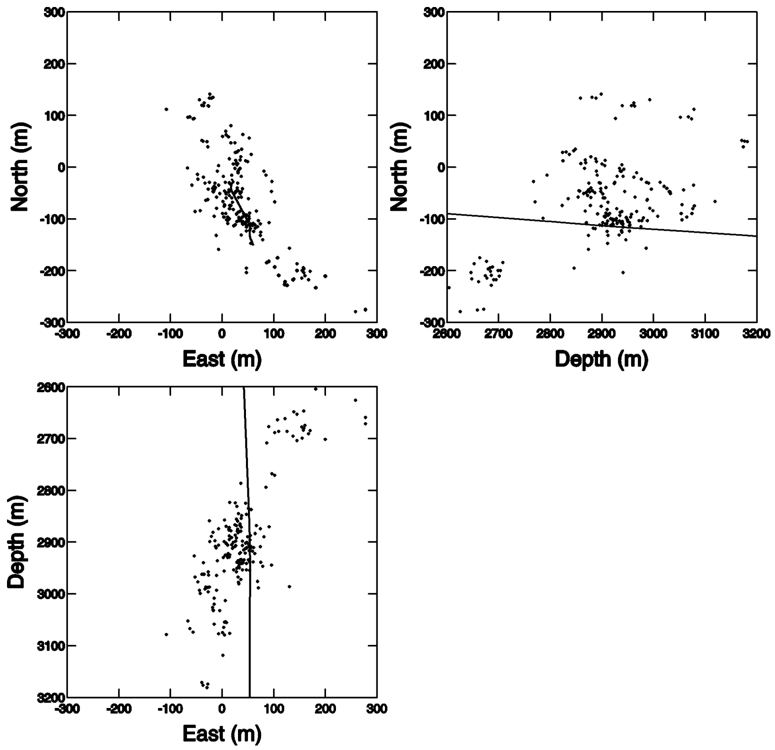


Figure 3. Source distribution of 44 multiplets before relocation.

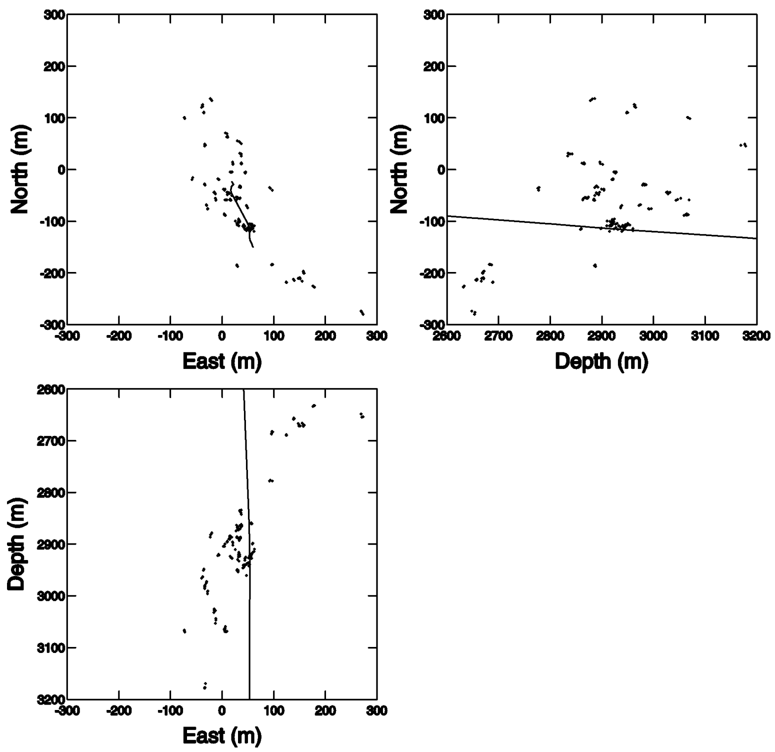


Figure 4. Source distribution of 44 multiplets after relocation.

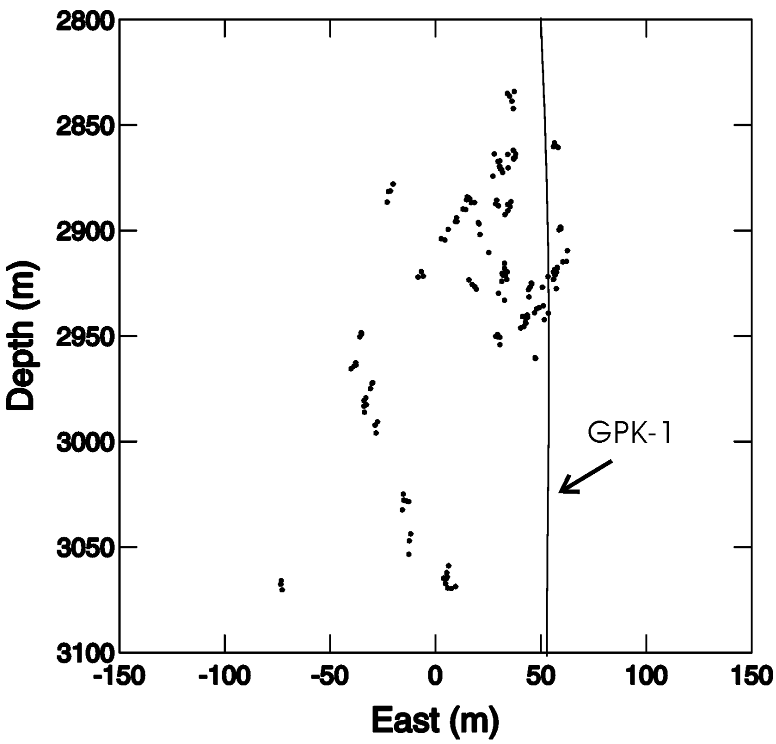


Figure 5. Source distribution of multiplets after relocation (enlargement of an area from figure 4). Each seismic cloud is the source location of each multiplet. The gravities of source Coordinates for each seismic cloud are the same to those before the relocation.

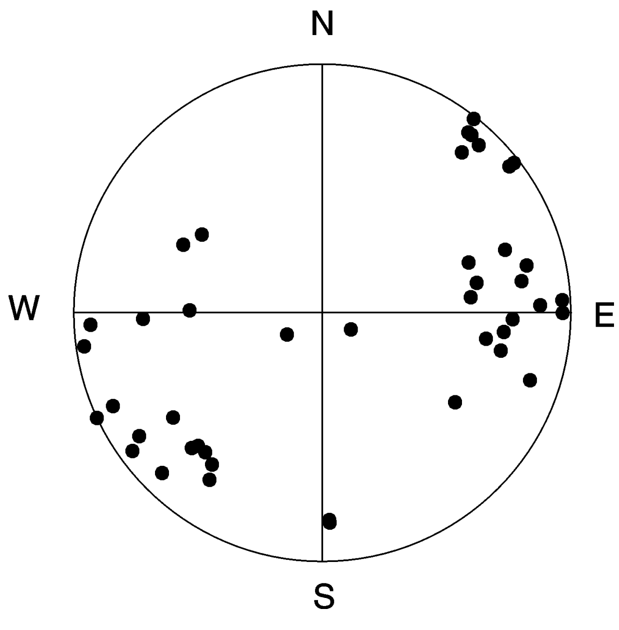
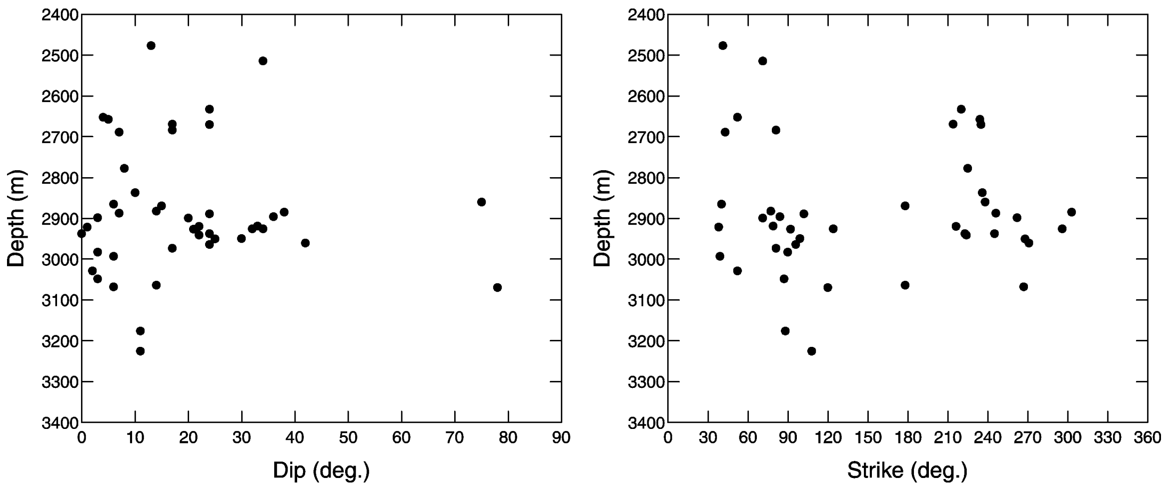
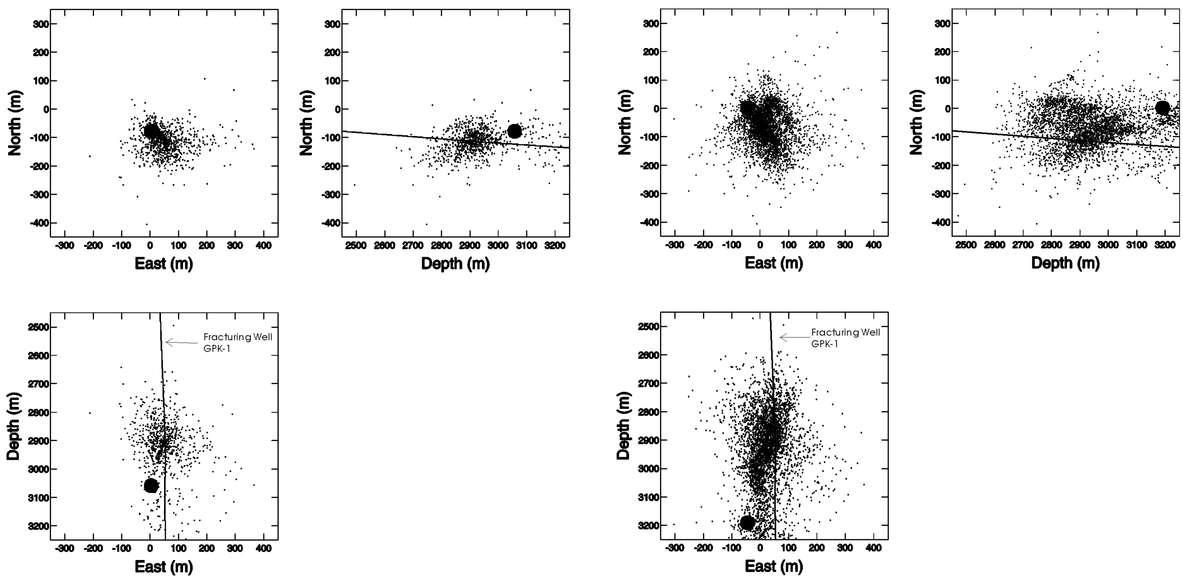


Figure 6. Poles of structural planes derived from 20 groups of multiplets (Lower hemisphere).



(a) (b)

Figure 7. Relationships between strike and dip of poles of structural planes with depths, where 0 degree corresponds north and 90 degrees is east.



(a) (b)

Figure 8. Source locations of a multiplet (closed circles) and other events (dots)observed before the initial times of the events in the multiplet. Two figures are the source distribution at different times. The differences of (a) and (b) is the occurrence times of multiplets. The multiplet in (a) occurred on an earlier stage of a hydraulic fracturing experiment.