Injection-Induced Seismicity Size Distribution Dependent on Shear Stress

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Abstract  Like natural seismicity, induced seismicity caused by injection also shows a power law size distribution, and its gradient b-value is used for seismic hazard analysis. Despite the well-known result that b-value is negatively correlated with differential stress for natural earthquakes, there is no similar correlation for b-value variations because the differential stress is nearly constant for injection-induced seismicity, we thus investigate the b-value dependence on the relative shear stress acting on existing fractures, using the fault orientation and in situ stress information. The seismicity occurring along existing fractures having high shear stress has significantly lower b-values than does that associated with lower shear stress fractures. We examine the b-value dependency on slightly changing differential stress, but the relationship is not clear. The b-value for injection-induced seismicity is dependent on relative shear stress on faults, which is a novel physical explanation for the b-value variations of induced seismicity.

Plain Language Summary  Frequency magnitude distribution of a series of natural earthquakes and laboratory earthquakes correlates with the applied stress. However, the variation of the frequency magnitude distribution for injection-induced seismicity has not been understood well since the stress state is rather constant in reservoir scale. This study investigates the stress state of the faults that caused the injection-induced seismicity. We found that the events that occurred from the fault that oriented to have relatively higher shear stress caused the b-value reduction. This finding provides the new perspective of the scaling law of frequency magnitude distribution for induced seismicity. This insight leads to seismic hazard mitigation due to fluid injection.

1. Introduction

Earthquake size distribution follows a power law (Gutenberg & Richter, 1944) known as the Gutenberg-Richter (GR) relationship over a large range of earthquake scales from the laboratory to large inter-plate earthquakes, in addition to anthropogenic earthquakes. The gradient of the power law, the b-value, is expressed in the relation \( \log_{10}(N) = a - bM \), where \( N \) is the number of events having magnitude larger than \( M \), and \( a \) is a scaling factor. A low b-value means high relative number of larger earthquakes and vice versa. The b-value is often monitored for earthquake prediction and hazard analysis (Nanjio & Yoshida, 2018). Insights from various studies ranging from laboratory experiments (Amitrano, 2003; Goebel et al., 2013; Scholz, 1968) to natural earthquakes (Mori & Abercrombie, 1997; Spada et al., 2013; Wiemer & Wyss, 1997) have led to the assertion that b-value negatively correlates with differential stress (e.g., Scholz, 1968, 2015). Thus, spatial and temporal variations of b-value are generally understood to reflect variations in the stress loading level. Recent interest in this topic has led to several physical explanations for the cause of the differential stress increase that is responsible for b-value variations (Ide et al., 2016; Nishikawa & Ide, 2014; Petruccelli, 2019; Schorlemmer et al., 2005).

Recently, the importance of induced seismicity to earthquake science and to society has increased along with the demand for subsurface development using fluid injection (Ellsworth, 2013; Evans et al., 2012; Majer et al., 2007). In the case of induced seismicity, b-value and its variation have also often been observed and used in various assessments of seismic risk analysis (Bachmann et al, 2011, 2012; Langenbruch et al., 2018; Langenbruch & Zoback, 2016; McGarr, 2014; Shapiro et al., 2010). However, unlike natural seismicity, there is no general understanding of the physical causes for these variations and we have no basis for evaluating...
the importance of such variations (Gaucher et al., 2015). We cannot explain the $b$-value variations during induced seismicity as being caused by variations in differential stress as we do for natural earthquakes because the time scale, tectonic setting and the stress state of the fractures are different from natural earthquakes. The region activated by fluid injection is on the scale of several km and its depth rarely exceeds 5 km. A significant variation in differential stress is not expected on these scales. The static stress change caused by earlier induced seismicity can change stress state locally, but, these changes are small so their effect on induced seismicity is much less significant than pore pressure change (Catalli et al., 2013). Of course, pore pressure cannot change the differential stress. Therefore, the question we address is what is the physical explanation of $b$-value variation for injection-induced seismicity?

During hydraulic stimulation, shear slip occurs along fractures having a range of orientations according to the in situ stress and injection pressure. The geometrical relationship between the orientation of an existing fault and in situ stress determine the stress state of the fault. Therefore, there is some variation of shear stress acting on the existing faults. The pore pressure increases required to destabilize an existing fault varies by the fault’s stress state. Thus, instead of using differential stress as is done for the natural earthquake case, we investigate the relationship between $b$-value and the shear stress on existing faults that slip, by integrated analysis of microseismicity data and measured in situ stress information.

2. Field and Data

We use the induced seismicity data recorded during the Basel Enhanced Geothermal System hydraulic stimulation (Häring et al., 2008) since high-quality microseismic data and in situ stress information are publicly available. Using the waveforms from 6 downhole stations (Figure 1d), Asanuma et al. (2008) located around 2,800 microseismic events that occurred from the start of stimulation until 3 months after the stimulation. The seismically activated region is roughly a cube 1,000 m on a side and the reservoir depth is 3,700–4,900 m in the granite basement (Figure 1). Asanuma et al. (2008) performed multiplet cluster analysis, and we obtained precise relative relocation (Figures 1a–1c).

Orientations of fault planes are obtained from the focal mechanisms estimated for about 100 of the relatively large events using data from the Swiss seismicity network operated by Swiss seismological service (SED) (Deichmann & Giardini, 2009; Terakawa et al., 2012). We select the slip plane using geomechanical information and confirmed them with the hypocentral distribution of events in the vicinity of those larger events (Mukuhira, Moriya, et al., 2017). The poles to the slip planes are shown in the inset in Figure 1a. We added additional fault plane orientation information by utilizing the results of multiplet clustering analysis (Figure S2). Multiplet clustering analysis grouped events that are located close to each other and delineated a planer or streak shape structure (Figures 1a–1c), based on waveform similarity and polarization of P-wave arrival (Moriya et al., 2003; Shelly et al., 2016). We extracted the orientation of faults using principal component analysis (PCA) on the hypocenter distribution of each of the clusters. The purple rose diagram inset in Figure 1a shows the frequency distribution of the strikes of events in seismic clusters. Consequently, fault planes of around 1,000 out of 2,800 events (1,000 events is referred hereafter as all available events) are available for this analysis. Note that all events $M > 2.0$ are included in all available events (see Figure S9).

Stress magnitude and stress orientation were estimated from borehole logging data and well-test results (Valley & Evans, 2009, 2015). Thus, stress data are independent of the seismological data. The state of stress in the reservoir transitions from strike slip to normal faulting type as depth increases (Figure S1). The differential stress decreases slightly with depth. The magnitude of the differential stress variation is significantly smaller than that in natural or laboratory earthquake settings.

Using the in situ stress model and orientation of an existing fault, we can estimate the shear stress on the fault; but the absolute value of shear stress can be influenced by the differential stress at each depth. To remove this influence, we introduce a measure called Normalized Shear Stress (NSS), which is the ratio of the shear stress on a fault to the maximum shear stress at the fault’s depth. For example, the stress state for the fault with maximum shear stress is the top of the Mohr stress circle, suggesting that the maximum shear stress can be expressed as the radius of the Mohr stress circle. NSS corresponds to the ratio of the height of the point showing the stress state of the fault on the Mohr stress circle to the radius of the Mohr stress circle.
3. Results: $b$-Value Dependency on Shear Stress

First, we examine the correlation between the magnitude of seismic events and NSS (Figure 2a). We observe a correlation between the magnitude and NSS with the large events showing a tendency to occur along the faults with higher NSS. Smaller events also occur along faults with high NSS, so the correlation between event size and NSS is not a simple one. To investigate the relation in a statistical sense, we introduce the concepts of $b$-value and investigate the relationship between $b$-value and NSS.

We divide the catalog by NSS Threshold (NSST) value into those with NSS higher than the threshold as the higher group: HG and those with lower NSS as the lower group: LG (Figure 2a). We plot the GR magnitude frequency distribution of the events (Figures 2b–2g) for each subset of HG and LG. We estimate the magnitude of completeness (Mc) with the entire magnitude range method (Woessner & Wiemer, 2005), and the $b$-value with the maximum likelihood method (Aki, 1965; Utsu, 1999). Calculation of Mc and $b$-value analysis are performed using ZMAP (Wiemer, 2011).

We confirmed that the binned data for both LG and HG fit power law slopes suggesting our subcatalogs follow the GR power law (Main, 2000). However, fitting to the cumulative data is not always good for LG and there is some deviation from the estimated power law line for large magnitudes. To confirm the GR relation for LG data set, which includes a relatively smaller number of events, we followed (Naylor et al., 2009) and generated 1,000 power law synthetic catalogs having our estimated $b$-values, and we show their binned...
frequency distributions in Figures 2b–2g. With the exception of very few samples in the HG data, the binned counts of our real data fall within the range of statistically possible variation. This confirms that the subcatalogs created by dividing data by NSSTs follow a GR power law.

We first look the $b$-value difference between HG and LG for NSST = 0.76 as an example. Note that NSST of 0.71, 0.76 and 0.87 correspond to the NSS of well oriented fractures having friction coefficients of 0.6, 0.85, and 1.0 respectively. $b$-value for HG (0.76) in Figure 2f is significantly smaller than that for LG (0.76) in Figure 2c. For two other NSST, the HGs show significantly lower $b$-values than those of LGs (Figures 2b, 2e, 2d, 2g). We also observe that $b$-values for LGs systematically decrease (1.31 → 1.21 → 1.12) when the NSSTs increase (0.71 → 0.76 → 0.87). For the HGs, $b$-value for NSS = 0.71 was 0.974, the highest value among three cases (Figures 2e–2g). But the $b$-value for NSST = 0.76 is slightly smaller than that for higher NSST = 0.87. We will thus further investigate the correlation between the $b$-value and NSS.

We further investigate the relationship observed in Figure 2, by determining $b$-value for a range of NSST. We estimate Mc for each subcatalog defined by NSST and estimate corresponding $b$-values for HG and LG (Figures 3a and 3b), when a subcatalog contains more than 100 events $\geq$ Mc. So, Mc and $b$-value are not available for HG (NSST = 0.95) and LG (NSST = 0.55). We observed dependency of $b$-values on NSST for every 0.05 increment in NSST for both HG and LG, although the dependency for HG is not as clear as LG considering the uncertainty. The overall trend of $b$-value is to decline with increasing NSST. As we estimate Mc for each subcatalog, Mc has some variation (Figure 3c), which possibly leads to a slight fluctuation of
The uncertainty in b-value estimates is influenced by the number of events used for b-value estimation (Figure 3e), which is why the uncertainty in b-value of HG for higher NSST is large. The b-value for all available events for this analysis is 1.07. The b-values for HG events are always smaller than this value. On the other hand, the b-value of LG groups systematically decreases with increasing NSST and finally converge to the b-value for all available events when the NSST is 0.95. The b-values from LGs become stable as NSST increases because of the increase in the number of events used for the b-value estimation (Figure 3e). Consequently, both cases show a b-value dependency on NSST. Furthermore, we observe that the b-values for HG groups are significantly lower than those for LG groups with the same NSST. The significance of the differences between them is evaluated with a statistical test (Utsu, 1999) and they show (Figure 3d) that differences are highly significant (Akaike Information Criterion (AIC) = 5 is highly significant line).

We now investigate b-value dependence on shear stress using constant values of Mc. We estimate the b-values for every 0.05 NSS with 0.2 MPa wide windows for several constant Mcs. Figure 3f shows the correlation between the b-value and NSS, showing a very clear dependency. The number of the events increases after the window center reaches 0.8. There is a gap around NSS = 0.4. This is due to the lack of data around NSS = 0.4, as shown in Figure 2a. These results strongly support our previous observation showing b-value dependence on NSST.

The variation in differential stress in the active portion of reservoir is more or less 20 MPa as given by our stress model. This variation is much smaller than that applied during lab experiments (100 MPa~).
Figure 3h shows the correlation between the $b$-value and differential stress, where we estimate the $b$-value every 1 MPa with 4 MPa wide bins. Note that we do not need fault orientation information for this analysis since differential stress is the function of depth. So, we used all located events. This is why the number of events used for $b$-value estimation is significantly larger. The $b$-value shows lower values for smaller and higher differential stresses. The $b$-value shows quadratic behavior with differential stress rather than simple linear relation. So, $b$-value variation is attributed by NSS rather than slight differential stress change in injection-induced seismicity situation.

We examined $b$-value dependency on NSS with $M_c$ estimated using another method, constant $M_c$, and intentionally overestimated $M_c$ and confirmed our findings (Figures S3–S7). We also confirmed our findings are still robust even when considering the effect from the uncertainty in in situ stress model (Figure S8). We also performed a statistical simulation of the influence of the approximately 1,400 events for which we cannot determine NSS. We found that our observations and conclusions are not changed (Figures S9–S12).

4. Discussion

Our observations demonstrate a $b$-value dependency on NSS for injection-induced seismicity for the Basel EGS stimulation. The discovered $b$-value dependency seems to be an analogy to the general interpretation of $b$-value dependency on differential stress, in terms of the dependency on the stress. However, we confirmed that $b$-value correlated with NSS rather than differential stress. In addition, the interpretation of our discovered dependency is slightly different from the general interpretation of $b$-value dependency.

First, we consider the general interpretation of $b$-value dependency on differential stress using the Mohr stress circle. The Mohr stress circle shown in Figure 4a shows how the diameter of the circle changes with increasing differential stress. The $b$-value reduction occurs with differential stress increase, i.e., the diameter of the Mohr stress circle. Many previous studies of $b$-value implicitly consider that most of the earthquakes occurred along a representative fault, which is often the well-oriented fault under the given stress condition. We indicate the stress state of well-oriented faults in the case of friction coefficient 0.6 with dots on the Mohr stress circle. As differential stress increases, the shear stress along well-oriented faults increases as well, and $b$-value reduction should also occur with shear stress increase (shown with yellow arrows conceptually). So, the general interpretation of $b$-value dependence on differential stress can be translated equivalently to the $b$-value dependence on shear stress (here absolute shear stress). Some of the $b$-value studies already include discussion of $b$-value dependence with shear stress (Ide et al., 2016; Nishikawa & Ide, 2014).

The physical meaning behind our observed $b$-value dependency with increasing NSS is interpreted differently from the $b$-value dependence on differential stress for natural seismicity. On the reservoir scale, differential stress does not change significantly with time and space, leading to a constant diameter Mohr stress circle (Figure 4b). The Coulomb failure criterion line moves to the right in relation to the Mohr stress circle due to the pore pressure increase. Pore pressure increase just increases the range of fault orientations available for slip but does not affect to differential stress nor shear stress. The faults on the left of the failure line reach a critical state and fail. Only variety of fault orientation can cause the variation of shear stress, that is, NSS in this context.
NSS is the relative height of the Mohr stress circle. Then, stress states of the high NSS faults are situated in the higher portion and critical part of the Mohr stress circle (dark shaded) and these are the events that lead a lower b-value (Figure 4b). Thus, when more events occur within higher NSS faults, the b-value is low, this is what we observed throughout this study. The upward pointing yellow arrow in Figure 4b suggests having more events from high shear stress faults causes a lower b-value. This is consistent with the conceptual explanation of b-value dependency on shear stress with the upward yellow arrow in Figure 4a.

So, we can explain the relation between b-value and shear stress in the case of injection-induced seismicity at Basel where the tectonic stress condition and triggering process are totally different from natural earthquakes, with a different view from the general understanding in seismology. At the end, our explanations are quite consistent with the general insight of b-value variation for natural earthquakes. From the insight of this study, on a reservoir scale, the larger events occurring along relatively higher shear stress faults is reasonable since the higher shear stress faults have more potential to the size of shear slip. Several fault mechanics studies demonstrated the shear stress is the key parameter for the condition of larger events to occur (Garagash & Germanovich, 2012; Gischig, 2015; Norbeck & Horne, 2018), which is supportive of our findings. Igonin et al. (2018) reported that b-value for each cluster of events induced by hydraulic fracturing is related to the orientation of the cluster. Yoshida et al. (2017) found b-value variation is related to frictional strength (alternative to NSS) in earthquake swarm data. While we need to generalize the insights of this study to other field sites, there are already some supportive numerical and field study results.

The largest event and several other large felt events in the Basel field occurred in the deeper part of the reservoir where the differential stress is slightly smaller than at shallower depths and where the state of stress is normal fault slip type. From previous studies, the larger events would thus be expected to occur from larger differential stress zone and within a strike slip stress regime rather than the normal fault slip stress regime (Schorlemmer et al., 2005). Our results show an opposite tendency even though they are just several examples. The differential stress interpretation behind of the b-value dependency on stress regime is not consistent with our observations in the Basel reservoir. So, normalized shear stress, not differential stress, is more responsible for the b-value variation and the occurrence of large events in our case.

5. Conclusions

We conclude that, on the reservoir scale, a lower b-value associated with fluid injection can be attributed to the occurrence of events along fractures that are oriented to have high shear stress. Our conclusion provides the first clear physical interpretation of variation in b-values for induced seismicity where earthquakes occur along fractures of various orientations in a nearly constant in situ stress condition. Also, this is the first case study to show the b-value dependency on directly measured stress data on scales larger than the laboratory scale. This helps to fill the gap in our understanding of b-value variation on scales larger than the laboratory scale and natural earthquakes, clarifying that even for the microseismicity occurring within one local region, b-value can be related to shear stress level.

Our findings contribute to our ability to assess seismic risk and to mitigate it when undertaking subsurface development associated with fluid injection since the b-value reduction can to some degree be controlled by the injection pressure. With an increase of injection pressure, the Coulomb failure criterion line shifts to the right (Figure 4b), meaning that the range of orientations of fractures that can have shear slip increases. A higher injection pressure generally increases the chance of slip along high shear stress fractures, which, due to the lower b-values of these events, are likely to have larger magnitude. In fact, it has been reported in location like the Basel field (Mukuhira et al., 2013) that many of the large events have occurred when injection pressure reached its highest level. Though there are other factors that control the size of the largest injection-induced earthquakes, our findings provide the basis for understanding of large induced seismicity and how to control the occurrence of large induced seismicity based on b-value statistics: avoiding high injection pressure that can induce events along faults with higher shear stress.

Conflict of Interests

The authors declare no competing interests.
Data Availability Statement

The microseismic catalog data containing the location, magnitude and cluster information are available in Mukuhira et al. (2021). In situ stress data and focal mechanisms are available from previous literatures (Deichmann & Giardini, 2009; Terakawa et al., 2012; Valley & Evans, 2009, 2015).

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