Stress state and fault slip susceptibility prior to the 2017 M\textsubscript{W} 5.5 Pohang earthquake
induced by enhanced geothermal system stimulation

Chandong Chang\textsuperscript{1}, John Townend\textsuperscript{2}, Jeong-Ung Woo\textsuperscript{3}, Junkee Rhie\textsuperscript{3}, Jiyeon Kim\textsuperscript{1}, Jai-Yong Park\textsuperscript{1}

\textsuperscript{1}Department of Geological Sciences, Chungnam National University, Daejeon, 34134, South Korea.
\textsuperscript{2}School of Geography, Environment and Earth Sciences, Victoria University of Wellington, PO Box 600, Wellington 6012, New Zealand.
\textsuperscript{3}School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea.

Corresponding author: Chandong Chang (cchang@cnu.ac.kr)

Key Points:

- We determine the stress state in the Pohang enhanced geothermal system site related to the 2017 M\textsubscript{W} 5.5 Pohang earthquake
- High-pressure stimulation of the PX-2 borehole induced microseismicity on near-critically-stressed faults, including the mainshock fault
- Stimulation of the PX-1 borehole induced slip on less favorably oriented faults, producing microseismicity with restricted magnitudes
Abstract

We determine the stress state at the Pohang enhanced geothermal system site, South Korea in order to understand the hydraulic and geomechanical processes controlling microearthquakes induced by water injection, which led eventually to triggering of the 2017 MW 5.5 Pohang earthquake. The stress orientations and magnitudes estimated from earthquake focal mechanism solutions, borehole dipole shear anisotropy logs, and borehole hydraulic stimulation pressure data suggest that stimulation of the PX-2 borehole activated near-critically-stressed patches of the fault, which coalesced into the mainshock rupture. Stimulation of the other borehole (PX-1) also induced microearthquakes but on less well-oriented fault planes and at lower magnitudes. In addition, our results suggest that pore pressure perturbation that induced the PX-2 seismicity propagated diffusively in the rock mass rather than via flow in a conduit. In contrast, the faults related to PX-1 seismicity appear to be in direct hydraulic communication via fractures to PX-1 open-hole section.

Plain Language Summary

We estimate the forces acting on subsurface faults to understand how the magnitude 5.5 earthquake that took place in Pohang city, South Korea in November 2017 was triggered by high-pressure water injection associated with geothermal development. Our study shows that the fault that ruptured in the magnitude 5.5 earthquake was susceptible to slip even before water injection began. A small increase in water pressure within the fault zone made some parts of the fault unstable, which eventually resulted in the entire fault plane slipping and generating the earthquake. Water injection into the other borehole stimulated minor faults, inducing earthquakes at low magnitudes. The latter faults were relatively stable and did not produce a large earthquake.

1 Introduction

The MW 5.5 Pohang earthquake on 15 November 2017 caused extensive damage to the city of Pohang in southeastern South Korea, due to its proximity (~10 km) and shallow focal depth (~4.3 km) [Grigoli et al., 2018; Kim et al., 2018]. Debate quickly ensued following the earthquake regarding whether it had been induced by hydraulic stimulation of a nearby enhanced geothermal system (EGS) development. Two major points of contention were whether the MW 5.5 earthquake occurred too late (~two months) after hydraulic stimulation had ended to have been triggered, and whether the net water volume injected (~5800 m³) was insufficient to induce an earthquake of this magnitude based on a hypothesized relationship between injected volume and maximum induced magnitude [McGarr, 2014].

Following a year-long investigation into the cause of the Pohang earthquake, the Korean Government Commission concluded that the earthquake was triggered by hydraulic stimulation associated with the EGS project [Geological Society of Korea, 2019; Lee et al., 2019]. The investigation concluded that the Pohang earthquake was neither too late nor too large to have been triggered by stimulation; the timing was similar to that observed previously in anthropogenic earthquake sequences and the magnitude was compatible with the magnitude-frequency characteristics of the prior seismicity [van der Elst et al., 2016]. In particular, the investigation revealed that all three phases of stimulation conducted in one of the two deep boreholes (PX-2), and an unintentional loss of mud from the same borehole during drilling, had triggered earthquakes whose hypocenters defined a planar structure intersecting the borehole at
the depth of a recognized fault zone where the mud loss had occurred. This plane ultimately ruptured in the $M_W$ 5.5 earthquake and constituted one of the nodal planes of most of the focal mechanisms associated with PX-2.

Here we analyze the stress state prevailing at the Pohang EGS site to understand the geomechanical processes that governed the sequence of injection-induced seismicity and the mainshock. We use complementary observational data sets — earthquake focal mechanism solutions, borehole dipole shear anisotropy logs, and water injection and pressure records during hydraulic stimulation — to constrain the stress tensor. By resolving the stress tensor on fault planes that were progressively delineated by microseismicity and the principal fault plane that ruptured in the $M_W$ 5.5 mainshock, we examine each plane’s slip susceptibility and the overall hydromechanical triggering process.

2 Water injection and induced seismicity at the Pohang EGS site

EGS technology uses a hydraulic stimulation method by injecting water to create an artificial geothermal reservoir in hot rock at depth. At the Pohang EGS site, two boreholes (PX-1 and PX-2) were drilled and used for hydraulic stimulation (Fig. 1). PX-1 is a deviated well (measured depth: 4362 m, true vertical depth: 4215 m) and PX-2 is vertical to a bottom-hole depth of 4340 m. The lateral distance between the two holes is 6 m at the ground surface and ~600 m at the bottom depths. The two boreholes were each cased along their length except for the bottom-most 313 m of PX-1 and 140 m of PX-2. Five hydraulic stimulations were conducted sequentially in the two boreholes between 29 January 2016 and 18 September 2017 (Fig. S1). The $M_W$ 5.5 earthquake occurred on 15 November 2017, ~2 months after the cessation of the fifth stimulation in PX-2.
Figure 1. Locations and lower-hemisphere focal mechanisms in (a) map view and (b) cross-sectional view along profile A–A’ of 53 earthquakes that were induced by stimulation of PX-1 and PX-2. The earthquakes associated with PX-1 and PX-2 are indicated by blue and red colors, respectively; the uncased open-hole sections of PX-1 and PX-2 are illustrated in the same respective colors. The fault plane inferred for each focal mechanism on the basis of fault slip instability [Vavryčuk, 2014] is indicated with a bold line. The plane of best fit through the hypocenters of seismicity associated with PX-2 injection is illustrated by a dashed line in (b).

Numerous microearthquakes occurred in association with water injection (Fig. S1). The absolute locations of individual earthquakes have been determined using a local seismic velocity...
model based on seismic reflection data, well-log data, and crustal velocity models of South Korea, and precise relative locations have been calibrated with respect to the hypocenter of an event recorded on surface stations and a 17-level borehole geophone string [Geological Society of Korea, 2019]. The earthquakes associated with injection into PX-1 and PX-2 are spatially distinct, indicating that injection into the two boreholes stimulated different rock masses (Fig. 1). Earthquakes associated with PX-2 injection lie along a plane (214°/43°), which is similar to the later Mw 5.5 mainshock fault plane solution (214°/51°). The inferred fault plane, if extrapolated towards PX-2, intersects the borehole at a depth of ~3.8 km. Most of the focal mechanisms associated with PX-2 have a nodal plane of similar geometry to this structure, which we refer to as the mainshock fault. Earthquakes associated with PX-1 injection extend northwest, roughly subparallel to but offset from the trend of the deviated borehole. The focal mechanisms for PX-1 earthquakes exhibit more variation than those for PX-2, but can be inferred to be NW–SE-striking overall based on the spatial distribution of hypocenters. In total, 53 focal mechanisms can be computed, consisting predominantly of reverse-faulting events (23 events), followed by mixed mode of reverse and strike-slip faulting (15 events), and strike-slip faulting (15 events).

3 Constraining stress state

3.1 Stress orientation

We estimate the stress state at the EGS site at different spatial scales and using different types of data (Fig. 2). The first data set comprises focal mechanisms of 21 natural earthquakes (2.6 ≤ M ≤ 5.5) that occurred within 70 km of the EGS site between 1997 and 2016 (i.e. prior to EGS stimulation), which constrains the regional tectonic stress state at depths of 8–18 km prevailing before the Pohang mainshock (Fig. 2a). We invert a set of preferred faults exhibiting higher instability out of two nodal planes from individual focal mechanisms [Vavryčuk, 2014]. The inversion yields a well-constrained maximum principal stress axis (S1) with N74°E azimuth, which is consistent with the regional ENE–WSW S1 orientation in the Korean Peninsula [Soh et al., 2018]. The orientations of the intermediate and the minimum principal compressive stresses (S2 and S3, respectively) form a girdle (as indicated by 95% confidence orientations), suggesting similar S2 and S3 magnitudes. This is corroborated by a high value of the stress ratio parameter R=(S1−S2)/(S1−S3)=0.88 derived from the inversion.
Figure 2. The orientations of the principal stresses in Pohang estimated from various methods: (a) focal mechanism inversion of 21 natural earthquakes, (b) focal mechanism inversion for 202 aftershocks of the Mw 5.5 earthquake, and (c) an unwrapped image of the PX-2 dipole shear anisotropy log. Results from all these methods show that the maximum principal stress ($S_1$) is subhorizontal with an ENE–WSW azimuth in the basement rocks (d), indicating that $S_1$ is the maximum horizontal principal stress ($S_{Hmax}$). The intermediate ($S_2$) and the minimum principal stresses ($S_3$) derived from the focal mechanism inversions are dispersed (a and b), implying that their magnitudes are similar. The similarity in magnitudes of $S_2$ and $S_3$ is corroborated by high $R$ values from the focal mechanism inversions. The shallow $S_{Hmax}$ orientations at ~0.6 km depth in (d) are from borehole stress measurements reported by Kim et al. [2017].

To estimate the stress tensor at ~4 km depth, where the Pohang earthquake and the previous microseismicity occurred, we utilize two types of data: aftershock focal mechanisms and borehole stress indicators. Stress inversion using 202 aftershocks that occurred at depths of 3–7 km yields a well-constrained $S_1$ azimuth of N85°E (Fig. 2b). The 95% confidence orientations of $S_2$ and $S_3$ are dispersed and the $R$ value is approximately 0.94, indicating very similar $S_2$ and $S_3$ magnitudes. Although the aftershock stress inversion result might be biased by the coseismic stress perturbation [Hauksson, 1994], the inversion result indicates that the stress state at ~4 km depth is similar to that at greater depths.
Borehole observations provide the most direct constraints on the state of stress prevailing at the M\textsubscript{W} 5.5 hypocenter. We undertook acoustic borehole televiewer logging of PX-1 and PX-2 in August 2018 in an attempt to detect borehole stress indicators such as breakouts. PX-2 was found to be blocked at a cased depth of ~3.8 km, which coincides with the fault zone recognized from cuttings observations, the interval in which substantial mud loss occurred, and the intersection of the borehole with the projected mainshock fault (Fig. 1b). In PX-1, the borehole wall was found to be covered by grout cement that precluded the observation of any stress indicators. However, a dipole shear anisotropy log collected at depths of 3.4–4.3 km in PX-2 in December 2015, just after the completion of drilling and before the final casing installation, provides useful indicators of horizontal stress orientations. The dipole shear anisotropy measurement expresses the difference between the fast and slow shear-wave velocities along the borehole wall, and is commonly used for stress orientation estimation [Brié et al., 1998]. The log shows that the highest-anisotropy zones are on opposite sides of borehole wall, resembling geometrical pattern typical of borehole breakouts (Fig. 2c). Since breakouts form at an azimuth orthogonal to the maximum horizontal principal stress (S\textsubscript{Hmax}) in a vertical borehole, we estimate the S\textsubscript{Hmax} azimuth from the central azimuths of zero anisotropy. We determine the S\textsubscript{Hmax} azimuth at 10 m depth intervals and obtain an average of N77°±23°E, similar to the pre-mainshock S\textsubscript{Hmax} estimate at 8–18 km depths (N74°E).

3.2 Stress magnitudes

In computing the magnitudes of the three principal stresses, we consider a depth of 4.2 km corresponding to the top of the open-hole section of PX-2. We estimate the magnitude of the vertical stress (S\textsubscript{v}) by assuming that it equals the weight of overburden, meaning that it can be estimated by integration with depth of the overlying rocks’ densities. We use densities measured from cores recovered from the 2.4 km-deep BH-4 borehole nearby and from PX-2 [Kwon et al., 2019], which span the necessary depth range of 0–4.2 km. This analysis yields an S\textsubscript{v} of ~106 MPa at 4.2 km depth.

Neither of the two horizontal principal stress magnitudes can be measured directly in the Pohang case and we must estimate them from other observations, particularly the injection pressure and injected water volume data recorded during hydraulic stimulation of PX-1 and PX-2 (Fig. S1). Although the open-hole sections of the boreholes are longer than typically used in leak-off tests [White et al., 2002], the initial stage of hydraulic stimulation in an undisturbed borehole may provide useful information on horizontal stress magnitudes [Zoback et al., 2003].

We first note that the increase of pressure as a function of injected water volume is linear during the first few days of injection into each of the two boreholes (Fig. 3). The linearity starts to deviate at well-head pressures of ~15 MPa for PX-1 and 65±1 MPa for PX-2, corresponding to bottom-hole pressures of ~54 MPa for PX-1 and ~106±1 MPa for PX-2. At these pressures, water leaked from the open-hole interval through either newly created fractures or reopened natural fractures.
The fractures most susceptible to opening in response to pressurization are those orthogonal to the minimum compressive stress axis, which tend to open when borehole pressure exceeds the minimum principal stress ($S_3$). Thus, these linearity-deviation pressures may approximate the $S_3$ magnitude. The leak-off pressure at PX-2 (106 MPa) is the same as the independently calculated $S_v$, which suggests either that $S_v$ is $S_3$ at 4.2 km depth, or that the vertical and the minimum horizontal principal stresses ($S_v$ and $S_{hmin}$, respectively) are so close as to be indistinguishable. On the other hand, if the downhole pressure of 54 MPa in PX-1 is taken to be $S_3$, it is not possible to explain the high-pressure buildup to 106 MPa in PX-2 unless the tensile strength of the borehole wall rock were of the order of $\sim$50 MPa. Since the tensile strength of most lithologies is much lower [Lama and Vutukuri, 1978] and the measured tensile strength of core from 4.2 km depth of PX-2 specifically is $<10$ MPa [Kwon et al., 2019], we do not consider the $\sim$54 MPa pressure in PX-1 to represent $S_3$. In that case, leak-off from PX-1 at a pressure substantially lower than $S_3$ of $\sim$106 MPa inferred from PX-2 requires explanation. We consider the most likely explanation to be shear-induced flow from PX-1 along faults intersecting the borehole [e.g. Samuelson et al., 2009] and address this scenario below in reference to our preferred stress model.

The PX-2 pressure and injection rate data enable additional insight to be gained into horizontal stress magnitudes. Step-rate tests (SRTs), in which the pressure was monitored while injection rate was increased in steps (Figs. S1 and S2), were conducted twice in PX-2, once on 2 February 2016 and the second on 4 September 2017. The results from both SRTs, despite the 1.5-year gap between them and the intervening stimulations, show a bilinear relationship between well-head pressure and injection rate, with a transition at $\sim$80 MPa that corresponds to a pressure of $\sim$121 MPa at 4.2 km depth (Fig. S2). The bilinear behavior implies that a new
fracture system was activated at pressures of <~121 MPa, providing an additional water conduit. We interpret this as the result of a fracture opening perpendicular to the intermediate principal stress, which is $S_{\text{hmin}}$.

During the three stimulations of PX-2, water was injected at rates of 5–30 l/s (Fig. S1). When the injection rate was kept constant, the well-head pressure was also constant, reflecting flow out of the borehole via propagating fractures. These fracture propagation pressures (FPPs), which exceed the fracture normal stress, tend to increase with injection rate (Fig. S3), which means that the borehole accommodated higher pressures as injection rate increased. The extreme value of fracture propagation pressure at zero injection rate is 74–79 MPa at well-head, corresponding to 115–120 MPa at 4.2 km depth, which we interpret as the fracture normal stress. This range of pressure is similar to the presumed $S_{\text{hmin}}$ magnitude (121 MPa).

As no direct source for estimating $S_{\text{Hmax}}$ magnitude is available, we employ the assumption that the tectonic stress magnitude is controlled by frictional failure of optimally oriented fractures [Sibson, 1974; Townend and Zoback, 2000]. In the case of a reverse-faulting regime, this assumption can be expressed by the Coulomb friction law as

$$S_{\text{Hmax}} - P = \left(\left(\mu^2 + 1\right)^{1/2} + \mu\right)^2 (S_v - P)$$

where $\mu$ is frictional coefficient of the most optimally oriented fault and $P$ is pore pressure [Zoback and Townend, 2001]. We assume that the ambient pore pressure before hydraulic stimulation is hydrostatic (=41.2 MPa at 4.2 km depth). Our use of Eq. (1) to compute the magnitude of $S_{\text{Hmax}}$ introduces a dependence on the assumed frictional coefficient. However, the absolute magnitude of $S_{\text{Hmax}}$ is less important than the orientations of the principal stresses and fault planes of interest when assessing susceptibility to slip. We assume a frictional coefficient of 0.6, as the representative lower bound suggested by Byerlee [1976], which yields an $S_{\text{Hmax}}$ magnitude of 243 MPa at 4.2 km depth.

3.3 Stress condition acting on faults

Using the pre-earthquake stress state estimated, we compute the shear and effective normal stress (normal stress minus pore pressure) on planes of interest and their respective slip susceptibilities. The Mohr diagram in Fig. 4 indicates that the Pohang mainshock fault (214°/43°) was critically stressed with respect to cohesionless friction of ~0.6, and thus well oriented for slip in response to small perturbation to the prevailing stresses. Reactivation of the fault by pressurization depends on the frictional coefficient of the fault. No direct measurements of fault friction are available for the plane that ruptured in the Mw 5.5 earthquake, but the frictional coefficients of natural fractures in cores and basement rock cuttings from PX-2 are 0.53–0.68 [Kwon et al., 2019; Geological Society of Korea, 2019]. We consider this to be an upper bound on the frictional coefficient of the fault that ruptured as the gouge observed in the 3.8 km fault zone in PX-2 likely contains a proportion of low-friction clay [Morrow et al., 2000]. Whatever the exact frictional coefficient is, it is clear that the fault plane that ruptured in the mainshock was critically stressed prior to hydraulic stimulation.
Figure 4. Mohr diagram showing shear stress ($\tau$) and effective normal stress ($\sigma$) acting on faults activated during PX-1 water injection (blue circle) and PX-2 water injection (red circle).

The majority of the earthquakes induced by PX-2 injection (red circles in Fig. 4) occurred on portions of the fault plane that eventually ruptured in the mainshock and had a nodal plane subparallel to this structure [Geological Society of Korea, 2019]. The stress analysis indicates that faults of this orientation could be caused to slip by fluid pressure changes of a few MPa or less (Fig. S4). Moreover, the rake of slip on this fault observed in the mainshock (128°) is well accounted for computing the direction of maximum shear using the stress tensor described above [Ellsworth et al., 2019].

In contrast, earthquakes associated with PX-1 injection involved slip on relatively stable planes subjected to relatively high effective normal stresses (blue circles in Fig. 4). The pressure data discussed above indicate that water injected into PX-1 leaked from the borehole at wellhead pressures of >15 MPa (corresponding directly to a pressure rise of >15 MPa over hydrostatic pressure at depth) via fractures and faults intersecting the open-hole, which acted as conduits between PX-1 and the faults producing seismicity.

To examine whether a pressure increase of >15 MPa during stimulation of PX-1 can account for slip on unfavorably oriented faults, we calculate the critical excess pore pressure for a uniform frictional coefficient of 0.6. The calculated values of critical pore pressure rise are 2–117 MPa (Fig. S4). However, the values are predominantly in a range of 20–30 MPa, comparable to the observed pressure.
4 Mechanisms of fluid pressure propagation

Throughout the three phases of PX-2 stimulation, the well-head pressure levels always rose to 65–89 MPa (corresponding to 106–130 MPa at 4.2 km depth), which exceeds the minimum principal stress. This indicates that the rock mass around PX-2 was impermeable due to fractures hydraulically closed by stress, and that permeable conduits formed only by extremely high-water pressure that created hydraulic fractures. The pressure data indicate that a direct hydraulic connection between the PX-2 open-hole section and the mainshock fault was not established during stimulation: if it had been, detectable seismicity would have occurred immediately along the critically-stressed fault. Detectable earthquakes started 4 days after the beginning of the first phase of PX-2 injection (Fig. S1). Since the near-critically-stressed faults associated with PX-2 could be activated by pressure increases of a few MPa, and given the delay in the onset of seismicity, it appears that the pore pressure perturbation that induced the PX-2 seismicity propagated diffusively rather than via flow in a conduit.

In the case of PX-1, detectable earthquakes started 2 days after the beginning of stimulation and persisted intensely as long as the well-head pressure was maintained above ~15 MPa (Fig. S1). The number of earthquakes induced by PX-1 injection was markedly higher than that for PX-2, despite occurring on faults less well oriented for slip. This suggests that the faults activated by injection in PX-1 were in direct hydraulic communication with the open-hole section of the borehole via small-scale fractures or the faults themselves.

The differences in triggering pressures and pressure migration between the two boreholes provide insight into the processes governing induced seismicity in highly stressed regions. In an intact rock mass, hydraulic fracturing essentially requires a pressure equivalent to the minimum principal stress. The reverse-faulting state of stress in the Pohang EGS reservoir means that fluid pressures had to exceed the vertical stress to create hydraulic fractures, as happened with PX-2. However, the presence of faults intersecting the injection interval can reduce the pressure required for hydraulic stimulation, as seen with PX-1. Fault patches can certainly be activated where pore pressure is raised sufficiently. However, if the faults are not well-oriented for slip, the resulting rupture area will be restricted to the zone in which pore pressure is sufficient to exceed the friction criterion, thereby limiting the earthquake magnitude.

5 Conclusions

Stress analysis reveals that the fault that ruptured in the Mw 5.5 Pohang mainshock was near-critically-stressed prior to stimulation. Patches of the fault were progressively stimulated by pressure increases of a few MPa caused by pressure diffusion away from the PX-2, inducing numerous earthquakes of low magnitudes. The stimulated patches of the fault eventually coalesced to the rupture of the entire fault plane, the size of which greatly exceeded the stimulated fault patches, producing the Pohang mainshock.

In contrast, pressure migration associated with PX-1 injection appeared to stimulate faults that were relatively poorly oriented for frictional failure. This resulted in active low-magnitude seismicity. The magnitudes seem to have been restricted by the sizes of the stimulated zones only, with faults not rupturing beyond their directly stimulated areas. The presence of such faults, when crossed by the injection borehole, reduce the water pressure required for hydraulic stimulation in a highly stressed reservoir.
Our study emphasizes that knowing the presence of critically oriented faults before stimulation commences is crucial for safe hydraulic stimulation. In the Pohang case, the data required to determine the stress had all been collected by the time of the first stimulation of PX-2 in February 2016. The hypocenters and focal mechanisms of seismicity that had occurred up until this point in the stimulation had begun to reveal the eventual mainshock fault plane. In other words, the key pieces of information required to analyze fault slip susceptibility and the recognition that pressure perturbations of as little as a few megapascals were sufficient to induce slip were in hand long before the mainshock. Moreover, the likelihood of a large-magnitude earthquake occurring could have been estimated from the magnitude-frequency characteristics of the seismicity observed [Ellsworth et al., 2019]. In future EGS activities, it is crucial that seismological and geomechanical data are analyzed in tandem during all phases of drilling, borehole completion, and stimulation to ensure hazardous scenarios are identified and appropriate steps taken to avoid or mitigate them.

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