Partitioned Fault Movement and Aftershock Triggering: Evidence for Fault Interactions During the 2017 Mw 5.4 Pohang Earthquake, South Korea

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Abstract The 2017 Pohang earthquake (Mw 5.4) is the largest earthquake associated with fluid injection activities. We report new characteristics of the earthquake and propose a dislocation-type model explaining previously reported observations. We identify fault geometry by relocating the hypocenters of 1,132 events that occurred during the first 3 months and then resolve their source regions as the northern, central, and southern patches, based on event groups with similar waveforms. The spatial features of these similar waveform groups, in addition to our obtained source mechanisms, indicate that oblique contraction is prevalent in the source region: Reverse faulting dominates the southern fault and the deeper part of the central fault; near-parallel strike-slip sense controls the northern fault and the shallower part of the central fault. Furthermore, we identify a migrating aftershock pattern that matches the fluid diffusion process along both sides of the northern and central faults. This observation suggests the interconnection of the two faults, allowing fluid transport, and implies mainshock coseismic movement along the fault intersection. The coseismic slip of the fault intersection can induce a fault-valve process, which explains the aftershock migration pattern along the two intersecting faults. The proposed fault interaction accounts for the previously reported uplift between the two intersecting faults and successfully reproduces the non-double-couple mechanism of the mainshock. Our results raise the question of fluid-faulting interactions in the aftershock seismicity of the Pohang earthquake, and the complex fault movement provides insight into the rupture process that allowed the Pohang earthquake runaway.

1. Introduction

The Pohang earthquake (Mw 5.4) that struck the southeastern region of the Korean Peninsula in November 2017 (Figure 1) has been reported as the largest destructive earthquake event related to fluid injection activities during the development of an enhanced geothermal system (EGS; Ellsworth et al., 2019; Grigoli et al., 2018; Kim et al., 2018; Woo et al., 2019). The earthquake occurred near the southern boundary of the Pohang Basin adjacent to the east coast of the Korean Peninsula. The Pohang Basin formed during a pull-apart process in the Middle Tertiary in accordance with the opening of the East Sea (Japan Sea; Jolivet et al., 1994; Sohn et al., 2001; Yoon & Chough, 1995). The stress field around the Korean Peninsula has transitioned from extension to compression since the opening of the East Sea ceased in the Middle Miocene (Choi et al., 2015; Kim & Park, 2006; Tamaki, 1995). The orientation of the most compressional stress axis changed from near N–S to ENE–WSW due to the change in the tectonic regime (Soh et al., 2018).

Grigoli et al. (2018) and Kim et al. (2018) suggested the possibility that the 2017 Pohang earthquake was induced by the activities of an EGS located near (<1 km to the east) the epicenter (Figure 2), although some controversy remains (Hong et al., 2018). Several researchers suggested that the Pohang earthquake was triggered by accumulated seismicity related to an unknown unstable fault (Ellsworth et al., 2019; Geological Society of Korea, 2019; Lee et al., 2019). Woo et al. (2019) explained the possibility of a runaway-style rupture process for the earthquake, based on excess seismic moment in the possible ranges derived from the injected fluid volume.

The Pohang earthquake was characterized by a full moment tensor with a large non-double-couple component, which implies the failure of multiple faults with different senses of slip (Grigoli et al., 2018). The complexity of the rupture process of the earthquake was also mentioned by Song and Lee (2019), who reported a local concentration of coseismic deformation northeast of the epicenter. Kim et al. (2019) reported geometry...
and focal mechanisms, in addition to the general NE-SW distribution of the hypocenters suggested by previous studies (Hong et al., 2018). Although surface ruptures were not observed, Ghim et al. (2018) and Choi et al. (2019) revealed surface deformation, including hundreds of sand blows that were restricted to the northeast of the earthquake epicenter.

In this study, we analyze the characteristics of the Pohang earthquake and its aftershocks in detail, incorporating previously reported observations, and propose a possible mechanism that explains them. We present a fault geometry model for the source region, based on the spatial distribution of the aftershock sequence grouped in space and time according to waveform similarities. Based on the coherent spatial distributions of similar earthquake mechanisms, we infer the slip senses of individual faults and construct a dislocation model that involves fault interactions. We examine whether this fault interaction model explains the local uplift in the area between the faults and the large non-double-couple components of the mainshock. Furthermore, we present an aftershock migration pattern comparable to the spreading from fluid diffusion and discuss the possible effects of fluids on the concurrent activation of a complex fault system.

2. Data and Methods

We deployed five temporary stations within ~10 km from the source region 26 h after the occurrence of the mainshock (POHM1 to 5; inverted triangles in Figure 1a). Each station had a broadband CMG-40T and an accelerometer Episensor2 with a Q330HRS recorder. We relocated one station (POHM4) 2 weeks after the deployment, at the request of the landowner, and renamed the station POHM6. One week after the relocation, we moved POHM6 to the POHM7 location (Figure 1a). All stations (POHM1, 2, 3, 5, and 7) operated until March 2018. In addition to these temporary stations, this study utilized the permanent stations of three seismic networks owned by the Korea Institute of Geoscience and Mineral Resources (KIGAM), the Korea Meteorological Administration (KMA), and the Korea Institute of Nuclear Safety (KINS) (see Table 1 and upright triangles in Figure 1).

We relocated the hypocenters of 1,124 earthquakes that occurred from 14 November 2017 to 20 February 2018, using the double-difference technique (Waldhauser & Ellsworth, 2000). We derived an event set, comprising two foreshocks, the mainshock, and 1,129 aftershocks, from the KIGAM earthquake catalog. We measured the travel-time difference for the relocation based on waveform similarities, instead of $P$- and $S$-wave arrival times. We quantified waveform similarity, using cross-correlation coefficients (CCs). We used the maximum CC and corresponding time lag, for both hypocenter relocation and further event associations, based on hierarchical waveform clustering. This cross-correlation approach has been successfully applied to earthquake sequences in the Korean Peninsula in the past (Han et al., 2019; Son et al., 2015, 2018).

To obtain time lags, $P$- and $S$-wave time windows were individually cross-correlated after applying a band-pass filter (see Table S1 for specified ranges by phase and station). We set the time windows based on

![Figure 1. Maps of the 2017 Pohang earthquake with fault traces: (a) epicenter of the earthquake and locations of seismic stations used for the relocation; the geological fault traces were obtained from the study conducted by Chwae et al. (1995); (b) the seismic stations used for the moment tensor inversion and solution for the earthquake. The mapped area of (a) is outlined in (b) in red. The rectangular areas surrounding the epicenter in (a) correspond to the area of the map views of Figures 2–5. The inverted and upright triangles represent the temporary and permanent stations, respectively.](image-url)
apparent travel times that were determined through the alignment of waveforms including P- or S-waves during preliminary cross-correlation. Event pairs were accepted when the travel-time differences presented CCs above 0.7 at more than five stations for either P- or S-waves. This analysis was based on data from 11 stations (the six permanent and five temporary stations depicted in Figure 1a). However, for the 206 events in the first 3 h of the sequence, we incorporated additional records from eight temporary stations, available online from Kim et al. (2018). Finally, we shifted the entire set of relative locations over the difference between the relative and absolute locations of a reference event (16 November, 16:19:53 UTC). We determined the absolute location of the reference event using the program HYPOSAT (Schweitzer, 2001), with additional seismic data recorded by the eight temporary stations of Kim et al. (2018). We used a one-dimensional velocity model (Figure S1; Hofmann et al., 2019; Kim et al., 2017), which was constructed from sonic logging and seismic refraction data.

We used a hierarchical classification approach with a dendrogram (hierarchical clustering tree) to classify events according to waveform similarities. The dendrogram was constructed by placing similar waveforms close together, with branch heights corresponding to one minus the average CC of the subentries (Figure S2). Therefore, we could determine subsets of similar waveforms by cutting the dendrogram at a specific height (i.e., clustering threshold) without considering affinities between event locations or arbitrarily

Figure 2. Results of the relocation and focal mechanism analysis for the 2017 Pohang earthquake sequence: map view of the relocated 1,132 events (open circles) and retrieved 39 focal mechanisms (beach ball diagrams). The blue curves show Gokgang and Chogok streams, and the black square shows the location of the EGS site. Detailed examples of first-motion polarity analysis results are presented on the upper left. The beach ball diagrams with event identifiers that do not overlap are shown in Figure S5. The epicenters and geomorphology of the studied area are visible in the Google Earth KMZ file, available in the electronic supplementary material.
selecting a master event (Harris, 1991; Son et al., 2015; West, 2013). We applied this method to the waveforms of 134 events (Mw > 3.5; Figure S3 for 280 events Mw > 1.5) recorded at a station (CHS) ~25 km northwest of the source area, where the event station direction corresponds to the maximum P-wave energy radiation from the mainshock among close stations. We calculated the CCs between windowed waveforms, including the P-wave and its coda, with a sampling rate of 100 Hz, after band-pass filtering from 1.2 to 6 Hz. Four event groups were obtained with a clustering threshold of 0.87, which we selected after the visual inspection of several test values (Figure S4). We used the event with the shortest branch (i.e., the most linked member of the dendrogram) as the reference event for the calibration of relative locations. When using this classification with cross-correlation coefficients, a rupture process that becomes more complex as the magnitude increases limits the available station, magnitude threshold, and pass bandwidth. Previous studies have made the following statements regarding this limitation: (1) The cross-correlation method is more effective for small events than large ones (Hauksson et al., 2012), and (2) correlation coefficients increase with decreasing difference in magnitude among event pairs (Waldhauser & Schaff, 2008).

We also estimated the source mechanisms of the Pohang earthquake sequence. For the eight relatively large aftershocks (Mw > 3.5), we evaluated moment tensors using a time-domain waveform inversion method (Dreger, 2003; Minson & Dreger, 2008) with the hypocenters and origin times obtained from our analysis in this study. We excluded the Mw 3.8 earthquake that occurred 3 min after the mainshock because of the high level of mainshock coda waves. Time-aligning the waveforms based on cross-correlation allowed the inversion to accommodate the possible uncertainties of the velocity model of Kim et al. (2011) (Son et al., 2018). We utilized waveform data with a frequency range of 0.04 to 0.1 Hz from permanent broadband stations (Figure 1b) and estimated the focal mechanisms of events with magnitudes below 3.5, based on the polarities of the first arrivals (Snoke, 2003).

Furthermore, we defined event families for the second largest aftershock to identify the zones that shared the source mechanism of the second largest aftershock, characterized by reverse faulting at a relatively deep depth. The event families had waveforms similar (CC > 0.85) to those of the second largest aftershock. We computed the correlation coefficients again with a time window 1.0 s longer than that used for the previous waveform classification, expecting that the newly included data points would result in a more detailed classification. The moment tensor of the second largest aftershock, previously determined by time-domain waveform inversion, allowed us to infer the fault solutions of the aftershock event families.

3. Results

Here we present our relocation results and our obtained source mechanism (section 3.1). We then specify the fault geometry with different senses of slip, noting previously reported observations and the geographical surroundings (section 3.2). The waveform clustering results provide spatiotemporal information of seismicity in the defined fault patches and allow us to identify the unreported migration of the aftershocks (section 3.3).

3.1. General Trends of Event Locations and Mechanisms

The relocated hypocenters of the 1,132 events extend horizontally ~8 km in the NE-SW direction, with a primary NW dipping trend at depths between 2.5 and 7.6 km (Figure 2; see Table S2 for the earthquake catalog). The horizontal distribution of the events can be divided into three different sections: (1) the central area close to the mainshock; (2) the northern patch off the mainshock, including deep (blue circles in Figure 2; e.g., E06 and E08) to shallow events (e.g., A5); and (3) the southernmost tip with an opposite dip direction, SE (see circles in the orange-yellow-green scale in Figure 2), where one of the last aftershocks (A7) belongs.

The fault parameters retrieved for the eight major events (Table 2) and 31 additional events (Table S3) mainly indicate strike-slip with slight reverse faulting (Figure 2; see Figure S5 for non-overlapping fault solutions). The full moment tensor of the mainshock has a large non-double couple term (55%; Table 2). The principal compressive stress direction of the mainshock is WNW–ESE, oblique to the mainshock patch (i.e., the central area). The moment tensor of A5, in the northern patch, also has a notable non-double-couple term (43%;

| Authority | KIGAM | KMA | KINS |
|-----------|-------|-----|------|
| Station   |       |     |      |
| CHS; DKJ; GKP1; HAK; HKU; JJB; KNUD; POHB; SND; TJN | BUS2; CHC2; CHJ2; DAG2; EJO2; PHA2; ULJ2; YOCB | WSN |
Table 2, likely indicating crack opening mechanisms. The moment tensor of the largest aftershock (A7) validates the change of dip direction at the southwesternmost tip (Figure 2 and Table 2).

Interestingly, in the central area, the earthquakes with predominant reverse faulting occur at medium to deeper depths (see circles in the cyan to blue scale in Figure 2), while strike-slip dominant events are prevalent at relatively shallow depths (circles in the red to yellow scale in Figure 2). The moment tensor inversions (Figure 2 and Table 2) of the four major events (A1, A3, A4, and A6), at depths of 2.5–4.7 km, present strike-slip dominant mechanisms, which contrast the reverse faulting of the second largest event (A2) at a depth of 5.6 km. This along-dip variation of faulting style is maintained in the focal mechanisms derived from P-wave first-motion polarities, except for the normal faulting event, E31, that bridges the deeper and shallower part of the mainshock patch (Figure 2 and Table S3).

3.2. Complex Fault Geometry and Different Movements

The fault geometries and movements for the hypocentral area of the Pohang earthquake sequence can be sectioned horizontally and vertically (blue, red, and green planes in Figure 3; see Table 3): (1) FN for the northernmost area, with right-lateral strike-slip; (2) FMd for the deeper part of the central area, with dip-slip (reverse faulting); (3) FMs for the shallower part of the central area, with right-lateral strike-slip; and (4) FS for the southernmost patch, with dip-slip (reverse faulting). The slip senses can be inferred from the moment tensor solutions of the major events of each fault patch (Figures 3a and 3b; Table 3).

The fault geometries were obtained by fitting the seismicity to the planes, based on orthogonal distance regression and singular value decomposition (svd command in MATLAB™). The boundaries of the northern, central, and southern areas (FN, Fm, and FS) were determined using spatiotemporal features of the seismicity. This is delineated in the next section (section 3.3). The intersection of the deeper and shallower parts of the central area (FMd and FMs) was resolved by considering the along-dip variation of the faulting style of the central area. Note that the event families of A2, characterized by reverse faulting, are located on the deeper part of the central area (red filled circles in Figure 3a). The normal faulting mechanism of E31 on the intersection between FMd and FMs (yellow filled circle in Figure 3a) supports our segmentation of the central fault FM, implying a locally induced pull-apart stress between the two segmented central patches FMd and FMs.

The map views (Figures 3b and 3c) illustrate that the fault jog between FN and FM corresponds to previously reported locations of coseismic deformation, sand blows, and uplift (Gihm et al., 2018; Song & Lee, 2019; pink and yellow-to-brown patterns in Figure 3c, respectively). The sand blows were observed along the junction of two meandering streams (Gihm et al., 2018; see the location of Gokgang and Chogok streams in Figure 2). The uplift is concentrated between the extension of the two patches, FN and FS (Figure 3c and inset in Figure 3d). The northern part of the central patch FM intersects with the northern patch FN at a depth of ~7 km, forming a wedge-like structure as shown in Figure 3d. The upward displacement drastically decreases in the southern part of the source region (yellow-to-brown pattern in Figure 3c; insets in Figures 3d and 3e).

The northern patch FN has an almost vertical dip (Figure 3d), whereas the dip angle of the central patch FM is ~60° (Figure 3e). The right-lateral strike-slip sense of the shallow FN and FMs fault planes is inferred from the moment tensors of A3 and A5, respectively. The reverse faulting in the deeper part of FM (FMd) is inferred...
from the spatial distribution of earthquakes resembling A2. The shallower part of FMs is illustrated by dashed lines in the insets (Figures 3d to 3f) due to the lack of seismicity. The seismicity of FMs ceases at the intersection to FS (Figure 3f). The plane FS slopes towards the southeast as if antithetically cuts FMs (green color in Figure 3f), where the Pohang Basin bounds the two mountains (Doeum and Myobong) (see Google Earth KMZ file in the electronic supplementary material). The reverse faulting for FS is inferred from the moment tensor solution of A7, located close to the center of FS.

3.3. Spatiotemporal Characteristics Based on Waveform Similarities

We used a correlation coefficient matrix for thorough clustering based on waveform similarity, without any prior assumptions (Figure 4a). Note that temporal transitions in waveform similarities are observed during the occurrence of major earthquakes (e.g., A2 and A7). Using a correlation coefficient of 0.87 as a branch cut in the dendrogram (Figure S2) identifies four event groups with similar waveforms (Groups 1 to 4; see Table 4). When reorganized based on the four groups, the correlation coefficient matrix (Figure 4b) validates the waveform coherence of each group.

The event groups based on waveform similarities show spatial consistency at the locations of individual earthquakes (Figure 4c). Two groups of earthquakes (Groups 1 and 3) mainly occur in the area around the mainshock (i.e., FM) and partly extend to the nearest parts of the northeastern and southwestern patches (i.e., FN and FS) (red and orange circles in Figure 4c). A small group of earthquakes (Group 2) is concentrated
in a separate segment, the northern patch FN (blue circles in Figure 4c). Group 4 earthquakes are concentrated in the southernmost tip FS. These observations indicate that the events of different waveform groups are, to a certain extent, characterized by different faulting properties based on the level of waveform similarity, although they belong to the same sequence of the Pohang earthquake in a relatively confined area. The associated waveform groups that spatially belong to each defined patch are listed in the last column of Table 3.

Considering the spatial distribution of the event groups, we inspect the temporal relationships between the event groups and the occurrence timing of the largest aftershocks and propose aftershock migration through the northern patch FN. Figure 5 describes the timings of earthquakes with respect to their spatial distribu-

| Strike/dip direction of dip (°) | Len./Wid. (km) | Reference position (southwesternmost vertex; Lon./Lat./Dep.; °E/°N/km) | Relative position | Slip sense | Major event | Similar waveform group (occurrence period) |
|--------------------------------|----------------|-----------------------------------------------------------------|-----------------|------------|-------------|------------------------------------------|
| FM 225/67NW                    | 5.6/2.1         | 129.34/36.08/2.99                                               | Central, shallower | Right-lateral strike-slip | A1 A3 M | Group 1 (before A2, within ~3 h after M) |
| Fmd 222/62NW                   | 4.4/2.8         | 129.35/36.09/4.14                                               | Central, deeper   | Reverse faulting           | A2 A4 A6 | Group 3 (after A2 or ~3 h after M)       |
| FN 229/88NW                    | 3.3/2.1         | 129.36/36.13/4.35                                               | Northeast from M  | Right-lateral strike-slip | A5     | Group 2 (between A2 and A3)              |
| FS 019/61E                     | 1.5/1.6         | 129.33/36.07/5.15                                               | Southwest from M  | Reverse faulting           | A7     | Group 4 (after A7 or ~3 months after M)  |

Note: The abbreviations for major events such as M and A with integers are defined in Table 2.

Figure 4. Four groups of the 2017 Pohang earthquake sequence classified according to waveform similarity: (a) matrix of the maximum cross-correlation coefficient for each event in temporal order; (b) correlation matrix sorted by four similar waveform groups; (c) epicenter distributions for the four groups composed of Group 1 (red circle), Group 2 (blue circle), Group 3 (orange circle), and Group 4 (green circle). Event abbreviations, such as M and A, are described in Table 2. Gray dots represent 998 events (ML < 2.0) not employed in the waveform classification and 31 events (ML > 2.0) not included in the four defined groups.
tions for 3 months. Note that the highest aftershock activity (M–A3 sequence) occurs within the first 18 h after the mainshock (Figure 5a).

The panels in the first row of Figure 5b display the occurrences of the mainshock M and two adjacent foreshocks. The Group 1 events occur within the mainshock patch FM during the first 3 h of the aftershock sequence (red circles in the panels in the second row of Figure 5b). The aftershock A2 (Mw 4.3) approximately corresponds to the termination of the Group 1 sequence and initiation of Groups 2 and 3 (Figure 5a). The spatial distribution of Groups 1 and 2 help determine the boundaries of FN and FMd.

The Group 2 sequence clusters in the northeastern patch FN and shows hypocenter migration in FN (blue circles in the panels in the third row of Figure 5b): The hypocenters progress upward from depths of 6 to 4 km within ~9 h after the occurrence of A2. Following Group 2, the shallowest major event, A3, occurs at the top of FM, which is the opposite side from FN considering the fault intersection of FN and FM (see the third row of Figure 5b and Figure 3d).

Group 3 (orange circles in the panels in the third row of Figure 5b) overlaps with Group 2 with respect to its timing but is located in the mainshock patch FM. The spatial gap left by Group 1 appears to be filled by Group 3 after the occurrence of A2 (the third and fourth rows of Figure 5b), implying the presence of continuous stress concentrate on FM. The spatial distributions of Groups 2 and 3 help in identifying the intersection points between FM and FS.

A small number of Group 4 events occur at the northern tip of FM (the fourth row in Figure 5b). The mainshock patch remains active for more than 2 months, mainly including Group 3 and two major events, A4 and A6, in addition to M. During this period in the separate northeastern patch FS, aftershock A5 occurs at a shallower depth (~4 km) than the Group 2 events colored in blue (the fourth row in Figure 5b). The number of events continuously decreases over the first 3 months (Figure 5a), implying that there is no continuous stress concentration in the source area.

However, due to the occurrence of the largest aftershock A7 (Mw 4.6) approximately 3 months after the mainshock (Figure 5a), an additional sequence of earthquakes is activated at the southwesternmost tip FS (bottom row in Figure 5b). These events correspond to Group 4, occurring within a radius of ~1 km relative to the hypocenter of A7 (see the clear correspondence between the spatial distribution of most of the events in Group 4 and the possible source region of A7, represented by green circles in the bottom row of Figure 5b).

Group 4 also appears on the edges of the central area FM (see green circles in the shallowest section around A3, the deep part around A2, and the hinge-like point between FM and FS). This observation allows us to infer that Group 4 could possibly identify a conjugate structure, such as FS. The inferred structure on the edges of FM would define the coseismic rupture of the mainshock. Furthermore, no Group 4 events occur in the northern bottom of FM where the northern patch FN intersects. Such events would indicate the susceptibility of the northern fault intersection to rupture during the mainshock.

4. Discussion

We scrutinize the aftershock migration across the northern source region and consider the possibility of fault interaction involving fault-valve processes along the fault intersection between the northern and central faults (section 4.1). We then reconstruct the non-double-couple mechanism of the mainshock based on the inferred fault interaction and explain the formation of the uplift in the northern source region, as well as inferring aseismic slip involvement in the fault-valve behavior (section 4.2). We discuss driving forces that can result in this complex fault movement and infer the rupture direction of the mainshock (section 4.3). Finally, we carefully review the 2017 Pohang earthquake in terms of earthquake initiation and termination, based on the complex fault geometry and its partitioned movement (section 4.4).

4.1. Fault Interactions Triggering Aftershocks and Surface Deformation

The spatiotemporal characteristics of the northern source region indicate the upward progression of the aftershock migration in the northern fault FN (blue arrow in the third row of Figure 5b) and the subsequent occurrence of A3 at the top of the opposite fault FM. We inspected the seismicity in the northern source region...
including the aftershock sequence in the fault intersection (i.e., the apex edge of the wedge-like structure; see fault configuration in Figures 3d and 6a). We computed hypocentral distances from the first migration event and compared the seismic migration front to spreading from fluid diffusion (Figures 6b and 6c), replacing the first migration event with the following event. We applied the relationship $r = (4 \times \pi \times D \times t)^{0.5}$, where $r$ is the distance, $D$ is the hydraulic diffusivity, and $t$ is the time (Shapiro et al., 1997).

Figure 5. Spatiotemporal features of the 2017 Pohang earthquake sequence based on the four event groups classified by waveform similarity (Groups 1 to 4) and the occurrence time of the eight major events ($M_w > 3.5$): (a) occurrence plot as a function of the time for 3 months and enlarged occurrence plot for ~27 h after the first foreshock; (b) spatial distribution of events occurring in the defined periods indicated by arrows. The occurrence periods are marked by the major events M, A2, A3, and A7. The double-headed arrow in the left panel of (a) indicates the enlarged window to emphasize the first 18 h of the aftershock sequence. The event colors (red, blue, orange, green, and gray) are defined in Figure 4.
The seismic migration front matches a hydraulic diffusivity (D) of approximately 20 m²/s (Figure 6c), when we suppose that the first migration event occurred in the fault intersection ~0.5 h after the mainshock (15 November, 06:02:06 UTC; see the filled circle in Figures 6b and 6c). The seismic front moves both upward and downward along the fault intersection during the first ~3 h after mainshock occurrence (Figure 6b). The seismic migration front then progresses only upward, along both sides of the wedge (i.e., along both of the intersecting faults) away from the fault intersection (Figures 6a and 6b). This upward progression halts at the top of the central fault FM with the occurrence of A3 (red star in Figures 6b and 6c).

The diffusivity on both sides of the wedge, ~20 m²/s, is much higher than the diffusivity estimated during a hydraulic fracturing experiment (Shapiro et al., 1997) or in earthquake swarms (Chen et al., 2012; Shelly et al., 2013). The diffusivity, however, can be large; for example, a diffusivity of 80 m²/s was reported for the aftershock sequence of the 2009 L’Aquila earthquake, suggesting a highly fractured medium (Luccio et al., 2010). Fluids tend to migrate through existing fractures with high permeability (e.g., Shelly et al., 2013). Therefore, migrating earthquakes highlight the fluid spreading along the faults. We conclude that the two faults FN and the northern part of FM, which form the wedge-like structure, are highly fractured and interconnected at depth (i.e., at the apex edge of the wedge). This suggests potential fault interaction between the two faults.

Figure 6. Fault interaction in the 2017 Pohang earthquake sequence: (a) fault configuration with hypocenter migration and local uplift between the central and northern faults (FM and FN); (b) aftershock migration and triggering along the central and northern faults (FM and FN); (c) seismicity front of the aftershock migration, following a diffusion process with a hydraulic diffusivity of 20 m²/s. The cross section (b) is outlined by a dashed line in (a). The filled circle in (b) and (c) is for the first event of the sequence examined in terms of hypocenter migration. The aftershock A5, denoted in gray in (b), is the largest event (Mw 3.6) in FN.
The discrepancy between the triggering front and potential fluid source (i.e., the fluid injection point or the hypocenter of the mainshock) is plausible if considering fault interaction at the fault intersection. The interaction of earthquakes with aqueous fluids in the crust and upper mantle is considered a common tectonic phenomenon (e.g., Cox, 2005; Sibson, 1996). Increased pore fluid pressure can trigger shear, tensile, or combined failure because the effective normal stress on the fault is reduced (e.g., Shelly et al., 2015; Sibson, 1990).

With respect to the 2016 Central Italy seismic sequence, an increase in the fluid pressure at a fault intersection during rupture is considered to have triggered an aftershock sequence that progressed from the end of the ruptured fault to the other fault (Walters et al., 2018). Fault interaction in the Pohang sequence may explain why the first migration event started close to the northern root of the central patch (i.e., the intersection of the two faults, F_N and F_M) and why the seismic activity expanded from the central patch F_M to the northern patch F_N.

Fault-valve behavior (Shelly et al., 2015; Sibson, 1992) can clarify our explanations of the aftershock migration that starts at the fault intersection between F_M and F_N. The rupturing of the Pohang earthquake is comparable to the opening of the valve, especially at the fault intersection, which is in the deepest part of the source region. The two intersecting faults, acting as permeable channels from the fault intersection to the top of each fault, could propel aftershock migration, if the fault intersection at depths below ~6 km ruptures into a suprahydrostatic fluid source, as suggested in previous studies on natural earthquake swarms (e.g., Ross et al., 2020; Shelly et al., 2015). For the migrating foreshocks of the 2008 Mogul earthquake, a shallow earthquake swarm (at depth <6 km), Ruhl et al. (2016) suggested the neighboring river and hot spring as facilitators of fluid saturation at shallow depths. The northern source region of the Pohang earthquake sequence is bordered by the East Sea (Japan Sea) (Figure 1b), and two meandering streams are forming a junction around the fault intersection where the fluid reservoir is hypothesized (Gogang and Chogok streams in Figure 2). It should also be noted that the occurrence of the Pohang earthquake is related to fluid injection activities, though the injection was performed with limited volume to saturate the hypothesized reservoir at depths exceeding ~6 km.

Direct evidence of the hypothesized fluid reservoir at depth is still lacking. The aftershock triggering observed in the northern source area (i.e., the fault intersection of F_N and F_M) requires detailed studies such as stress drop estimation (e.g., Chen et al., 2012; Ruhl et al., 2017) and critical fluid pressure analysis (e.g., Jansen et al., 2019; Yeo et al., 2020) from the perspective of fluid-driven earthquake sequences. This would be a valuable theme for future studies on the Pohang earthquake sequence, as well as on the general mechanism of fluid-faulting interactions.

We focus on possible fault interaction in the fault intersection between the two fault patches: F_N and F_M. By considering fault interaction between F_N and F_M instead of only considering F_M, we can explain the local coseismic uplift northeast of the mainshock. The deformation area is similar to the area bounded by the extension of F_N and F_M, and the configuration of the two faults is characterized by a near-parallel arrangement along the strike direction and interconnection at depth (Figure 6a). The fault configuration mimics strike-slip duplexes or jogs with oblique contraction, producing uplifts. Klinger et al. (2006) illustrated a push-up structure that was formed by the transfer of horizontal to vertical motions in the compressional jog between two strike-slip faults with identical motion senses during the 2001 Kokoxili earthquake in Tibet. Xu et al. (2009) reported a meter-scale uplift induced by coseismic reverse and oblique slip in the 2008 Wenchuan earthquake in China. The 2016 Kaikoura earthquake generated uplift of the fault-bounded block during the oblique convergence of multiple faults (e.g., Hamling et al., 2017). In addition, there are field examples, where oblique shear with a strike-slip fault strand leads to the deformation of fault jogs or the dislocation of a fault-bounded block involving uplift or subsidence (e.g., Cunningham & Mann, 2007; Wensoulsky & Jones, 1994), geophysical survey results (e.g., Ikeda et al., 2009; Rohr, 2015), and scaled analog and numerical models (e.g., Dooley & Schreurs, 2012; Sanderson & Marchini, 1984).

4.2. Reconstruction of the Non-Double-Couple Mechanism Based on the Fault Interaction

Based on the assumption that the two faults F_M and F_N interacted when the mainshock ruptured, we examine combinations of slip senses, inferred for the two intersecting faults, to reproduce the full moment tensor of the mainshock featured by the high non-double-couple component. We suggest the conceptual structural
We set the source mechanism for the central fault FM as the sum of two fault plane solutions that characterize the movements of the two segmented central faults FMd and FMs (Figure 7b). The two fault plane solutions are based on the strike and dip values of FMd and FMs listed in Table 3. The rakes of the two solutions describe the simplified movement of FMd and FMs noted in Table 3: pure reverse faulting for FMd and a pure strike-slip mechanism for FMs. These simple combinations of the two double-couple solutions for the central fault FM produce non-double-couple components (third column in Figure 7b), comparable to the two-subevent model suggested for the Pohang earthquake by Grigoli et al. (2018).

To mimic the fault interaction between FM and FN, we integrate the combinations defined for the central fault FM with each double-couple fault plane solutions of E06 (strike-slip with a small amount of reverse slip) and E08 (mainly reverse faulting). The location of the two events (i.e., E06 and E08) allows us to expect that the focal mechanisms of the two events could reflect the movement of the deeper part of FN intersecting with FM. The joint movement of FM and the root of FN successfully reproduces the non-double-couple mechanism of the 2017 Pohang earthquake (violet color, beach ball diagrams in Figures 7c and 7d). The squares in Figures 7c and 7d indicate the combinations with the highest variance reductions, 94.3 and 93.2%, when including E06 and E08, respectively. The variance reduction increases when considering the focal mechanism observed at the fault intersection between FM and FN instead of considering only FM. Figure 7e displays the records obtained for the Pohang earthquake and the waveforms generated by the synthetic moment tensors for the combination denoted by the square in Figure 7c. The synthetic waveforms (dashed lines) have a remarkable consistency (solid lines), with a variance reduction of 94.3% (Figure 7e).

This reconstruction of the mainshock mechanism that involves fault interaction between FN and FM excludes the faulting mechanism of the aftershock A5 at the top of FN (see the location of A5 in Figure 6). We suppose the faulting mechanisms of A5 do not reflect the mainshock coseismic movement, though A5 is the largest (Mw 3.6) of the events belonging to FN. Instead, we consider the aftershock A5 as one of the events related to the fault-valve behavior inferred in the two intersecting faults, FN and FM. In the seismicity related to fault-valve behavior, shallow earthquakes have been observed to occur above a fluid pathway that is dilatant and permeable (Ruhl et al., 2016; Shelly et al., 2015). The moment tensor of A5 exhibits a notable non-double-couple term (43%; Table 2) implying crack opening (see the beach ball diagram for A5 in Figure 2) at the top of the fluid pathway highlighted by the migrating hypocenters in the northern patch FN (Figure 6).

In a fault that acts as a pathway for fluid upwelling, Ruhl et al. (2016) suggested that aseismic slip occurs or has occurred. We can infer a possible pathway for fluid upwelling in FN based on the observation of the aftershock migration from the fault interaction to the top of FN, starting within ~3 h after the occurrence of the mainshock (Figures 5 and 6). A possible aseismic slip in FN in the early period of the Pohang sequence (i.e., within ~3 h of mainshock occurrence) involving the inferred joint movement in the fault intersection could form local uplift between the two near-parallel faults FN and FM. It should be noted that interferometric pairs used for the estimation of deformation (e.g., local uplift) do not constrain an immediate slip (see time gaps between the descending and ascending orbit in Song & Lee, 2019).

The multiple combinations producing the non-double-couple mechanism, to a certain extent, (Figures 7b to 7d) is an indicator of the non-uniqueness problem of moment tensor decomposition. The combinations could also be unreliable because of the simplification of the slip motions, the composition ratios, and uncertainties in the individual focal mechanisms. However, we focus carefully on general increments in variance reduction, after adding the movement of the bottom of FN to the mechanisms inferred in FM. The examined mechanism explains the other observations, the local uplift of the northern source region, and the aftershock migration starting from the fault intersection. We thus conclude that, as the mainshock coseismic phenomenon, the non-double-couple mechanism of the Pohang earthquake results from fault interaction at the northern fault intersection.
Figure 7. Reconstruction of the moment tensor solution for the 2017 Pohang earthquake: (a) moment tensor solution of the earthquake and conceptual structural model modified from Wesnousky (2005) and Toda et al. (2016); (b) combinations of the two fault solutions (FMd and FMs) for the segmented central faults; (c) combinations of the three fault solutions manifesting the movement of the northern fault intersection with the focal mechanisms of E06, in addition to the segmented central faults (b); (d) same as (c) but for E08; (e) synthetic traces from the composite mechanism denoted by a square in (c) and seismograms of the Pohang earthquake observed at the nine stations in Figure 1b. The focal mechanisms for the segmented central faults are colored red, and the mechanism for the northern intersection is shown in blue. The relative size of moment tensors (%) is declared at the bottom of the beach ball diagram whose radius is scaled to the relative size: For example, the composition ratio for the mechanism denoted by a square in (c) is 20:40:40 with the moment tensors for the movements of E06, FMs, and FMd. The variance reduction (%), which is the fit between the observed and synthetic traces, is noted at the top of the composite mechanism and represented in the order of grey-pink-violet.
4.3. Potential Mechanism of Complex Fault Movement

Here, we discuss the source mechanisms that could result in the proposed complex fault movement, especially in the northern fault intersection. The different movements of the two segmented central patches and the root of the northern patch may result from partitioned slip, which has been used to describe the coexistence of strike-slip and dip-slip faults in a single earthquake (Bowman et al., 2003; King et al., 2005). In addition, partitioned slip models can produce significant non-double-couple mechanisms, as shown in the case of the 2014 Northern Nagano and 2016 Kumamoto earthquakes (Himematsu & Furuya, 2016; Kobayashi et al., 2018).

Bowman et al. (2003) suggested that slip partitioning results from the upward propagation of oblique shear at depth. We have already observed the oblique shear condition: The principal stress direction of the Pohang earthquake is oblique to the strikes of FN and FM (section 3.1). We can verify the other condition at depth. We have already observed the oblique shear condition: The principal stress direction of the Bowman et al. (2003) suggested that slip partitioning results from the upward propagation of oblique shear (Kobayashi et al., 2018).

The case of the 2014 Northern Nagano and 2016 Kumamoto earthquakes (Himematsu & Furuya, 2016; Kobayashi et al., 2018).

Several previous studies have indicated that the stress field around the Korean Peninsula has transitioned from extension to compression since the Pliocene (Choi et al., 2015; Kim & Park, 2006). For the Pohang earthquake, Choi et al. (2019) inferred the reactivation of segmented normal faults with a reverse sense of motion, based on the observation of ground deformation. Hence, we deduce the following possible explanations for the Pohang earthquake: The earthquake occurred near the boundary of the Pohang Basin, which formed as a pull-apart basin comprising segmented normal faults; the segmented faults were reactivated by blind oblique compression, and the slip was partitioned into strike-slip and reverse faulting of the central fault FM intersecting the northern fault FN; the joint movement of reverse faulting and strike-slip led to the non-double-couple mechanism of the Pohang earthquake; and the joint movement, especially on the fault intersection acting as a fault-valve, induced uplift of the jog between the two near-parallel faults, FM and FN.

The consideration of a partitioned slip model for the Pohang earthquake raises concerns regarding seismic hazards because the southeastern part of the Korean Peninsula is a pull-apart basin whose boundaries are split into secondary segments, leading to the formation of multiple faults or fault strands (Yoon & Chough, 1995). The faults within one seismogenic source dimension could act together in a single earthquake by oblique shear, regardless of the differing senses of slip, as demonstrated by the Pohang earthquake in this study. If the different senses of slip of the multiple or segmented faults of the southeastern Korean Peninsula are considered, the zones experiencing strong ground motion become significantly broader and more complex.

4.4. Implications for the Earthquake Rupture Behavior

Ellsworth (2018) stated that induced seismicity is an unintended geophysical experiment because it provides important clues about the start and progress of earthquakes. The Pohang earthquake is considered a runaway earthquake because its seismic moment exceeded the possible ranges derived from the injected fluid volume (Lee et al., 2019; Woo et al., 2019). This idea raises fundamental questions with respect to whether the final rupture size can be predicted during the initial stages and if the maximum earthquake magnitude can be estimated properly based on fluid injection.

These questions have been answered in several previous studies suggesting the identical growth of large and small earthquakes (Abercrombie & Mori, 1994; Ide, 2019; Noda & Ellsworth, 2016; Uchide & Ide, 2010). The similarities between the onsets of earthquakes can be explained by a cascade model, that is, domino-style failure (Abercrombie, 2019). The rupture through the root of the northern fault and the segmented central faults of the Pohang earthquake reminds us of a small-scale cascading rupture model, although the joint movement of the fault intersection cannot guarantee the involvement of the entire northern patch in coseismic slip. Furthermore, Grigoli et al. (2018) showed that the onsets of the mainshock and one of the largest aftershocks (A2, the second-largest aftershock in this study) are similar, implying that the two events share an initial rupture process. Similar initial conditions indicate that the seismic magnitude is not controlled by
the initial conditions and that the final seismic magnitude based on multiple fault segments is unpredictable during the initial rupture process (Abercrombie, 2019; Wei et al., 2011).

However, rupture termination is known to be partly controlled by time-independent rupture conditions such as structural complexity (Biasi & Wesnousky, 2016; Okuda & Ide, 2019; Wei et al., 2011). We present structural complexities in the source region of the Pohang earthquake, such as fault intersections: The antithetic structure composed of the central and the southern faults may play a role in halting rupture; the fault intersection between the central and northern faults channels the fluid flow and controls the timing of aftershocks that progress along both sides of the two faults. Similar effects of fault intersections were reported for the 2016 Central Italy seismic sequence by Walters et al. (2018). Van der Elst et al. (2016) suggested that the maximum magnitude of induced earthquakes is related to the background tectonic conditions. Our observations of the fault interaction at a fault intersection with oblique shear deepen our knowledge of the process that allowed the Pohang earthquake to exceed the seismic moment ranges determined by the injected fluid volume.

5. Conclusions

Here we show new characteristics of the 2017 Pohang earthquake sequence and infer the fault geometry based on the aftershock sequence that occurred for 3 months: (1) We divided the fault geometry into right-lateral strike-slip mechanisms and reverse faulting in the deeper part of the source region; (2) we detected aftershock migration along both sides of the two intersecting faults northeast of the mainshock epicenter, which matches fluid diffusion process and fault-valve behavior through the two intersecting faults. Based on these new characteristics, we established a dislocation model involving the mainshock coseismic rupture of the fault intersection for the underground fault system, accounting for previously reported observations such as locally concentrated uplift and the non-double-couple mechanism of the mainshock. During model development, we identified oblique contraction prevalent in the defined fault geometry and derived the joint movement of reverse- and strike-slip, indicating a likely slip partitioning, for the two intersecting faults. The fault geometry and movements emphasize the issues associated with multiple faults as a single seismogenic source, even with different senses of slip. Our results represent a key step in the examination of both the fluid-faulting interactions and rupture dynamics for the Pohang earthquake.

Data Availability Statement

Continuous waveforms were acquired from permanent seismic networks and data centers in the region, including the Korea Institute of Geoscience and Mineral Resources (KIGAM), the Korea Institute of Nuclear Safety (KINS), and the Korea Meteorological Administration (KMA; http://neics.kma.go.kr). The seismograms of KIGAM and KINS used in this article are available via https://zenodo.org/record/4286355. The geotectonic lines can be viewed at https://mgeo.kigam.re.kr. The figures in this article were generated using Generic Mapping Tools (Wessel et al., 2013), MATLAB (https://www.mathworks.com/products/matlab.html), and Inkscape, a free open-source graphic editor (https://inkscape.org/).

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