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Migration of Shut-in Pressure and its Effect to Occurrence of the Large Events at Basel Hydraulic Stimulation

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ABSTRACT

The occurrence of induced/triggered seismicity is recognized as a serious environmental burden associated with hydraulic stimulation at Enhanced Geothermal System (EGS) development. We have conducted physics based study for understanding the physical process of the large induced events. Our fundamental analysis on Basel microseismic data set investigated the characteristics of the large events and we have revealed that the several large events occurred just after the shut-in phase. Large events at shut-in phase has become interest of many scientists to understand behind the physics. We took geomechanical approach for this research topic and implemented research to understand the reason of occurrence of the large events at the shut-in phase. We analysed microseismicity at shat-in phase and revealed fundamental characteristics of shut-in events. Seismic cloud extended around 100 m even after shut-in phase and many events occurred at periphery of previously stimulated zone. Simultaneously, few seismic events occurred within the previously seismically activated region. We estimated pore pressure increase necessary for shear slip on the fault planes. The stress orientation and magnitude at Basel has been investigated and Fault Plane Solutions (FPS) of the large events were estimated by other research group. We compiled this information and calculated shear/normal stress working on the fault plane. Eventually we computed pore pressure increase using Coulomb failure criterion with constant friction coefficient of 0.85. Estimated pore pressure had acceptable value comparing wellhead pressure. Under the assumption that all seismic events were triggered only by pore pressure increase, pore pressure increase was migrated on hypocenters of the events in time series and space. We found pore pressure at the edge of seismic cloud increased higher than during stimulation and pressure gradient from injection well to outside of reservoir no longer existed after shut-in. We interpreted that this caused migration of shut-in pressure. Therefore, there should be causality between migration of pore pressure and occurrence of the large events. We, at the present, interpreted that the shut-in pressure penetrated most part of the fault plane of the larger events and large part of existing fracture of the larger events reached critical state. Finally, this caused large scale of shear slip, which was not able to occur during the stimulation due to pressure gradient.

1. INTRODUCTION

1.1 Background

Induced/triggered seismicity with unexpectedly large magnitude is one of serious problem to be solved within Enhanced Geothermal System (EGS) development accompanying hydraulic stimulation (Majer et al., 2007). Hydraulic stimulation is crucial technology to enhance permeability/productivity or to generate artificial geothermal reservoir. Information provided from microseismicity associated with hydraulic stimulation is essential as well to monitor process of stimulation and design geothermal production system. Therefore, there is urgent need for development of method based on scientific knowledge to prevent the seismic hazard. In order to access seismic risk by large induced seismicity, traffic light system has been introduced into hydraulic stimulation operation process. However, we unfortunately found that operation to reduce seismic rate followed by traffic light system in case of Basel was not able to reduce seismic activity, resulting occurrence of maximum events with M_L 3.4 (Häring et al., 2008). This fact indicated that we still have not controlled induced seismicity for engineering usage and have not reached total understanding of physical mechanism behind the large induced seismicity. As the Basel case, the occurrence of larger events after shut-in or stop of injection operation were empirically known and reported from several EGS/HDR project (e.g. Soultz, Cooper Basin, Basel: Charléty et al., 2007; Asanuma et al., 2005; Häring et al., 2008 respectively). However, we have not investigated detailed characteristic and have not proposed even the conceptual model on physical mechanism of them. Recently, McClure (2015) attempted to investigate the mechanism behind shut-in event using their well established simulator and found that backflow from dead end fault come through into the larger fractures can be responsible for cause of larger induced seismicity after shut-in. We took observational approach based on analysis of microseismicity and investigate fundamental characteristics of large events in shut-in phase. Then, we researched causality between migration of shut-in pressure inferred from microseismic and stress information, and occurrence of large induced seismicity.

1.2 Outline of hydraulic stimulation at Basel

Geothermal Explorers Ltd. (GEL) drilled the Basel-1 injection well (depth 5 km) in an urban area into crystalline basement rock (GEL is current Geo Explorers Ltd.). Hydraulic stimulation was then conducted in lowermost section of Basel-1 in December 2006. The injected water stimulated several existing fractures in open-hole section. A total of 11,500 m^3 of fresh water had been injected over 6 days. The maximum wellhead pressure was about 30 MPa at flow rate of 50 L/s (Häring et al., 2008). In December 8th, 6th day from start of stimulation, first felt event with M_L 2.6 occurred. This event's magnitude was higher than criterion of traffic light system for Basel and this requested reduction of flow rate. As seismic activity did not cease even after flow rate drop, GEL decided to shut-in well finally. In consequence, just after several hours of shut-in, M_L 3.4; the largest event followed another M_L 2.7. Then, GEL opened well again which allowed injected fluid flow back from underground (Häring et al., 2008). After this operation, seismic activity declined quickly but seismic network still detected several events till two months after stimulation (Häring et al., 2008), and some events were detected even in 2015 (Deichmann et al., 2014). Time profile of hydraulic stimulation and magnitude history are shown in Figure 1 with one dimensional seismic cloud growth and time series extension in depth. A series of large induced seismicity were felt by local residents and caused slight damage on buildings in Basel city. After risk analysis of further induced earthquake (Baisch et al., 2009), Basel EGS project was finally cancelled (Häring et al., 2008).

2. DATA AND METHODOLOGY

2.1 Geophysical data used in this study

2.1.1Microseismicity

The well-designed seismic monitoring system consisted of 6 permanent seismometers in boreholes and 1 temporary seismometer in the injection well were operated for microseismic monitoring and microseismic activity was continuously monitored for at least half year. By February 2007, more than 13,000 seismic events were detected. Asanuma et al. (2007) determined the hypocenter locations of about 2,900 seismic events with conventional absolute hypocenter determination method and spatial error of hypocenter determination was several ten meter. The hypocenter distribution of the seismic events delineated a sub-vertical planar seismic cloud with a strike of about NWN-SES showing consistency with the regional stress state at Basel. Asanuma et al. (2008) relocated hypocenters for several events using the multiplet analysis technique (Moriya et al., 2003) and the double difference method (Waldhause and Ellsworth, 2000). They discovered that the stimulated reservoir at Basel consisted of a sub-vertical linear or planar structure. Figure 2 shows hypocenter distribution of microseismicity at Basel.

We used moment magnitude (M_w) estimated from amplitude of P wave recorded at the deepest station, which is equivalent to M_w in Dyer et al. (2010). We have to mention that several research group working for Basel data set had their own catalog and estimated own M_w for Basel microseismic data, which sometimes lead misunderstanding between them. Swiss Seismological Service (SED)/ETH also estimated M_w (e.g. Bethmann et al., 2011) as well as M_L which is the most common magnitude scale for Basel. Our M_w (Dyer's M_w) are not identical completely with SED M_w. After all, the largest magnitude in our M_w was 3.51 which is relevant of 3.4 in M_L.

2.1.2 Stress information

Valley and Evans (2006, 2009) analyzed the orientation of breakouts and drilling-induced tensile fractures in injection well (Basel-1) and the deepest monitoring well and reported that orientation of the maximum horizontal stress (S_{Hmax}), within the granite section at Basel is N144◦E±14◦. Their estimation is consistent with the focal mechanism of natural earthquakes in this region and larger events occurred by hydraulic stimulation. The magnitude of vertical stress (S_v) has previously been estimated from density logs and the magnitude of horizontal stress has also been estimated from core samples (Häring et al., 2008), which our previous study of Mukuhira et al. (2013) used. Valley and Evans (2015) newly reported stress magnitude inferred from borehole breakout width analysis. Summarizing these stress magnitude information, our best stress model is given by equation (1) ~ (4). According to the updated stress state, S_{Hmax} can be modeled as small gradient function of depth. meaning that stress state transits strike slip to normal faulting at around 4800 m depth because differential stress decreases with depth and S_v becomes larger than S_{Hmax} at that depth. This updated stress state also shows consistency with the observation that several large events have normal fault mechanism (Deichmann and Giardini, 2009).

$$S_{HMmax} = 0.00104z + 115 \tag{1}$$

$$S_{hmin} = 0.01990z - 17.78 \tag{2}$$

$$S_v = 0.0249z \tag{3}$$

$$P_h = 0.00981z \tag{4}$$

where S_{Hmax} is maximum horizontal stress, S_{hmin} is maximum horizontal stress, S_v is vertical stress, P_h is hydrostatic pressure, and z is depth respectively. Units for all parameters here are MPa.

2.1.3 Focal mechanism

Fault plane solutions (FPSs) for 28 larger events were estimated by Deichmann and Giardini (2009), using polarity information of first motion from SED monitoring network as well as microseismic network deployed by GEL. Many of FPSs showed strike slip type focal mechanism. Terakawa et al. (2012) showed more FPSs for total 118 events which were provided from SED. We used these FPS information for larger events. Catalog of SED which Deichmann and Giardini (2009) and Terakawa et al. (2012) were based on, was not identical with our microseismic catalog which basically provided by GEL. We identified events with FPS in our catalog by their trigger time. Then, we found 95/118 events in our catalog and used our hypocenter location for further study.

For many of other events which their fault mechanisms were not estimated due to their small magnitude, we used result of multiplet analysis. Many of multiplet cluster in this field showed ellipsoidal or streak geometry (Asanuma et al., 2008). So, we estimated geometry of multiplet cluster from hypocenter distribution of multplet events and used as orientation of fault plane under the assumption that multiplet event in one cluster occurred from same existing fracture. Reliability of fault plane orientation of multiplet events was much lower than fault mechanism for 118 stronger events, since results were highly effected by identification of multiplet events and their hypocenter distribution.

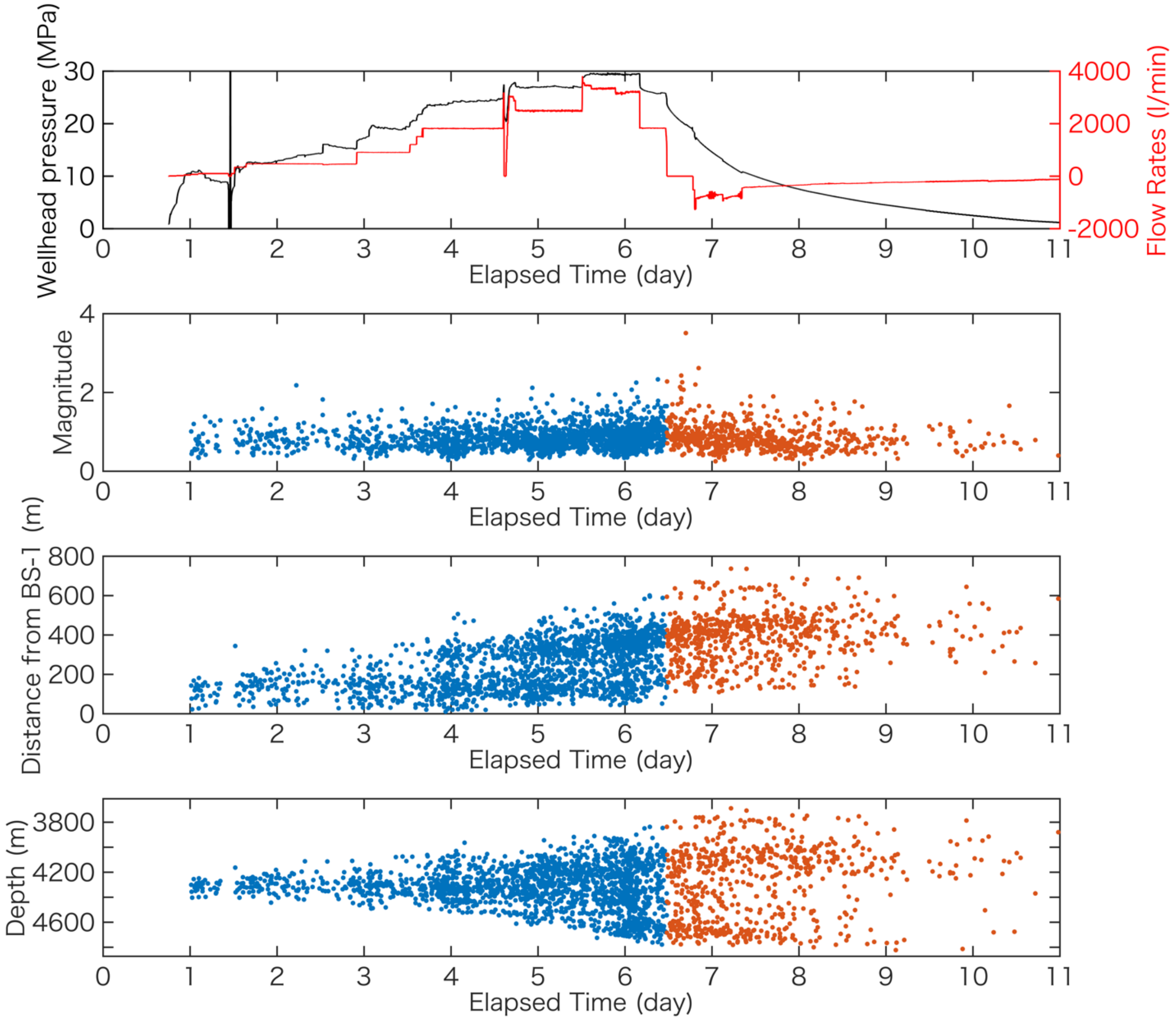

Figure 1: Wellhead pressure (black line) and flow rates (red line) profile of hydraulic stimulation at Basel, comparing fundamental characteristics of induced seismicity in time series. Magnitude history, distance from estimated injection point, and depth distribution of microseismic events. Color changed at time of shut-in. In this scale, depth is from sea level.

2.2 Estimation of pore pressure increase

When stress orientation and stress magnitude, and geometry of fault plane are available, shear/normal stress working on given fault plane can be computed with geomechanical theory. Then, friction coefficient is given, necessary pore pressure increase to have shear slip is estimated by Coulomb failure criterion:

$$\tau = \mu(\sigma_n - P_h - P_c) \tag{5}$$

where τ is shear stress, μ is friction coefficient, σ_n is normal stress, and P_c is pore pressure increase to have shear slip.

In the process of pore pressure estimation, we have several assumptions. First one is a homogeneous stress state in the reservoir in time and space, meaning that stress state can be expressed by stress model of Valley and Evans (2015) as function of depth. The assumption of homogeneous stress state has been reasonably well accepted for interpretation and modeling of EGS reservoirs as first approximation (e.g. Ito and Hayashi, 2003; Moriya et al., 2005). Observation that orientation of multiplet seismic structure did not change significantly with horizontal location also supports this assumption. As well as homogeneous stress model, heterogeneity of elastic property is not also considered for simplicity. As a second assumptions we used constant friction coefficient of 0.85 (Byerlee, 1978) for all fault planes.

In this analysis, we considered that all induced seismicity was triggered only by increase of pore pressure, meaning that effect of other parameter such as coulomb stress change by preceding events, nucleation of thermal stress caused by cold water injection, and chemical effect on friction coefficient were not considered here.

It should be mentioned that selection of actually slipped fault plane from two nodal planes of FPSs. In our previous study like Mukuhira et al. (2013), we chose one of the fault plane requiring lower pore pressure increase to have shear slip as actually slipped nodal plane. But in this study, we compared three dimensional geometry of both nodal planes and hypocenter distribution of periphery events for every single larger events and then one having harmonious geometry with neighboring events was chosen.

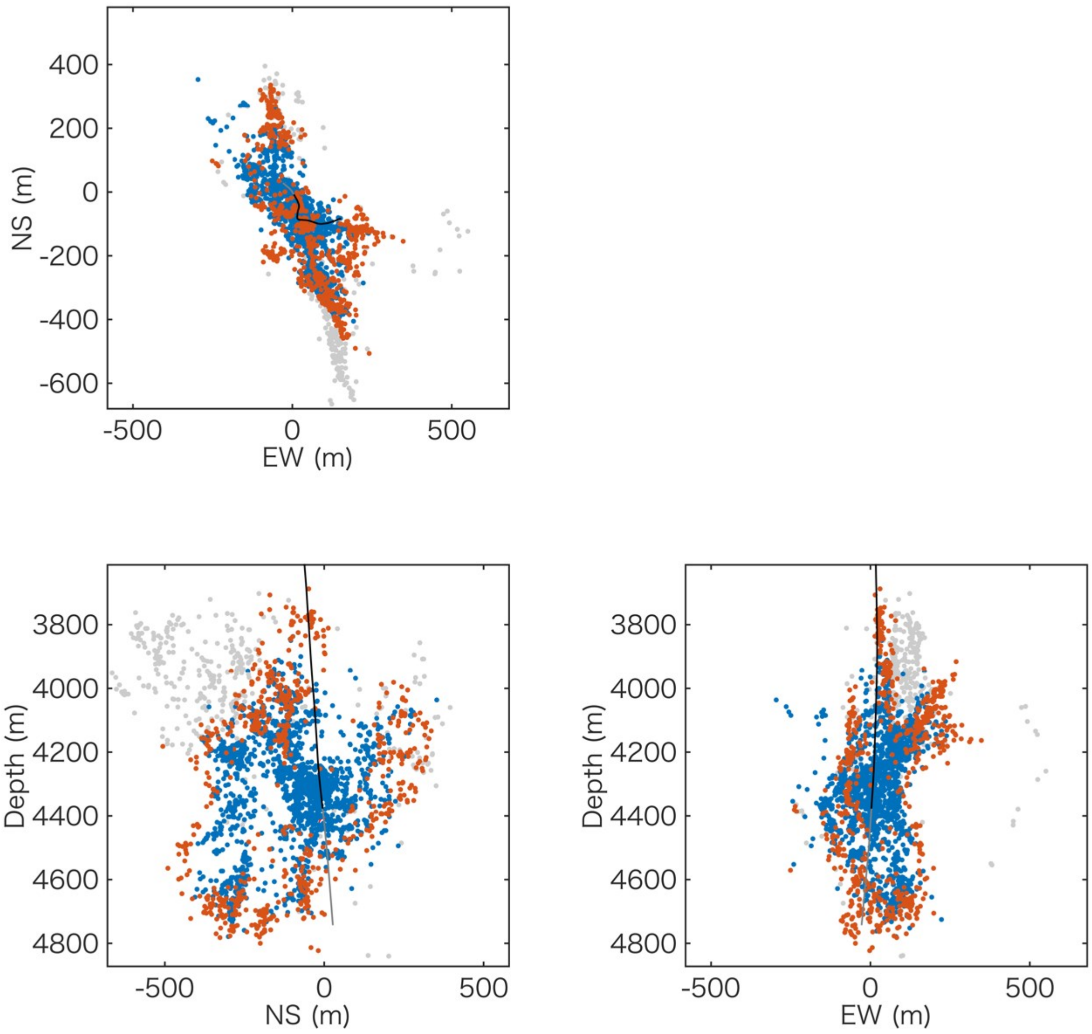

Figure 2: Hypocenter distribution of microseismic events. Hypocenters were determined with double difference method for multiplet events and conventional joint hypocenter determination method (JHD) for non-multiplet events. Color of dots correlates events during/after shut-in as previous Figure. Black line indicates injection well of Basel-1 and gray parts is open hole section. In this scale, depth is from sea level.

3. RESULTS AND DISCUSSION

3.1 Fundamental characteristics of shut-in events

Difference in magnitude history, distance from estimated feed point, depth distribution, and hypocenter distribution between events occurred during stimulation and after shut-in were compared in Figures 1 and 2. Several larger events with M_W>2.0 occurred significantly within half day after shut-in. This concentrative occurrence of larger events can not be observed any other part of stimulation, suggesting that there should be some causality between shut-in and occurrence of large events. One dimensional migration of event distance from injection well shows that seismic cloud has been expanding till 9th day of stimulation. This can be the evidence of propagation of high pore pressure even after several days of shut-in and that pore pressure remained high enough to trigger shear slip on existing fracture, if these events after shut-in were induced only by pore pressure increase. From depth migration of microseismic events, we can see seismic cloud progressed to shallower and deeper direction after shut-in and few events occurred after shut-in from middle part of the reservoir around 4200~4400 m where estimated feed point located. The observations from Figure 1 is explained in detail by Figure 2. It is quite significantly observed from cross sectional panels in Figure 2 that events after shut-in located periphery of activated zone during stimulation. We clearly observed that seismic events did not occur within previously activated zone around near field of injection well, and that seismic cloud extended externally by occurrence of many seismic events at the edge of seismic cloud. It is also observed that there were two no-negligible areas where many of shut-in events located at deep part (NS: -400~-200 m, Depth: 4600~4800 m) and shallow part (NS: -300~0 m, Depth: 4000~4200 m). Actually, several larger events occurred from these area, which should be investigated further in future study (partly observed in Figure 5).

3.2 Critical pore pressure

Estimated pore pressure increase is plotted in time series in Figure 3 with wellhead pressure. Pore pressure increase shown with circles based on FPS by SED was estimated to be at least lower than maximum wellhead pressure of 29.6 MPa. This is reasonable result and suggesting our assumptions and input data were also acceptable. There were several events with pore pressure increase larger than wellhead pressure during hydraulic stimulation shown in red line in Figure 3. It is generally accepted that pore pressure does not excess wellhead pressure unless flow path is isolated or formation permeability was quite low respect to injected volume. These unusually high pore pressure increase may be artifact due to uncertainty in stress orientation/magnitude, geometry of fault plane, anomaly of elastic property and friction of coefficient. After shut-in, wellhead pressure decreased with time exponentially and returned almost hydrostatic state at the end of 11th day from start of stimulation. There were also several events occurred under higher pore pressure increase than wellhead pressure after shut-in. In shat-in phase, high pore pressure in the well still remained higher than hydrostatic condition even though pressure source no longer exist. After shut-in, friction due to pressure gradient disappeared (Zoback, 2007) and pore pressure still propagate according to permeability of reservoir. For the pore pressure estimated from geometry of multiplet cluster, i.e. seismic events whose FPSs were not estimated, their pore pressure increase had various range from 5~70 MPa. Majority of them were under wellhead pressure which is reasonable, but some of these events had unrealistically high pore pressure increase which should be result of ridiculous estimates of geometry of multiplet cluster. So, we decided to use events which had pore pressure increase lower than maximum wellhead pressure of 29.6 MPa, based on geomechanical theory.

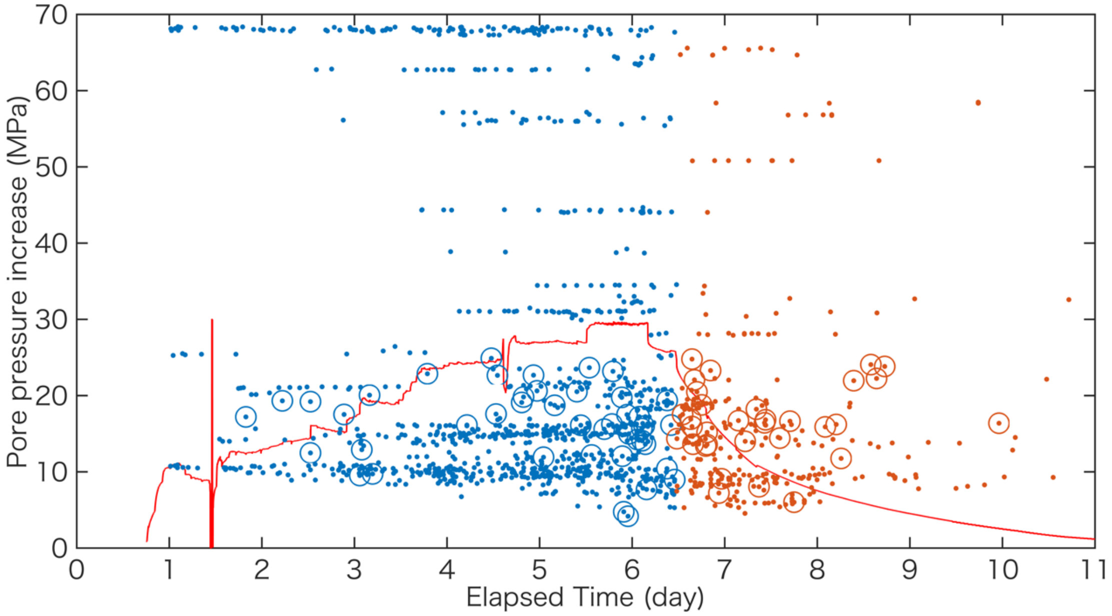

Figure 3: Estimated pore pressure increase as function of time comparing wellhead pressure (red line). Dots with circles indicates events which their pore pressure increase was estimated from FPS estimated by SED. Dots were events whose pore pressure increase was estimated by multiplet cluster analysis. Color of dots and circles change at the shut-in time.

3.3 Shut-in pressure

One dimensional migration of pore pressure increase before/after shut-in were compared in Figure 4. Pore pressure increase based on FPSs shows that pore pressure reached 15 MPa at 500 m apart from injection well during stimulation. Pore pressure from multiplet analysis also suggest it reached 10 MPa at 600 m apart from the injection well. In closer region to the injection well of around 200 m, pore pressure had risen 25 MPa which is almost similar to maximum wellhead pressure of 29.6 MPa. We observed that pore pressure increase decreased with distance from feed point as general trend in pore pressure increase. This is quite reasonable observation.

Because of pressure source, there should be flow resistance throughout flow path and, friction caused pressure loss with distance of flow path resulting pressure gradient.

On the other hand, in case of shut-in phase, high pore pressure increase propagated further. In the region 400~500 m distance from injection well, pore pressure increased around 25 MPa that is 10 MPa increase in pore pressure, though pore pressure was at the most 15 MPa during stimulation. In terms of distance, high pore pressure of around 22 MPa penetrated in the area of 600 apart from injection well. The area from 400~600 m where corresponds the deep and shallow edge of already stimulated zone were mainly pressurized by propagation of shut-in pressure. It is surprisingly observed that, propagation of shut-in pressure brought pore pressure increase of around 20 MPa at the edge of seismic cloud. In closer area to injection well (~300 m), seismic activity has ceased but several events occurred under moderate pore pressure increase of 13~18 MPa. Only from Figure 4, it was not clear where these events occurred. From Figure 2, we could expect they occurred from edge of seismic cloud in middle of reservoir. Pressure gradient from injection well to periphery of stimulated zone observed during stimulation disappeared after shut-in. Pore pressure distributed randomly after shut-in or it showed homogeneous-like distribution.

In Figure 5, pore pressure increase was projected on hypocenter distribution before and after shut-in. As observed in Figure 2, events induced in shut-in phase located in periphery of seismic cloud and several of them had large magnitude which were also observed in Figure 1. At every part where shut-in events occurred, we observed progress of seismic zone which was already seen in one dimensional hypocenter distribution in Figure 4. We newly observed in Figure 5 that larger events significantly occurred at the edge of previously stimulated zone and that they were triggered by 10~20 MPa increase of pore pressure. Some larger events which occurred shallow and deep edge of seismic cloud, were induced by relatively higher pore pressure than 20 MPa.

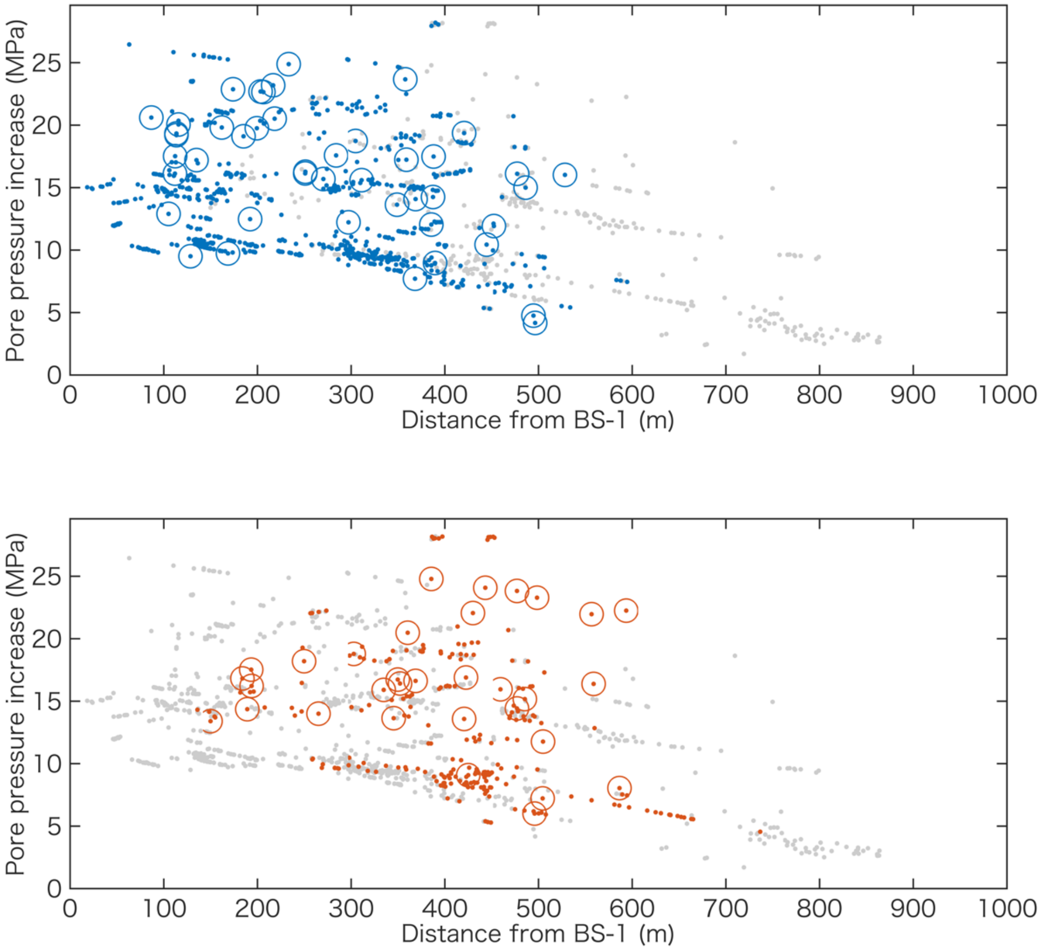

Figure 4: One dimensional distribution of pore pressure increase for events occurred during stimulation (Top) or after shut-in (down). Reference point is estimated feed point in injection well Basel-1. Dots with circles indicates events with FPSs and only dots were events of multiplet cluster analysis.

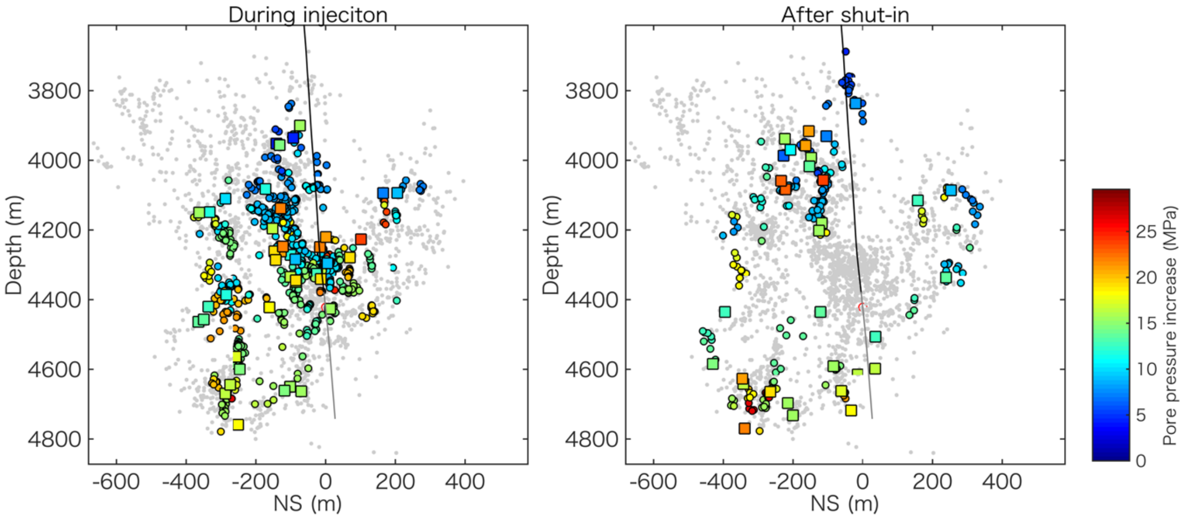

Figure 4: Pore pressure distribution on hypocenter distribution before and after shut-in. Squares correlates the events which their pore pressure increase were estimated from FPSs and dots were those estimated from multiplet analysis. Color correlates pore pressure increase scaled from 0 to maximum wellhead pressure (29.6 MPa).

3.4 Discussion

Only from the fundamental analysis of events migration in magnitude, time, and space, we found characteristics of shut-in events. Seismic cloud extended around 100 m at the edge of seismic cloud especially deep and shallow part of reservoir and seismic cloud had been extending for more than two days after shut-in. Among the events occurred after shut-in, there were significantly number of large events including the largest event from deep part of seismic could. When our basic assumptions behind this study that all seismicity in study period were induced by increase of pore pressure, pore pressure migration associated with shut-in was responsible for these observation and we can investigate behavior of shut-in pressure migration and its contribution to occurrence of larger events by tracking pore pressure increase.

Even though there are several assumptions and uncertainties in process of estimation of pore pressure increase, we could have reasonable value of pore pressure increase. This is because pore pressure increase estimated from FPSs were lower than maximum wellhead pressure. Pore pressure increase for several events during stimulation had higher value than wellhead pressure at the time. This can be artifact since it is generally difficult to exceed wellhead pressure in permeable formation. Even if permeability in part of reservoir was significantly low, there should be other connected flow path which release concentration of pressure. On the other hand, pore pressure increase after shut-in exceeded wellhead pressure. At the moment of shut-in, pressure/volume feeding from pump disappeared, which disappear flow resistance. Then, high pressure in the well or vicinity of injection well is released and migrate to far field according to permeability or connectivity of flow path. How pore pressure migrate is the problem between reservoir permeability (enhanced permeability) and amount of higher pore pressure injected into the reservoir. Higher pressure migrates and eventually becomes hydrostatic condition. In this relaxation process, pore pressure at some part of reservoir can temporarily exceed than that during stimulation. Therefore, it is not impossible for pore pressure to increase or higher than wellhead pressure after shut-in. Indeed, pore pressure increase estimated in this study still have plenty room of discussion for their quantitative reliability. However, we think their value is enough reliable to discuss over all behavior of shut-in pressure and causality to occurrence of large events qualitatively.

From pore pressure migration shown in Figure 4 and Figure 5, it is suggested by extension of seismic cloud that pore pressure at the shut-in phase migrated 100 m at the most and that pore pressure migration by shut-in brought significant pore pressure increase of around 10 MPa higher than that during stimulation. Figure 4 shows that distribution of pore pressure increase decrease as function of distance from injection well during stimulation and after shut-in, this pressure gradient disappeared or decreased because of stop of stimulation. As a result, high pore pressure vicinity of injection well transmitted to periphery of the stimulated zone. We interpreted that this cause pore pressure increase and occurrence of seismic events significantly in shut-in phase. Therefore, edge of previously stimulated area can be “hot zone” after shut-in phase in terms number and magnitude of seismic events, especially deep and shallow part of reservoir in case of Basel.

Only the increase in pore pressure can not explain the reason why occurrence of large events concentrated at after shut-in and in edge of seismic zone. Considering pore pressure distribution after shut-in of Figure 4, there was no longer pressure gradient with distance. In addition to this, in hot zone of 400~600 m apart from injection well, pore pressure increase distributed evenly or it had very small gradient to distance. During stimulation, there would be somehow pressure gradient in one big fracture which made one part of fracture critical state resulting moderate magnitude events. After shut-in, these should be almost homogeneous pressure distribution in one big fracture which made most part of fracture critical state resulting larger scale of shear slip of large events, if pore pressure in given fracture was critical level to overcome shear strength. This is our conceptual model based on analysis or observation of this study.

Progress of seismic cloud after shut-in was especially observed at deep or shallow edge of current seismic cloud. This observation suggest that shut-in pressure propagated mainly to upward and downward directions. To explain this phenomena, there should be high permeable flow path. Considering strike slip stress state in this field except very deep part of reservoir and many strike slip type FPSs were observed, many seismic events were caused by horizontal direction of shear slip on existing vertical fracture. This phenomenon finally caused permeability enhancement especially vertical direction as shear displacement enhances permeability perpendicular to the direction of shear displacement (Yao et al., 1998). This assumption can explain progress of seismic cloud after shut-in in deep and shallow edge, and further more thin vertical seismic cloud at Basel EGS reservoir.

5. CONCLUSIONS

We investigated behavior of migration of pore pressure at shut-in phase and their effect to occurrence of large induced seismicity. Microseismic migration of their magnitude, distance from feed points and hypocenters were compared before and after shut-in to discover basic characteristics of shut-in events. We inferred the values of pore pressure when seismic events induced by injected fluid using information on available stress orientation and magnitude, and geometry of fault planes. We successfully estimated pore pressure increase which is consistent with other independent parameter as wellhead pressure. Analysis of pore pressure increase showed that seismic cloud extended around 100 m at the edge of seismic cloud especially to the direction of long axis of seismic cloud and that pore pressure in those area increased more than those during stimulation. We concluded that shut-in pressure migration we discovered in this study should be responsible for occurrence of large events. Pore pressure distribution in the reservoir had changed after shut-in due to disappearance of pressure gradient. We assumed that almost homogeneous pore pressure distribution after shut-in in a area of periphery of stimulated area cause large scale slip resulting large seismic events.

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