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Findings and Lessons Learnt from Hydraulic Stimulations for Pohang Enhanced Geothermal Systems Project

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ABSTRACT

There have been numerous technical and social studies related to the Pohang EGS project and associated Mw 5.5 seismic event offering unprecedented lessons to be learned. This presentation intends to present a series of recent studies associated with hydraulic stimulations at the Pohang EGS project. Deep rock cores retrieved from the 4.2 km deep geothermal reservoir directly confirmed prevalent fractures existing in the reservoir and provided invaluable information of mechanical and thermal properties in situ. Among other key parameters, we emphasize the need to better characterize the stress dependent dilation angle and nonlinear fracture normal behavior. Combination of numerous observations of drilling, induced seismicity, hydraulic stimulation and borehole logging provided a more reliable comprehensive stress model of the site. Two contrasting stimulation mechanisms were identified in a very clear manner in two boreholes in Pohang – one hydraulic shearing dominant and the other hydraulic jacking dominant. The contrasting hydromechanical responses observed in the same reservoir at the two nearby wells emphasize the importance of proper design and operation of drilling and completion with close consideration of stimulation strategy. Coupled hydro-mechanical numerical modeling for hydraulic stimulations improves the understanding on the coupled behavior caused by hydraulic stimulations. The key hydro-mechanical processes of shear slip and dilation and hydraulic jacking observed in the fractured reservoir can be successfully reproduced in the numerical modeling. Coupled hydromechanical numerical modeling of five stimulations showed that injection-induced hydraulic jacking and fracture shearing induce immediate stress transfer that plays a significant role in understanding seismic response at the fault associated with the Mw 5.5 event. Coulomb failure stress (CFS) immediately increases after the initiation of the water injection prior to the migration of fluid. During all stimulation periods, the stress change has a dominant impact on the CFS change at the Mw 5.5 fault. Geothermal energy may be duly called 'hydrogeothermal energy' in order to do justice on the underlying principle and emphasize the critical role of securing sufficient permeability and water.

1. INTRODUCTION

Currently, most deep geothermal energy is produced through hydrothermal systems around the basin of the Pacific Ocean (Bertani, 2020). In order for geothermal energy to be a universal option, its applicability to other areas must be demonstrated. An enhanced geothermal system (EGS) is a system that uses hydraulic stimulation of a hot, comparably-impermeable rock mass at depths typically deeper than 3 km to create an artificial geothermal reservoir (Tester et al., 2006).

Significant efforts have been made to develop EGS technology to exploit geothermal resources from the hot crystalline basement for electricity generation or direct heat use in the past few decades. Early research activities at the Fenton Hill project in the United States (Brown et al. 2012) were followed by a series of research and demonstration projects worldwide. In spite of longstanding efforts to test of concept of EGS, a sustainable commercial MW scale power generation is very rare. Therefore, EGS technology is still in the learning curve and concerted efforts are critically important for fuller communication of research and operational efforts undertaken in various EGS projects.

This paper intends to introduce a suite of recent studies associated with hydraulic stimulations at Pohang EGS project (Kwon et al., 2019; Park et al., 2020; Yoo et al., 2021; Park, 2021; Kim et al., 2022).

2. OVERVIEW OF POHANG ENHANCED GEOTHERMAL SYSTEMS PROJECT

The first EGS project in Korea was initiated in December 2010 in Pohang, a city located in the southeastern part of the Korean Peninsula (Figure 1 (a)). The project aimed to achieve 1 MW geothermal power generation in a doublet system. The geothermal gradient and heat flow in the Pohang region are among the highest in South Korea, which were identified by oil and gas exploration drilling in the 1960s (Lee et al. 2015) and geothermal resource assessment across the country in the 2000s (Lee et al. 2010). Four wells named BH-1 to BH-4 were drilled to a maximum depth of 2.4 km (BH-4) between 2003 and 2008 for a low-temperature geothermal application (Lee and Song 2008). Additionally, a 1-km deep well (EXP-1) was drilled for stress measurement in the Pohang area prior to the Pohang EGS project (Figure 1 (a)).

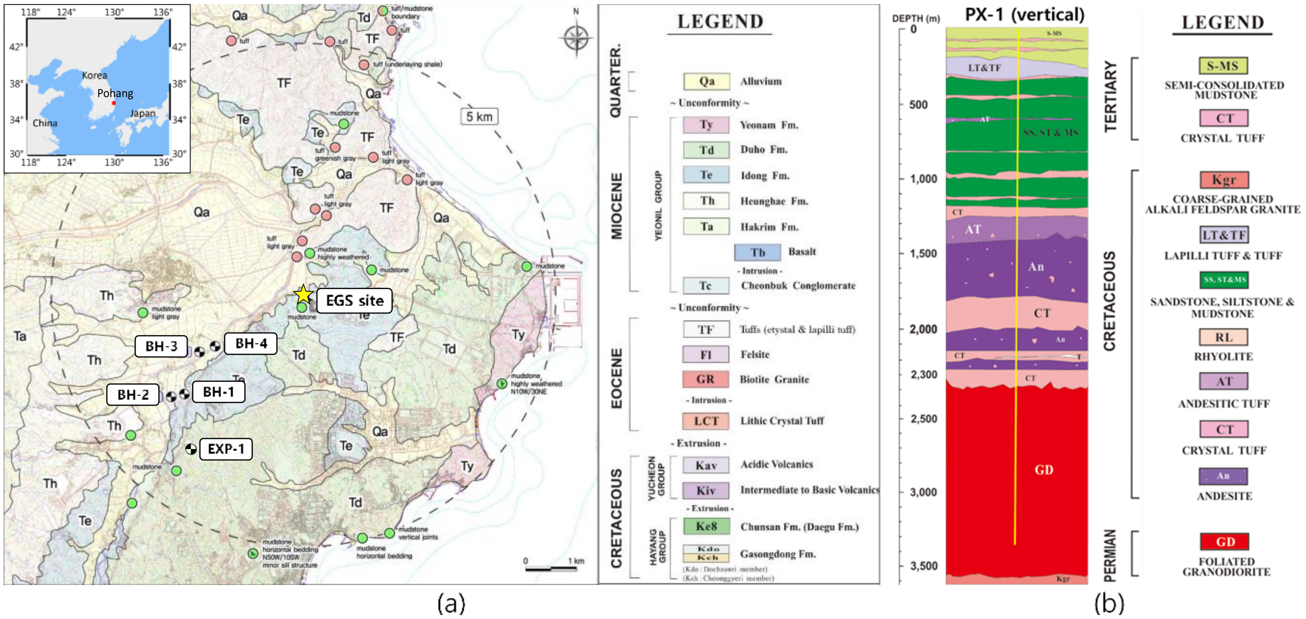

Figure 1: (a) Geologic map of the Pohang region including the locations of the EGS site and the five nearby wells; (b) stratigraphy of the Pohang EGS site (modified after Lee et al. 2015; Park et al. 2020)

Table 1: Timeline of Pohang EGS project. Injected volume, maximum wellhead pressure, and maximum seismicity magnitude are shown for each of the five stimulations.

Date	Operation / Event	
	PX-1 well	PX-2 well
Dec 2010	Start of the Pohang EGS Project	
Sep 2012–Oct 2013	Vertical drilling	
Apr–Dec 2015		Drilling / coring
Jan–Feb 2016		1st stimulation 1,970 m^3 / 89.2 MPa / M_L 1.7
Jul–Nov 2016	Sidetracking / directional drilling	
Dec 2016	2nd stimulation 3,907 m^3 / 27.7 MPa / M_L 2.2	
Feb–Mar 2017		Well cleaning
Mar–Apr 2017		3rd stimulation 2,831 m^3 / 88.8 MPa / M_L 3.2
Aug 2017	4th stimulation 1,756 m^3 / 22.8 MPa / M_L 1.8	
Sep 2017		5th stimulation 2,335 m^3 / 84.6 MPa / M_L 1.7
Nov 15, 2017	M_w 5.5 Pohang earthquake	

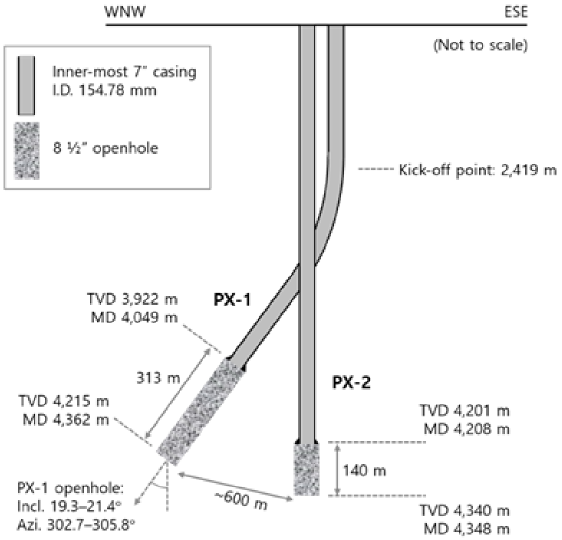

Figure 2: Simplified well dimensions in the Pohang EGS site (Park et al. 2020)

The geology of the Pohang site can be classified into four layers (Figure 1 (b)). A thick Tertiary semi-consolidated mudstone covers the Pohang area; its thickness varies from approximately 200 m in the northern part to more than 400 m in the southern part. The mudstone layer overlays a 1-km thick Cretaceous sedimentary layer consisting of sandstones and mudstones interlayered with volcanic intrusions or eruptions. Underneath the sedimentary rocks lays a sequence of andesites and crystal tuffs, as well as the deeper Paleozoic granodiorite basement rock of below 2.4 km (Lee et al. 2015). All the hydraulic stimulations conducted in the Pohang EGS project were below 4 km, located in the granodiorite basement rock.

Table 1 summarizes the history of the drilling and stimulation operations at the Pohang EGS site. The PX-1 well was initially drilled as a vertical well from September 2012 to October 2013, but after reaching its final depth of MD 4,127 m, the drill pipe was stuck in the well and could not be retrieved below MD 2,485 m. The PX-2 well was drilled to its final depth from April to December 2015 (Figure 2). The downhole temperature in the PX-2 well was measured as 140°C at MD 4,209 m on November 25, 2015 after 52 hours of temperature recovery time. Core samples were collected at MD 4,219 m in the PX-2 well, which belongs to the final openhole section and became the deepest rock cores ever collected in Korea (Kwon et al. 2019).

Five hydraulic stimulations were conducted in Pohang with a total injected volume of 12,798 m^3. Two months after the fifth hydraulic stimulation, on November 15, 2017, the Mw 5.5 Pohang earthquake occurred. The net injected volume, expressed as (injected volume) – (bled-off volume), was 5,841 m^3 by the time of the Mw 5.5 earthquake. After a year-long study, the Korean government commission concluded that the Mw 5.5 earthquake had been triggered by hydraulic stimulation operations primarily based on the spatio-temporal sequences of microseismic events during and after hydraulic stimulations (Lee 2019). Along with the commission report, numerous studies are currently being conducted to search for causal linkage, triggering mechanisms, refined seismic analysis, and lessons learned.

3. GEOMECHANICAL CHARACTERIZATION

3.1 Characterization of 4.2 km deep core

Mechanical and thermal characterization of rock and rock fractures are essential for borehole stability analyses as well as understanding the flow and transmissivity development when hydraulic stimulation is performed in a fractured reservoir. These properties are indispensable inputs for other deep geological applications such as deep borehole disposal of nuclear waste and geosequestration of CO_2. A set of mechanical and thermal properties were determined in the laboratory for the granodiorite rock core and fractures retrieved from a depth of 4.2 km in the Pohang reservoir (Figure 3, Kwon et al., 2019). The cores were scanned using 3D X-ray computed tomography (Diaz et al. 2017) and the rock quality designation (RQD) was evaluated as 50.8%. The physical properties we measured included density, porosity, and P- and S-wave velocities. Uniaxial and triaxial compressive tests were conducted to determine the deformation and strength parameters of intact rock that include elastic modulus, Poisson's ratio, uniaxial compressive strength (UCS), tensile strength, cohesion, and internal friction angle. Fracture properties, including JCS (Joint Wall Compressive Strength), JRC (Joint Roughness Coefficient), basic friction angle, residual friction angle, normal stiffness, shear stiffness, and dilation angle, were determined for natural fractures in the core. Thermal properties, including thermal conductivity, heat capacity, and thermal expansion coefficient, were determined from measurements on the intact cores. The determined mechanical and thermal properties of rock core and fractures were in the range typically expected in a granodiorite rock and a few notable observations were made (Kwon et al., 2019).

The stress-dependent normal stiffness of fractures matched reasonably well with observations made during in situ hydraulic stimulation at the deep fractured reservoir, which demonstrates that the laboratory fracture test can help the interpretation of the hydraulic jacking mechanism. The friction coefficient of fracture was measured as 0.53, which is lower than the one typically used in practice because of the smooth fracture surface and infilling material. P- and S-wave velocities detected from well logging were 36.4% and 22.4% larger, respectively, than the ones estimated by laboratory tests, which is explained by the stress dependency of wave velocities.

The dilation angles of the fracture determined from the laboratory tests with normal stress up to 8 MPa are within the range expected by existing empirical formula (Figure 4). However, the experiment with much higher normal stress corresponding to deep reservoir of 4-5 km is critically needed for more realistic evaluation of the dilational behavior of fractures as this is directly related to the permanent increase of permeability through hydraulic stimulation which is a core underlying principle of EGS.

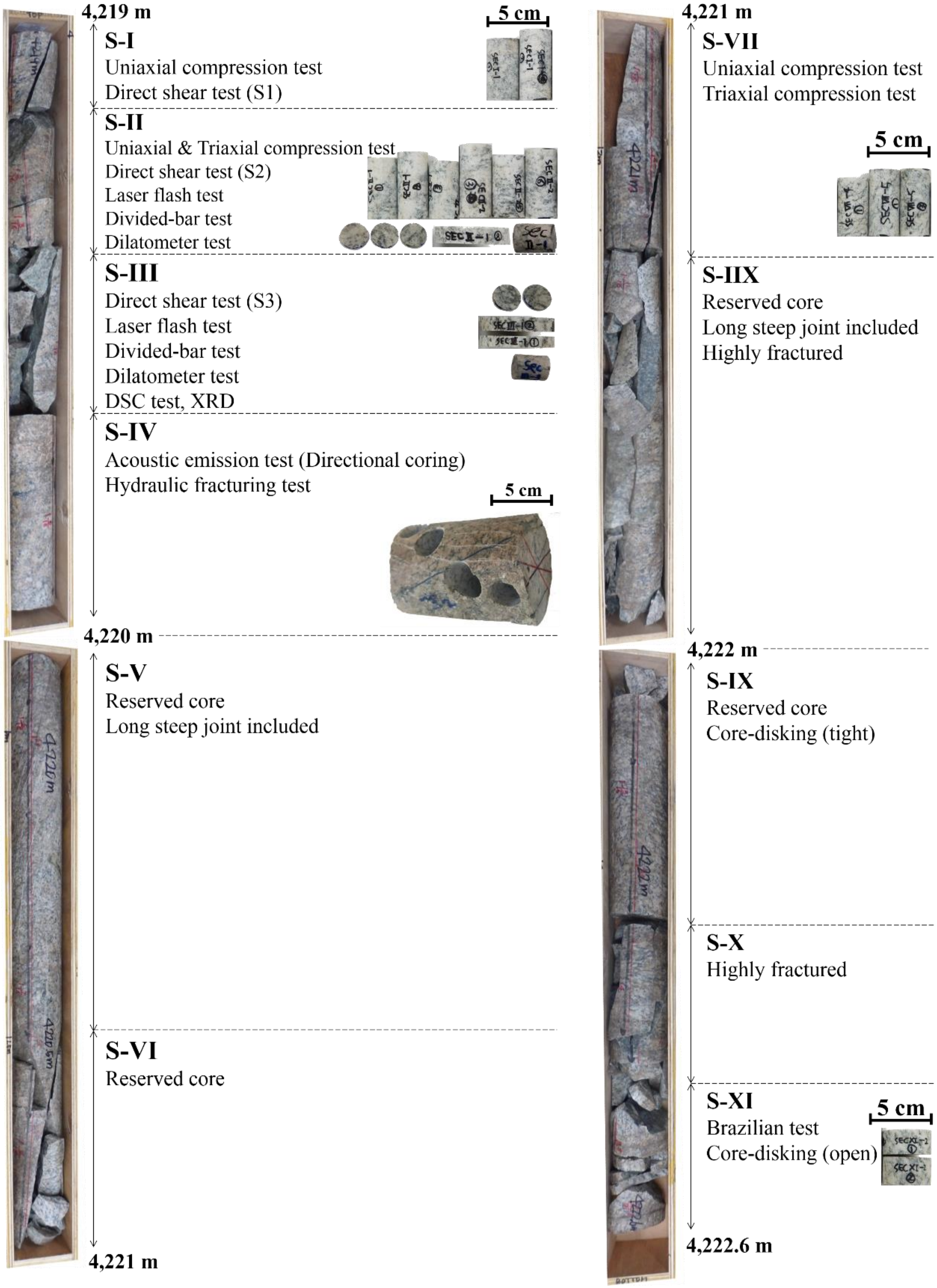

Figure 3 Rock core samples obtained from the PX-2 well (3.6 m long and 100 mm in diameter) and detailed division of core samples for various tests (Kwon et al. 2019)

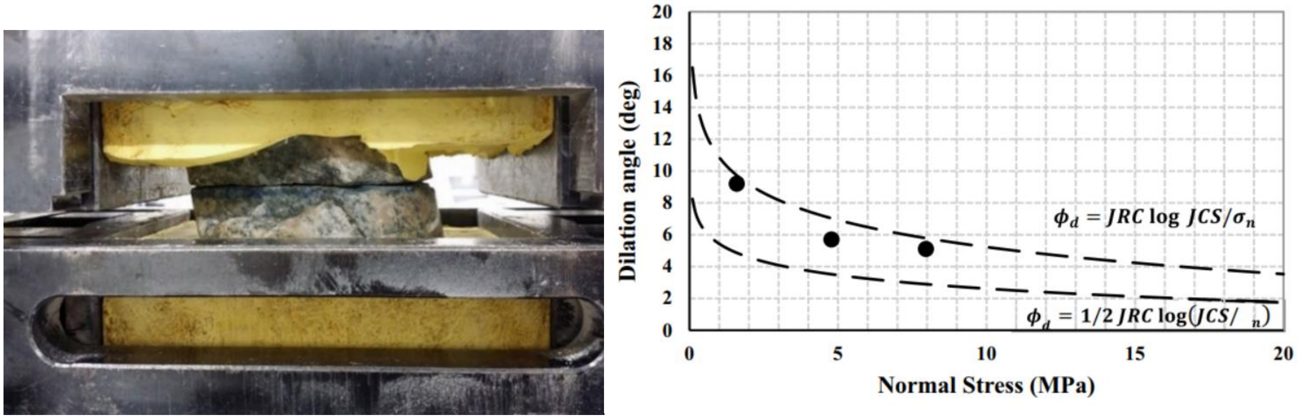

Figure 4: Trend lines of dilation angle with respect to normal stress based on an empirical equation developed by Barton and Choubey (1977) where ϕ_d is the dilation angle, JRC is the joint roughness coefficient of fracture, JCS is the joint wall compressive strength, and σ_n is the normal stress applied on the surface of the fracture. The results of S2 (three dots) are within the trend lines (Kwon et al., 2019).

3.2 Integrated estimation of in situ stress

A comprehensive estimation of in-situ stress model in the reservoir depth at the Pohang enhanced geothermal system development site was conducted. Stress indicators were collected from field observations of drilling, logging, hydraulic stimulations, and seismicity occurrence, and the in-situ stress model was suggested by integrating the stress constraints (Park, 2021).

Based on the understandings on the reservoir responses observed during hydraulic stimulations and various stress indicators, the in-situ stress state of the reservoir volume at the Pohang EGS site was reassessed by virtue of integrated stress estimation. The fault shearing induced by the mud loss in PX-2 3.8 km depth and the hydraulic shearing within the PX-1 open hole were used, and contributed as the stress constraints varying with the friction coefficient and stress orientation. The condition to enable both borehole breakout and washout in PX-2 was used considering realistic field operational parameters such as flowing bottom hole mud pressure and the cooling of the well during drilling. The observed fracture closure pressure, the previously reported focal mechanism stress inversion data, and the acoustic emission test data were also included as the stress constraints. The resulting stress model suggests the possible stress ratio for the reservoir depth at the Pohang EGS site as Sv:Shmin:SHmax = 1:0.92-0.94:1.42-1.66, based on the compilation of direct and indirect stress indicators. The result also suggests the possible range of friction coefficient as 0.35-0.50, which can best explain the involved stress constraints.

Comprehensive in-situ stress estimation suggested in this study demonstrates that the appropriate integration of direct and indirect stress indicators from various field records can improve the credibility of the in-situ stress model at a fractured reservoir. The resulting stress model is coherent with the field observations during the geothermal development activities such as drilling, logging, hydraulic stimulation, and induced seismicity, and also can explain the characteristics of the Pohang earthquake. The stress model suggested in this study can be used for clarifying the causal mechanism of the Pohang earthquake. Furthermore, the stress model from this study can provide an insight for fault stability analysis or possible geoenergy application, such as CO2 geo-sequestration, in the southeastern part of the Korean Peninsula (Park, 2021).

3. ANALYSIS OF HYDRAULIC STIMULATIONS

The summary below presents the main observations and analyses of the first and second hydraulic stimulations conducted in the PX-2 and PX-1 wells, respectively, among a total of five hydraulic stimulations at the site (Figure 5).

During the first stimulation, 1,970 m^3 of water was injected into the PX-2 well. The maximum wellhead pressure was 89.2 MPa and the maximum injection rate was 46.8 L/sec. Pressure peaks were observed on the first day at 64–67 MPa and the differential injectivity increased at 73 MPa, which was comparable to the pressure peaks on the first day. The transmissivity change was reversible, non-linear and highly pressure-dependent. The stimulation mechanism in the PX-2 well is interpreted as a combination of tensile fracture extension and hydraulic jacking of mated fracture.

During the second stimulation, 3,907 m^3 of water was injected into the PX-1 well. The maximum wellhead pressure was 27.7 MPa and the maximum injection rate was 18.0 L/sec. Pressure peaks were observed on the first day at 15–17 MPa and the differential injectivity increased at 16 MPa, which was consistent with the pressure peaks on the first day (Figure 6). The transmissivity change was more gradual and less pressure-dependent than in PX-2, and showed 6.4 times of permanent increase during the stimulation. The stimulation mechanism of the PX-1 well is interpreted as a combination of hydraulic shearing and hydraulic jacking of unmated or shear-dilated fractures.

Despite the relatively close distance of approximately 600 m in the same rock formation, the two wells showed distinctly different hydromechanical characteristics, in terms of the overall pressure ranges, pressure peaks, pressure for differential injectivity increases, transmissivity changes, and the stimulation mechanisms. It is postulated that drastic differences between the two wells are possibly affected by heavy mud and LCM during the drilling and completion of PX-2. In PX-1, no heavy mud or LCM was used in the openhole section which is 2.3 times longer than that of PX-2, leaving a higher possibility of maintaining hydraulic connections to natural fractures. The contrasting hydromechanical responses observed in the same reservoir at the two nearby wells emphasizes the importance of proper design and operation of drilling and completion with close consideration of stimulation strategy.

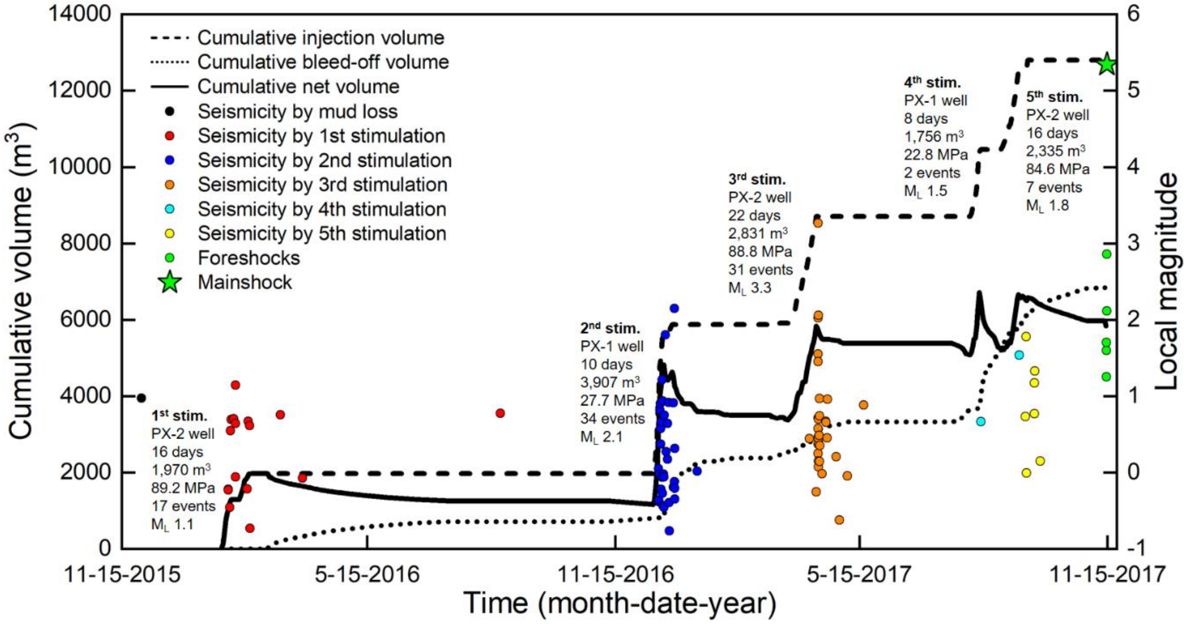

Figure 5: Temporal variations of the injection, bleed-off and net volume of water at the PX-1 and PX-2 wells presented with summary of the five hydraulic stimulations operated in the PX-1 and PX-2 wells including duration, injected volume of water, maximum wellhead pressure, and number and maximum local magnitude of seismic events for each stimulation. An event by mud loss at PX-2 as well as foreshocks and the main shock associated with the Pohang earthquake are presented (Kim et al., 2022).

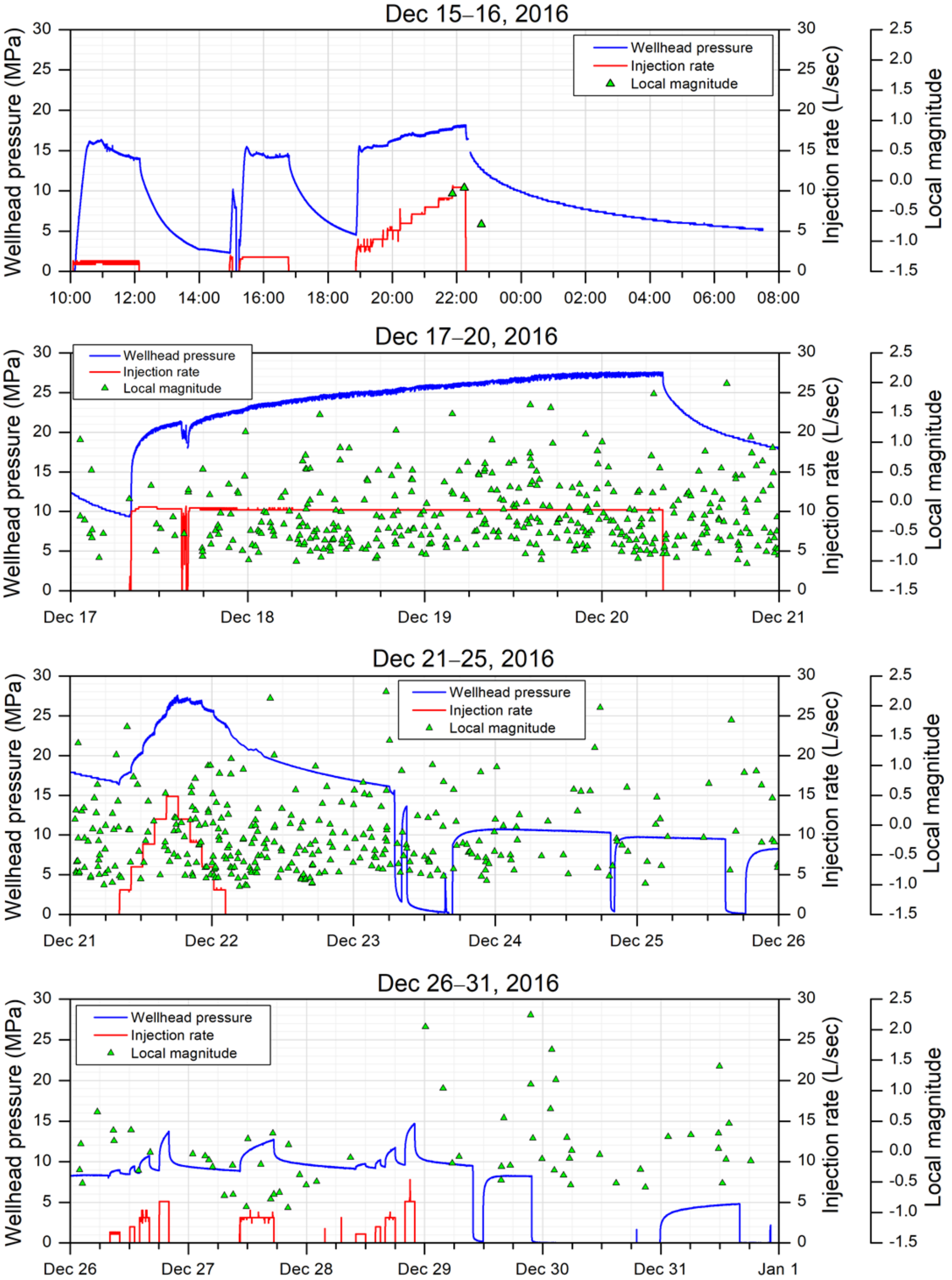

Figure 6: An example of hydraulic stimulation at PX-1 showing wellhead pressure, injection rate and seismicity evolutions. Clear pressure peaks on December 15 indicating clear hydraulic shearing (Park et al., 2020).

4. COUPLED HYDROMECHANICAL NUMERICAL MODELING

The TOUGH-FLAC simulator (Rutqvist, 2017) was used for coupled hydro-mechanical modeling of the Pohang geothermal reservoir for hydraulic stimulation and analysis of triggered seismicity (Yoo et al., 2021; Kim et al., 2022). Due to the cubic-flow-aperture relation, the fracture flow is likely dominated by a fracture having the largest aperture even when multiple parallel fractures exist. Solid element representation of fractures along a fracture zone were applied in this study. The geometry of the fracture zone was explicitly defined including the location and orientation, whereas the fracture opening and shear dilation of a dominant single fracture was implicitly modeled and evaluated from normal and shear strains of the fracture zone.

4.1 Numerical modeling of hydraulic stimulations

Comprehensive coupled hydro-mechanical numerical modeling of the first and second hydraulic stimulations at the Pohang EGS site improved the understanding on the key stimulation mechanisms in the fractured reservoir. Numerical modeling of the early days of each stimulation confirmed the candidate mechanisms of the fractured reservoir and significantly enhanced the understanding on the coupled behavior caused by the hydraulic stimulations. This study demonstrates that the key hydro-mechanical processes of shear slip and dilation and hydraulic jacking observed in the fractured reservoir can be successfully reproduced in the numerical modeling.

Non-linear hydraulic jacking in the PX-2 hydraulic stimulation was confirmed through close history matching and comparison of simulated and observed aperture changes. Possible hydraulic fracturing or opening of pre-existing fractures observed in PX-2 was also found in the numerical modeling as the wellhead pressure stabilized around 67 MPa due to the use of exponential stress dependent permeability.

Hydraulic shearing in the PX-1 hydraulic stimulation was successfully reproduced through the shear dilation and plastic strain softening model implemented in the fracture zone (Figure 7). The combined effect of shear dilation and hydraulic jacking was confirmed to be the main hydraulic stimulation mechanism in the reservoir near PX-1 borehole. Simulated critical wellhead pressure for shear slip near PX-1 well was greater than the prediction by a simple slip potential analysis in PX-1 due to local stress changes by the poroelastic effect. This shows that a coupled hydro-mechanical analysis is necessary for accurate estimation of critical pressure for shear slip and simple shear slip potential analyses may underestimate the critical wellhead pressure.

Spatio-temporal changes in pressure, total stress, and permeability evaluated in the fracture zones greatly enhanced the understanding on the coupled behaviors in the fractured reservoir caused by the hydraulic stimulations. Considerable changes in total stress corresponding to the poroelastic effect and frictional-weakening shear slips have been found from the numerical investigation in the fracture zone.

An alternative model with a lower permeable zone away from the injection well showed much better history matching after continued injection. This better fit at the later stage of injection strongly suggests the possible presence of zones with less permeability or even an impermeable barrier. Additional analysis may be required in this regard as a further study.

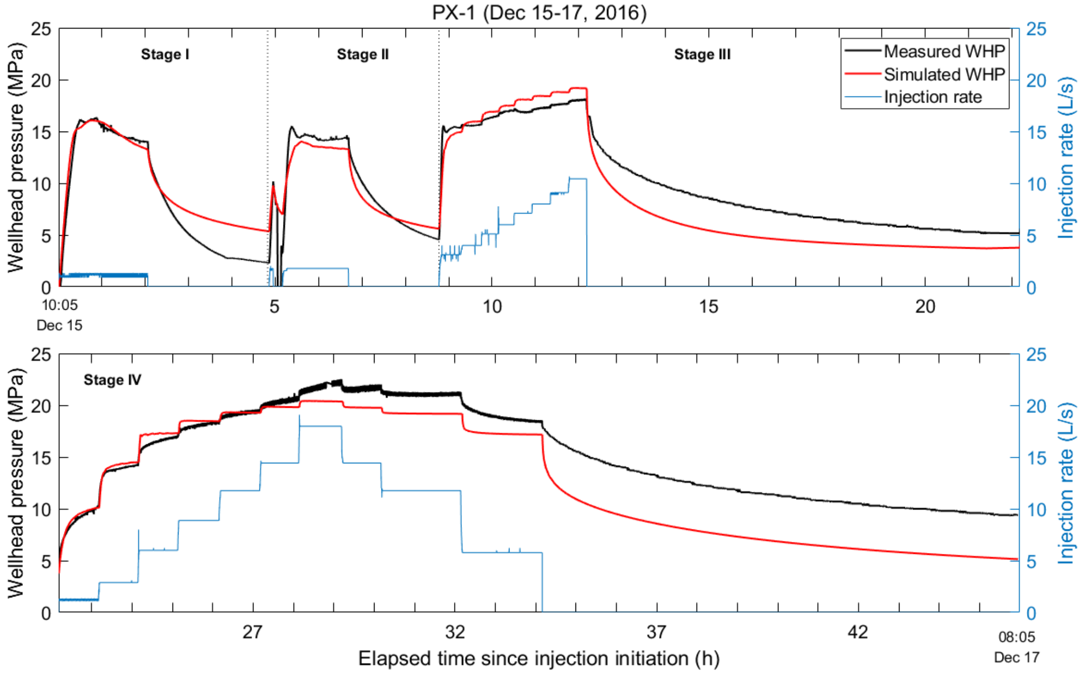

Figure 7: Simulated and measured wellhead pressure of the first 46 hours of the hydraulic stimulation in PX-1 (Yoo et al., 2021).

4.2 Numerical modeling of triggered seismicity

Coupled hydromechanical numerical modeling of five stimulations performed in the PX-1 and PX-2 wells, showed that injection-induced hydraulic jacking and fracture shearing induce immediate stress transfer that plays a significant role in understanding seismic response at the Mw 5.5 fault (Kim et al., 2022). Figure 8 shows the variations in the CFS and fluid pressure at the location of the Mw 5.5 earthquake from the first stimulation to November 15, 2017, with the local magnitude of the observed seismicity located at the Mw 5.5 fault and the PX-1 fracture. The five stimulation periods are marked by blue and yellow shaded areas. The stress change (ΔCFS-$\mu\Delta p$) mainly contributes to the reactivation of the Mw 5.5 fault rather than fluid pressure perturbations. During the first stimulation, the fluid pressure barely increases because of the low permeability of the PX-2 fracture, whereas CFS immediately increases after the initiation of the water injection. Seismic events at the Mw 5.5 fault occurring in the first stimulation are induced by the transfer of stress change from the PX-2 fracture, as the stress transfer occurs immediately. During all stimulation periods, the stress change has a dominant impact on the CFS change at the Mw 5.5 fault. Indeed, the friction coefficient times fluid pressure change is calculated to be 0.028 MPa on November 15, 2017, and it accounts for only 20 % of the total CFS change, which is 0.145 MPa.

Presence of the fractures intersecting the PX-1 and PX-2 openholes (PX-1 and PX-2 fractures) in the Pohang EGS site is based on a comprehensive analysis of various data produced from drilling, hydraulic stimulations, and seismicity monitoring. The role of the PX-1 and PX-2 fractures accounts for the mechanisms of characteristic observations related to induced and triggered seismicity that has not been addressed in previous studies. This includes distinct observations such as the absence of seismic events at the Mw 5.5 fault by the PX-1 stimulations and the Kaiser effect of injection-induced seismicity. The absence of seismic events at the Mw 5.5 fault by the PX-1 stimulations is attributed to the transfer of reduced shear stress at the PX-1 fracture due to shear slip and low permeability of the host rock between the PX-1 fracture and the Mw 5.5 fault that obstruct the diffusion of fluid pressure from the PX-1 fracture to the Mw 5.5 fault.

Similarly, stress transfer is key mechanism of the seismic events by the PX-2 stimulations. During the PX-2 stimulation periods, the CFS change at the Mw 5.5 fault was mainly caused by the transferred stress from the PX-2 fracture, while the pore pressure change was relatively small due to the low permeability of the PX-2 fracture. The continuous pressure diffusion in the low-permeability PX-2 fracture explains the mechanism of post-injection seismicity observed during the PX-2 stimulations with a time delay between active injection and seismicity. Thus, it can be concluded that immediate stress transfer and delayed fluid migration with consideration of the PX-1 and PX-2 fractures played key roles in understanding the characteristic field observations in the Pohang EGS project. The current modeling study suggests that coupled hydromechanical analysis with appropriate consideration of fractures is a powerful approach in understanding the mechanism of injection-induced seismicity in fractured geological media.

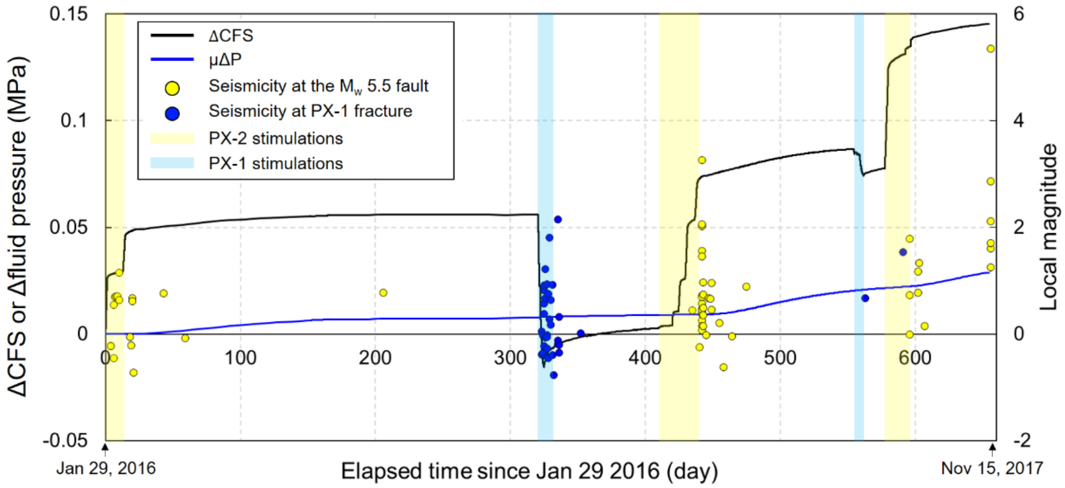

Figure 8: Variations of Coulomb failure stress and friction coefficient times fluid pressure at the location of Mw 5.5 earthquake from January 29, 2016, to November 15, 2017. The local magnitude of observed seismicity located at the PX-1 fracture and the Mw 5.5 fault are plotted with the PX-1 and PX-2 stimulation periods as blue and yellow colors, respectively. Each stimulation period includes shut-in or bleed-off between several injection operations. (Kim et al., 2022).

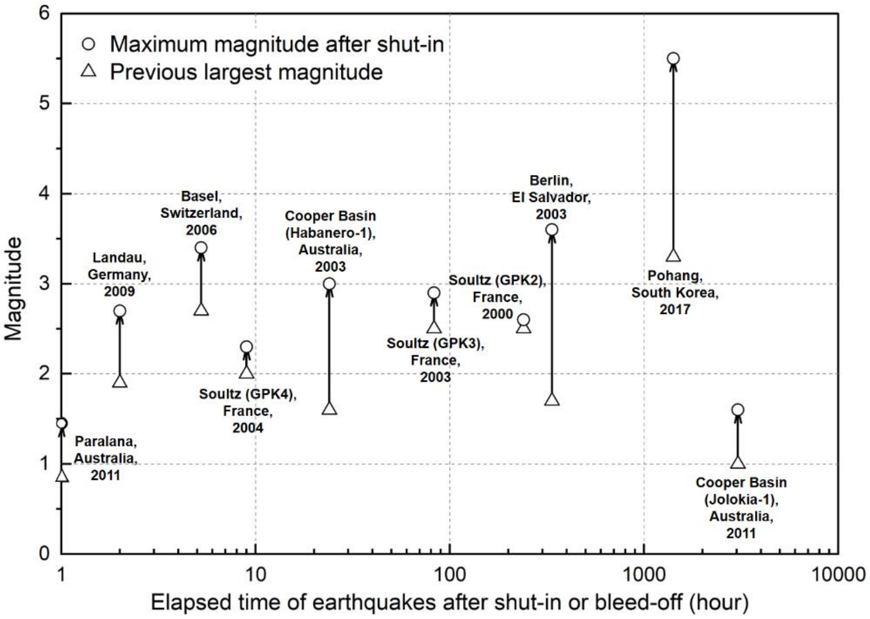

Figure 9: Earthquake magnitude jump with respect to the elapsed time of earthquakes after shut-in or bleed-off in the geothermal projects with hydraulic stimulation. Black arrows indicate the magnitude jump from the previous largest earthquake and the largest earthquake after shut-in (Kim et al., 2022).

Induced seismicity often occurs after the termination of fluid injection in numerous injection-related projects. Such post-injection seismicity was also characteristically observed in the Pohang EGS project. Among 97 events after the start of hydraulic stimulation, only 16 events were induced during the active injection periods (Kim et al., 2022). All seismic events larger than ML 1.0 occurred a few hours or days after shut-in or bled-off. Post-injection seismicity was more remarkable in the PX-2 stimulations than in the PX-1 stimulations. Among 55 seismic events from the PX-2 stimulations, only one single event was induced during the injection period. The Pohang Mw 5.5 earthquake sequences occurred 59 days after the termination of the fifth stimulation, which is a longer delay compared with the previous observation in Pohang or other geothermal operations (Figure 9). In particular, a large earthquake magnitude jump during shut-in from the previous largest earthquake of Mw 3.3 to Mw 5.5 is unprecedented in other geothermal operations (Figure 9). For example, the elapsed time after shut-in was a matter of a few hours or days in Basel or Soultz, and their magnitude jump during shut-in was normally less than 1.0. On the other hand, delays on the order of years have also been reported in other applications such as wastewater injection where much larger amount of volume were injected. This unprecedented large jump during shut-in observed in Pohang poses a major challenge in managing the injection-induced seismicity in EGS operations, especially for traffic light system which relies on the incremental increase of induced seismicity.

5. CONCLUDING REMARKS

Earthquake Mw 5.5 occurred at Pohang EGS project site in Nov 2017 remains the most damaging earthquake in the world associated with Enhanced Geothermal Systems Project history. The magnitude of the earthquake startled the world especially relative to the low injected volume of ~10,000 m^3. There have been numerous technical and social studies related to Pohang EGS project offering various lessons to be learned from this unprecedented event. This presentation intends to present a series of recent studies associated with hydraulic stimulations at Pohang EGS project. A notable findings and lessons from these studies may be summarized as follows;

- Deep rock cores retrieved from the 4.2 km deep geothermal reservoir directly confirmed prevalent fractures existing in the reservoir and provided invaluable information of mechanical and thermal properties in situ. Among other key parameters, we emphasize the need to better characterize the dilation angle, in particular its stress dependency. Nonlinear fracture normal behavior is also an important phenomenon when evaluating the hydraulic jacking of fractures. More extensive laboratory investigation would greatly enhance the understanding on this important mechanism.

- In situ stress estimation is one of the most important prerequisites for understanding EGS. While direction borehole image logging was not carried out in Pohang EGS project, combination of numerous observations of drilling, induced seismicity, hydraulic stimulation and borehole logging provided more reliable stress model. Integrated and progress stress model is needed for EGS project.

- Two contrasting stimulation mechanisms were identified in a very clear manner in two boreholes in Pohang. The stimulation mechanism in the PX-2 well is interpreted as a combination of tensile fracture extension and hydraulic jacking of mated fracture. The stimulation mechanism of the PX-1 well is interpreted as a combination of hydraulic shearing and hydraulic jacking of unmated or shear-dilated fractures. Despite the relatively close distance of approximately 600 m in the same rock formation, the two wells showed distinctly different hydromechanical characteristics. It is postulated that drastic differences between the two wells are possibly affected by heavy mud and LCM during the drilling and completion of PX-2. The contrasting hydromechanical responses observed in the same reservoir at the two nearby wells emphasizes the importance of proper design and operation of drilling and completion with close consideration of stimulation strategy.

- Comprehensive coupled hydro-mechanical numerical modeling was carried out for hydraulic stimulations to improve the understanding on the coupled behavior caused by the hydraulic stimulations. This study demonstrates that the key hydro-mechanical processes of shear slip and dilation and hydraulic jacking observed in the fractured reservoir can be successfully reproduced in the numerical modeling. Non-linear hydraulic jacking in the PX-2 hydraulic stimulation was confirmed through close history matching and comparison of simulated and observed aperture changes. Possible hydraulic fracturing or opening of pre-existing fractures observed in PX-2 was also found in the numerical modeling.

- Coupled hydromechanical numerical modeling of five stimulations performed in the PX-1 and PX-2 wells, showed that injection-induced hydraulic jacking and fracture shearing induce immediate stress transfer that plays a significant role in understanding seismic response at the Mw 5.5 fault. Variations in the CFS and fluid pressure at the location of the Mw 5.5 earthquake from five stimulations are numerically reproduced. CFS immediately increases after the initiation of the water injection even prior to the migration of fluid. During all stimulation periods, the stress change has a dominant impact on the CFS change at the Mw 5.5 fault.

- The Pohang Mw 5.5 earthquake sequences occurred 59 days after the termination of the fifth stimulation, which is a longer delay compared with the previous observation in Pohang or other geothermal operations. In particular, a large earthquake magnitude jump during shut-in from the previous largest earthquake of Mw 3.3 to Mw 5.5 is unprecedented in other geothermal operations. This unprecedented large jump during shut-in observed in Pohang poses a major challenge in managing the injection-induced seismicity in EGS operations, especially for traffic light system which relies on the incremental increase of induced seismicity.

- Water is the main medium to transport the heat and reservoir permeability is critically important component of geothermal energy. EGS targets to achieve sufficient permeability to maintain economical supply of geothermal power or heat. Therefore, ‘geothermal energy’ can be duly called ‘hydrogeothermal energy’ in order to do justice on the underlying principle and emphasize the critical role of securing sufficient permeability and water.

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