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Interpretation of Reservoir Creation Process by Super-Resolution Mapping of Microseismic Multiplets Collected at Basel, Switzerland

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ABSTRACT

Microseismic multiplets, which are groups of events showing highly similar waveform despite different origin time and magnitude, can be effectively used to determine relative location of the hypocenters with high accuracy. The authors clustered multiplets from microseismic events collected during a hydraulic stimulation in the Deep Heat Mining Project at Basel, Switzerland in 2006. The similarity of waveform was quantitatively evaluated in the frequency domain using the magnitude square coherence function, and this made it possible to cluster the events with different criteria which correlate to different physical phenomena associated with shear slip on fractures. We then interpreted the behavior of each multiplet cluster from the orientation and size of the multiplet seismic structure, fault plane solution, source radius, and hydraulic record. Multiplets which correlate to (a) identical shear slip on a macroscopic single fracture or thin fracture network, (b) repeating slip within a microscopic fracture, and (c) extension of rupture zone on a microscopic fracture, are identified and their response to the stimulation was also interpreted.

1. INTRODUCTION

Geopower Basel AG with its operator Geothermal Explorers Ltd. (GEL) has been developing a co-generation system of electrical power and heating energy (3MW electric and 20MW thermal) around a city of Basel (Switzerland) since 1996. This is because Basel is located at the southern end of the Rhine Graben, which is widely regarded as one of the highest potential geothermal fields in Europe. A 5,000m total vertical depth (TVD) deep borehole (Basel-1) was drilled penetrating into granitic basement beyond 2,507m (TVD), and GEL made the first stimulation to enhance permeability in December 2006. They have a total amount of 11,500m^3 of fresh water over six days of stimulation operation (Häring et al., 2008) to the openhole section below 4629m (TVD). The project is currently suspended for risk analysis and investigation of suitable stimulation methods in urban areas because of the risk of developing seismic events with large magnitudes (Mukuhira et al., 2008).

Over 13,000 microseismic events were detected by a microseismic monitoring network which consists of 7 seismic monitoring stations in boreholes during and after the stimulation (until Feb., 2008), (Asanuma et al., 2007). It has been found that the collected signals had sufficient signal to noise ratio and bandwidth for processing in the frequency domain. Approximately 2,900 events were located by conventional single event determination (SED) and joint hypocenter determination (JHD) techniques. The resulting cloud of seismic hypocenters defined a thin (< 200 m) sub-vertical planar structure with an azimuth around NNW-SSE, which is consistent with the estimated stress orientation around Basel (Häring et al., 2008). The authors have found migration of the microseismic hypocenters associated with ongoing injected volume, and the presence of “aseismic” zones in the spatio-temporal distribution of the hypocenters (Asanuma et al., 2007). Researchers in Swill Seismological Service (SED) have found that the dominant source mechanisms determined for larger events were f strike-slip in character along NE or EW directions (Häring et al., 2008).

A group of microseismic events with high waveform similarity despite differences in the origin time and the magnitude can be found by observation of the traces of the events. Such a group of events is referred to as a “multiplet” and the events are considered to be related to identical shear slip on a fracture or neighboring sub-parallel fractures. Multiplet analysis is an integrated method that capitalizes on waveform similarity. The collected microseismic events are classified into multiplet clusters either by manual observation, or cross-correlation in time or frequency domains. The relative location of the events within a multiplet cluster can be determined with high resolution and reliability, because correlation-based techniques enable us to estimate relative time of arrival (TOA) among the multiplet events much more accurately than the ordinary used absolute TOA (Moriya et al., 2003, Waldhauser and Ellsworth, 2000, Kumano et al., 2006). The hypocenter distribution within a multiplet cluster often shows planar structure which might be correlated to a fracture/asperity where the events occur (Moriya et al., 2000). The focal mechanism of a multiplet cluster can be estimated by a composite focal mechanism analysis assuming that all the events within a cluster had the same focal mechanism.

The similarity of the waveform among the multiplet events is dependent on source function and the Green’s function. This suggests that events with various corner frequencies, which are normally correlated to the moment magnitude (Aki and Richards, 1980), may show lower similarity even though their focal mechanisms are identical and hypocenters are close. However, such frequency dependence of the similarity among the multiplets has not been investigated well in the previous studies (Michelet and Toksoz, 2007, Phillips, 2000). Therefore, it is expected that new information on the origin of the multiplets can be obtained by the identification of multiplet in the frequency domain.

It is necessary for the collected microseismic signals that the attenuation in the higher frequency range while propagation to the monitoring station is negligible around at the expected corner frequency. The sensing/recording system must be sufficiently wideband as well. Considering these restrictions on the frequency characteristics, we have decided to investigate frequency dependence of the multiplet clustering using a data set collected during a hydraulic stimulation in the Deep Heat Mining Project at Basel, Switzerland in 2006 (Asanuma et al., 2007). In this paper, we will show multiplet clustering in the frequency domain and interpret the physics behind the clustered multiplets.

2. OUTLINE OF DATA

The hydraulic stimulation was carried out by pumping a total of 11,500m^3 of water into a 5,000m (TVD) borehole (Basel-1) for over 6 days. The whole open-hole section (from 4,603m to 5,000m TVD) which included some pre-existing permeable zones was pressurized. The maximum wellhead pressure was around 30MPa at a flow rate of 50L/s.

The microseismic monitoring network consists of 6 permanent and 1 temporary seismometer station located in boreholes (Figure 1). During and after the stimulation (period until Feb. 2008), over 13,000 possible microseismic events were detected, and over 2,900 of these were located by conventional absolute mapping technique (Asanuma et al., 2007). Some seismic activity continued after this period. The distribution of the hypocenters determined by the single event determination (SED) method, one of the absolute location methods, is shown in Figure 2. The microseismic cloud showed sub-vertical planar structures with an azimuth of around NNW-SSE. This orientation is consistent with the known horizontal maximum stress direction around Basel. Dominant source mechanisms for some of the larger events were found to be strike-slip on N-S sub-vertical fractures (Deichmann et al., 2007). In the present study preliminary multiplet clustering and mapping using signals from different stations has revealed that most of the multiplets show sub-vertical structures with a NNW-SSE azimuth except for one vertical planar branch trending to the SE. After consideration of the signal to noise ratio, bandwidth, and radiation angle from the events in the microseismic cloud, we chose signals detected by one of the deep sensors in Riehen-2 (1,178m) for multiplet identification. The signals detected at Riehen-2 had power up to 200Hz, and a limited range of radiation angles from NNW-SSE trending vertical features because of the distance from the seismic cloud. It should be noted that some multiplet clusters from vertical fractures with an azimuth of ENE at the south end of the seismic cloud may have been missed by only using signals from Riehen-2, because one of the nodal planes of such multiplets is in a direction toward the Reihen-2 station. However, a preliminary study showed that such events are very rare case for this data. The first few cycles of the S wave were used to evaluate coda similarity, because the energy of the S wave was higher than that of the P wave due to the radiation pattern from a NNW-SSE sub-vertical fracture with a strike-slip mechanism.

3. IDENTIFICATION OF THE MULTIPLET CLUSTER

An example of the waveforms for different coherency to a reference event (top waveform) is shown in Figure 3. It is seen from the figure that though the presence of higher frequency components influence the coherency a similar envelope (low frequency component) can still be commonly seen. Power spectra for events with different moment magnitudes (Figure 4) show that the corner frequency, f_c, correlated to the magnitude for this data set because of its wideband nature. It is suggested from these results that the similarity of the waveform is correlated to the f_c, which is determined by the size of the ruptured area (source radius), and the hypocentral distance, as well as the focal mechanism. We, therefore, define the following two frequency criteria to evaluate the similarity of the waveforms:

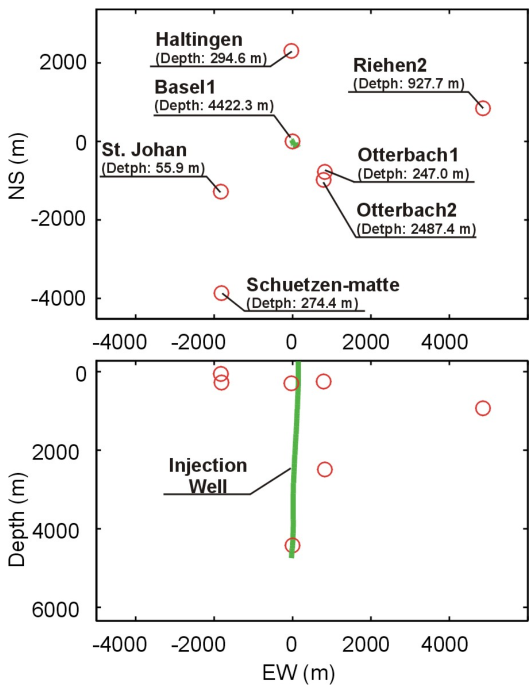

Figure 1: Microseismic monitoring network at Basel.

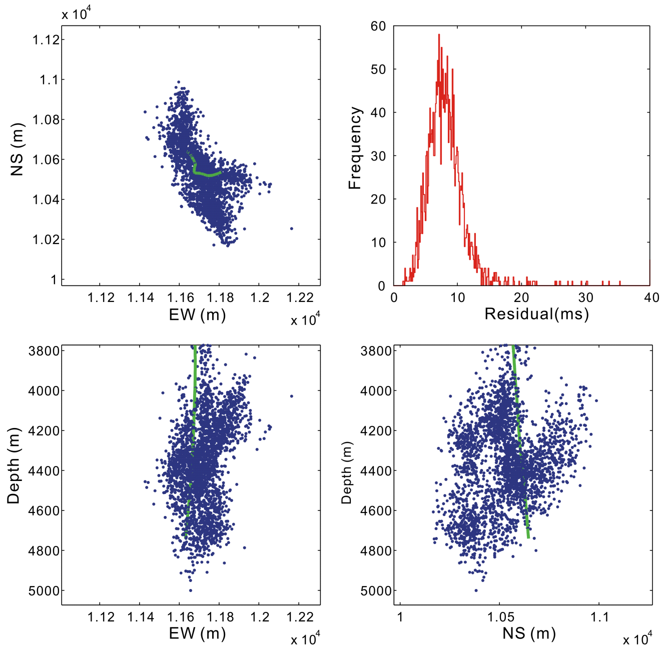

Figure 2: Distribution of hypocenters by single event determination (SED).

Criterion A (identification in low frequency): Similarity is evaluated around or less than the f_c of the event with the largest magnitude (1-40Hz in this study). Multiplets with identical focal mechanism are clustered, and where the source radius does not affect the clustering. The effect of the travel path does not strongly affect the clustering because the spatial variation of the Green's function is expected to be smaller in lower frequency as in this case.

Criterion B (identification in high frequency): Similarity is evaluated around the f_c of the event with the average magnitude (40-97Hz in this study). Multiplets with identical focal mechanism and source radius are clustered. Because of the spatial variation of the Green's function, multiplets within focused region are identified.

Using either criterion (A) or (B), we identified multiplet clusters within the approximately 2,900 events located by SED. Multiplet clusters were defined in this study to include any event which had a coherency above a threshold (in this study: 0.68) to any other event within the cluster. The results of the analysis using criteria A and B indicated that approximately 70% of all the located events belonged to a multiplet cluster. This is higher than that for a comparable data set collected at Soultz (Moriya et al., 2002). An example of waveforms for an identified multiplet cluster using criterion (B) (high frequency) is shown in Figure 5.

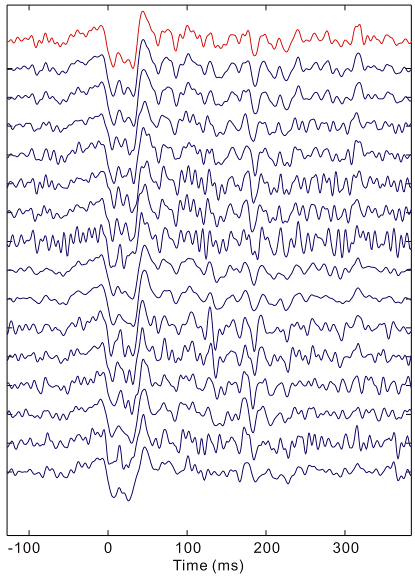

Figure 3: An example of the waveforms for different coherency to a reference event (top waveform)

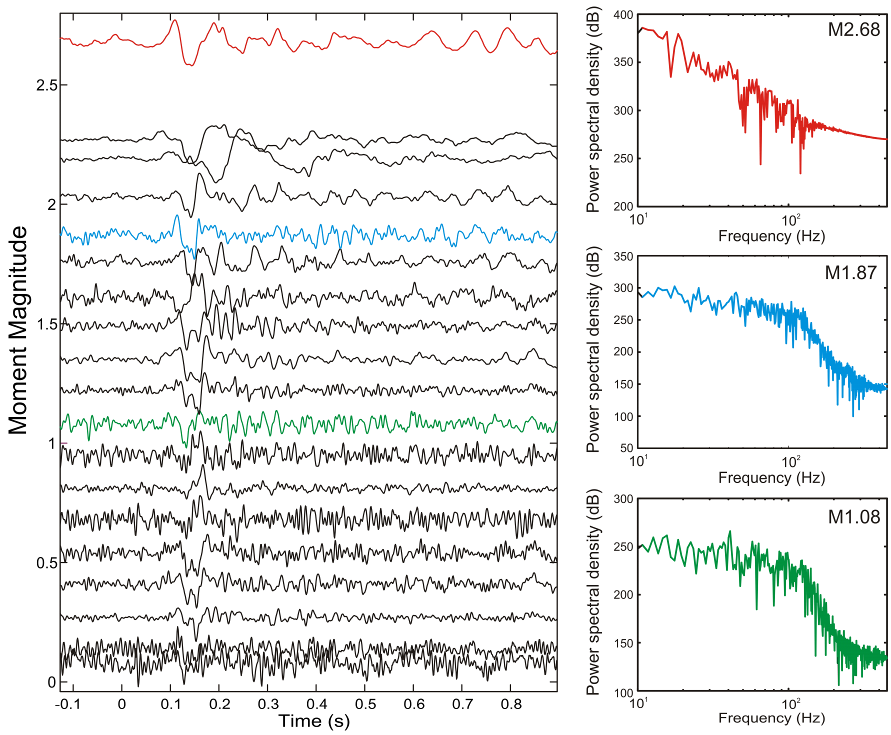

Figure 4: Waveform and power spectral density for events with different moment magnitude.

4. SPATIO-TEMPORAL DISTRIBUTION OF MULTIPLETS

We have estimated the relative location of events within each multiplet cluster by optimizing the double difference (DD) equation (Waldhauser and Ellsworth, 2000), which represents the relative time of arrival for all available pairs of multiplets within the cluster. The relative time of arrival was obtained by manually aligning the first peak of the seismic traces. The absolute location of each multiplet cluster was fixed to the center of gravity of the hypocenters determined by JHD, one of the conventional absolute location techniques. Vertical projections of the distributions of multiplet hypocenters are shown in Figures-6 and 7, where the color of the circles correlates to each multiplet group, the size of the circles indicates the estimated source radius, and grey dots show the hypocenters of uncorrelated (single) events. Figure 6 shows hypocenter distribution of multiplets identified using criterion (A) and Figure 7 is for (B). The multiplets identified in the lower frequency domain (criterion (A)) show large sub-vertical seismic structures up to 400m and heterogeneous source radii (10-100 m), while the multiplets identified in the high frequency domain (criterion (B)) show smaller sub-vertical seismic structures less than 200m and their source radii are more homogeneous. It is also noticeable that large multiplet clusters in the south part of the seismic cloud identified by criterion (A) are sub-clustered into smaller clusters applying the identification with criterion (B).

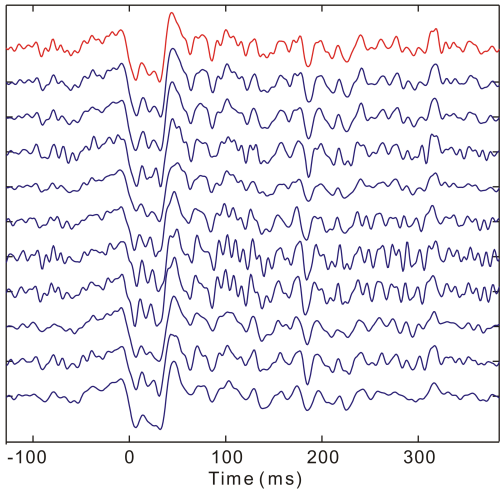

Figure 5: An example of waveforms for an identified multiplet cluster using criterion (B) (high frequency).

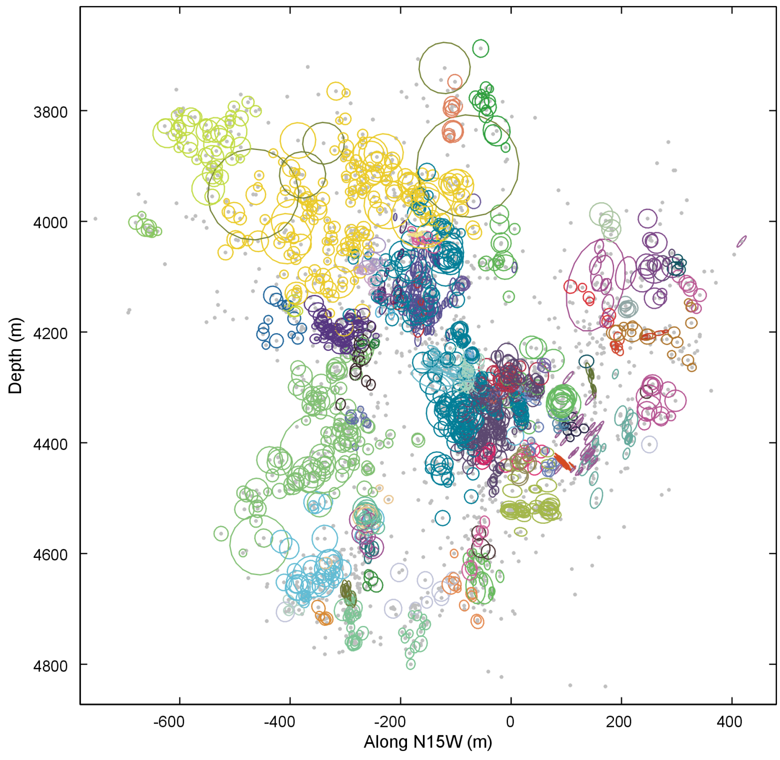

Figure 6: Hypocentral distribution of multiplets identified in the low frequency range. The color of the circles correlates to each multiplet group. The source radii are indicated by the circle sizes. Uncorrelated (single) event locations are shown in grey.

Origin time of each multiplet event identified by the criterion (A) and their distance from one of the dominant injection (feed) points is compared with hydraulic record in Figure 8. The following behaviors of the multiplets have been found.

(a) Migration of the multiplets from the feed point is seen,

(b) Occurrence of multiplet cluster is correlated to the change in the pumping rate,

(c) Multiplet events near the feed point continuously occur during the pumping and became inactive after bleed-off,

(d) Seismic activity of the multiplets distant from the feed point remained after bleed-off.

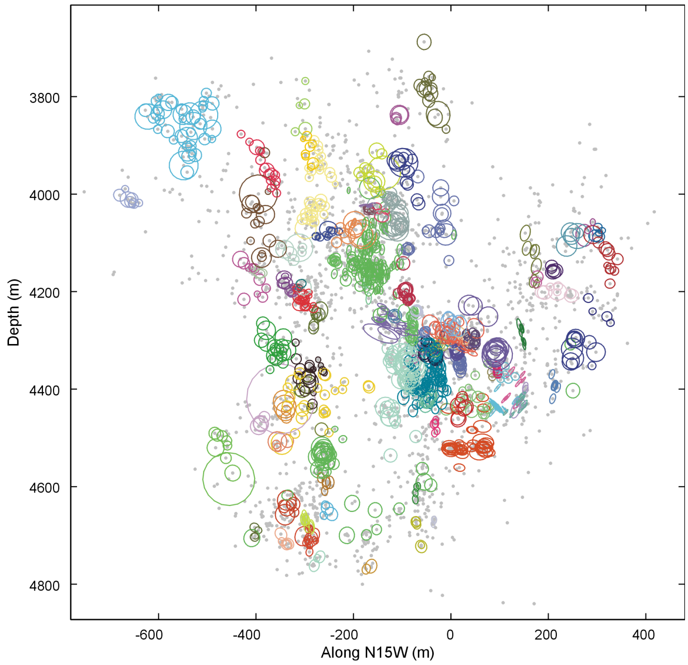

Figure 7: Hypocentral distribution of multiplets identified in high frequency range. The source radii are indicated by the circle sizes. Uncorrelated (single) event locations are shown in grey.

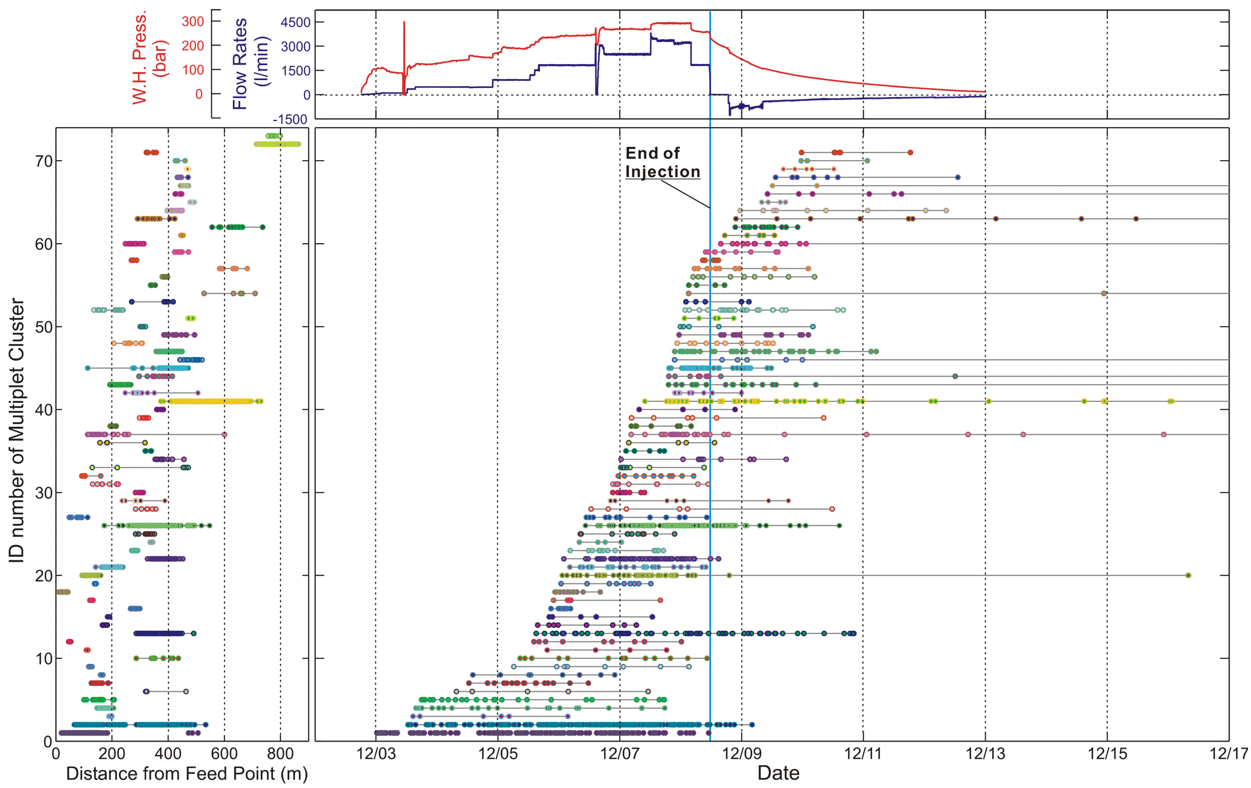

Figure 8: Occurrence of multiplets identified in low frequency. The referenced feed point has been identified at 4672 m (TVD).

We have evaluated the spatio-temporal distribution of multiplet events identified by criterion (B) (high frequency) as well as their source radii (Figures-9 and 10). In the figures the color of the source radius correlates to the order of the origin time of each event. In Figure 9 the source radii of the events overlap for the multiplet clusters near the feed point. However, multiplets distant from the feed point (Figure 10) show extension of the hypocenters to the far field and less overlap. Some of these far field clusters showed aseismic zones within. The orientation of the multiplet seismic structure identified by criterion (B) has also been evaluated by principal component analysis. This has revealed the presence of sub-vertical linear or planar structures within the macroscopic NNW-SSE seismic cloud with azimuths within ±30 degrees with respect to the direction of the maximum horizontal stress around the stimulated zone (N144±14°E) and the azimuth of pre-existing fractures (Häring et al., 2008).

From these observations, we have interpreted the physics behind the multiplets identified by two criteria as;

1) Multiplet clusters identified in the low frequency: The identical direction of shear slip on single/sub-parallel macroscopic pre-existing fracture is the origin of these multiplets. The size of the ruptured area is heterogeneous on the fracture correlating to the size of ruptured asperity. Repeated slip might occur where source radii of the multiplets overlap. An increase in the pore pressure associated with pumping caused migration of rupture area. The local concentration of pore pressure may made extension of the rupture area and repeated slip after bleed-off.

2) Multiplet clusters identified in high frequency: Two particular types of shear slip within a small area on the macroscopic fracture system generated these multiplets. One case is a repeating slip of a part of the fracture system. Such phenomena occurred mainly around the feed point where the pore pressure is sensitive to the change in the pumping rate and reduction of the friction on the fracture surface associated with water flow can be expected. The other case is a gradual rupture of one fracture. The migration of the hypocenters occurs in this case. Each fracture has an angle of around ±30 degrees to the maximum horizontal stress composing a mesh-like fracture network (Hill, 1977). Strike slips on these fractures might contribute to enhanced permeability along a vertical direction (Yeo et al., 1998). The role of these kinds of multiplets may be similar to those observed at Soultz (Evans et al., 2005).

Summarizing the two interpretations given above, it can be said that several sub-vertical fractures or thin fracture networks with an extension of 200-400m were mainly stimulated at Basel. Strike-slip was the dominant rupture mechanism and improvement of vertical permeability can be expected by break through of the asperities. Repeating slip occurred around the feed points.

Estimation of critical pore pressure for shear slip at each multiplet cluster (Moriya et al., 2005) was not carried out in this study, because information on the magnitude of tectonic stress around the stimulated zone was not available.

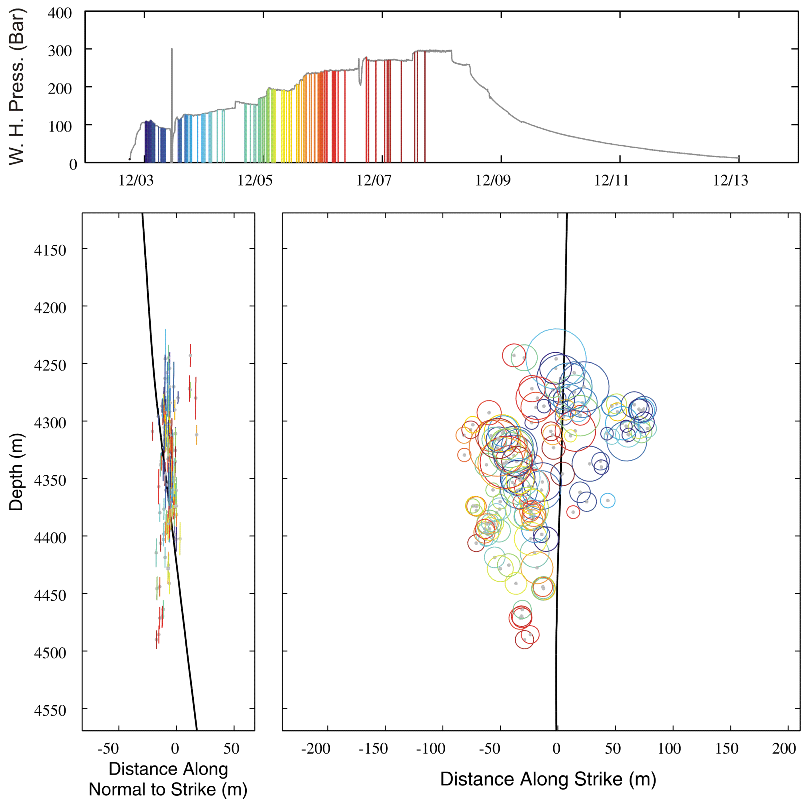

Figure 9: Hypocenter location and source radius of a cluster of multiplets identified in high frequency (repeating slip case). The hypocentral location of these multiplet clusters is close to the feed point at 4672 m (TVD) identified by a spinner flow log.

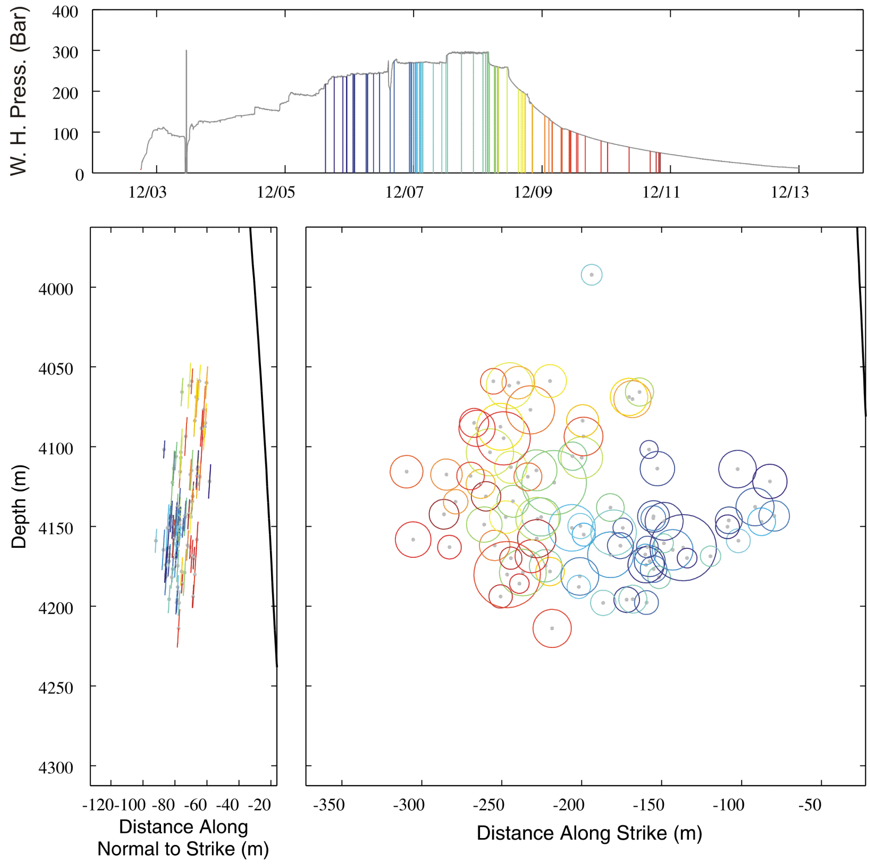

Figure 10: Hypocenter location and source radius of a cluster of multiplets identified in high frequency (rupture extension case). The clustered multiplets are distant from the identified feed point at 4672 m (TVD).

CONCLUSIONS

Physical phenomena related to multiplets were successfully interpreted in this study. Integrated analysis of the multiplets, where multiplet identification considering the corner frequency, spatio-temporal analysis of the hypocenter distribution, and estimation of source radius and fault plane solution, made it possible to estimate the underlying physics behind the multiplets. In the previous studies, multiplet identification was made only either in the lower frequency (Phillips, 2000) or in the higher frequency (Moriya et al., 2003, Michelet and Toksoz, 2007), and the relationship of multiplets defined by the different criteria has not been well established. We think physics of the multiplets have been more clearly demonstrated through this study. This kind of study can be undertaken only when the recorded signals have a wide bandwidth, showing the advantage of downhole microseismic monitoring. Although further investigation is needed, especially studies to clarify the relationship between multiplets and improved permeability, we have demonstrated that multiplet analysis plays a role in understanding the response of the reservoir during stimulation.

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