Title

The 2017 Pohang, South Korea, Mw 5.4 main shock was either natural or triggered, but not induced

Authors

McGarr, Art
Majer, Ernest L

Publication Date

2023

DOI

10.1016/j.geothermics.2022.102612

The 2017 Pohang, South Korea, Mw 5.4 main shock was either natural or triggered, but not induced

Art McGarr and Ernest L. Majer

Corresponding Author: Art McGarr, mcgarr@usgs.gov
U.S. Geological Survey, Earthquake Science Center
350 N. Akron Rd.
Moffett Field, CA 94035

Ernest L. Majer, elmajer@lbl.gov
Lawrence Berkeley National Laboratory
1 Cyclotron Rd.
Berkeley, CA 94720

Key words: Induced seismicity; triggered earthquakes; natural earthquakes; Enhanced Geothermal Systems (EGS)

Highlights:

1) The 17 November Mw 5.4 Pohang, South Korea, main shock could have been either triggered or natural.
2) The Pohang main shock was not induced by the nearby EGS project.
3) The dominant source of seismic hazard in and around the city of Pohang is natural crustal strain accumulation.

Conflict of interest statement: The authors have no conflicts of interest to declare.

ABSTRACT

Understanding the cause of the November 2017 Pohang main shock is of considerable importance to the future of the geothermal industry because of its large magnitude compared to prior expectations based on case histories of other projects involving underground fluid injection. Of the three possibilities – induced, triggered or natural, “induced” can be ruled out based on the disproportionately large seismic moment of the main shock. Whether natural or triggered, the source of seismic hazard at Pohang was tectonic strain accumulation, not fluid injection. Arguably, the most timely indicator of seismic hazard and risk in the environs of Pohang was the September 2016 Mw 5.4 Gyeongju earthquake, which was natural and located about 40 km south of Pohang along the same active fault system.

INTRODUCTION

On 15 November 2017, the southeastern coastal region of South Korea experienced damaging ground motion from a moment magnitude (Mw) 5.4 earthquake near the port city of Pohang (Figure 1). Had there not been a nearby Enhanced Geothermal System (EGS) project, there would have been little doubt that this earthquake was due to crustal strain accumulation along the Yangsan fault zone. The proximity of the EGS project, however, led to suspicion that the Pohang main shock was caused by injection activities, as reported initially by Grigoli et al. (2018) and Kim et al. (2018). This suspicion evolved into the Summary Report (2019), prepared on behalf of the South Korean Government and summarized by Ellsworth et al. (2019).

The question of the extent to which the occurrence of the Mw 5.4 Pohang main shock was influenced by a nearby geothermal project is of considerable importance because of implications for the future of the geothermal industry, especially in South Korea. Of the numerous published reports on the Pohang earthquakes, nearly all conclude that these earthquakes were either induced or triggered by injection activities intended to develop this geothermal resource (e.g., Kim et al., 2018; Grigoli et al.,2018; Ellsworth et al., 2019; Yeo et al., 2020; Westaway, 2021; Farkas et al. 2021; Yoo et al., 2021; Chang et al., 2020; Lim et al., 2020; Wassing et al., 2021; Hofmann et al.,2019; Woo et al.,2019; and Alcolea et al., 2021).

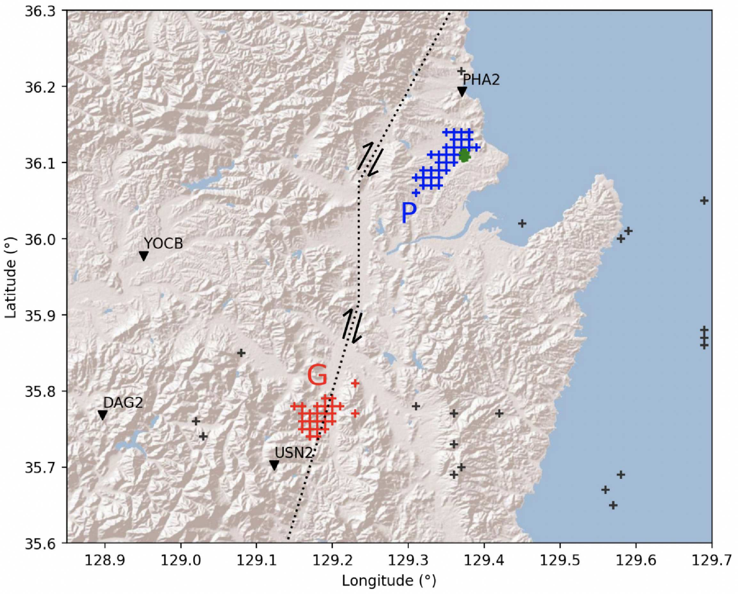

Figure 1. Locations of seismicity in southeastern South Korea, including the Pohang earthquakes (blue symbols) and the Gyeongju earthquakes (red symbols) determined by the Korea Meteorological Administration (KMA) National Earthquake Comprehensive Information System (NECIS). Locations of the Pohang foreshocks identified by the Summary Report (2019) are represented by the small cluster of green symbols. Black crosses show epicenters of earthquakes not associated with either the Gyeongju or the Pohang sequence.The Yangsan fault system (dotted line), and the stations in the South Korean regional network used for the detection of earthquakes using template matching (black triangles) (Skoumal et al., 2019) are also shown. The port city of Pohang is located a short distance to the southeast of the Pohang earthquakes, around the bay.

The hypothesis that the Pohang main shock was natural, however, is difficult to rule out, as noted in numerous articles including Grigoli et al. (2018) and Ellsworth et al. (2019). To add some balance to the discussion concerning the cause of the Pohang main shock, we consider all three possible origins for the Pohang main shock: induced, triggered, and natural. It turns out that the hypothesis of an induced origin for the Pohang main shock can be readily dismissed, but choosing between triggered and natural causes is more challenging.

Induced, triggered, or natural?

The initial motivation for this study came from remarks by Ellsworth et al. (2019) who claimed that the 2017 Mw 5.4 Pohang main shock is a counter-example to the relations developed by McGarr (2014) relating maximum seismic moment or magnitude to the net volume of injected liquid. We will show that this claim has no merit. To this end, we begin with the definitions of “induced” and “triggered” earthquakes given by Ellsworth et al. (2019):

> “**Induced earthquakes** occur within the volume of rock in which pressure or stress changes as a consequence of injection. Their magnitudes are consistent with the spatial dimension of the stimulated volume. They can occur both during injection and after injection ceases. They may release tectonic strains or strains created by injection pressure or volume.”

> “**Triggered earthquakes** are runaway ruptures, initiated by anthropogenic forcing, that grow in size beyond the bounds of the stimulated region. They release tectonic strain.”

These definitions are useful for distinguishing between induced and triggered seismicity at the Pohang EGS site. As will be shown, however, resolving the question of whether the Pohang main shock was triggered or natural is more challenging because the two possibilities have much in common.

We start by first showing that the Pohang main shock was not induced and is, therefore, not a counter-example to the relations developed by McGarr (2014). We then consider the other two possibilities, triggered and natural.

The 2017 Pohang main shock was not induced by injection operations

The reason for including the definition of induced seismicity is to highlight several problems with the claim by Ellsworth et al. (2019) that the Pohang main shock represents a counter-example to the relationships developed by McGarr (2014). First, in the last paragraph on page 1854 of Ellsworth et al. (2019) we read:

"Part of the rationale for selecting the magnitude thresholds comes from an empirical hypothesis that the largest magnitude of induced earthquakes is bounded by a function of the injected volume (McGarr, 2014)."

This characterization by Ellsworth et al. (2019) is incorrect because the relationships between seismic moments and injected volumes were developed **analytically**, not **empirically**, using 13 equations in Section 3 of McGarr (2014). Furthermore, the title of McGarr (2014) is "Maximum magnitude earthquakes **induced** by fluid injection" because that article is intended for induced, not triggered, earthquakes. Indeed, one of the five assumptions in the development of the relations between moment release and injected fluid volume is "The induced earthquakes are localized to the region where the crust has been weakened due to fluid injection." (Section 3 of McGarr, 2014). This assumption is consistent with the definition from Ellsworth et al. (2019), given above, for induced, but not triggered, seismicity.

In contrast, the title of Ellsworth et al., (2019) is "Triggering of the Pohang, Korea, earthquake (M_W 5.5) by Enhanced Geothermal System Stimulation". If the Pohang main shock is, in fact, a triggered earthquake, then it would not have been expected to adhere to the seismic moment limits developed by McGarr (2014) because the upper bounds on moment (see Section 3 of McGarr, 2014) were intended only for induced earthquakes; triggered earthquakes were not considered.

Evidence against an induced origin for the Pohang main shock is seen in Figure 2, which shows that the volume of injected liquid at the Pohang site is too small by several orders of magnitude to account for the moment release of the Pohang earthquake sequence (Upper blue star in Figure 2). In a similar vein, Figure 8 of Ellsworth et al. (2019) indicates that the main shock rupture area, based on aftershock locations, was substantially larger than the area affected by pore pressure increase (Figures 6 and 8 of Ellsworth et al., 2019; see also Bethmann et al., 2021) before the main shock occurred in November 2017. Both types of evidence are consistent with the definition, given by Ellsworth et al. (2019), for "triggered", but are not compatible with "induced". These observations are also in accord with a natural origin for the Pohang main shock.

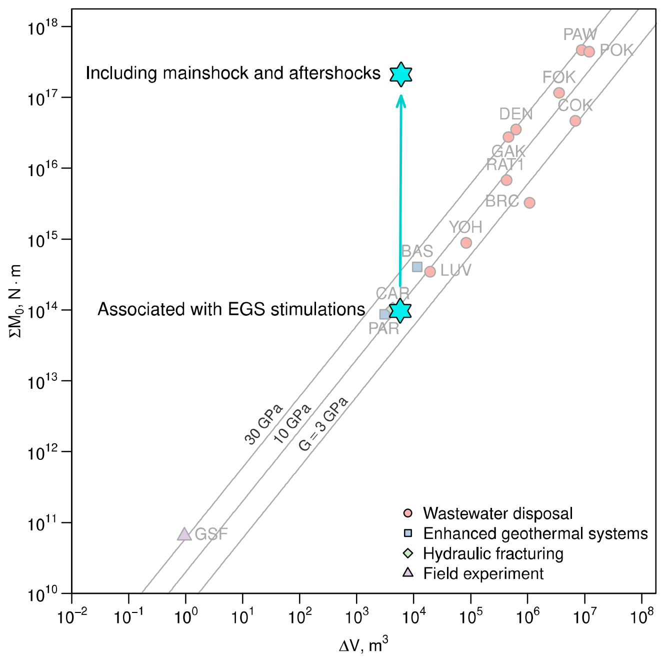

Figure 2 (Adapted from Figure 1 of McGarr and Barbour, 2018) Moment release $\sum M_0$ *as a function of injected volume* ΔV *compared to upper bound lines for 3 values of shear modulus G. The upper-bound lines were calculated using* $\sum M_0 \leq 2G\Delta V$ *(McGarr 2014). Lower blue star indicates moment release near Pohang from beginning of EGS project until beginning of November 2017. Upper blue star shows moment release from beginning of EGS project until January 2019.*

2016 Gyeongju and 2017 Pohang sequences are similar

Having explained why the Pohang M 5.4 main shock was not induced and therefore not a counter-example to the relations for maximum seismic moment developed by McGarr (2014), we now address the more challenging question of whether the Pohang main shock was triggered or natural. To this end, we first compare the 2017 Pohang sequence to its natural counterpart located about 40 km to the south along the same active fault zone (Figure 1), the 2016 M5.4 Gyeongju earthquake.

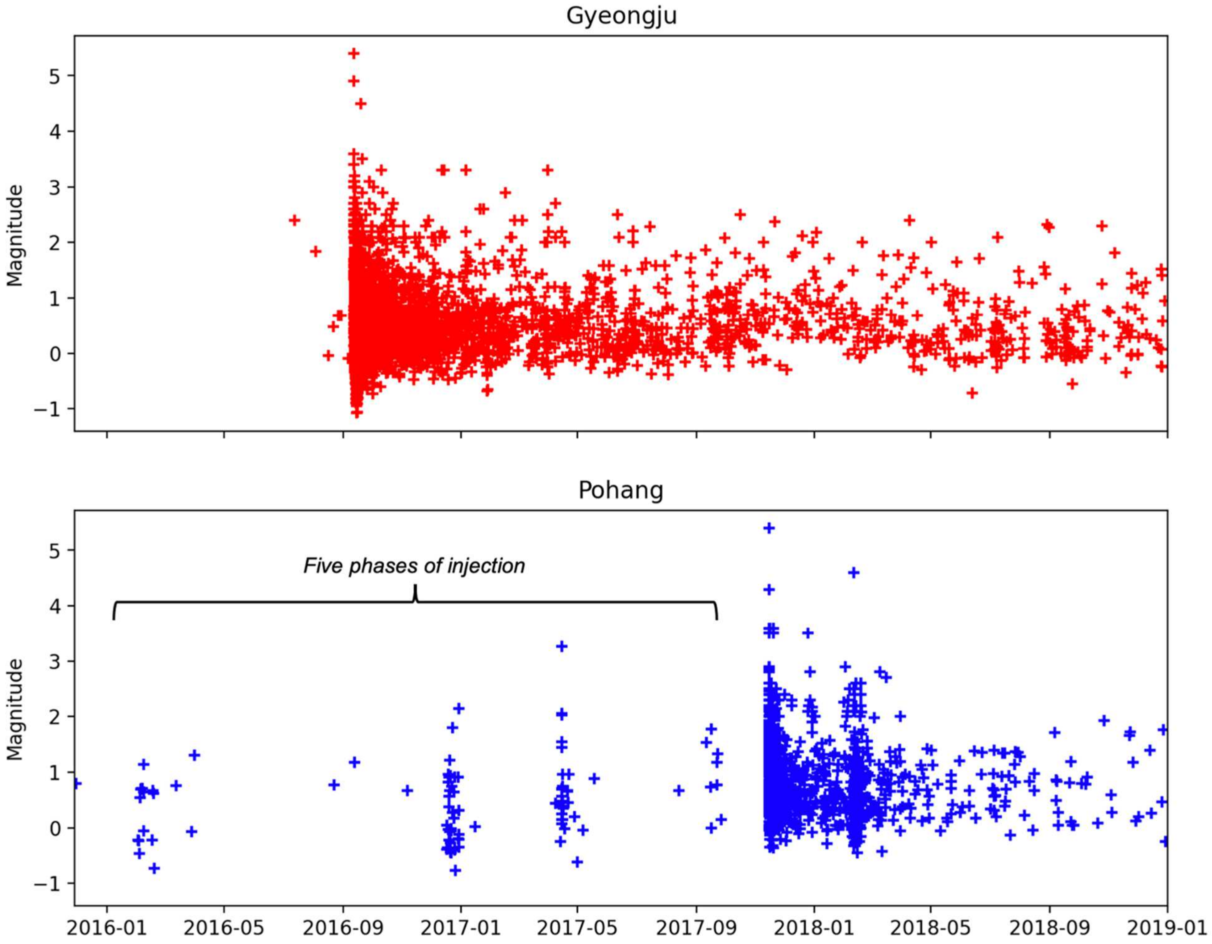

Figure 3 *Gyeongju (upper panel) and Pohang (lower panel) sequences. Also shown in the lower panel are the magnitudes of the earthquakes induced by the five phases of injection.*

As observed by Grigoli et al. (2018), the region of southeastern South Korea that includes Pohang was already in a state of elevated seismic activity before the 2017 Pohang earthquake, activity that included the 2016 Gyeongju earthquake sequence (Figures 1 and 3). The two earthquake sequences show considerable similarity: both were located along the Yangsan fault zone, an active fault system (Hwang et al., 2010); the two main shocks had moment magnitudes of 5.4; both were preceded by a small number of foreshocks; and each main shock was followed by a lengthy sequence of aftershocks (Figure 3).

Seismograms recorded by the regional network Station YOCB (Figure 1) from both the Gyeongju and Pohang main shocks show waveforms (Figures 4a and 4b) that are consistent with the tectonic setting. Most notably, the transverse components of their S waves are impulsive, of high amplitude, and consistent with right-lateral shear across the Yangsan fault zone (Figure 1).

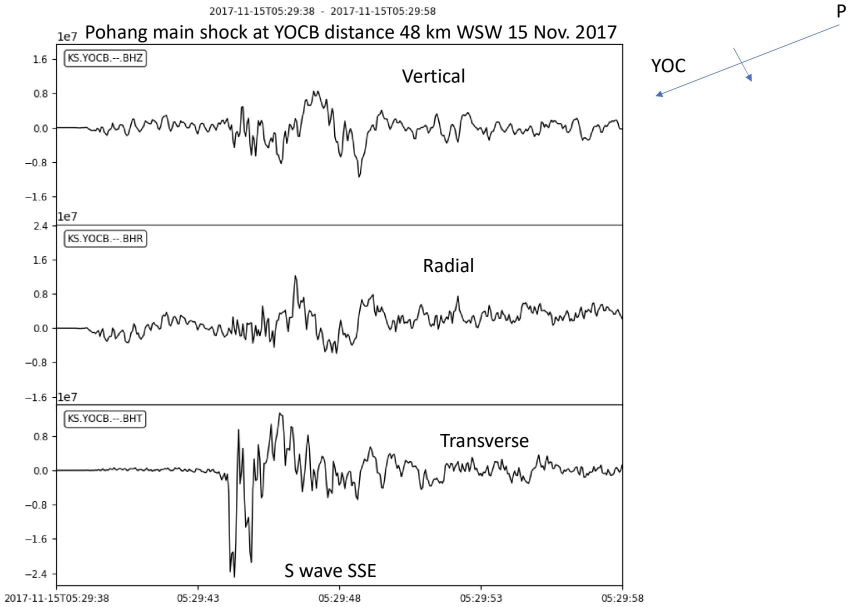

Figure 4a *Groind displacement from Pohang main shock. At upper right is a map view of the ray path from the Pohang main shock (P) to station YOC (Figure 1) showing the SSE polarization of the horizontal S wave. Following the S wave, the lower-frequency Love wave (transverse component) is followed by the Rayleigh wave (radial and vertical components), which shows retrograde elliptical ground motion. The upward drift seen on the radial trace is likely an artifact introduced during integration from ground velocity to displacxement. Each unit on the vertical scale is 0.1 micron.*

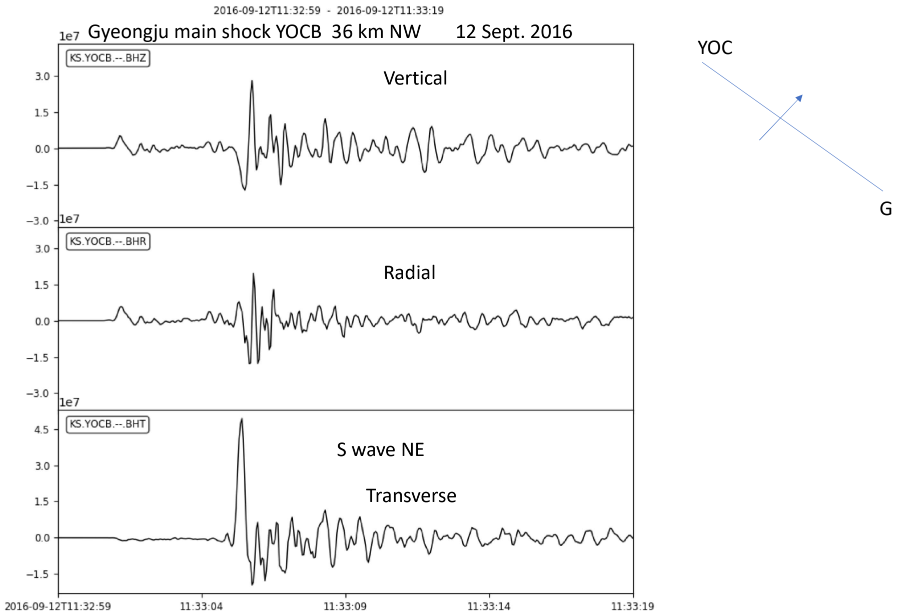

Figure 4b *Ground displacement from Gyeongju main shock. At upper right is map view of ray path from Gyeongju main shock (G) to station YOC (Figure 1) showing NE polarization of horizontal S wave. Each unit on the vertical scale is 0.1 micron.*

Similar remarks apply to the magnitude-frequency distributions, which both have typical *b-values* close to 1 (Figure 5). The larger uncertainty for the *b-value* at Pohang is due to the smaller number of events owing partly to the shorter duration of recording considered there. Interestingly, both distributions show similar behavior at magnitudes greater than 3.6 or 3.7 (Figure 5).

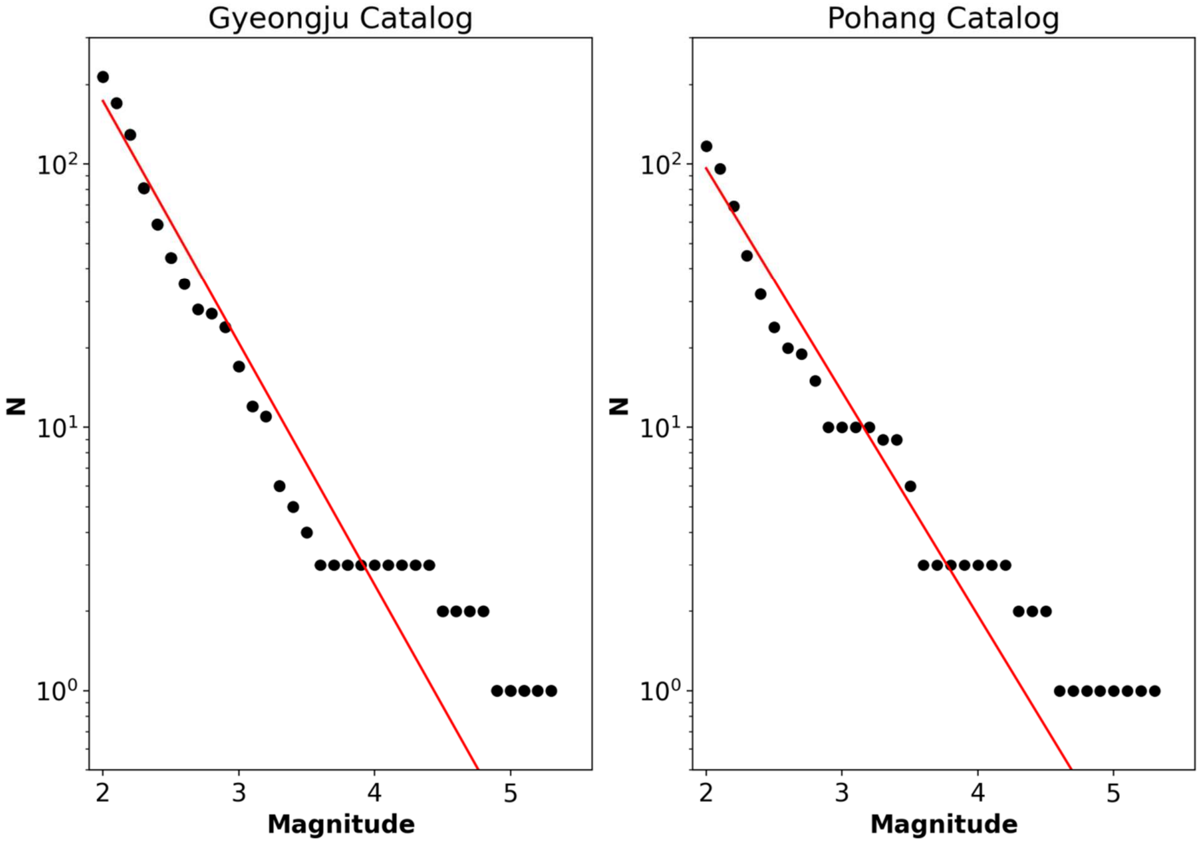

Figure 5 *Magnitude-frequency distributions for Gyeongju and Pohang sequences. Note that b-values, determined using maximum likelihood method (Aki, 1965), for both sequences, are 0.9.*

There are a few differences between these sequences, however. The main shock of the Gyeongju sequence was preceded by an Mw 4.9 foreshock by less than an hour. And the Pohang aftershocks include a magnitude 4.6 earthquake on 10 February 2018 that was followed by a secondary aftershock sequence (Figure 3).

The main difference between the Pohang and Gyeongju main shocks, however, is in their distributions of slip with depth. For the Pohang main shock, slip was distributed between about 2 km and 6 km whereas the slip for the Gyeongju main shock showed a depth distribution of similar extent that was centered at about 15 km depth (Kim et al., 2017; Kim et al., 2018; Ellsworth et al. 2019); evidence for this difference is seen in Figures 4a and 4b. Whereas Figure 4a shows surface waves following the impulsive S wave, no surface waves are seen following the S wave in Figure 4b. The shallower slip range of the Pohang earthquake is likely a consequence of an elevated brittle-ductile transition, commonly found in the environs of geothermal resources.

In summary, from the seismic data, it is clear that the two earthquake sequences, Pohang and Gyeongju, have much in common. The Gyeongju sequence was natural, the result of strain accumulation along the Yangsan fault system. The similarity of the Pohang sequence to its Gyeongju counterpart is consistent with either a natural or a triggered cause for the Pohang main shock. If the Pohang main shock was triggered, then its time of occurrence and, possibly, hypocentral location may have been affected, but neither perturbation would have been expected to affect its moment release significantly.

Measures taken by the operator to avoid felt earthquakes

Because the EGS site is located in the outskirts of Pohang, a major population center of about 500,000, the operator evidently attempted to reduce the likelihood of felt earthquakes in several ways. First, the average injection rate was kept exceedingly low, about 10 m^3/day, by distributing the five phases of injections over about 600 days (Figure 3). In contrast, EGS stimulations are often completed in less than a week resulting in average injection rates of the order of 2000 m^3/day (e.g., Majer et al., 2007; Bommer et al., 2006; Deichmann and Giardini,

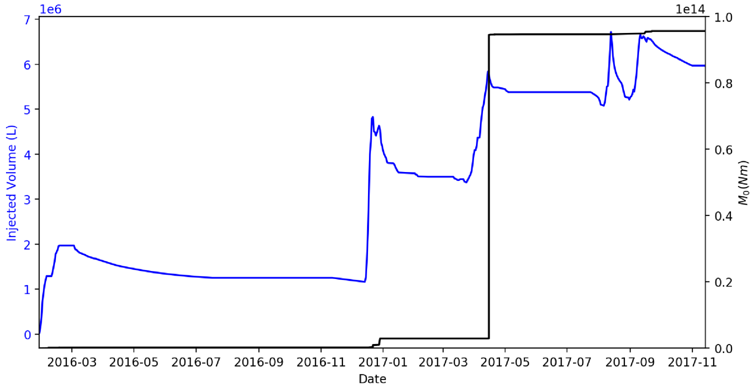

Figure 6 Injection in liters (blue line) and moment release (black line) as functions of time during the injection activities at the Pohang EGS site. The 1st, 3rd and 5th injection phases were into borehole PX-2 whereas the 2nd and 4th were into PX-1.

2009; Albaric et al., 2013). Second, the injections alternated between the two boreholes PX-1 and PX-2. Third, after each injection, there was flowback to reduce the net injected volume and pore pressure of fluid in the formation (Figure 6). Fourth, the Pohang stimulation plan for PX-1 was based on the EU “DESTRESS” program, with “soft” cyclic stimulation designed specifically to minimize the potential for induced seismicity (Hofmann et al., 2018; Yoon et al., 2019).

In more detail, within each of the five injection phases at Pohang, there was a series of separate small-volume injections. For example, the first phase, which used PX-2, entailed 16 separate small-volume injections distributed over about 3 weeks (Park et al., 2017).

Concluding discussion

The claim by Ellsworth et al. (2019) that the Pohang main shock is a counter-example to the relationship, developed by McGarr (2014), between seismic moment release and net injected volume is inappropriate because that relationship was intended for earthquakes induced, not triggered, by fluid injection. Accordingly, even if the main shock was triggered (Ellsworth et al., 2019), there is no reason to expect the moment release at Pohang, South Korea, to adhere to the relations developed by McGarr (2014).

From the start of the Pohang EGS Project until early November 2017, however, moment release in the vicinity of this project appears to have been limited by the net injected volume (Figure 2, lower blue star) as expected for induced seismicity (McGarr, 2014; McGarr and Barbour, 2018). From mid-November onward, in contrast, the moment release near this project exceeded the same limit by a factor of several hundred, indicating that the Mw 5.4 main shock was almost certainly not induced (Figure 2, upper blue star); this implies that the Pohang main shock was either triggered (Ellsworth et al., 2019) or natural.

The 2017 Pohang and 2016 Gyeongju main shocks, and their sequences, were similar in many ways. Both sequences were located in the environs of the Yangsan fault zone and had the same *b-values* and maximum magnitudes. Because the Gyeongju sequence was natural, it follows that an earthquake of Mw 5.4, or larger, near Pohang, could have occurred with or without nearby EGS injections. The similarity of the Pohang and Gyeongju sequences supports both triggered and natural causes for the Pohang main shock.

An important difference between our interpretation and those reported previously (e.g., Ellsworth et al., 2019; Yeo et al., 2020; Palgunadi et al., 2020) is the implication from our study that the most useful evidence for assessing earthquake hazard and risk near Pohang was provided by the Gyeongju main shock, which occurred about 14 months before its counterpart at Pohang. If the 2016 Gyeongju earthquake had been located near the Pohang EGS site, the consequences would probably have been similar to what actually happened 14 months later in November 2017.

Although we have not been able to determine whether the Pohang main shock is natural or triggered, this uncertainty may be of little consequence because, in either case, the extent of rupture, and its damaging effects in Pohang, resulted from natural crustal tectonics, although the timing of this earthquake may have been perturbed owing to the EGS injections. This implies that the only effective mitigation strategy would have been to act on the information provided by the 2016 Gyeongju earthquake by preparing for an earthquake elsewhere along the Yangsan fault zone (Figure 1), including near Pohang, of moment magnitude at least 5.4.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Geothermal Technologies Office, under Award Number DE-AC02-05CH11231 with LBNL. We thank J. Ole Kaven, Lane Johnson, Elizabeth Cochran, Justin Rubinstein, Andrew Michael, Michelle Robertson, Julian Bommer, and William Foxall for their comments that improved this manuscript substantially. We thank Andrew Barbour and Robert Skoumal for their generous contributions to the preparation of this manuscript.

DATA AND RESOURCES

All data needed to evaluate the conclusions in this paper are present in the paper. Additional data may be requested from the authors.

REFERENCES

Aki, K. (1965), Maximum likelihood estimate of b in the formula logN=a-bM and its confidence limits, Bull. Earthquake Res. Inst., Univ. of Tokyo, 43, 237-239.

Albaric, J., V. Oye, N. Langet, M. Hastings, I. Lecomte, K. Irampour, M. Messeiller, and P. Reid (2013), Monitoring of induced seismicity during the first geothermal reservoir stimulation at Paralana, Australia, Geothermics, doi: 10.1016/j.geothermics.2013.10.013.

Alcolea, A., P. M. Meier, V. Vilarrasa, S. Olivella, and J. Carrera, (2021), Geomechanical analysis of the hydraulic stimulations in borehole PX-2 at Pohang EGS site, South Korea, Proceedings World Geothermal Congress 2020+1, Reykjavik, Iceland, April – October, 2021.

Bethmann, F., Ollinger, D., Tormann, T., and Meier, P. (2021), Seismicity analysis with spatial or temporal relation to the deep geothermal project in Pohang, Korea, Proceedings World Geothermal Congress 2020+1, Reykjavik, Iceland, April – October 2021.

Bommer, J. J., S. Oates, J. M. Cepeda, C. Lindholm, J. Bird, R. Torres, G. Marroquin, and J. Rivas (2006), Control of hazard due to seismicity induced by a hot fractured rock geothermal project, Engineering Geology, 83, 287-306.

Chang, K. W., H. Yoon, Y. Kim, and M. Y. Lee (2020). Operational and geological controls of coupled poroelastic stressing and pore-pressure accumulation along faults: Induced earthquakes in Pohang, South Korea. Scientific reports, 10(1), 1-12.

Deichmann, N. and D. Giardini (2009), Earthquakes induced by the stimulation of an enhanced geothermal system below Basel (Switzerland), Seismol. Res. Lett., 80, 784-798, doi: 10.1785/gssrl.80.5.784.

Ellsworth, W. L., D. Giardini, J. Townend, S. Ge, and T. Shimamoto (2019), Triggering of the Pohang, Korea, earthquake (M_W 5.5) by enhanced geothermal system stimulation, Seismol. Res. Lett., 90, 1844-1853, doi: 10.1785/0220190102.

Farkas, M. P., H. Hofmann, G. Zimmermann, A. Zang, F. Bethmann, P. Meier, M. Cottrell and N. Josephson (2021), Hydromechanical analysis of the second hydraulic stimulation in well

PX-1 at the Pohang fractured geothermal reservoir, South Korea, Geothermics, 89, 101990. https://doi.org/10.1016/j.geothermics.2020.101990

Grigoli, F., S. Cesca, A. P. Rinaldi, A. Manconi, J. A. Lopez-Comino, J. F. Clinton, R. Westaway, C. Cauzzi, T. Dahm, and S. Wiemer (2018), The November 2017 M_W 5.5 Pohang earthquake: A possible case of induced seismicity in South Korea, Science, 360, 1003-1006, doi:10.1126/science.aat2010.

Hofmann, H., G. Zimmermann, A. Zang, and K.-B. Min (2018), Cyclic soft stimulation (CCS): a new fluid injection protocol and traffic light system to mitigate seismic risks of hydraulic stimulation treatments, Geothermal Energy 6:27 https://doi.org/10.1186/s40517-018-0114-3

Hofmann, H., G. Zimmermann, M. Farkas, E. Huenges, A. Zang, M. Leonhardt, G. Kwiatek, P. Martinez-Garzon, M. Bohnhoff, K.-B. Min, et al. (2019). First field application of cyclic soft stimulation at the Pohang Enhanced Geothermal System site in Korea, Geophys. J. Int. 217, no. 2, 926–949, doi: 10.1093/gji/ggz058.

Hwang, B.-H., J.-D. Lee, K. Yang, M. McWilliams (2010), Cenozoic strike-slip displacement along the Yangsan fault, southeast Korean peninsula, International Geology Review, 49:8, 768-775, doi: 10.2747/0020-6814.49.8.768.

Kim, Y., X. He, S. Ni, H. Lim, and S.-C. Park (2017), Earthquake source mechanism and rupture directivity of the 12 September 2016 M_W 5.5 Gyeongju, South Korea earthquake, Bull. Seismol. Soc. Am., 107, 2525-2531, doi: 10.1785/0120170004.

Kim, K.-H., J.-H. Ree, Y. Kim, S. Kim, S. Y. Kang, and W. Seo (2018), Assessing whether the 2017 M5.4 Pohang earthquake in South Korea was an induced event, Science, 360, 1007-1009, doi:10.1126/science.aat6081.

Korean Government Commission (2019), Summary Report of the Korean Government Commission on relations between the 2017 Pohang earthquake and EGS project, Geological Society of Korea, Seoul, South Korea, doi: 10.22719/KETEP-201830101118.

Lim, H., Deng, K., Kim, Y. H., Ree, J. H., Song, T. R., & Kim (2020). The 2017 Mw 5.5 Pohang earthquake, South Korea, and poroelastic stress changes associated with fluid injection. Journal of Geophysical Research: Solid Earth, e2019JB019134.

Majer, E. L., R. Baria, M. Stark, S. Oates, J. Bommer, B. Smith, and H. Asanuma (2007), Induced seismicity associated with enhanced geothermal systems, Geothermics, 36, 185-222, doi: 10.1016/j.geothermics.2007.03.003.

McGarr, A. (2014), Maximum magnitude earthquakes induced by fluid injection, J. Geophys. Res., 119, 1008-1019.

McGarr, A. and A. J. Barbour (2018), Injection-induced moment release can also be aseismic, *Geophys. Res. Lett.,* 45(11), 5344-5351, DOI: 10.1029/2018GL078422

Palgunadi, K. H., A. A. Gabriel, T. Ulrich, J. Á. López-Comino, and P. M. Mai (2020), Dynamic fault interaction during a fluid-injection-induced earthquake: The 2017 M_w 5.5 Pohang event, *Bull. Seismol. Soc. Am.*, *110*(5), 2328–2349, doi:10.1785/0120200106.

Park, S., L. Xie, K.-I. Kim, S. Kwon, K.-B. Min, J. Choi, W.-S. Yoon, and Y. Song (2017), First hydraulic stimulation in fractured geothermal reservoir in Pohang PX-2 well, *Procedia Engineering,* 191, 829-837.

Park, S., K.-I. Kim, L. Xie, H. Yoo, K.-B. Min, M. Kim, B. Yoon, K.-Y. Kim, G. Zimmermann, F. Guinot and P. Meier, (2020), Observations and analyses of the first two hydraulic stimulations in the Pohang geothermal development site, South Korea, Geothermics, 88, 101905. https://doi.org/10.1016/j.geothermics.2020.101905

Skoumal, R. J., J. Kaven, and J. Walter (2019), Characterizing seismogenic fault structures in Oklahoma using a relocated template matched catalog, Seis. Res. Let., 90(4), 1535-1543. https://doi.org/10.1785/0220190045.

Wassing, B. B. T., Q. Gan, T. Candela,, and P. A. Fokker (2021), Effects of fault transmissivity on the potential of fault reactivation and induced seismicity: Implications for understanding induced seismicity at Pohang EGS, Geothermics, 91, 101976. https://doi.org/10.1016/j.geothermics.2020.101976

Westaway, R. (2021), Extrapolation of populations of small earthquakes to predict consequences of low- probability high impact events: The Pohang case study revisited, Geothermics, 92, 102035. https://doi.org/10.1016/j.geothermics.2020.102035

Woo, J.-U., M. Kim, D.-H. Sheen, T.-S. Kang, J. Rhie, F. Grigoli, W. L. Ellsworth, and D. Giardini (2019), An in-depth seismological analysis revealing a causal link between the 2017 M_W 5.5 Pohang earthquake and EGS project, J. Geophys. Res. Solid Earth, 124, https://doi:org/10.1029/2019JB018368.

Yeo, I. W., M. R. M. Brown, S. Ge, and K. K. Lee (2020), Causal mechanism of injection-induced earthquakes through the Mw 5.5 Pohang earthquake case study, *Nat. Commun.*, *11*(1), 2614, doi:10.1038/s41467-020-16408-0.

Yoo, H., S. Park, L. Xie, K.-I. Kim, K.-B. Min, and J. Rutqvist (2021), Hydro-mechanical modeling of the first and second hydraulice stimulations in a fractured geothermal reservoir in Pohang, South Korea, Geothermics,. 89,101982, https://doi.org/10.1016/j.geothermics.2020.101982

Yoon, S., J. W. Choi, T. J. Lee, and K. Y. Kim (2019), First field application of cyclic soft stimulation at the Pohang Enhanced Geothermal System site in Korea, *Geophysical Journal International*, Volume 217, Issue 2, 1 May 2019, Pages 926–949, doi: 10.1093/gji/ggz0