Stress state analysis of a fault plane with large induced seismicity

Mukuhira, Y. and Ito, T.
Institute of Fluid Science, Tohoku University, Sendai, Miyagi, Japan

Asanuma, H.
Fukushima Renewable Energy Institute AIST, Koriyama, Fukushima, Japan

Häring, M.
Geo Explorers Ltd., Liestal, Switzerland

ABSTRACT: Induced seismicity associated with hydraulic stimulation for the development of underground resources has been recognized as a risk factor in causing seismic hazards and is of public concern. To understand the simple physics behind induced seismicity, we analyzed the stress state of a fault plane where large seismicity was induced during hydraulic stimulation in the Cooper Basin, Australia and Basel, Switzerland. Using information regarding the stress magnitude and orientation, and the geometry of the fault plane where large events occurred, the stress state of these events was evaluated and the pore pressure necessary to cause shear slip was estimated. The fault plane of the large event in the Cooper Basin was close to being well oriented and only needed small increase in pore pressure (~10MPa) to induce shear slip. It was also discovered that the fault plane of the largest event at Basel required a moderate increase in pore pressure of around 20 MPa to induce a seismic event. Other large events occurring at different depths needed much lower pore pressures to induce shear slip. On the fault planes at Basel where these large events occurred, large shear stress was present, suggesting causality between shear stress and event magnitude.

1. INTRODUCTION

Hydraulic stimulation is a necessary technology for the enhancement of formation permeability or improvement in system productivity in Enhanced/Engineered Geothermal System (EGS) projects. With the increasing demand for renewable energy, this technology has been used in many EGS projects to create economically feasible geothermal reservoirs. This method, also known as “fracking”, is used in the extraction of unconventional resources such as shale gas/oil. Fluid injection can induce shear slip on existing fractures or can initiate fractures leading to increased permeability. Acoustic energy released simultaneously with rock failure is often observed as induced seismicity, which is considered as the evidence relating these phenomena.

The growing number of large-magnitude, induced seismic events has recently been recognized as a serious problem associated with hydraulic stimulation in geothermal development (Majer et al., 2007). Although the magnitude of induced seismicity is typically less than 1.0, these large magnitude events have had moderate magnitudes ($M_w$ 2~) and it is possible for them to be felt by local residents and also cause seismic hazards. Therefore, a quick development of methods to control seismic activity is necessary, and regulations or protocols based on scientific knowledge for sustainable and reliable geothermal development are required. However, many aspects of the physical mechanism related to large events remain unknown.

In modeling the propagation of injected fluid, as fluid flows through the flow paths in an existing fracture, pore pressure in the reservoir increases with pumping pressure. In an arbitrary existing fracture under tri-axial stress, this increase in pore pressure weakens the effective normal stress. When the shear stress working on a given fracture overcomes shear friction, the result is shear slip. This is known as the Coulomb failure criterion and is the principal behind induced seismicity. It can be described mathematically using equation (1).

$$\tau = \mu (\sigma_n - P_h - P_{over} - P_{inc})$$

where $\tau$ is shear stress, $\mu$ is friction coefficient, $\sigma_n$ is normal stress (in this context compression is positive), $P_h$ is hydrostatic pressure at depth of fault plane, $P_{over}$ is overpressure (usually zero), and $P_{inc}$ is the increase in pore pressure (pore pressure is positive). Usually, however, these pore pressure terms are compiled into one term. Though thermal, poroelastic, and chemical effects can cause failure in the long-term (e.g. Jeanne et al., 2015), here we consider instantaneous phenomena in the short-term meaning the problem is going to be just of
hydro-mechanical effect. By doing so, we can neglect the associated thermal, poroelastic, and chemical effects. When information about the magnitude and orientation of horizontal stress is known and the geometry of the fault plane (fault mechanism) is also known, one can compute shear stress $\tau$, and normal stress $\sigma_n$ using stress tensor theory. This then allows us to evaluate the forces working on that fault plane and finally infer the increase in pore pressure necessary to produce shear failure.

In much of EGS/conventional geothermal development, stress measurement has not been conducted due to cost limitations and high temperature conditions. Furthermore, orientation of fault planes has not been well constrained since a limited number of monitoring stations cannot provide enough information to reliably estimate the fault plane solution. Such limitations in geophysical data make it difficult to study the stress state of the fault plane where there may be large induced seismicity. This being the case, the stress state along fault planes that causes large induced seismicity has not been well investigated despite the simple geomechanical mechanism involved.

This study addressed this problem by collecting data from recent EGS projects where information regarding stress and geometry of the fault planes had been accumulated over a number of studies. Using this data, we attempt to reveal the characteristics of the stress state of the fault plane where there has been large induced seismicity.

2. STUDY FIELD OUTLINE

2.1. Cooper Basin, Australia

The Cooper Basin in the central part of Australia has high potential as a geothermal resource due to the temperature in the granite basement being greater than 270 °C at 5 km depth (Swenson et al., 2000). In 2003, Geodynamics Limited drilled the first injection well (Habanero #1) into granitic basement to a depth of 4,421 m. Several sub-horizontal fractures were found in the granitic section of the well. The initial state of the reservoir showed over pressure condition with the pressure being around 35 MPa higher than the hydrostatic state (Baisch et al., 2006). The orientation of these existing fractures was consistent with the maximum horizontal tectonic stress in the central part of Australia (Reynolds et al., 2005).

The main stimulation of Habanero #1 was conducted after several fracture initiation tests (FITs) and long term flow tests (LFTs). The total amount of injected liquid was 20,000 m$^3$ with a maximum pumping rate of 48 L/s and maximum well head pressure of around 70 MPa.

The microseismic network consisted of one deep high temperature (150 deg C) seismometer and four near surface seismometers. Seismic signals were recorded by the deep detector, and in most cases, also by the near-surface stations with a clear onset of P and S waves being noted in the data. The authors recorded 32,000 triggers in total, with 11,724 of these located on site during stimulation (Asanuma et al., 2005). Multiple analyses were then conducted to more precisely determine the hypocenter location. As we show in Fig. 1, mapping the hypocenter distribution delineated a sub-horizontal planar structure (Asanuma et al., 2005; Baisch et al., 2006), suggesting that most of the events occurred along sub-horizontal fracture planes as would be expected from a reverse fault stress regime. The failure criterion of the large magnitude events was not clearly defined, although the personal experience of the operator and scientists was that events with Mw >between 1.6 and 2.0 were fairly likely to be felt (personal communication Geodynamics). The hypocenters of the large events were widely distributed in the seismic cloud without a clear pattern or local concentration (Fig. 1). The large events occurred at the edge of the seismic cloud, while the seismic cloud later extended over the source area for the large magnitude events.

![Fig. 1. Hypocenter distribution of microseismic events at Cooper Basin. Larger events are showed with stars.](image_url)

2.2. Basel, Switzerland

In December 2006, Geothermal Explorer ltd. (GEL) drilled a deep borehole (Basel-1) to penetrate the granitic basement to a depth of 5000 m. The drilling was then followed by hydraulic stimulation. A total of 11,500 m$^3$ of fresh water was injected into Basel-1 over the 6 day stimulation operation (Haring et al., 2008). The openhole section, having pre-existing permeable zones, was pressurized. The maximum wellhead pressure was around 30 MPa with a flow rate of 50 L/s (Haring et al., 2008).

The microseismic monitoring network within the borehole consisted of 6 full time and 1 temporary
More than 13,000 triggers were detected during and after the stimulation period (up to Feb. 2008). Around 2,900 events were located using the conventional absolute mapping technique known as the Joint Hypocenter Determination (JHD) method (Asanuma et al., 2007). Following this, multiplet cluster analysis was conducted. Around 60% of the seismic events were identified in clusters, though most were smaller events. Their hypocenters were relocated after detection of the relative time of arrival. The distribution of the hypocenters showed a sub-vertical planar structure with an azimuth of approximately NNW-SSE (Fig. 2). This is consistent with the horizontal maximum stress around Basel.

The first observed felt events occurred on the fifth day of stimulation, prompting a reduction in flow rate and wellhead pressure. Subsequently, the injection well was shut-in (Haring et al., 2008). Further large events, including a $M_L$ 3.4 one, which was the largest recorded ($M_w$ 3.51 in our catalog), occurred mostly in the deep part of the reservoir within one day of shut-in (Haring et al., 2008). Two additional large events occurred several weeks after bleeding off (Mukuhira et al., 2013). At Basel, seismic events of greater than $M_w$ 2.0 were likely to be felt at the surface. Hypocenter locations of the largest event and two other large events in the post-stimulation phase are shown in the seismic cloud in Fig. 2.

### 3. STRESS ANALYSIS

#### 3.1. Cooper Basin, Australia

The orientation of the fault planes of the microseismic events was estimated from their $P/S$ amplitude ratio and $P$-wave polarity (Asanuma et al., 2010). The first-motion patterns of $P$-waves for large events at each station were identical to those of smaller events, suggesting that their fault plane solutions are similar to those of smaller events. Considering the shape of the seismic cloud, it can be interpreted that large events occurred on sub-horizontal fractures, similar to other microseismic events (Asanuma et al., 2010; Baisch et al., 2009). In this analysis, we used focal mechanism solutions for large events that GeoScience Australia has estimated to be representative of the orientation of the fault. The Nodal plane of the sub-vertical fault has an azimuth of 187° and an inclination of 73°. For the sub-horizontal fault, the azimuth is 30° with an inclination of 18°, which is in agreement with what was observed in the microseismic cloud.

The latest study on the stress state in this region (Barton et al., 2013) modeled stress orientation and stress magnitude based on several preceding studies (e.g. Reynolds et al., 2005). This model showed a thrust faulting stress regime ($S_{\text{max}}=150.9$ MPa, $S_{\text{min}}=124.4$ MPa, $S_T=97.9$ MPa, $P_{\text{over}}=30$ MPa at 4267 m respectively) and orientation of $S_{\text{max}}$ to be N80°E.

The stress state of the fault planes of the large events is shown on a Mohr stress circle in Fig. 3. The circle is shown with Coulomb failure criterion lines for frictional coefficients of 0.6 and 1.0. The Mohr stress circle plotted with solid lines indicates the initial condition of the stress state, estimated from the principal stress mentioned above minus overpressure and hydrostatic pressure. The Mohr stress circle plotted with a broken line indicates the stress state under maximum well-head pressure. Here, the increase in pore pressure is estimated as 40MPa; calculated from the difference between a maximum well-head pressure of 70 MPa and reservoir pressure of 30 MPa. The Mohr circle drawn with a broken line is shifted to left because of an increase in pore pressure. With this increase in pore pressure, some fractures may open, i.e., undergo hydraulic fracturing, as the minimum principal stress can be negative under high pressure conditions. However, it is unlikely that such high pore pressures propagated to a large part of the reservoir since the reservoir at Cooper Basin was such a wide as 3000 m along one side of the reservoir. The pore pressure should decrease with the distance from the injection well, so opening fractures are not considered and there were also not any observations to support this. The circle on the Mohr diagram corresponds to a sub-horizontal fracture plane. The stress state of conjugate nodal plane (sub-vertical fault plane) is plotted as squares in Figs. 3 and 4. The polar distribution of the

![Fig. 2. Hypocenter distribution of microseismic events at Basel. Hypocenter was determined by Double difference method after JHD method. The largest event and large events occurred at one month later of stop stimulation were plotted with stars. Black line indicates injection well. The depth in this figure is from sea level.](image-url)
pore pressure increase necessary to induce shear slip is also shown in Fig. 4, assuming constant friction coefficient of 0.85. The poles of nodal planes are plotted in the lower hemisphere.

This diagram indicates that shear slip on the sub-vertical fault plane requires an impossibly high increase in pore pressure. In contrast, sub-horizontal fractures were not in a critical state before stimulation, but were in critical state with a moderate increase in pore pressure of around 10 MPa seen during stimulation. Considering the identical geometry of the fault planes for the dominant smaller events, it is quite reasonable to assume that they reached critical state with a moderate increase in pore pressure, resulting in an extensive migration of fracturing in the artificial reservoir.

Fig. 4. Polar color contours of increase in pore pressure for shearing in the Cooper Basin. The white circle and white square are poles of the conjugate nodal planes of the large event and may also represent smaller events. Black arrows indicate the orientation of maximum horizontal stress. The stress state is a reverse faulting regime.

3.2. Basel, Switzerland

Using polarization information recorded by their surface network and microseismic network, the Swiss Seismological Service (SED) estimated Fault Plane Solutions (FPSs) of 118 seismic events with relatively large magnitudes (Deichmann and Giardini, 2009). FPSs of many of these large events show a strike-slip faulting mechanism, which is consistent with the regional strike-slip stress regime. Several events showed normal slip faulting mechanisms. From borehole analysis, the orientation of $S_{Hmax}$ was estimated to be N144°E ± 14° (Valley and Evans, 2009). Several studies attempted to constrain stress magnitudes. Our previous study (Mukuhira et al., 2013) used stress magnitudes estimated from core analysis (Haring et al., 2008), although there was still considerable uncertainty in the magnitude of stress $S_{Hmax}$ and $S_{hmin}$. A more reliable stress model for Basel has been reported recently, based on borehole breakout width analysis (Valley and Evans, 2015). This model gives stress state as function of depth.

$$S_{Hmax} = 0.00104z + 115$$ (2)

$$S_{hmin} = 0.01990z - 17.78$$ (3)

$$S_V = 0.0249z$$ (4)

where $S_{Hmax}$ is maximum horizontal stress (MPa), $S_{hmin}$ is minimum horizontal stress (MPa), $S_V$ is vertical stress (MPa), which all are in and $z$ is depth (m).

As equations (2) to (4) suggest, strike-slip faulting changes to normal faulting at around 4600 m due to the small gradient of maximum horizontal stress. We chose to focus on the depth of 4800 m where the largest event occurred and plotted the stress state using a Mohr stress circle (Fig. 5). As in the case of the Cooper Basin, we plotted the stress state under initial conditions with a solid line using principal stresses derived from equations (2) and (3), and hydrostatic pressure. After applying the maximum well-head pressure of 30 MPa, the Mohr stress circle shifted to the left hand side.

At this depth (4800 m), the stress state is a normal faulting regime. The stress states of the fault plane for the largest events were again plotted using circles and squares. One of nodal planes striking NWW-SEE is shown with a circle and was considered to be an actually slipped fault plane based on its geometry and adjacent microseismic events. The other fault plane plotted with squares shows a strike of almost NNE-SSW direction. Because the maximum horizontal stress and maximum vertical stress interchange but remain similar, the stress state of these faults plots in a limited area. In this case, they were plotted in the upper part of the Mohr stress circle. The fault plane where slippage occurred, was closer to failure than the others. As the critical pore
pressure contour map and poles plot in the lower hemisphere of Fig. 6, this indicate that fault plane where slippage occurred needed around a 20 MPa increase in pore pressure. In geomechanical terms, we cannot deny the possibility of a slip in the other fault plane as it would only require an increase in pore pressure of around 25 MPa, which is smaller than maximum well-head pressure. However, considering the microseismic distribution around the hypocenter of the largest event, it is reasonable to consider that the largest event occurred due to shear slip on the NWW-SEE fault plane.

Since the ratio of maximum/horizontal and vertical stress is not constant, stress state transition happens in this field. This makes it difficult to analyze the stress state of other events, including other large events. We also evaluated the stress state of the fault plane of the large events, which occurred a few months after the end of injection, and their hypocenters were located in the shallower part of the reservoir, as shown in Fig. 2. The Mohr stress circles at 4300 m depth at Basel and the stress state of nodal planes for two large events are shown in Fig. 7. As this depth is shallower than in the case of largest event, the stress state is seen to be strike-slip faulting and the Mohr stress circle is larger than in the deeper case. The Mohr stress circle is shifted to the left as much as 30 MPa similar to the deeper case. The stress state of the faults associated with large event was plotted in the upper part of Mohr stress circle again. For these two events, the N-S striking fault was considered to be the failure fault plane from the comparison between its geometry and whole seismic cloud. The N-S striking fault corresponds to the circles plotted in Fig. 7 and it reaches a critical state only after several increases in pore pressure. This is confirmed in Fig. 8, which shows the contour distribution of critical pore pressure for all possible faults. Due to the larger differential stress in the shallower part of the reservoir, the critical pore pressure for the optimally orientated fault was lower than in the deeper case.

Fig. 5. Mohr stress circle at 4800 m depth at Basel. The stress regime is normal faulting. The solid line and dashed line are Coulomb failure criterion in the initial condition and pressurized condition for a coefficient of friction of 0.6 and 1.0. Circles indicate the stress state of the estimated slipped plane and squares show the other nodal plane calculated from the focal mechanism solution estimated by SED.

Fig. 6. Polar color contours of increase in pore pressure for shearing at the depth of 4800 m for Basel. Stress state is normal faulting regime. The white circle and square are poles of the conjugate nodal planes of the large event. They also correspond to circle and square plots in Fig.5. Black arrows indicate orientation of maximum horizontal stress.

Fig. 7. Mohr stress circle at 4300 m depth at Basel. The stress regime is strike-slip faulting. Solid lines and dashed lines are Coulomb failure criterion in initial condition and pressurized condition for a coefficient of friction of 0.6 and 1.0. Circles indicate the stress state of estimated slipped plane for larger events which occurred in the shallower part of the reservoir. Squares show the other nodal plane from the focal mechanism solution estimated by SED.

4. DISCUSSION

The stress state of the fault plane of large events and other smaller events in the Cooper Basin were evaluated on the assumptions that they occurred along almost same sub-horizontal fault plane. As a result, we found that the shear stress on the fault plane of the large event was around half of the possible maximum shear stress (approximately 25 MPa). This can be interpreted as being that this event did not occur along the fault plane where there was high shear stress.
On the other hand, the stress state of the fault plane for large events at Basel shows their fault plane had higher shear stress despite variation between their stress regimes. In contrast to the Cooper Basin simple planar reservoir, the Basel EGS reservoir consists of many several sub-vertical fractures with an orientation of ±10-30° in respect to the direction of maximum horizontal stress (Asanuma et al., 2007). Despite only testing the three largest magnitude events for the Basel case, we can form the hypothesis that large events selectively occurred along the fault plane with higher shear stress. A qualitative correlation between high shear stress and the occurrence of larger events can be considered a reasonable theory. The mechanism of high shear stress causing larger shear slip has been found in laboratory shear failure experiments (Goebel et al., 2012). However, as the number of the events, which were estimated with reliable FPSs, is limited, we cannot show the statistical significance of this theory. In future studies we plan to show evidence such as $b$-value correlation.

The estimated critical pore pressures for shallow large events are lower than that of the largest event from a deeper part of reservoir. This is because the differential stress becomes larger in the shallower parts of the reservoir. Considering that shallower large events occurred after stimulation, it is reasonable to assume that they were triggered by a smaller increase in pore pressure, though it is quite unimaginable that 5 MPa of pore pressure remained 2 months after shut-in.

In the case of the Cooper Basin, most of the seismic events were thought to occur along a sub-horizontal fracture. Hypocenter migration and other geophysical data suggest that sub-horizontal fractures are dominant in the Cooper Basin reservoir meaning there was a low possibility of selective occurrence of large events. If high shear stress is responsible for the occurrence of large induced seismicity, some physical mechanism to accumulate shear stress is necessary. It was observed that large events in the Cooper Basin occurred at the edge of seismic cloud during the measurement period and occurrence of the large events created a significant development of the seismic cloud as shown in Fig. 8 (Asanuma et al., 2005). This observation implied that large events occurred due to tight asperity, which played the role of a type of hydraulic barrier. If so, shear slip on this impermeable asperity caused considerable enhancement of permeability and development of the seismic cloud. In this process, it is expected that the shear slip from preceding events accumulates shear strain on that asperity. Therefore, shear stress on the fault plane could have played an important role for causing large shear slip, even in the Cooper Basin.
5. CONCLUSIONS

We analyzed the stress state of the fault plane of the large induced seismic events, which occurred during hydraulic stimulation in the Cooper Basin, Australia and Basel, Switzerland. Using the information about stress magnitude/orientation and geometry of the fault plane of these large events, the stress states of the large events were evaluated and the pore pressure necessary to induce shear slip was estimated. We found that the large event at Basel selectively occurred along the high shear stress working fault plane, suggesting causality between shear stress and large shear slip. For the large events at Cooper Basin, correlation with shear stress was not observed. The distribution of microseismic events before and after the large events at Cooper Basin suggest that preceding event accumulates shear strain on asperities which then causes large events. This also suggests causality between shear stress and the occurrence of large events for Cooper Basin.

REFERENCES


