Identification of Fracture Orientation for Large Induced Seismicity Recorded at Basel, Switzerland in 2006

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ABSTRACT

One of the most critical problems in the development and operation of worldwide HDR/HFR/EGS geothermal reservoirs is the occurrence of induced seismicity with moment magnitude (Mw) > 2.0. Seismic activity with large magnitude has been also observed in the hydrothermal geothermal reservoirs.

At Basel, Switzerland, events with moment magnitude (Mw) larger than 2.0 occurred in the deeper and middle part of the seismic cloud during and just after a hydraulic stimulation in 2006. Three more Mw>2.0 events occurred in the shallower part of the seismic cloud one to two months after the bleeding-off. Because of the occurrence of these events, the project at Basel was suspended for risk analysis and finally discontinued in 2009.

We identified the orientation of fracture planes on which the Mw>2.0 events and other smaller events occurred. We found that there were four types of orientation of fracture planes around at the hypocenter of the Mw>2.0 events. The stress states along these fracture planes were evaluated considering the tectonic stress state around Basel. We found that most of the seismically activated fractures could be interpreted by Coulomb failure criterion for shear slip of pre-existing fractures and that the Mw>2.0 events occurred on one of the conjugate pair of fracture planes.

Introduction

Recently recognized practical problem in subsurface development which includes HDR/HFR/EGS development, geothermal production from hydrothermal reservoir, CCS, and EOR operation of hydrocarbon reservoirs is occurrence of induced seismicity with large magnitude (Majer et al., 2007; Roger and Charles, 1982; Suckale, 2010). We refer to induced seismicity with large magnitude (Mw>2.0) as "large events" in this paper. Large events during and after stimulation of HDR/HFR/EGS reservoirs had been observed at Cooper Basin (Australia), Soultz (France), and Basel (Switzerland) (Asanuma et al., 2005; Baria et al., 2005), and some degree of damage to buildings and infrastructure in urbanized area have been reported.

Seismic activity associated with liquid injection has been considered as evidence of human-induced shear slip to improve permeability in reservoirs. It has been accepted in seismology that there is a strong correlation between the magnitude of the natural earthquakes and the size of ruptured areas. However, relationship between the magnitude of induced seismicity and improvement of permeability/productivity of the geothermal reservoirs has not been well understood. Moreover, there is some possibility that geothermal development is misinterpreted as to increasing the risk of catastrophic natural earthquakes. Hence, a clear understanding of the physics behind the large induced seismicity is needed, and technologies for "soft stimulation" must be developed. Research to investigate the characteristics of such events has been undertaken by researchers worldwide (e.g., Bromley, 2005; Majer et al., 2007).

Geothermal Explorers Ltd. (GEL), operating for Geopower Basel AG, started development of a co-generation system of electrical power and heating energy (3MWe and 20MWt) at Basel, Switzerland, in 1996. GEL drilled a deep borehole (Basel-1) into a granitic basement, and carried out the first hydraulic stimulation in December 2006. A total of 11,500m^3 of fresh water was injected into the openhole section of the borehole over a stimulation period of six days (Häring et al., 2008). Seismic events with Mw larger than 2.0 occurred in the deep and mid-depth parts of the seismic cloud during and just after the hydraulic stimulation. Three more large events occurred in the shallow and middle part of the seismic cloud two months after the bleeding-off. Because of these large events, the Basel project was suspended for risk analysis and finally discontinued in 2009.

We have previously concluded that most of the large events from the mid-depth and deep parts of the seismic cloud originated in ruptures involving single/multiple asperities (Mukuhira et al., 2008). It has been also concluded that the large events in the shallow part of the seismic cloud occurred in fractures which were sub-parallel to the stimulated zone, because their hypocenters were spatially independent of the main seismic cloud and wavetraces had lower similarity than those inside the main seismic cloud. We have also found that the critical pore pressure for shear slip of the large events is relatively low and most of them occurred in an area where the increase in pore pressure from the hydrostatic condition was also relatively low. These observations suggest that local concentration of critical pore pressure is not the trigger of the large events at Basel (Mukuhira et al., 2009). We also investigated the characteristics of the shear slip on a fracture plane which induced the large events, estimating source parameter of the shear slip of large events and other induced seismicity. It was revealed that many of the fault plane solutions of the large events showed N-S azimuth and that the large events follow "scaling low in stress drop" from the evaluation of the source parameters (Mukuhira et al., 2010).

In this paper, the authors show results of the identification of the orientation of fracture planes on which the large events and other induced seismicity occurred and discuss possible physical models considering various stress state and coefficient of friction.

Outline of the Stimulation and Seismic Monitoring

The hydraulic stimulation at Basel was conducted by pumping a total of 11,500m^3 of water into a 4750m true vertical distance (TVD) borehole (Basel-1) over six days. The entire open-hole section (from 4379 to 4750m TVD), which includes some pre-existing natural permeable zones, was pressurized. The maximum wellhead pressure reached around 30MPa at a flow rate of 50L/s (Ulrich et al., 2007).

The seismic monitoring network, which consists of six permanent seismometers and one temporary seismometer placed in boreholes, detected more than 13,000 triggers during and after the stimulation period (up to February, 2008). The number of events located by conventional absolute mapping technique was around 2,900 (Asanuma et al., 2007). The distribution of hypocenters showed a sub vertical planar seismic cloud which had an approximately NNW–SSE azimuth, coinciding with the horizontal maximum stress around Basel region. Dominant source mechanisms for 28 largest events were estimated to be strike-slip type by the Swiss Seismological Service (SED) (Deichmann et al., 2007). Asanuma (2008) concluded that the hydraulic injection stimulated several sub vertical fractures (or thin fracture networks) with NNW–SSE azimuth and a horizontal extent of 200–400m.

Identification of the Orientation of Fracture Plane

a) Methodology

Fault Plane Solutions

Fault plane solutions (FPS) for 28 largest events were estimated by SED with a surface earthquake monitoring network. SED also determined the local magnitude of these 28 events to be within a range from M_L 1.7 to 3.4 (Deichmann et al. 2009). We have determined one fault plane as an actually slipped fracture from a pair of conjugate fault planes estimated by FPS, selecting one of the fractures whose critical pore pressure for shear slip is smaller (Mukuhira et al., 2009).

We also estimated the orientation of the fault planes for the smaller events, of which FPSs were not estimated by SED, but from the orientation of the multiplet seismic structure. This is because Asanuma (2008) reported that the multiplet clusters identified at high-frequency at Basel are strongly correlated with the existing microscopic fracture system. Hence, we assumed that all the multiplet events in one cluster occurred on one existing fracture.

Orientation of the Maximum Horizontal Stress and Stress State

Valley and Evans (2009) estimated the orientation of the maximum horizontal stress in the granite section at Basel to be N144°E ± 14° from the analysis of the orientation of breakouts and drilling induced tensile fracture at Basel 1 and OT-2. Häring (2008) estimated the magnitude of vertical stress and horizontal stress. They concluded that the stress state near the Basel-1 was of strike slip type.

b) Identification of the Fracture Plane Orientation

The Large Events (Mw > 2.0)

The pole distribution of the identified fault planes and the rose diagram of azimuths of the identified fault planes for the 9 large events (Mw > 2.0) are shown in Figure 1.

Three large events, including the largest events, occurred from on a fault plane with azimuth of around N111°E. Two of these large events occurred in the deep part of the seismic cloud and the

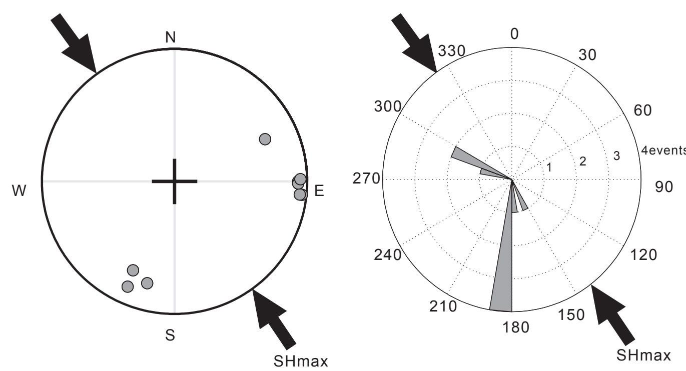

Figure 1. (Left) Pole distribution of identified fault planes in lower hemisphere projection for the 9 large events (Mw > 2.0). Arrows indicate the orientation of maximum horizontal stress. (Right) Rose diagram of the azimuths of the identified fault planes for the 9 large events.

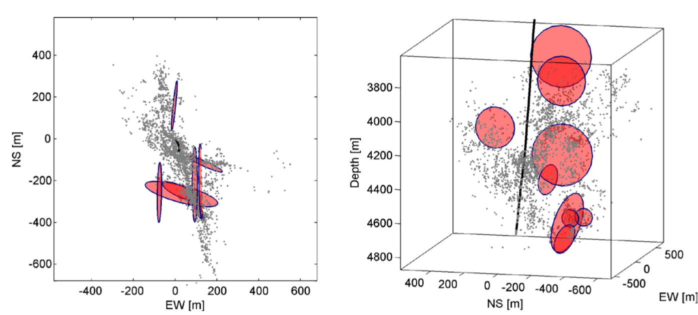

Figure 2. Spatial distribution of identified fault planes and hypocenters of induced seismicity. The red circles delineate the rupture area as is defined by the hypocenter and source radii.

other one occurred in its middle part (Figure 2). Meanwhile, the remaining other 6 large events were estimated to have occurred on fracture planes with N-S trend. All the fault planes on which the large events occurred have almost vertical inclination.

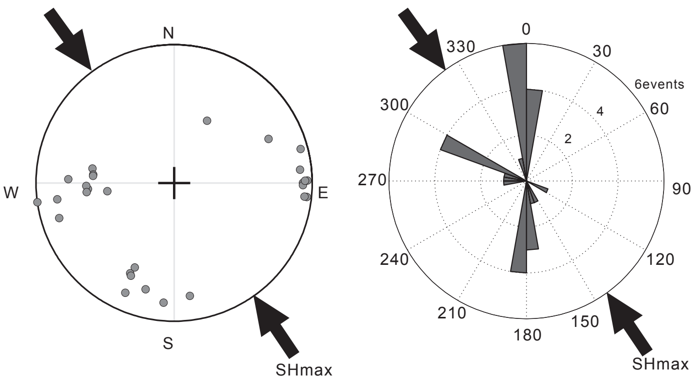

Figure 3. (Left) Pole distribution of identified fault planes in lower hemisphere projection for the 28 largest events. Arrows indicate the orientation of maximum horizontal stress. (Right) Rose diagram of azimuths of the identified fault planes for the 28 largest events.

Events with FPSs from SED

Poles of the fault planes for the 28 largest events including the 9 large events, are projected onto the lower hemisphere in Figure 3 (left). The corresponding rose diagram for their azimuths is also shown in Figure 3 (right).

We found that more of these events occurred on fault planes with nearly N-S azimuths than events on fault planes with azimuth around N111°E.

Multiplet Events

FPSs based on the first motion at surface monitoring stations could not be estimated with SED for most of the induced seismicity because of their small magnitude. Thus FPSs for these events were estimated using multiplet analysis. As a result, around half of all recorded induced seismicity was clustered into 100 multiplet groups (Asanuma et al., 2008). The rose diagrams of the azimuths for the fracture planes of these multiplet events are shown on the left side of Figure 4. Frequency distribution of azimuths for the 100 multiplet seismic structure is represented on the right side of Figure 4.

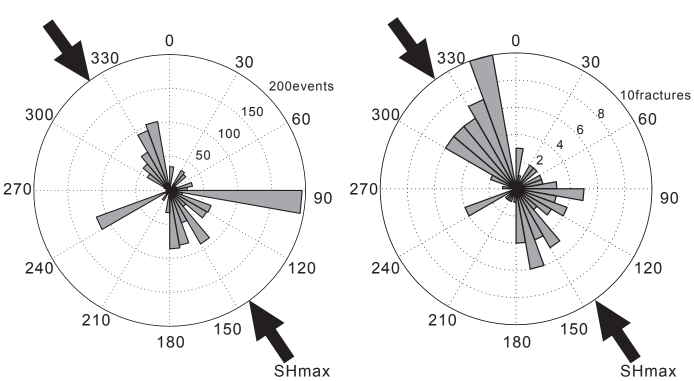

Figure 4. (Left) Rose diagram of azimuths of all multiplet events. (Right) Rose diagram of azimuths of the multiplet seismic structures.

In left side of Figure 4, there is a peak around at N95ºE, which means approximately 200 of induced seismicity occurred from the fracture plane with N95ºE. Azimuth of most of other multiplet seismic structure are distributed between N120ºE ~ N180ºE.

We found that the most significant multiplet seismic structure was one with azimuth of N160ºE ~ N170ºE from Figure 4 (right). Meanwhile, the number of the multiplet events which occurred from the fault planes of N160ºE ~ N170ºE was not large (Figure 4 (left)). We also found that the orientation of most of multiplet seismic structures were within N90ºE ~ N180ºE.

Discussion

We found that there were four types of fracture orientations around the hypocenters of the large events from the identification of the orientation of the fracture planes.

Type-1: Azimuth: N111ºE: Three large events, including the largest event, occurred on fracture planes with this azimuth.

Type-2: Azimuth: N182ºE: Other 6 large events had a shear slip on fracture planes with this azimuth.

Type-3: Azimuth: N100ºE: A number of multiplet events with smaller magnitudes occurred on the fracture with this azimuth. The hypocenters of the multiple events showed branched seismic structure which extended to eastward of the main seismic cloud (Asanuma et al., 2008).

Type-4: Azimuth: N165º: Many of the multiple seismic structures had azimuth around N165ºE. This azimuth is approximately consistent with the orientation of the whole seismic cloud at Basel.

Type-1: Azimuth: N111ºE:

Three large events, including the largest events, occurred on fracture planes with this azimuth. This azimuth is approximately 30º different from the orientation of maximum horizontal stress (N144ºE). Coulomb criterion for shear slip shows that sub-vertical fracture planes with this azimuth can be interpreted as the most “slip-able” at a friction coefficient of 0.6 and that the stress state of this fracture plane becomes critical with small increase in pore pressure. Even if the friction coefficient is 0.8, these fracture planes would be able to have shear slip with around 7MPa of increase in the pore pressure. It is also revealed that not too many multiplet events occurred on the fault planes.

Type-2: Azimuth: N182ºE:

Total number of 6 large events with hypocenters in the deep, middle and shallow parts of the seismic cloud and a number of other larger events occurred on sub-vertical fracture planes with this azimuth. This fault plane can not be interpreted as the most “slip-able” fracture, because the directional difference to the SHmax is larger than 30º. However, 10MPa of increase in pore pressure turns the stress state into a critical state. It is noticeable that many larger events occurred on this fault plane even though it was not the most “slip-able”.

Type-3: Azimuth: N100ºE:

Around 200 multiplet events occurred on this fault plane. These events consist of one large multiplet cluster, which correlates with brunch structure of the seismic cloud at Basel as shown in Figure 5. This type of seismic structure is not dominant in the reservoir, because the number of this type of seismic structure is 5 (Figure 4). We also found that the stress state of this fracture was not critical state before the hydraulic stimulation. However, 15MPa of increase in the pore pressure can trigger shear slip on this fracture plane and actually most of these multiplet events occurred during the stimulation.

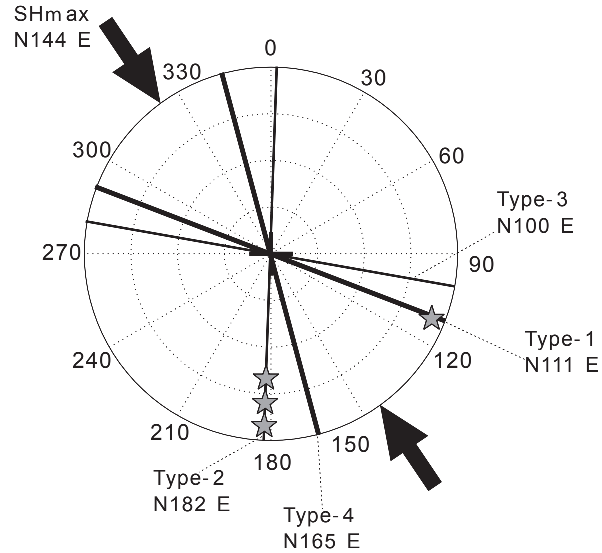

Figure 6. Model of the four types of fracture planes. Heavy black line indicates the orientation of a pair of the weakest conjugate planes in respect to the maximum horizontal stress. Thin black lines indicate the orientation of possible pair of conjugate fracture planes. The stars and its number indicate the occurrence of large events.

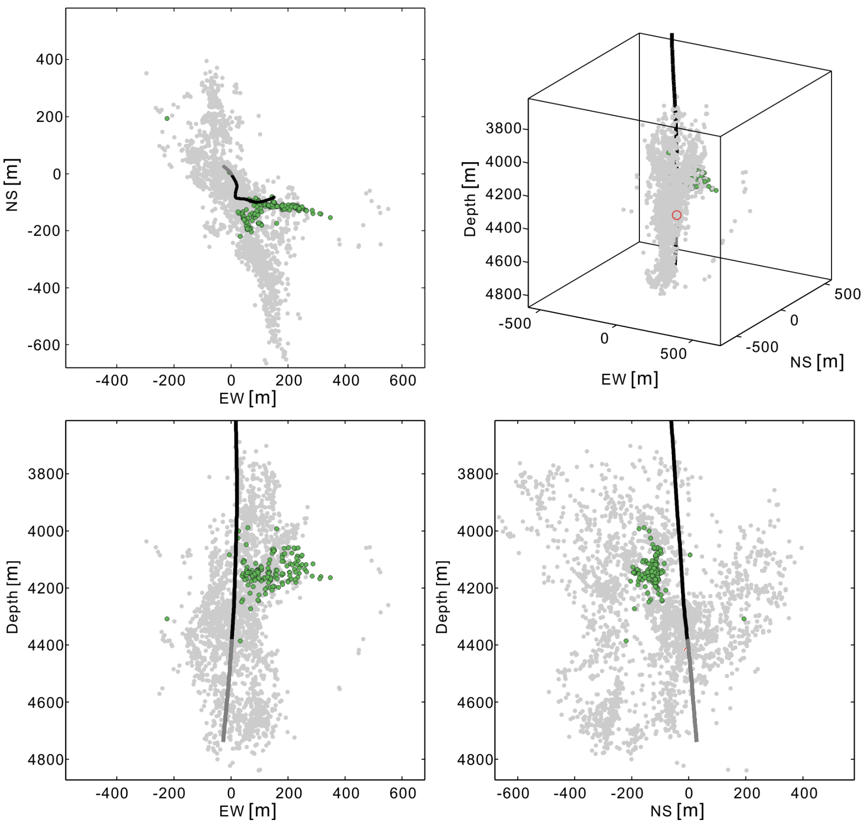

Figure 5. Hypocenter distribution of the multiplet events which constructed the branched structure of the whole seismic cloud at Basel. 157 multiplet events belong to this multiplet cluster. Black line indicates the trace of injection well, Basel-1.

Type-4: Azimuth: N165ºE:

We found that there are many multiplet seismic clusters with N165ºE, but the total number of multiplet events on this fracture plane is not the largest. It can be clarified that there were a number of small size of existing fracture whose azimuth was N165ºE in the reservoir and 5~10 multiplet events occurred on these fracture planes. The azimuth of fault plane of Type-4 is almost consistent with the orientation of the whole seismic cloud. The shear slip on this fracture plane can be triggered by as low as 5MPa of increase in pore pressure when the friction coefficient is 0.8.

The distribution of the four types of fracture planes is summarized in Figure 6. Fracture planes of Type-1 and Type-4 can be interpreted as the most slip-able planes when the coefficient of friction is 0.6 (Type-1) and 1.0 (Type-4). Both fault planes were under subcritical stress state during the hydraulic stimulation. There is some possibility that the fracture planes of Type-1 and Type-4 are a pair of conjugate weakest planes, considering several degree of ambiguity in the orientation of maximum horizontal stress. However, it has not been solved why large events occurred only on the fracture plane of Type-1 and a number of multiplet events with smaller magnitude occurred only on fracture plane of Type-4 even the stress states for fracture planes of Type-1 and Type-4 are almost identical.

It is also reasonable to consider that fracture planes of Type-2 and Type-3 are a conjugate pair of fracture planes, even though they are not most "slip-able". They need around 10~15MPa of increase in pore pressure to have a shear slip. Physics behind the observed unbalanced seismic activity and released seismic energy from this pair of fractures should be investigated in our further study.

Conclusions

We have identified the orientations of fracture planes on which the large events and smaller induced seismicity occurred. We revealed that there are four types of dominant fracture planes in the reservoir at Basel and evaluated the stress working on these fracture planes based on Coulomb failure criterion. We have found that most of the origin of seismicity at Basel can be interpreted by this method as shear slip of pre-existing fractures.

Asanuma et al., (2008) have reported that the fracture system around the stimulated zone in Basel can be modeled by a meshlike fracture network (Hill, 1977), where the reservoir consists of conjugate pairs of the most "slip-able" fractures to a given stress state. This is because the azimuth of the multiplet seismic structures distributed within ±30º in respect to the maximum horizontal stress. We have previously reported that most of the large events in the deep part of the stimulated zone occurred on one of a pair of conjugate fracture planes which has nearly N-S azimuth. However, it has been revealed in this study that the fracture planes on which the largest event and two other large events occurred had azimuth of N111ºE and that this fracture plane can be interpreted as the most "slip-able" fracture plane. We have also found that many other large events occurred on a fracture planes with azimuth N182ºE even they are not the most "slip-able".

This study revealed the fracture planes on which the large events occurred and pointed to seismically active fracture planes more precisely. However, there are still many unanswered questions including the reason of the unbalanced seismic activity and released energy among the dominant fractures. Further studies and establishing a geomechanical model will make it possible to interpret the unbalanced seismic activity and the seismic energy released from the conjugate pairs of fractures.

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