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Understanding the Pohang EGS Reservoir and the Need for Advanced Traffic Light Systems

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ABSTRACT

On November 15, 2017, a magnitude 5.4 earthquake occurred near a geothermal project under construction in Pohang, South Korea. Based on the information available and its own analysis of the situation, Geo-Energie Suisse (GES) decided to immediately inform the Government of the Canton Jura. The Government reacted on November 28, 2017, by asking Geo-Energie Suisse to provide a report on the Pohang events and their possible implications on the Haute-Sorne EGS project. Therefore, based on information available through our participation in the DESTRESS project, we evaluated micro-seismicity and hydraulic data from the stimulation campaigns, geological well data, well logging data, information from borehole drilling and information on the regional stress field. Only by an integration of all this information, we were able to derive a plausible conceptual model for the basic understanding of the Pohang EGS reservoir and the probable triggering of the magnitude 5.4 earthquake.

The Pohang EGS project has had a well-defined traditional magnitude based traffic light system. However, our evaluation highlights the need for advanced traffic light systems taking into account the spatial distribution of seismicity and integrating continuously throughout all project stages information about fault structures. Such a procedure has been the basis for the permit by the authorities of the Canton Jura for the Haute-Sorne project and is also recommended by the Good practice guide for managing Induced Seismicity in Deep Geothermal Energy Projects in Switzerland published by the Swiss seismological survey in 2017.

With our contribution we want to sensitize the geothermal community to understand seismic risk assessment as an accompanying process through all project stages and as a multidisciplinary task, and we want to stress the importance for an advanced traffic light system allowing a timely and qualitatively good localization of micro-seismic events, especially in the case that EGS projects are close or within fault structures.

1. INTRODUCTION

The findings and conclusions presented in this paper are part of the report GES submitted in January 2019 to the Government of the Canton of Jura. Timely parallel to the GES work but independently from each other the South Korean government had created official investigation commissions (ORAC/KERT) of the Pohang earthquake which published their report on March 20, 2019 (Geological Society of Korea (2019)).

It is important to note that the main conclusions of both reports on the understanding of the trigger mechanisms of the Pohang earthquake are in very good agreement, although several details have been interpreted to some degree differently. These mostly minor differences concern mainly the detailed geometry and absolute values for (1) the stress field, (2) the locations of micro-seismicity and (3) the modeling of the effects of the high pressure injections into the vertical borehole PX2. It is out of scope to compare the details of the two reports here.

Because seismic risk evaluation shall be done throughout all stages of a geothermal project, we start in chapter 2 with a review of the site selection process and the stimulation concept. Chapter 3 highlights the importance to take into account for risk assessment many drilling aspects such as mud weight, mud losses and lost circulation materials including the possible consequences for formation/reservoir damage. Also, cuttings can contain very important information on the size, the importance and the maturity of faults. Such information is ideally complemented by borehole logging data, and whenever possible should include borehole televiewer measurements. In chapter 4, 5 and 6 we develop a conceptual model for the basic understanding of the Pohang reservoir and the triggering of the earthquake including the importance of the very high injection pressures of up to 90 MPa. In chapter 7 we show that the traditional magnitude based traffic light system failed in Pohang, but that recognizing the spatial alinement of micro-seismicity on a structure several hundred of meters away from the injection point during the very first stimulation would have allowed (1) to halt the project at very early times, (2) to evaluate the seismic risks and then (3) to take an informed decision on continuing the stimulation or not. Such a procedure – which we refer to as an advanced traffic light system - is foreseen in the permit delivered 2015 by the Cantonal authorities for the Haute-Sorne multi-stage stimulation EGS project.

2. SITE SELECTION AND STIMULATION CONCEPT

In Switzerland both the Basel EGS project in granite and the St. Gallen project based on a hydrothermal doublet concept in a large regional fault in sedimentary rocks had to be abandoned 2006, respectively 2013 after induced seismicity with magnitudes 3.4, respectively 3.5 had occurred. The objectives of both projects were to deliver energy to the cities district heating systems and to co-produce electricity.

The lessons learnt from the Basel project were among others (1) to reduce the stimulated areas of fractures by applying a multi-stage stimulation concept for EGS in the Swiss crystalline basement instead of massive stimulation of long open borehole sections and (2) to locate deep geothermal projects in areas of relatively low seismic risk (Meier et al., 2015). Low seismic risk in Switzerland refers to a relatively low natural seismic hazard and project sites outside of urban areas. Please note that Basel is considered to be one of the most seismically active areas in Switzerland.

The circumstances of the St. Gallen project are more complex because seismicity occurred as a consequence of mud injection to control a gas kick. Despite the complexity of the geology it appears to be clear in hindsight that the regional fault passing the city of St. Gallen is seismic active and well oriented in the regional stress field for hydro-shearing.

Both cases highlight the importance of site selection and the stimulation concept for the risk evaluation of geothermal projects. Therefore, we examined for our report to the government of Canton Jura also the site specific conditions and the stimulation concept of the Pohang EGS project for the comparison with the Haute-Sorne multi-stage stimulation project.

2.1 Site selection

The region along the 250 km long Yang-san fault passing at a distance of about 10-15 km from the EGS project site is considered in scientific literature to be one of the most seismic active regions of South Korea (e.g. Ree and Kwon (2005)). Furthermore, recent scientific studies (Hong et al. 2015, Hong et al., 2018) indicate a seismic destabilisation of the region as a consequence of the 2011 Tohoku M9 earthquake in Japan, which may also have a relation with the 2016 Gyeongju M5.8 earthquake at a distance of about 40 km from the EGS site.

According to Kim et al. (2018a) five candidate sites for an EGS project were investigated and the site selection was based on five categories (1) type of geothermal energy (2) the quality of existing geological data (3) geothermal gradient (4) regional infrastructure (5) allowed time for site investigation. Pohang was chosen as the most suitable site for the first EGS project in South Korea mainly because of confirmed higher geothermal gradients with existing deep boreholes and an easier access to the city. Kim et al. (2018a) do not mention seismic risk aspects among the site selection criteria.

2.2 Stimulation concept

The Pohang EGS concept is based on stimulation of existing major fractures zones (Park et al. 2017). Therefore, geophysical campaigns were carried out upfront since 2003. In particular, indications from magnetotelluric surveys and geothermal gradient mapping were interpreted as the presence of a large geothermal fluid-bearing fault zone below the project site. Several exploration wells were drilled following these campaigns. The deepest one, BH-4, reached the granodioritic basement at 2.2 km depth and confirmed the presence of the expected fluid-bearing fractures.

2.3 The importance of seismic risk studies specially in case of stimulating potentially active faults close to urban areas

We are not the first to bring up the discussion about the seismic risks of stimulating larger fracture zones or faults. Many studies and scientific articles discuss the risks of fault stimulation. For example, Majer et al. (2007) and Zoback (2012). We first cite Majer et al. (2007):

"Extent of faults and fractures: the magnitude of an earthquake is related to the area of fault slippage and the stress drop across the fault. Larger faults have more potential for a larger seismic event, …." and ..*"Several conditions must therefore be met for significant (damaging) earthquakes to occur. There must be a fault system large enough to allow significant slip, forces must be present to cause this slip along the fault (as opposed to some other direction), and these must be greater than the forces holding the fault together (the sum of the forces perpendicular to the fault, plus the strength of the material in the fault)."*

Zoback (2012) recommends in "Managing the seismic risk posed by wastewater disposal" the following:

"Five straightforward steps can be taken to reduce the probability of triggering seismicity whenever we inject any fluid into the subsurface. First, it is important to avoid injection into active faults and faults in brittle rock. Second, formations should be selected for injection (and injection rates should be limited) to minimize pore pressure changes. Third, local seismic monitoring arrays should be installed when there is a potential for injection to trigger seismicity. Fourth, protocols should be established in advance to define how operations will be modified if seismicity is triggered. And fifth, operators need to be prepared to reduce injection rates or abandon wells if triggered seismicity poses any hazard. These five steps provide regulators and operating companies with a framework for reducing the risk associated with triggered earthquakes."

Majer et al. (2012) recommend in the "Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems of the U.S. Department of Energy" a stepwise pre-screening for site selection:

"A bounding type of analysis should be performed to quickly establish the likelihood that the project would obtain regulatory approval to proceed. The likelihood should be categorized as one of four levels: (I) High-to-very high, (II) Medium-to-high, (III) Medium-to-low, or (IV) Low-to-very low. Potential EGS geographic areas may vary significantly in terms of their populations and the existing level of seismicity. The screening analysis for some projects may be quite clear; for example, a remote site with little natural seismicity would be categorized as a clear Level I, and an urban site with active faulting would be a clear Level IV. For those projects in all but category Level IV (which should be discarded after initial screening), this process will highlight the areas of risk that need to be addressed."

From the classification of Majer et al. 2012 we would infer that Pohang EGS site would fall either in category Level IV or Level III, for which a detailed risk analysis is recommended. We know that for the stimulation activities a traditional traffic light system was operational, but we do not know to which degree seismic risk had been considered for selection of the site and the stimulation concept.

3. DRILLING DATA AND BOREHOLE LOGGING

In view of future projects we emphasize in this chapter the importance (1) to acquire and analyze carefully drilling data and borehole logs with the aim of identifying potentially intersected active faults and (2) to integrate such data immediately in a continuous seismic risk evaluation.

3.1 Drilling data

Two vertical wells, PX1 and PX2 have been drilled from 2012 until the end of 2015. Because the PX1 well had to be given up below 2485 m a side-track, PX1-ST has been drilled in the second half of 2016. In total 5 hydraulic stimulation campaigns were carried out in PX-2 and PX1-ST between January 2016 and September 2017.

The first well of the Pohang EGS project, PX1, was drilled in two phases. The first stage was drilled in 2012 to a depth of 2250 m. Drilling was resumed in 2013 and the well was deepened to 4127 m. On October 19, 2013, the drill string broke off while the string was being pulled out of the hole. 2267 m of drill string and the bottom-hole assembly (BHA) were lost in the hole. Several consecutive fishing attempts were carried out in 2014 but only succeeded in recovering 656 m of the broken string. As a consequence, the well was finally considered lost below 2485 m. The reported mud density is in the order of 1.2-1.25 kg/l. Only few mud losses occurred or are reported at a depth between 3400 and 3500 m.

PX2 was drilled from April to December 2015 to a final depth of 4348 m. Three logging surveys were run between December 14 and 17, 2015. The reported mud density during drilling PX2 was in the order of 1.6 kg/l (max. 1.64 kg/l) considerably higher than in PX1. The reasons for the high mud density in PX2 are not completely clear. The effects of a high mud density of 1.6 kg/l are important: in comparison to drilling with fresh water the overpressures are about 220 bar at a depth of 3800 m and 255 bar at 4250 m, or compared with the mud density of 1.2 kg/l during PX1 drilling, the overpressures are 152 bar at 3800 m and 170 bar at 4250 m. These overpressures are high enough to increase permeabilities by fracture shearing or opening, and if higher natural fracture permeabilities are encountered during drilling to provoke strong mud losses. Indeed, some mud losses were reported between 3000 and 3200 m. However, strong mud losses occurred below about 3800 m.

The mud losses were stopped with an injection of LCM (Lost Circulation Material). We cannot exclude that the formation properties, especially the intersected fault zone properties and the formation at the injection point in PX2 below 4208 m, may have been altered negatively by injecting larger quantities of LCM. Also, we cannot exclude that the low permeable zone observed between PX2 and PX1-ST and believed to be a natural low permeable fault core zone (see later discussion in 3.2) has not been created artificially by injection of LCM. However, we do not have detailed data to investigate such a hypothesis.

In order to establish a hydraulic communication for geothermal circulation between two boreholes, a side-track (PX-1ST) was drilled in 2016 at a depth of 2419 m from PX1 and deviated with a maximum angle of 28° to a final depth of 4362 m. The mud density was in the order of 1.2 to 1.25 kg/l and only a few mud losses occurred. The vertical part of PX1 below the side-track was cemented. The final wellbore schematics is shown on Figure 1.

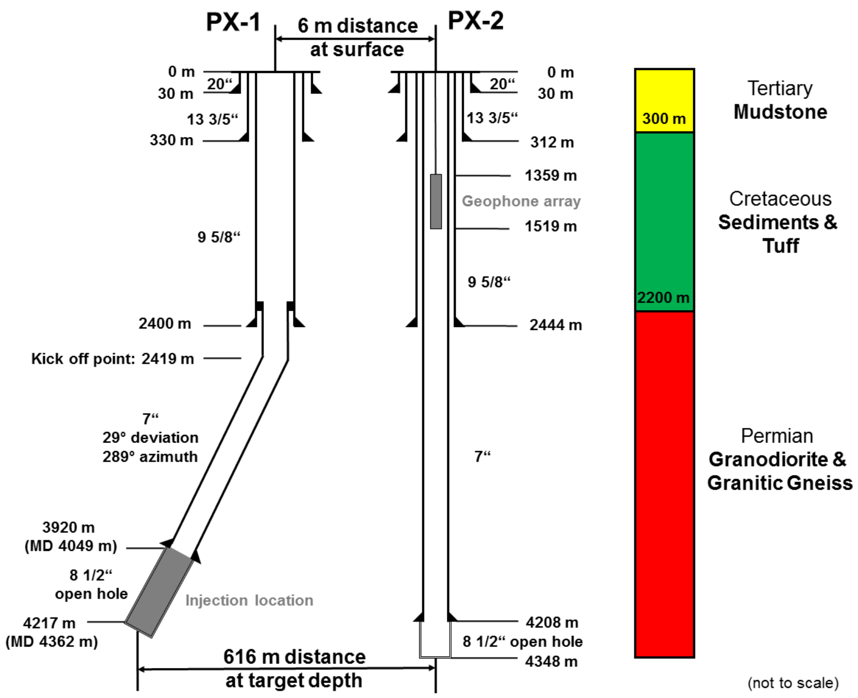

Figure 1: Schematic drawing of the final borehole configuration PX1 side-track and PX2 well completions (from H. Hofmann, DESTRESS internal document).

3.2 Geology of the PX2 borehole section from 3760 – 3890 m

A complete and extensive description and analysis of the geological borehole data cannot be provided here, details can be found in Geological Society of Korea (2019). Therefore, we summarize only the conclusions for the PX2 borehole section from 3760 – 3890 m, because this interval can be interpreted as an important fault zone. The upper part (3760 – 3815 m) is dominated by mafic and dioritic dykes. Followed in depth by an important mud loss zone (3815 – 3840 m) with almost no cuttings returned to the surface, the lower part of the interval is dominated by "granitic gneiss" with mafic dyke intrusions. Our conclusions are summarized in a conceptual fault zone model in Figure 2, which is based primarily on the following arguments:

- The mafic rocks underwent hydrothermal alteration at the top of the interval (3760-3770 m).
- High density of "microcracks" and quartz veins observed from the cuttings over most of the interval.
- Presence of fault gouges (up to 40% between 3790 and 3815 m).
- Important mud losses between 3816 and 4348 m, among which 240 m^3 between 3831 and 3835 m) with associated induced seismicity (Kim et al. (2018b), Geological Society of Korea (2019)).
- Temperature increase and change in the temperature gradient from 3810 to 3840-3850 m.

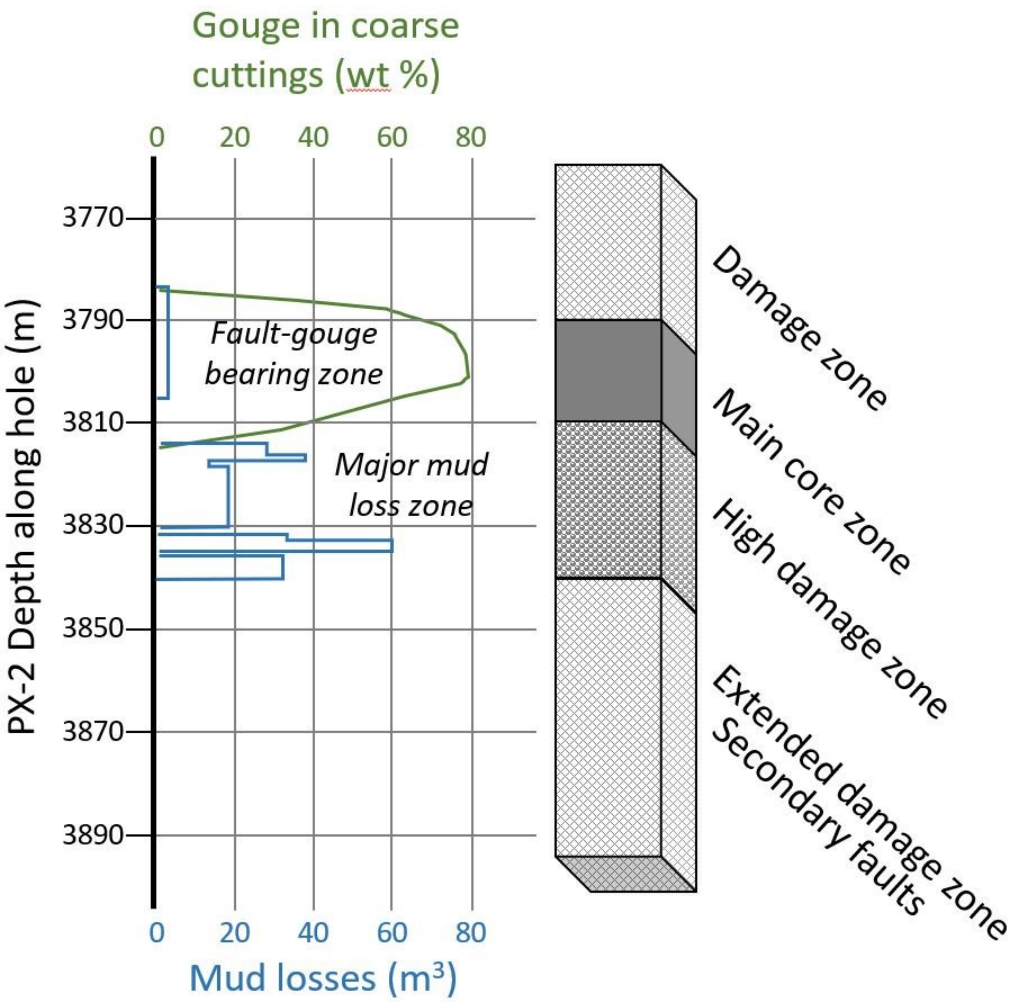

Figure 2: Conceptual fault model applied to PX-2 3760 – 3890 m interval.

4. UNDERSTANDING THE POHANG EGS RESERVOIR AFTER VARIOUS STIMULATION CAMPAIGNS AND THE SPATIAL RELATION WITH THE M5.4 EARTHQUAKE

An overview of the stimulation activities is provided in Figure 3, in the upper part for the sidetrack of borehole PX1 and in the lower part for borehole PX2. The spatial distribution of seismicity in the reservoir is presented in Figure 4, Figure 5 and Figure 6. The details of seismicity analyses during all stimulation campaigns and the spatial relation with the M5.4 earthquake can be found in Bethmann et al. (2018).

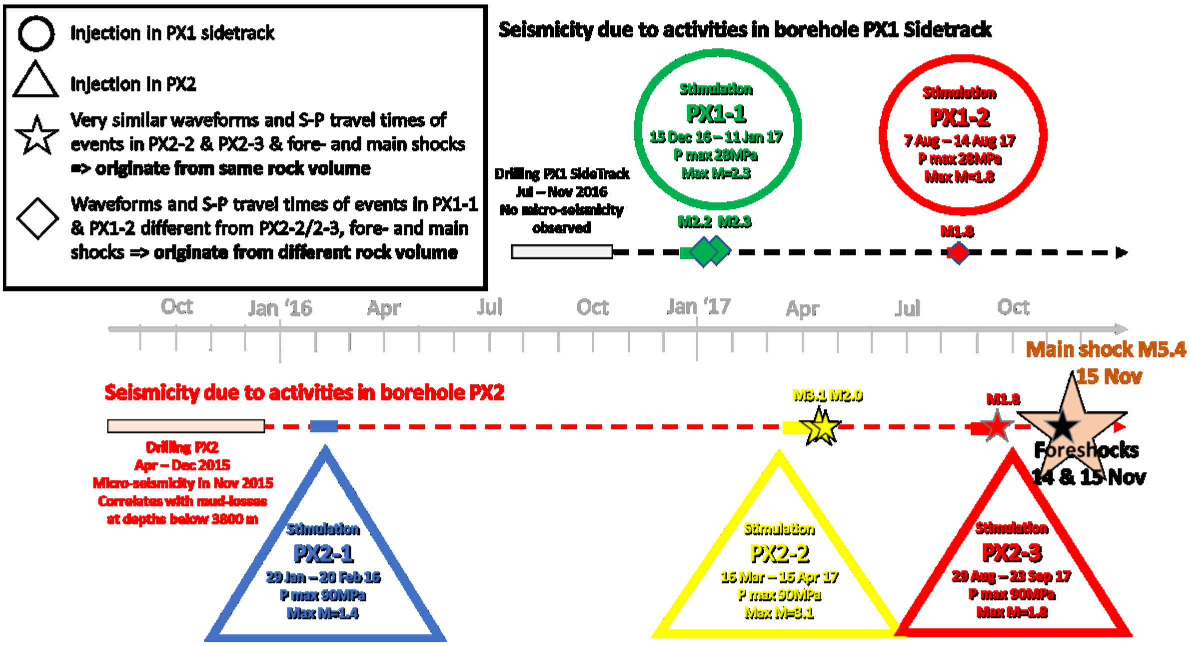

Figure 3: Upper part: the timeline of the activities in PX1 sidetrack are shown with round symbols (the colours refer to the stimulation campaign: green for PX1-1, red for PX1-2). Lower part: the timeline of the activities in PX2 borehole are shown with triangles (blue for PX2-1, yellow for PX2-2 and red for PX2-3). The same symbol and colour codes apply to the following figures. Only this figure: High magnitude events with high waveform similarities and similar S-P travel times are labelled with stars (main shock brown, foreshocks black, PX2-2 yellow and PX2-3 red), these events originate from the same stimulated rock volume. The higher magnitudes during the PX1-1 and PX1-2 as well as all other localized seismic events for PX1-1 and PX1-2 do not have waveforms similar to the foreshocks, they originate from a rock volume different from where the events of PX2-2, PX2-3, the fore- and the main shock are located.

4.1 Seismicity due to stimulation activities in PX1-ST (the sidetrack of borehole PX1)

The first stimulation campaign PX1-1 was performed with pressures of up to 28 MPa in December 2016 and January 2017. The hydraulic and seismicity data of a 3 days constant rate injection period at the beginning of the PX1-1 stimulation campaign are discussed in detail in Meier et al. (2019) with focus on an observed linear no-flow boundary between the PX1 sidetrack and the PX2 borehole (see insert picture in upper right corner of Figure 5). This no-flow boundary is considered to be the low permeable main fault core material of the M5.4 earthquake fault (see chapter 4.3) passing in between the injection intervals of PX1 sidetrack and PX2 and separating hydraulically both sides of the fault. According to our conceptual geological model presented in Figure 2, the PX2 borehole cuts this low permeable main fault core material between about 3790 and 3810 m depth.

Please note that one could also speculate that such a low permeable zone could have been created artificially by a large amount of injected LCM (Lost Circulation Material) used for stopping the mud losses crossing the highly disturbed and very permeable zone of the fault. Please note also that the PX1 sidetrack does not intersect the main fault.

Because of the sealing effect of the fault core zone no seismicity due to injection in PX1 sidetrack (green circles in Figure 4 and in Figure 5) occurred on the side of the hanging wall of the M5.4 earthquake fault zone. A subvertical structure has been stimulated during the early times of the PX1-1 campaign (see grey plane in Figure 4) oriented almost perpendicular to the suggested M5.4 earthquake fault (see Figure 5). After some days the stimulated volume extended also outside of the planar subvertical PX1 structure predominantly towards north-east. After the occurrence of the first event with M> 2.0 the injection was stopped according to the traffic light system and the water was allowed to flow back.

In August 2017 an additional stimulation campaign PX1-2 was conducted in PX1 sidetrack managed by Geoforschungszentrum Potsdam (GFZ) as part of the DESTRESS project with the objective to demonstrate cyclic stimulation as a soft stimulation technique. Because of the weak seismic signals of the permanently installed monitoring system and because not having had the resources for analysing the data set from the seismometer chain installed by GFZ, the GES team localized only two stronger events, both on the subvertical structure previously stimulated during PX1-1. Because one of the events attained a magnitude M1.8 the stimulation campaign was terminated according to a traffic light system specifically determined for the PX1-2 campaign.

Among all localized events for PX1-1 and PX1-2 no event was found with a waveform similar to the waveforms of the foreshocks of the M5.4 earthquake, and also no waveform similarity was detected either with the events of PX2-1 and PX2-2. Only for PX2-3 a moderate degree of waveform similarity was observed with PX1-1, which is not surprising since some events of the PX2-3 campaign are located within the PX1-1 reservoir and we conjecture that during PX2-3 some pumping took place also in PX1-ST. Thus, except for PX2-3, waveform analysis confirms the existence of two separate rock masses one stimulated by injecting in PX1 and one by injecting in PX2.

4.2 Seismicity due to stimulation activities in borehole PX2

Because the stimulation of PX2 was not part of DESTRESS, only seismicity data published by Geological Society of Korea (2019) and by Kim et al. (2018b) can be shown here for PX2. However, because our own seismic event localizations are in good general agreement these published data are utilized here for the conceptual understanding of the reservoir.

During drilling borehole PX2 - before the first stimulation in PX2 started - seismicity has been reported by Kim et al. (2018b). We believe that this seismicity is associated to the strong mud losses during PX2 drilling through the highly disturbed fault zone (see Figure 2). Because we do not have access to seismicity data of this time period, we conclude this based on the temporal coincidence (with an uncertainty approximately +/- 1 days) of the seismicity reported by Kim et al. (2018b) and the mud losses from the drilling reports.

The first stimulation campaign PX2-1 was conducted in January and February 2016 by injecting water during about two weeks cyclically with very high pressures of up to 90 MPa and an injected volume of about 1970 m^3 (Park, 2017). The seismic events which could be localized (denoted with blue triangles in Figures 4, 5, 6 and 9) are several hundreds of meters away from the injection point in the open borehole interval below the casing shoe in PX2. Some of the events show waveforms very similar to events of PX2-2, PX2-3 and the foreshocks of the M5.4 earthquake (Bethmann et al., 2018).

The same has been observed for the second stimulation campaign PX2-2 (yellow triangles in in Figures 4, 5 and 6) following a similar injection procedure as in PX2-1. At the end of the stimulation in PX2-2 two larger events occurred with M3.1 and M2.0. The waveforms and the S-P travel times of the fore- and aftershocks of the M3.1 event and of the M2.0 event are very similar to the waveforms and S-P travel times of the foreshocks of the M5.4 earthquake (Bethmann et al., 2018).

The third stimulation campaign PX2-3 followed a similar procedure as the earlier ones with the objective to circulate water between PX2 and PX1. However, despite of the again very high injection pressures in PX2 of up to 90 MPa no circulation could be achieved between the two boreholes, probably because of the low permeable fault core zone located between the two boreholes. The seismic events of PX2-3 are denoted with red triangles in Figures 4, 5 and 6. Most of the PX2-3 events are located within the volumes already stimulated during PX2-1 and PX2-2. Most importantly, the waveforms and the S-P times of at least two PX2-3 events (one of them M1.8) are very similar to the foreshocks of the M5.4 earthquake. Furthermore, the PX2-3 M1.8 event is similar to the foreshock of the PX2-2 M3.1 event.

Therefore, from the above we conclude that the rock volume where the epicentre of the M5.4 earthquake is located has been stimulated previously during PX2-1, PX2-2 and PX2-3.

The orientation of the best fit PX2 plane in Figures 4 and 5 is – within the possible resolution – similar to the suggested mainshock strike derived independently from the aftershock cloud by other authors (Bethmann et al., 2018). However, the estimated dip of the resolved PX2 plane is shallower than that derived from the mainshock focal mechanism or the aftershock cloud by other authors. This is not surprising, because as discussed in Bethmann et al. (2018) the absolute location, strike and dip estimates are affected by the data complexity driven localisation biases of the individual events.

In all PX2 stimulation campaigns no seismicity was observed close to the injection point in the PX2 borehole. It is noteworthy that the permeability of the injection fracture supposed to be somewhere below the casing shoe at 4208 m did not increase permanently despite the very high pressure injection cycles exerted during the three stimulation campaigns (PX2-1, PX2-2 and PX2-3), each with a duration of about two weeks. The data during the many injection and shut-in cycles suggest a pressure dependent permeability similar to a fracture opening and closing (for PX2-1 see Park et al., 2017). Whether this fracture is natural or artificially created by fracturing and how it is oriented cannot be determined because no acoustic borehole image logging has been done, neither before nor after one of the stimulation campaigns. In any case, this structure behaves aseismic, which could be a consequence of injecting lost circulation material to stop the mud losses during drilling or clay rich fault gouge material, or a pure tensile opening without a shear component.

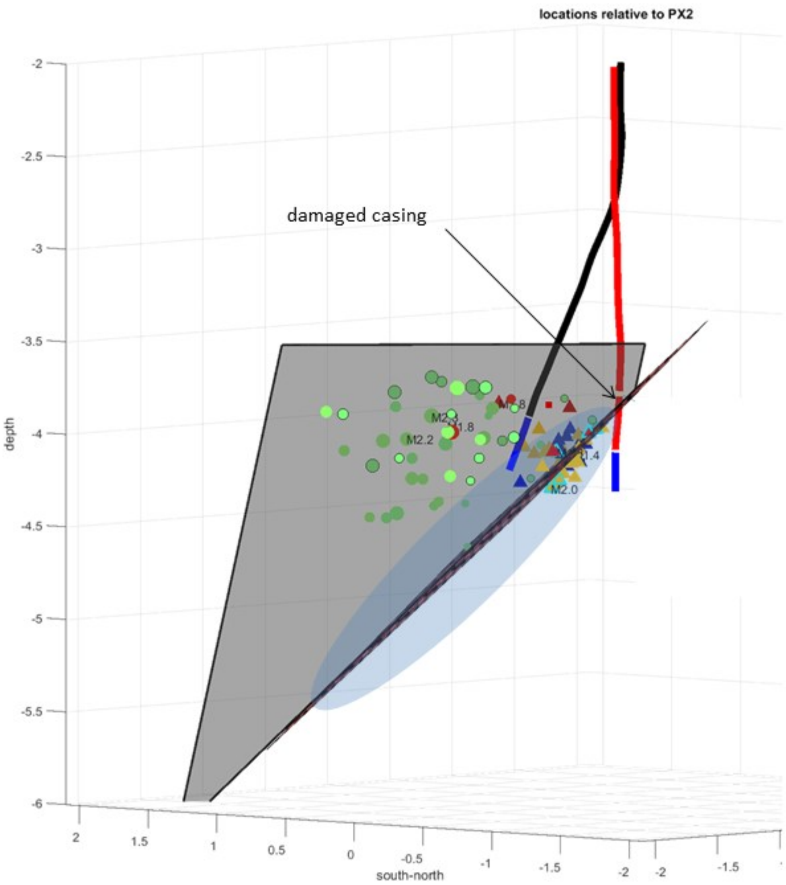

Figure 4: Located seismic events from all periods, colours as in Figure 3. The data for PX2 (all triangles) are from Geological Society of Korea (2019), our own event localizations scatter within the blue ellipsoid. .

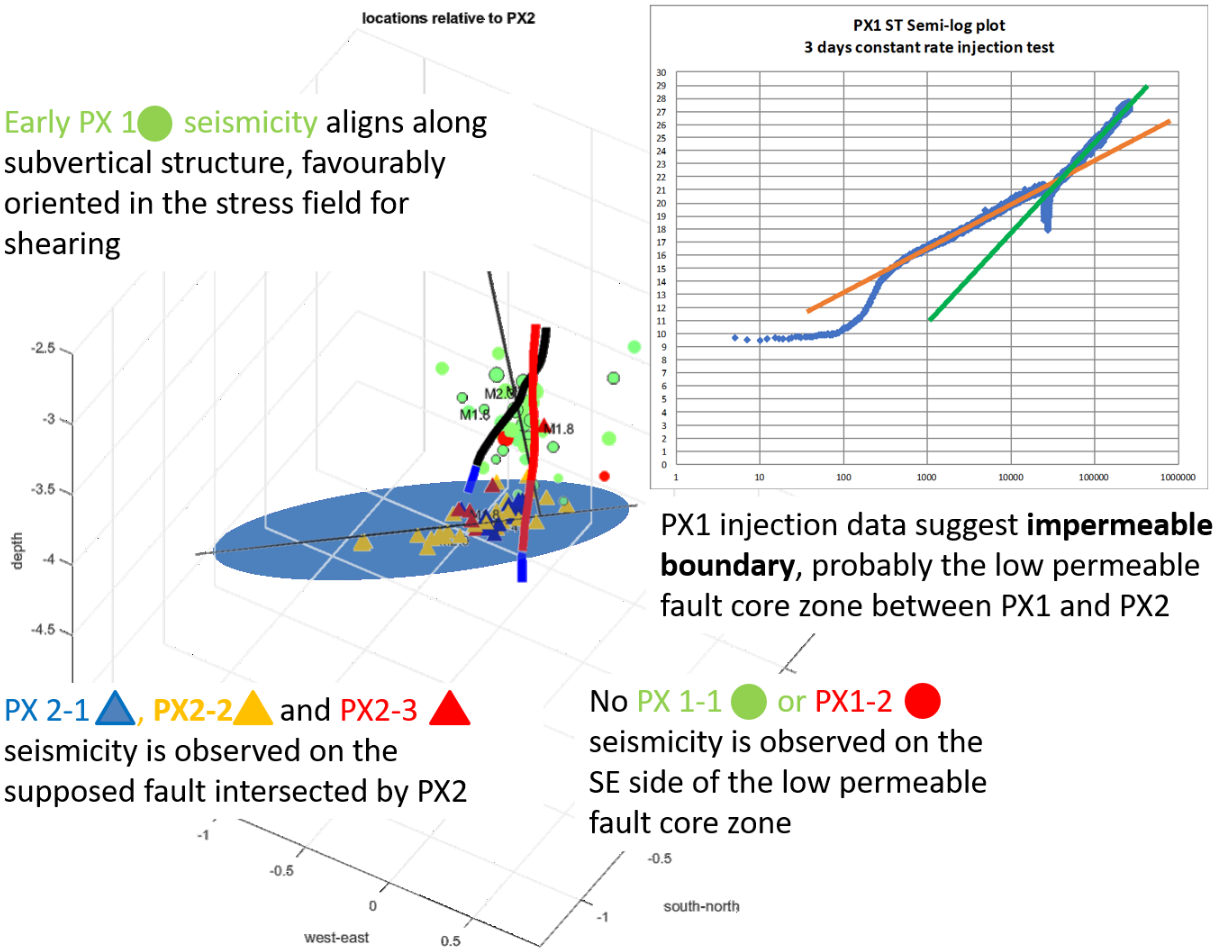

Figure 5: Geometry of the structures interpreted from the seismic clouds of PX1 (circles) and PX2 (triangles) injections, colours as before. Inset is taken from Meier et al.(2019): it shows a semi-log plot of injection pressures (MPa) versus time (s) during the 3-days constant rate injection period. The doubling of the slope is characteristic for a linear non-flow boundary at some distance from the injection point in PX1. The data for PX2 (all triangles) are from Geological Society of Korea (2019), our own event localizations scatter within the blue ellipsoid.

4.3 Location of foreshocks and the rupture plane of the M5.4 mainshock

The foreshocks and the mainshock are specifically difficult to locate with the available recordings, but can be constrained (Figure 6) in depth to around 4 km, based on well-constrained distance from deep borehole sensor, and consistent with the best estimate from InSAR analysis and to within the previously stimulated volume of PX2 (based on waveform similarity analysis and S-P travel-time comparison), i.e. in close vicinity of the fitted PX2 plane. We note that we find similarity with some higher magnitude PX2-2 and PX2-3 events, but with none of the PX1 events, strengthening the finding of the distinct nature of the clouds. Therefore, we conclude that the epicentre of the main shock is located within the fault area previously stimulated in PX2-1, in PX2-2 and in PX2-3.

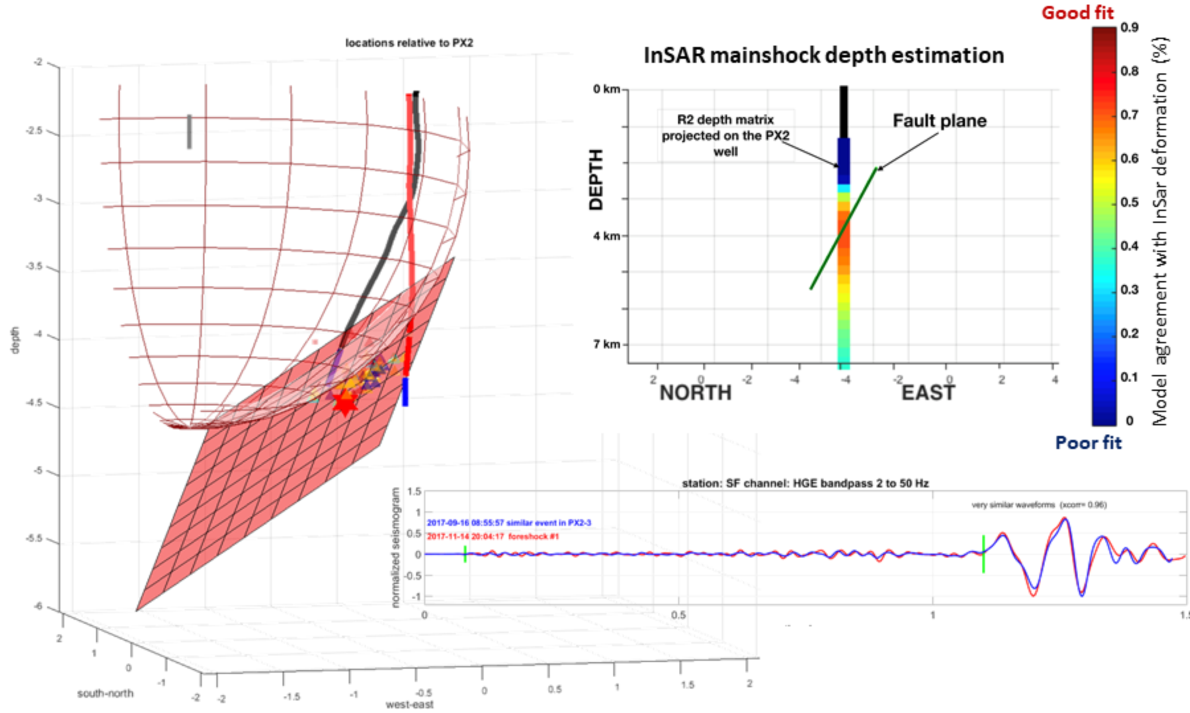

Figure 6: Only PX2 events and main shock shown from Geological Society of Korea (2019). Depth and location constraints derived for the foreshocks and mainshock: S-P traveltime-distance sphere around the deep sensor BT in BH4 (left) is consistent with depth of best fit solution from modelling InSAR displacement observations (top right, from Heimlich et al.(2018). (Bottom right) shows the same S-P times for foreshock #1 and PX2-3 M1.8 on station HGE at the surface of BH4 (located 2.5 km from the EGS site) and the high similarities in waveforms, i.e. those events come from the same location. The S-P traveltime-distance sphere intersects the supposed fault not far from the localization of the main shock by Geological Society of Korea (2019).

All the following observations are compatible with a rupture taking place within the impermeable gouge-filled core of the fault crossed between 3790 and 3810 m in PX-2.

The geometry of the Nov. 15, 2017 M=5.4 rupture plane has been assessed by KIGAM (2018) from the shape of the seismic cloud of the aftershocks sequence. The main rupture plane has a strike azimuth of 222° N and a dip of 61° towards NW. The geometry of the rupture plane was confirmed by models of the surface deformation revealed by satellite radar interferometry (InSAR) (Heimlich et al., 2018). This study also helped precising the location and depth of the rupture plane. According to this model, the rupture plane runs between the open hole sections of wells PX-1ST and PX-2 and intersects PX-2 at a depth close to the interval described in the previous section.

During an attempt to run a new logging survey in PX-2 in summer 2018 an obstruction in the casing was encountered at 3781 m (Geological Society of Korea, 2019). The obstruction probably results from a deformation of the casing caused by the M=5.4 earthquake. This obstruction must not necessarily be directly associated to the main rupture plane but sets an upper bound to its depth in the well. It is noteworthy that in PX1 sidetrack the logging tools were run without problems into the open borehole section.

5. MODELING THE EFFECTS OF VERY HIGH PRESSURE INJECTIONS IN THE VERTICAL WELL PX2

5.1 Very high injection pressures

Kim et al. (2018a) and Park et al. (2017) report the very high and cyclic well head injection pressures of up to about 90 MPa during about 2 weeks stimulation campaign for the first stimulation in PX2 at depths between 4208 and about 4348 m. Also, the second and third PX2 stimulation have been conducted in a similar way (Geological Society of Korea, 2019). At these depths the total injection pressure equals 132 MPa (=sum of the water column in the well of 42 MPa (10 MPa/km) plus the injection pressure at the well head of 90 MPa). The weight of the rock mass (vertical stress) at 4200 m equals about 109 MPa (= 4.2 km (depth) * 26 MPa/km (density of the rock). In conclusion, the downhole injection pressure of 132 MPa has largely exceeded the vertical stress by a factor of 1.2. This simple calculation illustrates the enormous pressure which has been applied repeatedly in PX2. For comparison, the maximum injection pressure in Basel of about 30 MPa at the well head or 76 MPa at a depth of 4600 m has been considerably smaller than the vertical stress of 120 MPa by a factor of 0.63. In France the maximal injection pressure at the well head is limited by law to 10 MPa irrespectively of the depth of the injection.

5.2 Long-lasting over pressure along the earthquake fault

As explained in the chapters 4.2 and 4.3, because the foreshocks are located within the rock volumes previously stimulated in PX2-1, PX2-2 and PX2-3, the probability is high that the M5.4 earthquake has been triggered by the last two stimulation activities PX2-2 and PX2-3 with very high pressures. However, it is difficult to understand the physical processes in detail of the triggering mechanism and to explain the rather long duration between the stimulation activities in April 2017 and in September 2017 and the occurrence of the M5.4 earthquake in November 2017. Therefore, we conducted a modelling study (Alcolea et al. 2020, in preparation for WGC2020) using the numerical code BRIGHT to take into account poro-elastic hydro-mechanical effects in a 2-D vertical plane containing the low permeable rupture plane and the point source where water is injected through the open borehole section of PX2 below the casing shoe at 4208 m. For simplicity and because we have no data on the orientation of the different rock materials discerned by well logging along the PX2 borehole, we assume that the different materials extend parallel to the rupture plane. We believe that these simplified assumptions are justifiable because the architecture of fault zones are highly anisotropic (Figure 2).

The focus of the model was to calculate the effects of high-pressure injections utilizing the actual injection schemes in PX2, but assuming that there is no direct highly conductive pathway from the point of injection to the rupture plane. We justify this assumption (1) by the observation that during the PX2 stimulations practically no seismic events where localized between the injection interval in PX2 and the rupture plane and that the spatial distribution of the micro-seismicity does not resemble to be caused by a direct fluid injection as point or line source into or close to the RP, and (2) our assumptions correspond to the conservative case with the objective to check if pure poro-elastic hydromechanical effects can trigger an earthquake due to a very high pressure injection.

Detailed modelling results of pressure and stress changes on the earthquake fault plane are given in Alcolea et al. (2020). Here we show only the development of overpressures along the rupture plane (Figure 7) at the end of the PX2-1, PX2-2, PX2-3 and at the time of the 5.4 earthquake. The overpressures extended over a large part of the rupture plane at all times and were still in the order of 2 to 3 MPa at the time of the magnitude 5.4 earthquake two months after the last stimulation PX2-3. Thus, the pressures at the time of the mainshock are in the same order as derived by McGarr (2014) for the typically average pressure increase of 2.5 MPa necessary to cause slip across a fault patch.

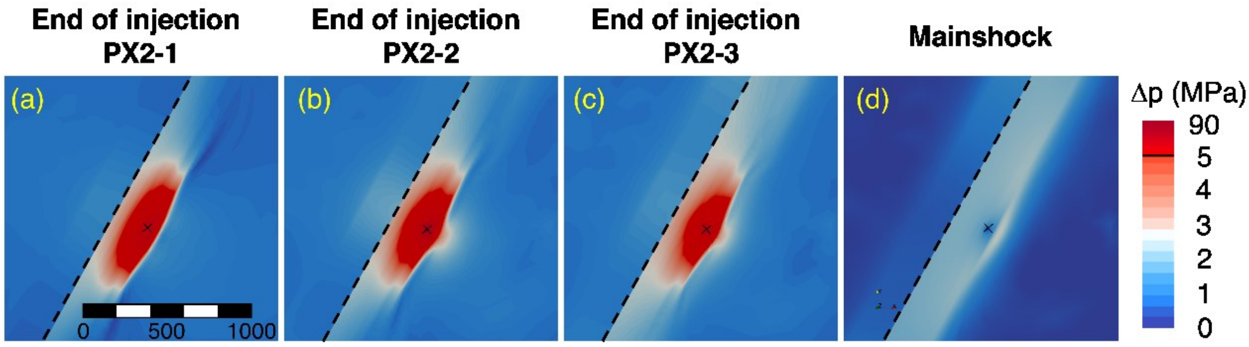

Figure 7: Contours of overpressure Δp (a to d) at the end of hydraulic stimulations PX2-1, PX2-2, PX2-3, and at the time of the mainshock. The injection source at a distance of about 200 m from the rupture plane is depicted by a cross and the rupture plane by a dashed black line. Note that the colour scale of Δp (panels a to d) is truncated at Δp=5 MPa to better display the lowest values.

Assuming that the model reproduces the most important features of the actual system reasonably well, we conclude (1) that the pressure level at the injection interval plays an important role and (2) that as a safety measure according to the precautionary principle very high injection pressures (compared to the vertical stress) shall be avoided for long term stimulation campaigns in future EGS projects, especially when the probability of larger fracture zones or faults being close to a geothermal project is high.

6. MOST PROBABLE SZENARIO FOR EXPLAINING THE POHANG MAGNITUDE 5.4 EARTHQUAKE

We summarize the most important features explaining the triggering of the magnitude 5.4 earthquake schematically in Figure 8 and as follows:

- The Pohang EGS site is located within a seismic active region of South-East Korea.
- Borehole PX2 intersects an important fault at about 3800 m with a low permeable core.
- The epicenter of the magnitude 5.4 earthquake is located within the same rock volume that was stimulated in January 2016, April 2017 and September 2017 with high pressures of up to 90 MPa at the well head of borehole PX2. These pressures correspond to a downhole pressure at a depth of 4200 m of 132 MPa which is much higher than the vertical rock stress (overburden) of 109 MPa. The high pressures - when injecting with several tens of liters per second - were probably the consequence of clogging the reservoir with lost circulation materials injected during drilling to stop important mud losses, which in turn were a consequence of drilling with an unusual high mud density of 1.6 kg/l.
- The high pressures were probably motivated to (desperately) establish a circulation between both wells PX2 and PX1 side track, in hindsight an unattainable objective in view of the low permeable fault core located between the two wells.
- Slow overpressure diffusion destabilizing progressively larger parts of the fault (maybe in combination of creeping fault core material) can explain the two months between the last stimulation in PX2 and the earthquake occurring in November 2017.

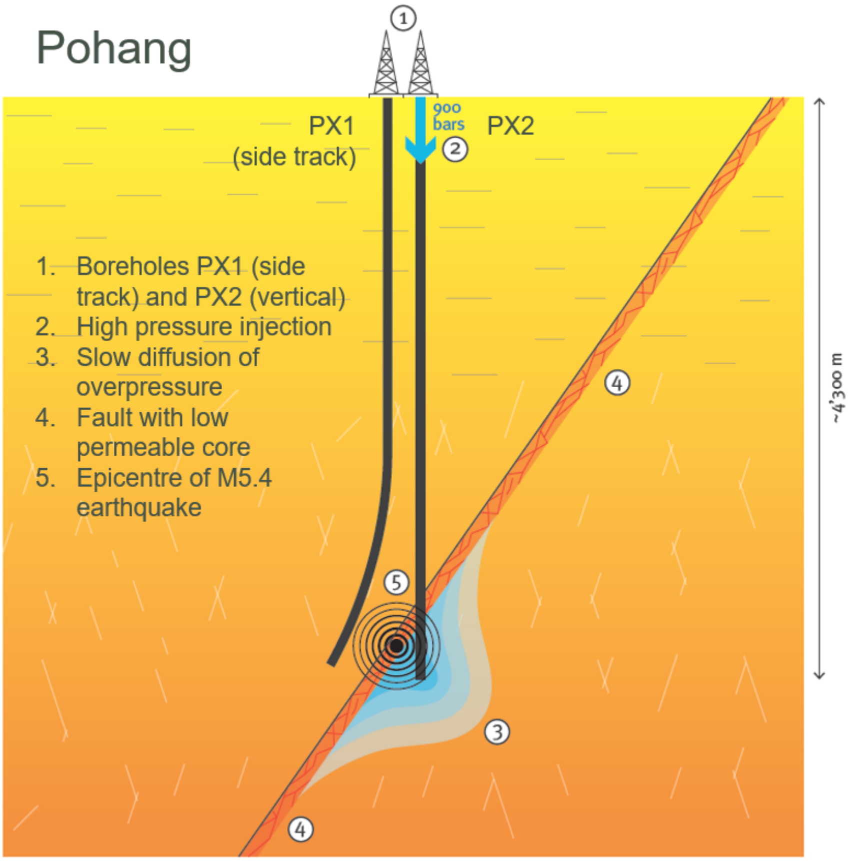

Figure 8: Conceptual model explaining triggering the Pohang earthquake

7. THE NEED FOR ADVANCED TRAFFIC LIGHT SYSTEMS AND FOR A CONTINUOUS INTEGRATIVE SEISMIC RISK EVALUATION FOCUSING ON THE ROLE OF FAULTS

Many enhanced geothermal systems (EGS) projects rely solely on traditional magnitude based traffic light systems in order to mitigate seismic risks. However, in several geothermal projects (e.g. Basel and St. Gallen in Switzerland, Pohang in South Korea) traditional traffic light systems have fallen short to limit induced seismicity to a predefined level of event magnitude.

Our risks studies for the planned EGS project in Haute-Sorne in Canton Jura (Switzerland) and the evaluation of the Basel case highlight the need (1) for an advanced traffic light system taking into account the spatial distribution of seismicity and integrating continuously throughout all project stages new data and especially information about fault structures and (2) to update the risk studies throughout the duration of the project.

Such a procedure has been the basis for the permit by the authorities of the Canton Jura for the planned EGS project in Haute-Sorne and is also recommended by the "Good practice guide for managing Induced Seismicity in Deep Geothermal Energy Projects in Switzerland" published by the Swiss Seismological Survey (Wiemer et al., 2017). In the following we examine if the rules of the permit for the Haute-Sorne project would have taken effect given the spatial distribution of micro-seismicity.

In the Pohang EGS project already during the first stimulation PX2-1 a real-time localization of seismicity would have revealed that seismicity aligns on a structure at several hundreds of meters away from the injection point (Figure 9). However, because (1) the maximum magnitude of M=1.4 did not exceed the threshold of M=2.0 that was defined as a stop criteria of the traditional traffic light system, and because (2) the event locations were possibly not available, the potential problem of activation of a larger fault may not have been realized.

In Haute-Sorne, based on permit condition number 55, such a situation would lead to an immediate halt of the stimulations and a careful analysis of the situation, and to a stop of the project if the probability of activation of a larger fault structure cannot be ruled out. This condition of the permit specifically states that the spatial development of the seismic cloud will have to be monitored continuously. In the case of specific observations, like the development of a lineament or the acceleration of the cloud growth, the stop protocol will be immediately enforced and the seismic risk will be re-evaluated. After a review by an independent expert panel authorities may allow either to continue the stimulations as planned, or with modifications or will request a stop of the project.

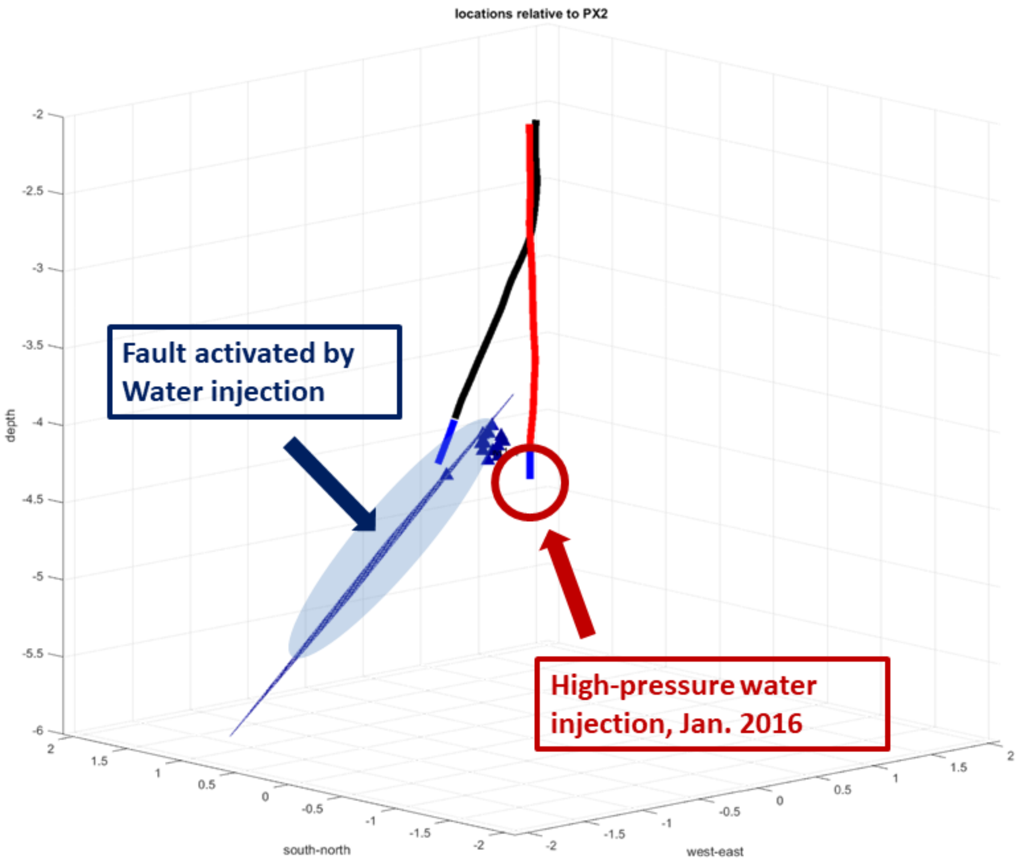

Figure 9: Representation of the first stimulation PX2-1 performed in Pohang in January 2016 in the vertical well. The water is injected into the red borehole. Seismicity, represented by blue triangles, develops several hundred metres from the injection point. It defines a plane (in blue) that represents a fault that is remotely activated by high-pressure injections. This is probably the fault whose failure caused the earthquake of 15 November 2017. The data are from Geological Society of Korea (2019), our own event localizations scatter within the blue ellipsoid.

8. CONCLUSIONS

An integrated analysis of data from drilling and hydraulic stimulation allowed us to derive a conceptual model for the triggering of the Pohang earthquake fault by very high injection pressures in the vertical borehole located at a distance of a few hundred of meters. We anticipate that in future more detailed scientific analyses by researchers from around the world will be published and will contribute to a better understanding of the relevant processes even some which have not been addresses yet. However, we do not expect that the main features and the basic factors contributing to triggering the Pohang earthquake will change fundamentally from what has been found until today by the official investigation commissions (ORAC/KERT) of the Pohang earthquake (Geological Society of Korea (2019) and our study, which are both in good general agreement.

In our view - besides of further detailed scientific analysis - the geothermal community needs to reflect on how to prevent similar cases to occur in future. A first important step on how to proceed after the Pohang experience has been made by the authors of the ORAC report (Kang-Kun Lee et. al., 2019). They urge the necessity of best practices including a formal process of risk assessment, with input of competent authorities, and the updating of this assessment as knowledge of the potential hazard evolves including scenarios of a triggered large earthquake.

In Switzerland after the two projects in the cities of Basel and St. Gallen have been stopped because of seismic risks, conditions corresponding to the ones proposed by Kang-Kun Lee et. al. (2019) have been established in 2015 in the permit for the planned EGS multi-stage stimulation project in Haute-Sorne. Furthermore, the Swiss seismological survey has published a “Good practice guide for managing Induced Seismicity in Deep Geothermal Energy Projects in Switzerland” (Wiemer et al., 2017).

For other countries where deep geothermal energy projects are initialized and where experiences with seismic risk management may not yet be available, we recommend project developers, authorities and other stakeholders to get inspired and to develop corresponding best practices customized to their geologic and tectonic conditions. Most importantly, we recommend to study the potential seismic risks of faults already during site selection and when defining the stimulation and operations concept and update the risk studies continuously taking into account all newly available data during all phases of a project. Furthermore, traditional traffic light systems are not sufficient and must be upgraded to advanced traffic light systems.

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REFERENCES

Alcolea Rodríguez, A., Meier, P.M., Vilarasa, V., Olivella, S., Carrera, J.: Hydromechanical Modelling of the Hydraulic Stimulation in borehole PX2 in Pohang (South Korea), *Proceedings,* World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020, submitted

Bethmann, F., Ollinger D., Tormann T., Heimlich C., Meier, P.M.: Seismicity Analysis with Spatial or Temporal Relation to the Pohang EGS Project, *Proceedings,* World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020, submitted

Majer, E., Baria, R., Stark, M., Oates, S., Bommer, J. and Smith, B.: Induced seismicity associated with enhanced geothermal systems. *Geothermics*, **36**, (2007), 185–222.

Majer, E., Nelson, J., Robertson-Tait, A., Savy, J. and Wong, I.: Protocol for addressing induced seismicity associated with enhanced geothermal systems [Report no.: DOE/EE-0662]. U.S. Department of Energy; (2012).

Meier, Peter M., Alcolea Rodríguez, A., and Bethmann, F.: Lessons learnt from Basel: New EGS projects in Switzerland using multistage stimulation and a probabilistic traffic light system for the reduction of seismic risk, Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015, (2015).

Meier, P.M., Ollinger, D., Alcolea Rodríguez, A.: Analysis of the 3 days constant rate injection test in PX1 from December 17 to 20, 2016 with respect to an observed non-flow boundary conjectured to be low permeable fault core material extending laterally over several hundred meters almost perpendicular to the sub-vertical structure stimulated during the PX1-1 stimulation campaign, Paper submitted to *Geothermics*, (2019)

Geological Society of Korea, "Summary report of the Korean Government Commission on relations between the 2017 Pohang earthquake and EGS project" (2019); https://doi.org/10.22719/KETEP-20183010111860.

Heimlich, C., Tormann, T., Meier, P.M.: InSAR measurements and analysis of the 15th November 2017 event in South Korea, Geo-Energie Suisse, Internal report (2018)

Hong, T. K., Lee, J., & Houng, S. E.: Long-term evolution of intraplate seismicity in stress shadows after a megathrust. Physics of the Earth and Planetary Interiors, 245, 59-70. (2015). https://doi.org/10.1016/j.pepi.2015.05.009

Hong, T.K., Lee, J., Park, S. and Kim, W.: Time-advanced occurrence of moderate-size earthquakes in a stable intraplate region after a megathrust earthquake and their seismic properties, Nature Scientific Reports, (2018), 8:13331 | DOI:10.1038/s41598-018-31600-5

Lee, K-K., Ellsworth, W. L., Giardini, D., Townend, J., Ge, S., Shimamoto, T., Yeo, I-W., Kang, T-S., Rhie, J., Sheen, D-H., Chang, Ch., Woo, J-U., and Langenbruch, C. (2019), Science 364 (6442), 730-732. DOI: 10.1126/science.aax1878

KIGAM, Public information brochure (in Korean) on the status of the Korean Peninsula earthquakes, Gyeongju ML 5.8 earthquake September 12, 2016, and Pohang ML 5.4 Earthquake 2017.11.15. (2018).

Kim, K-I., Min, K-B., Kim, K-Y., Choi, J-W., Yoon, K-S., Yoon, W-S., Yoon, B., Lee, T-J., and Song, Y.: Protocol for induced microseismicity in the first enhanced geothermal systems project in Pohang, Korea, Renewable and Sustainable Energy Reviews, Volume 91, (2018a), Pages 1182-1191, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2018.04.062.

Kim, KH., Ree JH., Kim, YH, Kim, S., Kang SY, and Seo, W.: Assessing whether the 2017 Mw 5.4 Pohang earthquake in South Korea was an induced event. Science. (2018b) doi: 10.1126/science.aat6081.

Ree, J-H., and Kwon, S-T.: The Wangsan Fault: One of the most 'active' faults in South Korea?. Geosciences Journal. (2005), 9. 223-226. 10.1007/BF02910581.

Park, S., Xie, L., Kim, K-L., Kwon, S., Min, K-B., Choi, J., Yoon, W.S., Song, Y.: First Hydraulic Stimulation in Fractured Geothermal Reservoir in Pohang PX-2 Well, Procedia Engineering, Volume 191, (2017), Pages 829-837, ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2017.05.250

Wiemer, S., Kraft, T., Trutnevyte, E. and Philippe R.: "Good Practice" Guide for Managing Induced Seismicity in Deep Geothermal Energy Projects in Switzerland. (2017). Swiss Seismological Service at ETH Zurich.doi:10.12686/a5

Zoback, M.D.: Managing the seismic risk posed by waste water disposal, Earth, (2012) pp. 38-43 (https://www.earthmagazine.org/article/managing-seismic-risk-posed-wastewater-disposal