Stress-Drop Scaling of the 2016 Gyeongju and 2017 Pohang Earthquake Sequences Using Coda-Based Methods

Gyeongdon Chai¹‡, Seung-Hoon Yoo³, Junkee Rhie*¹, and Tae-Seob Kang²

ABSTRACT

Two M 5 earthquakes struck the southeastern Korean Peninsula in September 2016 and November 2017, causing damage near the epicentral areas. We analyze the stress-drop scaling of these two earthquake sequences using coda-based methods and Bayesian inversion. The 2016 Gyeongju earthquake sequence is a typical earthquake sequence generated by tectonic processes. In contrast, the 2017 Pohang earthquake sequence is believed to be related to fluid injections conducted for the development of enhanced geothermal systems. As the two sequences occurred in the same tectonic regime, our study provides a good opportunity to compare the stress-drop scaling between a tectonic earthquake sequence and an earthquake sequence influenced by fluid injections. We found that the stress drops of events in the Pohang sequence are lower than those of the Gyeongju sequence with similar magnitude. Although it is likely that this difference results from focal depth variations, a reduction of stress drop due to fluid injections cannot be ruled out.

KEY POINTS

• Tectonic (Gyeongju) and possible anthropogenic (Pohang) earthquakes occurred in the same tectonic regime.
• The stress drop of the Pohang sequence is lower than that of the Gyeongju sequence.
• Low stress drop may be attributed to the fluid injection.

INTRODUCTION

A study of the scaling relationship between magnitude and stress drop for earthquakes occurring in a given region is important not only for understanding the fundamentals of the earthquake rupture process but also for mitigating earthquake damage by estimating the ground motions in future earthquakes. There are many historical documents on the occurrence of large earthquakes (M > 6) in the southeastern part of the Korean Peninsula. However, the largest earthquake recorded in this region with instruments is the M_{L} 5.8 Gyeongju (GJ) earthquake of 12 September 2016 (Korean Meteorological Administration [KMA]). This region is susceptible to large earthquakes. Efforts toward mitigating the seismic risk in this region are very important because this region has valuable infrastructure, including nuclear power plants and cities with dense populations. In this study, we analyze the stress-drop scaling of two moderate earthquake sequences that occurred in the southeastern Korean Peninsula using the analysis of coda waves, which is known to be more stable than the analysis of direct waves (Mayeda et al., 2007; Yoo et al., 2010).

The two earthquake sequences considered in this study are the 2016 M_{W} 5.6 GJ earthquake and the 2017 M_{W} 5.5 Pohang (PH) earthquake sequences (Figs. 1 and 2). The distance between the epicenters of the GJ and PH mainshocks is approximately 43 km, and both earthquakes occurred in the Gyeongsang basin. The Gyeongsang basin is a tectonic unit classified based on the tectonic evolution in the Korean Peninsula. Although the PH basin, where the PH sequence occurred, had been tectonically active until recently compared with the epicentral region of the GJ sequence, the current tectonic environment for generating earthquakes in both regions should be similar because they belong to the same tectonic unit (Park et al., 2007; Soh et al., 2018). We can also expect that tectonic stresses in both regions are similar because they are spatially close to each other. However, the reported source characteristics of the two sequences, especially the mainshocks, are quite different. The focal depths of the GJ and PH mainshocks are 14.5 km (Woo, Kim, et al., 2019) and 4.27 km (Lee et al., 2019; Woo, Rhie, et al., 2019), respectively. The focal mechanism for the GJ mainshock determined by moment tensor inversion is strike

1. School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea; 2. Division of Earth Environmental System Science, Pukyong National University, Busan, South Korea; 3. Applied Research Associates, Inc., Arlington, Virginia, U.S.A.
*Corresponding author: rhie@snu.ac.kr

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slip. The faulting style of the PH mainshock is strike slip with a significant thrust component. Strike-slip and thrust mechanisms are both popular mechanisms in our study area (Rhie and Kim, 2010). The most important difference between the two earthquakes is whether fluid injection affected the occurrence of the earthquake.

The GJ mainshock is a natural earthquake generated because of tectonic stress, whereas the PH mainshock is a “runaway” earthquake triggered by stress perturbation caused by injecting fluids for the development of enhanced geothermal systems (EGSs) (Ellsworth et al., 2019). The objective of this study is to test whether different mechanisms between tectonic and “runaway” earthquakes could be revealed by comparing source parameters such as the stress drop.

DATA AND METHODS

Data used in this study are seismic waveforms recorded at broadband stations operated by the KMA and the Korea Institute of Geoscience and Mineral Resources (KIGAM) (Fig. 1), and they were divided into two sets for different research purposes. The first data set was used to define a reference coda envelope, which is necessary for calculating the source spectrum. For the lower frequency range (0.05–8.0 Hz), we used waveforms from earthquakes with magnitudes greater than 4.0 that occurred in and around the Korean Peninsula between 2006 and 2012. The sampling rate of this data set is 20 Hz. For the higher frequency range (8.0–14.0 Hz), we used waveforms from earthquakes in the 2016 GJ sequence with magnitudes greater than 3.0; their sampling rate is 100 Hz. The second data set was used for analysis of source spectra for the GJ and PH sequences.

To determine a reference coda envelope, we defined its theoretical functional form following a previous study (Mayeda et al., 2003) as

\[
E(t, f, r) = H \left( t - \frac{r}{v(f, r)} \right) \left( t - \frac{r}{v(f, r)} \right)^{-\gamma(f, r)} \times \exp \left[ b(f, r) \left( t - \frac{r}{v(f, r)} \right) \right].
\]
in which \( r, f, \) and \( t \) indicate the distance in kilometers, the frequency in hertz, and the time elapsed from the event origin in seconds, respectively; \( H \) is the Heaviside step function; and \( v(f, r) \) is the velocity of the peak arrival in kilometers per second. Two functions, \( b(f, r) \) and \( y(f, r) \), control the shape of the coda envelope. To define the reference coda envelope, we determined \( v(f, r), b(f, r), \) and \( y(f, r) \) from the observed data by following the procedures presented in Yoo et al. (2011). We defined reference coda envelopes for 14 consecutive narrow frequency bands (Table 1, Fig. 3). Because the coda envelope shapes for both sequences are similar, we used the same set of reference coda envelopes for both sequences.

The relation between the observed and reference coda envelopes is represented as follows:

\[
A_C(t, f, r) = W_0(f)S(f)P(f, r)E(t, f, r),
\]

in which \( A_C(t, f, r), S(f), P(f, r), \) and \( W_0(f) \) are the observed coda envelope, site correction, path correction, and S-wave source amplitude, respectively.

To measure \( A_C(t, f, r) \), we removed the instrument response of two horizontal component waveforms to velocity seismograms. A four-pole two-pass Butterworth filter, for which corner frequencies correspond to 14 consecutive narrow frequency bands, was applied, and then an envelope for each frequency was calculated using

\[
E_{\text{obs}} = \sqrt{v(t)^2 + h(t)^2},
\]

in which \( v(t) \) and \( h(t) \) are the band-pass-filtered horizontal velocity seismogram and its Hilbert transform, respectively. To distinguish the observed and reference envelopes, we use \( E_{\text{obs}} \) for the observed envelope. The final observed envelope was calculated by taking the logarithm base 10 of two horizontal envelopes and then averaging them. By doing this, we measured \( A_C(t, f, r) \) for each frequency and epicentral distance. We can see in equation (2) that changes in \( A_C(t, f, r) \) with time for a given frequency and distance should be the same as the changes in \( E(t, f, r) \). The difference between \( A_C(t, f, r) \) and \( E(t, f, r) \) is called nondimensional coda amplitude (NDCA), and it can be measured by finding the optimum direct current shift, which minimizes the L1 norm between \( A_C(t, f, r) \) and \( E(t, f, r) \). We then compared the reference and observed coda envelopes at each frequency band.

Two methods are widely used to study seismic sources using measured NDCA. The first method involves directly estimating \( W_0(f) \) by correcting \( P(f, r) \) and \( S(f) \) from NDCA. The

Figure 2. Study areas where the Gyeongju (GJ, right lower inset) and Pohang (PH, right upper inset) earthquake sequences occurred. The focal mechanisms determined by ISOLA software (Sokos and Zahradnik, 2008; Vackář et al., 2017) are plotted in the inset of each study area. Symbols in red, blue, and green indicate the mainshock, foreshock, and largest aftershock, respectively. The Gyeongju sequence has only strike-slip faulting events, but the Pohang sequence has reverse and strike-slip faulting events. The color version of this figure is available only in the electronic edition.
The reliability of estimated source spectra can be low. The second method is to estimate $f_c$ only, or $f_c$ and $M_0$ together, from the ratio of NDCA between two events without calculating the individual source spectrum of each event (Mayeda et al., 2007). This method is based on the assumption that, if NDCA are measured at the identical station and two earthquakes occurred at close locations, $P(f, r)$ and $S(f)$ for both events should be identical and the ratio of NDCA is the same as the ratio of the source spectra. In this case, we do not need to determine $P(f, r)$ and $S(f)$ to apply the method. However, this method is only applicable to event pairs with similar hypocenters but large differences in magnitude. In this study, we are interested in examining the source characteristics of two earthquake sequences in which the earthquakes in each sequence are spatially clustered. Therefore, a combined procedure of the two methods can be applied. We used the information obtained from the ratio of the NDCA to define the site-correction terms and then applied these terms to study the source spectra of the events. The detailed procedure is as follows. First, we selected event pairs with a magnitude difference larger than one in each sequence. Total numbers of selected events and corresponding event pairs for the GIJ sequence are 9 and 15, respectively, and 6 and 7, respectively, for the PH sequence. The maximum distance between hypocenters among event pairs is 8.24 km. $M_o$ for each event was independently calculated using ISOLA (Sokos and Zahradnik, 2008; Vackár et al., 2017) software based on the waveform inversion method (Fig. 2). We considered 66 stations for our analysis, but the actual number of data points used for each process was not consistent (Fig. 1). To estimate $f_c$ of both events from the spectral ratio for a given event pair, we used the Bayesian inversion method. A hierarchical scheme was applied to account for data error in the inversion (Bodin et al., 2012; Kim et al., 2016). We assumed that prior probability of $\Delta \sigma$ is uniform in the range $10^{-3}$ to $10^3$ MPa. Once we selected $\Delta \sigma$, we calculated $f_c$ using the following equation, because $M_o$ of the event is predefined:

$$f_c = \frac{2.34 \beta}{2\pi (\frac{M_o}{\Delta \sigma})^{\frac{1}{2}}}.$$  \(\text{(4)}\)

Equation (4) was derived from the following two equations based on the circular fault model (Eshelby, 1957). Shear wave velocity ($\beta$) was set to be 3.5 km/s.

$$\Delta \sigma = \frac{7 \times M_o}{16 \times r^2},$$  \(\text{(5)}\)  

$$r = \frac{2.34 \beta}{2\pi f_c}.$$  \(\text{(6)}\)

Using $f_c$ and $M_o$ of both events, we define a spectral ratio between two events based on Brune’s source model as follows (Aki, 1967; Brune, 1970, 1971):

$$R(f) = \frac{M_o [1 + (f/f_c)^2]}{M_o [1 + (f/f_c')^2]}.$$  \(\text{(7)}\)
The misfit between the synthetic and observed spectral ratio was measured using the L1 norm, and the likelihood function was defined as

\[ L = \frac{1}{2\sigma} \times \exp \left[ \sum_{i=1}^{n} \frac{|R_{\text{syn}}(f_i) - R_{\text{obs}}(f_i)|}{\sigma} \right] \]

in which \( R_{\text{syn}} \) and \( R_{\text{obs}} \) indicate the synthetic and observed spectral ratio, respectively, and \( f_i \) represents the center frequency of a given frequency band. To consider the data error in the inversion, we assumed that \( \sigma \) has a positive uniform prior probability.

We updated model parameters (two stress drops and \( \sigma \)) 200,000 times using the Metropolis–Hastings sampling (MHS) method (Metropolis et al., 1953; Hastings, 1970). After the first half of the calculations, which is considered a burn-in period, we selected 1 sample per every 100 calculations to estimate the posterior probability density (PPD) of two values of stress drop (or \( f_c \)) and \( \sigma \). For each event pair, we selected the \( f_c \) with the highest PPD. The final \( f_c \) value for each event was calculated by averaging selected \( f_c \) values for all event pairs. Because the final \( f_c \) values for large events (\( M_w \geq 4.0 \)) are more accurate owing to their large signal-to-noise ratios, we used the \( f_c \) values of only large events for further analyses. The number of final \( f_c \) values was three for each of the PH and GJ sequences. Once we determined \( f_c \) and \( M_0 \), the theoretical Brune’s source spectrum was calculated using the following equation:

\[ M(f) = \frac{M_0}{(1 + (f/f_c)^{2})^{\frac{\alpha}{2}}} \]

For each station, a site-correction term can be determined by measuring the difference between the theoretical Brune’s source spectrum and the corresponding NDCA. We note that a site-correction term contains \( P(f, r) \) and \( S(f) \) in equation (1). Because we define the site-correction terms of individual stations separately for PH and GJ sequences, we can ignore variation in the site-correction term with distance. We calculated the difference between the theoretical Brune’s spectrum and the NDCA for each event and then averaged them for each sequence to determine the final site-correction term as a function of frequency. Once a site-correction term was defined, we calculated the source spectrum for each event by correcting NDCA. By averaging the estimated source spectra of each event for all available stations, we calculated the final source spectrum for each event. To estimate the PPD of stress drop (or \( f_c \)) and \( M_0 \) from the final source spectrum, we used Bayesian inversion, which is similar to the method previously applied for spectral ratio. We assumed that the stress drop and \( M_0 \) have uniform prior probability in the ranges between \( 10^{-3} \) and \( 10^{3} \) MPa and between \(-2 \) and \( 2 \) in logarithmic scale about the maximum value of the corrected NDCA, respectively. The parameter \( f_c \) was determined from a given stress drop and \( M_0 \).

To consider data error, we adopted two parameters, \( \sigma_{\text{rms}} \) and \( \sigma_{\text{SD}} \). Here, \( \sigma_{\text{rms}} \) indicates an envelope fitting error when measuring coda amplitudes of observed envelopes at a given frequency, and \( \sigma_{\text{SD}} \) is defined as one standard deviation of the site-correction term at the given frequency. The likelihood function is defined as

\[ L = \frac{1}{2\sigma} \times \exp \left[ \sum_{i=1}^{n} \frac{|M_{\text{syn}}(f_i) - M_{\text{obs}}(f_i)|}{\sigma_{\text{rms}} + \sigma_{\text{SD}}} \right] \]

The same sampling procedure of Bayesian inversion using the MHS method that was used for the spectral ratio method was applied to estimate the PPD of \( M_0 \) and \( f_c \). The PPD of stress drop was also determined from equations (5) and (6). We can technically estimate source parameters of all events with measured NDCA. However, low signal-to-noise ratio of small events can distort the results. Therefore, we used nine and six events with \( M_w \) larger than 3.0 for the GJ and PH sequences, respectively. We calculated Brune’s source spectrum using \( M_0 \) and \( f_c \) estimated by Bayesian inversion and used this spectrum to calculate a site-correction term.

**RESULTS AND DISCUSSION**

We applied coda-based methods and Bayesian inversion to the GJ and PH earthquake sequences. We calculated the reference coda envelopes and compared them with the observed coda envelopes. Figure 3 depicts an example of the comparison between the reference and observed coda envelopes at selected frequency bands. Because the excitations of the coda waves are nearly insensitive to the radiation pattern (Mayeda et al., 2003), we were able to obtain azimuthally averaged source spectra, even though the stations were mainly located west of the events. The final \( f_c \) value was calculated for each event using the MHS method, and the PPD was estimated; for each event pair, we selected the \( f_c \) with the highest PPD. Figure 4 shows examples of spectral ratios determined for selected events. The calculated difference between the theoretical Brune’s spectrum and the NDCA for each event was averaged for each sequence to determine the final site-correction term as a function of frequency, as shown in Figure 5 for three events in the GJ sequence.

If the site-correction term is well-defined, we can expect the estimated source spectra of the events involved in determining the site-correction terms to be consistent with the site-corrected NDCA for the same event. In the case of the GJ sequence, we can see that the two values are well-matched, as expected (Fig. 6a). However, there are significant discrepancies in the PH sequence (Fig. 6c). The reason for these discrepancies appears to be that the original estimates of \( f_c \) obtained from the spectral ratio method for the PH sequence are not accurate because the number of applicable earthquakes is insufficient. To overcome this problem, we recalculated the site-correction term for the PH sequence.
the Brune spectra, which fit the corrected NDCA for each event, and then recalculated the site-correction terms by averaging the differences between the Brune spectra and the NDCA for the three events. The corrected NDCA using the recalculated site-correction term demonstrates a significantly improved fit to the theoretical Brune’s spectrum (Fig. 6b).

Using coda-based methods and Bayesian inversion, we estimated the PPD of $M_w$, $f_c$, and stress drop for 12 and 7 earthquakes in the GJ and PH sequences, respectively (Table 2). The stress-drop scaling for both the GJ and PH sequences show that stress drop increases with increasing magnitude on the overall scale (Fig. 7). The observed trends in stress-drop scaling cannot be explained by the self-similar model with a constant stress drop (Aki, 1967). The estimates of the stress drop appear to be considerably scattered for smaller earthquakes ($M_w < 3.5$) in both sequences. This may indicate that estimates of stress drop for smaller events are not stable because of the low signal-to-noise ratio. The stress drop of the smallest PH event (PH01 in Table 2) is much smaller than that of other events with similar magnitudes. For relatively larger events ($M_w \geq 4.0$) in the GJ sequence, it is likely that the stress drop increases with increasing $M_w$ in a range between $M_w$ 4.5 and 5.5. This observation is consistent with other previous studies using similar coda-based methods (Mayeda and Malagnini, 2009; Malagnini et al., 2010; Yoo et al., 2010; Yoo and Mayeda, 2013). For the PH sequence, we do not observe an increasing trend in the given magnitude range because the stress drop of the PH mainshock (PH02) is smaller than those of the shocks of similar magnitude in the GJ sequence. No significant increase in the stress drop for the specific magnitude range was reported for the Parkfield sequence (Allmann and Shearer, 2007). Additionally, the stress drops of two other PH events (PH04 and PH07) with $M_w$ larger than 4.0 are also smaller than the stress drops of similar-sized GJ events.

To summarize the characteristics of stress-drop scaling for the two sequences, the stress drops of the PH sequence appear to be smaller than those of the GJ sequence, and two PH events (PH01 and PH02) have much smaller stress drops in comparison with those of events with similar magnitudes in the GJ sequence. The stress drop of PH01 ($M_w$ 3.3) is smaller than that of GJ13 ($M_w$ 3.3) by a factor of approximately 4. The stress drop of PH02 ($M_w$ 5.5) is smaller than that of GJ03 ($M_w$ 5.6) and GJ01 ($M_w$ 5.1) by a factor of 4.3 and 2.5, respectively. Estimates of the stress drops for the GJ and PH mainshocks reported by other studies show similar results. Son et al. (2018) reported that the stress drop of GJ03 is 11.2 MPa based on the analysis of the $S$-wave source spectrum. The mean stress drop of the same event derived from finite-fault inversion using the empirical Green’s function method is 23 MPa (Uchide and Song, 2018). These values are somewhat larger than our estimate (8.29 MPa). For PH02, Song and Lee (2019) estimated the mean stress drop of PH02 to be approximately 2 MPa from finite-fault inversion using Interferometric Synthetic Aperture Radar data, and this value is consistent with

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Figure 4. Spectral ratio of GJ (red) mainshock and foreshocks and PH (blue) mainshock and largest aftershock with the same empirical Green’s function (EGF) events in sequence. The focal mechanisms and PH event depth information were determined using ISOLA, and the Gyeongju event depth information was obtained from Woo, Rhie, et al. (2019). Dashed lines (yellow) indicate the use of posterior distribution to determine corner frequency by full-Bayesian Markov Chain Monte Carlo (MCMC). The black and white colors of triangles indicate the corner frequencies of the target and EGF events. The color version of this figure is available only in the electronic edition.
the influence of fluid injections. There have been several studies reporting that stress drops of induced earthquakes are smaller than those of tectonic earthquakes (Hough, 2014; Boyd et al., 2017; Sumy et al., 2017). Hough (2014) argued that the stress drops of induced earthquakes are smaller than those of tectonic earthquakes by a factor of 2–10 based on differences in intensity between tectonic and induced earthquakes measured by a “Did You Feel It?” system. Although the difference in the stress drop between the PH and GJ mainshocks derived in this study lies within the range proposed by Hough (2014), it is not sufficient to conclude that the low stress drops observed in the PH sequence, especially for PH02 and PH01, are caused by fluid injections. It is well known that the stress drop is controlled by many other factors, such as focal depth, faulting type, and heat flow. Therefore, it is possible that the discrepancy in the stress drop can be attributed to other factors. The PH and GJ mainshocks differ in several ways in addition to fluid injection.

First, the focal depth of the PH mainshock (4.27 km; Lee et al., 2019) is much shallower than that of the GJ mainshock (14.5 km; Woo, Kim, et al., 2019). Second, the faulting type of the GJ mainshock is nearly pure strike slip, whereas that of the PH mainshock is strike slip with considerable thrust-faulting component. Although several studies have found that there is no clear depth dependence of stress drop (Allmann and Shearer, 2009; Wu et al., 2018), most previous studies support the theory that shallow earthquakes have lower stress drops than deep earthquakes (Oth, 2013; Huang et al., 2017). Huang et al. (2017) reported that induced earthquakes with deep focal depths (<5 km) show stress drops similar to those of tectonic earthquakes in the central United States and concluded that induced and tectonic earthquakes are not distinguishable based only on differences in stress drop. Therefore, it is possible that the lower stress drop of the PH mainshock compared with the GJ mainshock is caused only by the difference in focal depth. The difference in focal depth can explain why the stress drops of the PH events are relatively lower than those of the GJ events. Regarding the faulting style of earthquakes, the relations between faulting style and stress drop reported by previous studies are not consistent. In general, it is well-accepted that reverse-faulting earthquakes have higher stress drops (e.g., McGarr, 1984; McGarr and Fletcher, 2002). However, Allmann and Shearer (2009) suggested that the stress drop of strike slip is higher than that of other faulting types. Our observation shows that the stress drop of the GJ mainshock, which has a pure strike-slip mechanism, is higher than that of the PH mainshock, which has considerable reverse-faulting components; this is consistent with the result presented by Allmann and Shearer (2009). Oth (2013) suggested that stress-drop variations are strongly correlated with heat flow variations in crustal earthquakes in Japan. Therefore, heat flows can be another factor that affects stress drop; however, we do not have sufficient information on whether there is a

Figure 5. To correct the site effect, we prepared the site-term with the GJ mainshock ($M_w 5.58$), foreshock ($M_{w} 5.13$), and largest aftershock ($M_{w} 4.49$) records at the station (DAG2). In addition, we created the synthetic Brune model (the lines overlaying the squares) for the events. By subtracting the observed amplitude (black dashed lines) from the synthetic model, we determined the correction term (gray dashed lines) for each event. The site term (black line) of this station was obtained by averaging all of the correction terms. The site term of the station was applied to obtain the site-corrected amplitudes for every recorded event. The color version of this figure is available only in the electronic edition.
considerable difference in heat flow between the epicentral regions of the GJ and PH sequences.

CONCLUSIONS

We analyzed the stress-drop scaling of two moderate earthquake sequences that occurred in the same tectonic regime. The stress drop seems to increase with an increasing magnitude in both sequences. The observed magnitude dependence in stress-drop scaling cannot be explained by a self-similar model with a constant stress drop (Aki, 1967). The scaling of the GJ sequence is similar to the results of other earthquake sequences studied using similar coda-based methods (Mayeda and Malagnini, 2009; Malagnini et al., 2010; Yoo et al., 2010; Yoo and Mayeda, 2013). The characteristic feature is that stress drop rapidly increases with $M_w$ in the range between $M_w$ 4.5 and 5.5. This rapid increase in stress drop is not found in the PH sequence. On average, stress drops of the PH sequence are lower than those of the GJ sequence. Stress drops of PH02 and PH01 are much smaller than the events with similar magnitude in the GJ sequence. Considering previous studies on factors controlling the stress drop, it is likely that differences in focal depth between the two sequences cause differences in the stress drop. Although the focal depths of all PH events are similar, the stress drops for the two PH events (PH01 and PH02) particularly are lower than those of the other PH events. In addition, these two events are likely to be influenced by fluid injections. It may be inferred that the much lower stress drops

Figure 6. Source calibration results of two earthquake sequences, (a) GJ and (b,c) PH. The symbols represent the mean values of the site-corrected amplitude data with one standard deviation. Synthetic Brune curves (black lines) are the results of the source calibration. The stars denote the corner frequencies on the Brune curve with posterior distributions (yellow lines) as a result of full Bayesian MCMC and Metropolis–Hastings Sampling (MHS) method. The same colors as in Figure 2 are used for the corresponding events. (c) Yellow dashed lines indicate the Brune spectra calculated using the $f_c$ values from the spectral ratios. The symbols (open triangles, squares, and circles) show the nondimensional coda amplitudes (NDCAs) for stations after revision using the recalculated site-correction terms. Blue lines are the same as the black lines in (b). The color version of this figure is available only in the electronic edition.
<table>
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<th>Sequence</th>
<th>Event (Number)</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth</th>
<th>$M_w(1)$</th>
<th>$M_w(2)$</th>
<th>$f_c(1)$ (Hz)</th>
<th>$f_c(2)$ (Hz)</th>
<th>$\Delta \sigma$ (1) (MPa)</th>
<th>$\Delta \sigma$ (2) (MPa)</th>
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<td>35.77</td>
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<td>13.96</td>
<td>3.03</td>
<td>3.81 ± (0.01)</td>
<td>0.47 ± (0.03)</td>
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<td>15.80</td>
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<td>2.47 ± (0.02)</td>
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<td>3.43</td>
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<td>129.19</td>
<td>12.96</td>
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<td>2.98</td>
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<td>8.0 (KMA)</td>
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The hypoDD relocation data from Woo, Rhie, et al. (2019) were used for Gyeongju, and the Pohang sequence location data were obtained from the Korean Meteorological Administration (KMA) catalog; focal depths were computed by ISOLA. (1) and (2) denote the results of coda spectral ratio and source calibration methods, respectively.
for the two events are caused by fluid injection. However, it is not conclusive that the effect of fluid injection is adequate for explaining the lower stress drops based on only the observations in our study.

**DATA AND RESOURCES**

Waveform data were acquired from seismograph networks and data centers in the region, including those of the Korea Institute of Geology and Mineral Resources (KIGAM) and the Korea Meteorological Administration (KMA) (the event catalog and data are available from the authors upon request). Geotectonic lines were obtained from KIGAM (https://mgeo.kigam.re.kr). The figures in this article were generated using Generic Mapping Tools (GMT; https://www.soest.hawaii.edu/gmt/). All websites were last accessed in March 2017.

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**REFERENCES**


