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Seismicity Analysis with Spatial or Temporal Relation to The Deep Geothermal Project in Pohang, Korea

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ABSTRACT

We investigate seismic events between January 2016 and November 2017 that occurred in close vicinity to the deep geothermal project in Pohang, Korea. Using cross correlation analysis, we show that the epicenter of the M5.5 event is located within the stimulated reservoir volume and that the location of the hypocenter can be attributed to a rock volume that was stimulated by specific high-pressure injection campaigns.

For our analysis we use data from locally installed networks (0-150m depth) and a deep borehole sensor at 2.3 km depth. However, we restrict our analysis to a few stations that were running during most of the 5 stimulation campaigns and establish a link between events using waveform similarity analysis. We derive dependencies between each of the five individual stimulations and to foreshocks of the M5.5 event which originated up to 10h before the mainshock and have similar S-P times. We show, that in the case of Pohang simple cross-correlation analysis can link the mainshock to a specific area within the stimulated reservoir volume.

1. INTRODUCTION

The Pohang geothermal project consists of two boreholes PX-1 and PX-2, which both reach a depth of around 4.2 km (Figure 1). To enhance permeability and to establish a circulation between the two open-hole sections of the boreholes, both boreholes were alternately stimulated (Figure 2). A seismic network was put in place and seismicity was monitored by a surface and borehole network. Two months after the last stimulation an earthquake of magnitude M5.5 occurred, which caused more than $75M (USD) in direct damage and over $300M (USD) of total economic impact, Lee et al. (2019). Soon the question was raised, if this event could have been caused by the geothermal reservoir creation nearby.

Whereas in many cases a direct relation between human activity and significantly larger events is difficult to prove, the case of Pohang is clear, e.g. Lee et al. (2019) and Kim et. al (2018). In the following we show, that it is possible to link the initial rupture of the M5.5 fault-plane to a specific area within the geothermal reservoir.

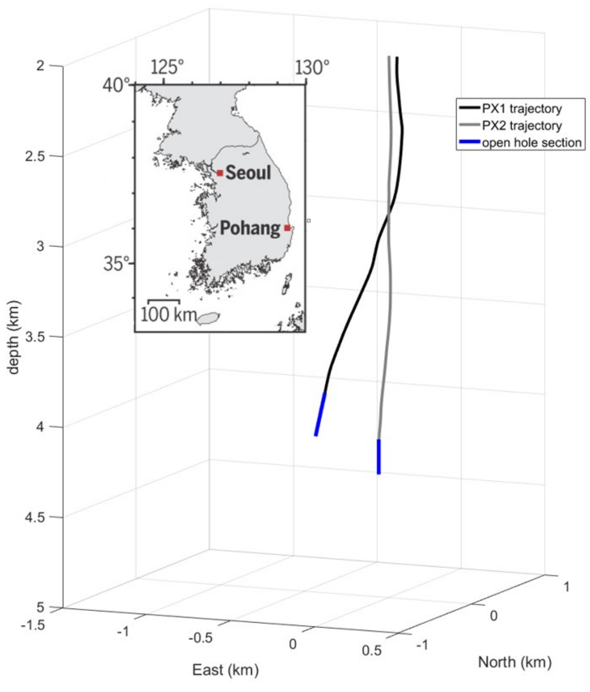

Figure 1: Location and borehole trajectories of the Pohang geothermal project.

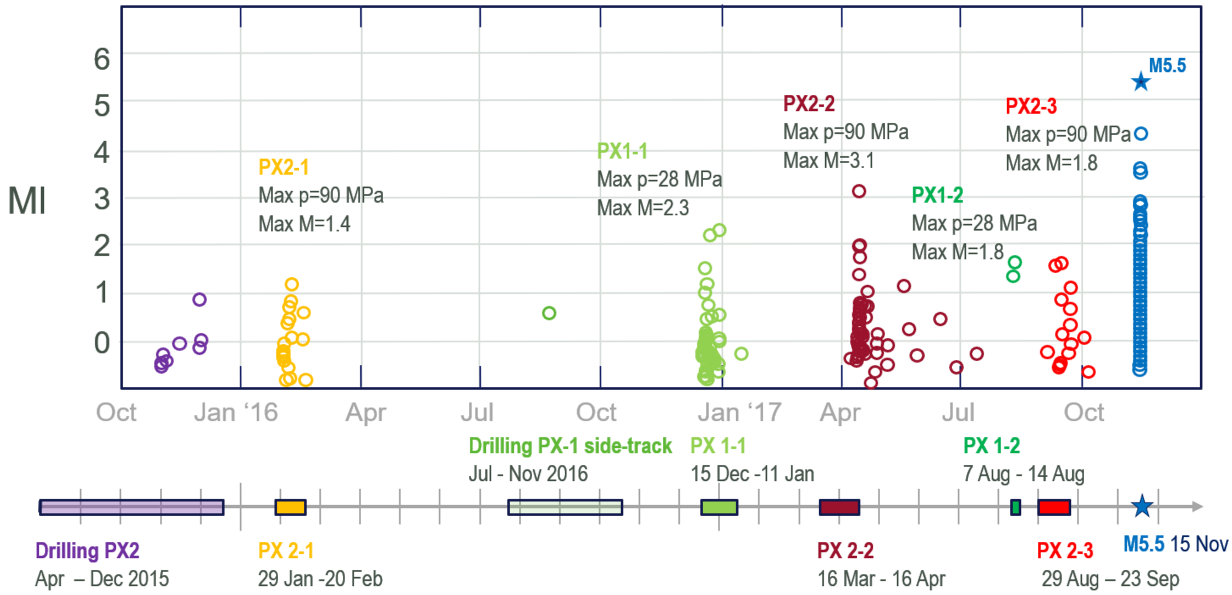

Figure 2: Drilling and stimulation history of the Pohang project, note the high injection pressures of PX2 well (90 MPa) in comparison with PX-1 (28 MPa). Seismicity data taken from Kim et al. (2018) with additional data from the PX1-2 stimulation, Hofmann et. al (2019).

3. METHOD AND DATA

The seismic events in Pohang were monitored by a variety of subnetworks over two years, which were operated by different institutions. In principle, waveform recording was continuous, at least during the distinct stimulation periods. The seismic dataset by itself is challenging, for many reasons (Bethmann et al.). Therefore, we concentrate our analysis onto a few stations, that were active during at least 4 out of 5 stimulation periods. We identify 5 foreshocks, that occurred within a 10 hours period prior to the main shock and have similar P to S travel times (Δt<15ms). If these events are similar in waveform to previously recorded reservoir events, then these events can also be interpreted as originating within the geothermal reservoir.

To identify similar events, we use a cross-correlation technique (e.g. Rabiner et. al, 1975). For our analysis we focus on foreshocks, which have occurred in close vicinity to the mainshock. The mainshock itself is not well suited for this type of analysis due to partially clipped waveforms, complex source mechanism (Grigoli et. al, 2018) and due to the magnitude difference of more than 3.5 magnitude units producing a different frequency content. However, due to the close proximity of the foreshocks to the mainshock (almost identical travel-times, Figure 3), conclusions for the foreshocks are also thought to be valid for the mainshock.

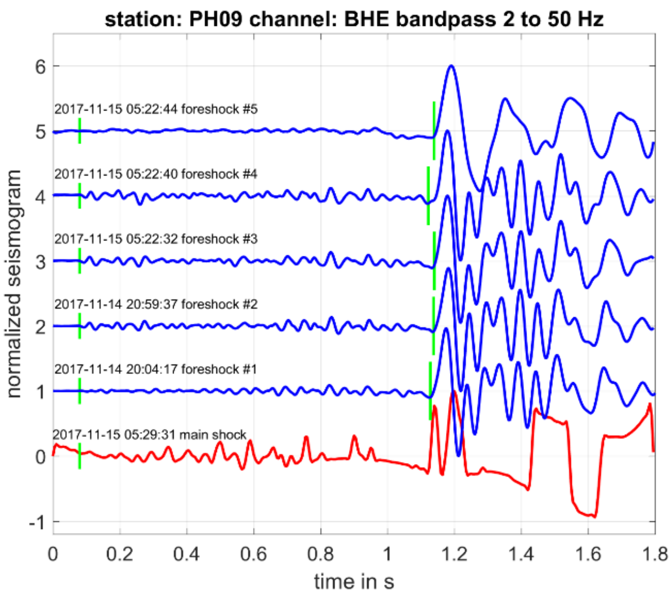

Figure 3: Comparison of travel-times between mainshock (red) and foreshocks (blue), travel-time differences are in the order of 15ms, the weakest cross-correlation coefficient between foreshocks #1 – #4 is 0.93. Note that main shock data is clipped and suffering from instrumental filter effects after the S-onset. Data from Kim et. al (2018).

In order to establish the similarity between events, we use waveform snippets that include P and S wave coda of the events, starting 20ms before the associated P-pick. We filter the raw data with a bandpass filter of 2-50Hz and compare all channels on all stations on which P- and S-picks are available for the event. The algorithm aligns the waveforms to maximize the cross-correlation coefficient. To avoid arbitrary correlations, we restrict the maximum lag to the respective P-pick uncertainties of the compared channels.

We note that in cross-correlation analysis, some parameter choices are somewhat arbitrary, such as the filters used to limit the frequency bandwidth, or the threshold for the cross-correlation coefficient above which two events are considered similar (Deichmann et al., 2014). We thus complement our systematic analysis of cross-correlation coefficients with a manual inspection of the seismograms: We verify that two events are similar by matching P- wave polarities, checking for almost identical S-P travel times and applying a close visual inspection regarding the similarity of the wave train in general.

In principle, it is enough to find one similar event in a stimulation period to draw the conclusion that the area where the foreshocks (and mainshock) happened was activated before. We interpret a relationship between reservoir event and foreshock if the cross-correlation factor exceeds the cross-correlation coefficient between the four most similar foreshocks (e.g. 0.93 for station PH09 E-component, Figure 3).

4. THE RELATION OF THE MAINSHOCK TO RESERVOIR SEISMICITY

We compare all 5 foreshocks to all located events shown in Figure 2 and show the highest similarity to an event for each stimulation period in Figure 4. It can be seen, that similarities are highest between foreshocks and PX-2 events, where water was injected at very high pressures (Figure 2). In contrast PX-1 events show less similarity. Figure 5 shows the best correlated events of this dataset which is foreshock #1 compared to a PX-2 event, that happened during the last stimulation. Based on this analysis it is evident that foreshocks originated from the PX2 part of the reservoir. In addition, the almost identical S-P travel-times of the foreshock and main shock (Figure 3) means, that we may interpret that the main-shock also had its origin in the PX-2 part of the reservoir.

Figure 4: Comparison of cross-correlation coefficients for stations phbs2 and phbs3, that were online during 4 out 5 stimulation periods. Foreshock similarity is higher to PX2 events. Note that station phbs3 has in general low cross-correlation values due to lower signal to noise ratio.

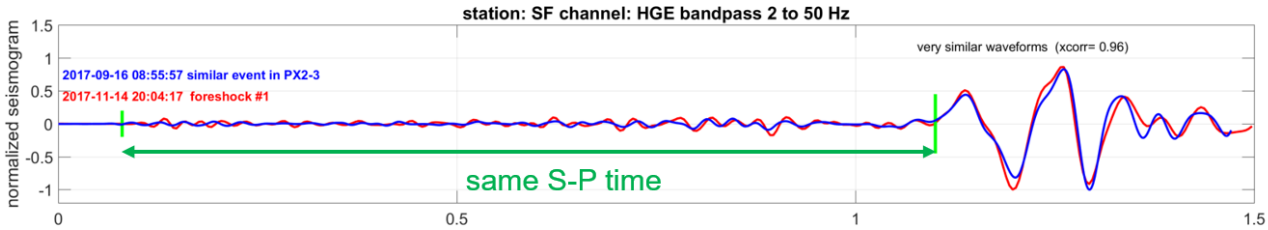

Figure 5: Comparison of a foreshock and a reservoir event that happened during stimulation phase PX 2-3. The waveforms show a high similarity, linking the reservoir stimulation to the earthquake of M5.5 that happened 2 months after.

5. DISCUSSION AND CONCLUSION

Using waveform cross-correlation techniques, we could show that the Pohang M5.5 earthquake had its origin from the PX-2 part of the geothermal reservoir. This part was stimulated with up to 90 MPa well-head pressure in contrast to stimulations in well PX-1 at 28 MPa. In this case similarity analysis has proven to be very effective to show a causal relationship between earthquake and stimulation activities. We suggest performing this kind of analysis early in the investigation process.

Note that if there is no correlation, this does not mean that a stimulation is not contributing to the triggering of a large event. Foreshocks which are similar in magnitude/frequency content to reservoir events may not exist, and therefore the mainshock cannot be linked. Also, injection of fluids to the underground especially under high pressures can change stresses on nearby faults, e.g. by poro-elastic effects (Alcolea, 2020) or by migrating fluids into different rocks under different stresses, and consequently leading to events with different waveforms (Pollyea, 2019).

This analysis does also not conclude that the geothermal project is the only contributor to the M5.5 event. The rupture area of the mainshock is much larger than the stimulated area, Kim et al. 2018. Based on Lee et al. (2019) the Pohang earthquake grew through the release of already accumulated tectonic stress (Hong, 2018).

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