Short Note

Deep Fault Plane Revealed by High-Precision Locations of Early Aftershocks Following the 12 September 2016 $M_{\rm L}$ 5.8 Gyeongju, Korea, Earthquake

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Abstract An M_L 5.8 earthquake, which is large for a stable continental region, occurred in southeastern Korea on 12 September 2016. Ten days of data from a temporary seismic network deployed immediately after the mainshock are combined with data from permanent seismic stations to determine high-precision locations of early aftershocks to reveal the geometry of the causative structure at depth. Well-constrained relative earthquake hypocenters and focal mechanisms are used to define the subsurface fault plane with a strike of ~N28°E and dip of ~78° to the east-southeast. This fault plane extends from 12 to 15 km depth and may have been responsible for most of the early earthquakes in the Gyeongju earthquake sequence. A pre-existing weak zone in a strike-slip duplex that formed from subsidiary Riedel shears beneath the Yangsan fault system may have been reactivated to nucleate the mainshock and aftershocks.

Electronic Supplement: Table of origin times and hypocenter locations.

Introduction

A significant earthquake of M_L 5.8 occurred on 12 September 2016 at 11:32:54 (UTC) near the town of Gyeongju, southeastern Korea (Fig. 1; e.g., K.-H. Kim *et al.*, 2016; Y. Kim *et al.*, 2016; Chung and Iqbal, 2017). This was the largest earthquake recorded in the southern Korean Peninsula since the beginning of instrumental monitoring in 1903. The earthquake was widely felt in the southern peninsula and had a maximum modified Mercalli intensity (MMI) VIII in the epicentral region. The nearest seismic station USN ~8 km south of the epicenter, measured a horizontal peak ground acceleration of 0.58g (J. W. Park, 2016; S.-C. Park, 2016). Serious damage to property and injuries were reported, but no fatalities (Ministry of Public Safety and Security [MPSS], 2016).

Multiple megascale industrial parks and critical facilities, including nuclear power plants and disposal sites for radioactive waste, are located in the Gyeongju area and vicinity. Because of their significance to the Korean society and economy, seismicity in the region has been intensely monitored. Before the Gyeongju earthquake, instrumental seismicity in the area mostly occurred to the east of the Ulsan fault and consisted of $M \leq 4.2$ earthquakes. Most recently, Han *et al.* (2017) studied recent microseismicity and revealed a direct link between minor earthquakes and known fault structures to the east of the Ulsan fault. Although there has been a long academic dispute concerning the potential reactivation of the Yangsan fault system, seismicity in the source region has been low during the modern seismic observation period. For this reason, seismic hazard in the region has been overlooked (e.g., Kyung *et al.*, 1999, 2010; Chiu and Kim, 2004; Lee and Yang, 2006).

The Gyeongju earthquake and its aftershocks require a complete rethinking of the assessment of seismic hazards in Korea. In this regard, the following questions should be considered: Where are these earthquakes occurring? Which faults are responsible for the seismic crisis? What are the mechanisms of the earthquakes? To answer these questions, this study analyzes data from permanent and temporary seismic stations in the source region during the first 10 days of the aftershock sequence of the Gyeongju earthquake. We focus on earthquake hypocenter locations and associated rupture mechanisms with the goals of (1) obtaining reliable earthquake source parameters using an advanced earthquake

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Figure 1. (a) Regional seismicity and major tectonic boundaries (red lines) around the Gyeongju region of the Korean Peninsula. Epicenters of earthquakes between 1973 and 2016 with magnitudes ≥ 4.0 are shown (National Earthquake Information Center [NEIC], 2017). The black square shows the study area. Tectonic plates and their boundaries are from Bird (2003). EU, Eurasian plate; NA, North American plate; PS, Philippine Sea plate; PA, Pacific plate. Major geologic units in the Korean Peninsula are shown: NM, Nangrim massif; PB, Pyungnam basin; IB, Imjingang belt; GM, Gyeonggi massif; OFB, Okcheon fold belt; YM, Youngnam massif; and GB, Gyeongsang basin. (b) Distribution of seismic stations and seismicity before the Gyeongju earthquake. Seismic stations of the Korea National Seismograph Network operated by the Korea Meteorological Administration and stations operated by the Earthquake Research Centre of the Korean Institute of Geosciences and Mineral Resources are indicated by blue squares and blue triangles, respectively. Temporary seismic stations are indicated by other triangles; those selected for this study are shaded red. The epicenter of the 2016 $M_{\rm L}$ 5.8 Gyeongju earthquake is represented by a red star. Two historic earthquakes in A.D. 779 (est. M 6.7) and A.D. 1306 (est. M 6.4) are indicated by yellow and white stars, respectively. Earthquake epicenters since 2007 are shown as open circles and are scaled by magnitude. The location of the nuclear power plant in the area is indicated by a red square and the abbreviation WS (Wolsong). Major urban centers are indicated by concentric circles and are labeled. Solid black lines represent faults: USF, Ulsan fault; DRF, Dongrae fault; YSF, Yangsan fault; MoRF, Moryang fault; and MiRF, Miryang fault.

location method, (2) obtaining focal mechanism solutions for select events, (3) recognizing spatial clusters in seismicity to map the subsurface geometries of activated faults, and (4) understanding the relationships between newly revealed subsurface structures and mapped geological surface features in the area.

Geologic Setting and Seismicity

The Korean Peninsula has long been regarded as a typical example of a stable continental region. It is composed of three major Precambrian massifs: the Nangrim, Gyeonggi, and Youngnam massifs, separated by the Imjingang belt and the Okcheon fold belt, respectively (Fig. 1a; e.g., Cho et al., 1995; Ree et al., 1996, 2003; Rachman and Chung, 2016). The 12 September 2016 Gyeongju, Korea, earthquake occurred in the Gyeongsang basin, which is located on top of the Youngnam massif in the southeastern part of the Korean Peninsula (Fig. 1b). The earthquake was located near the Yangsan fault system, which comprises at least five faults in the area (from east to west): the Ilkwang, Dongrae, Yangsan, Moryang, and Miryang faults (Fig. 1b). They are dominantly right-lateral strike-slip faults and run mostly parallel to each other, striking north-northeast. The most prominent of these, the Yangsan fault, can be traced for ~170 km from Youngduk in the north to Busan in the south. Farther to the east, another active fault, the Ulsan fault, trends north-northwest.

Because the duration of instrumental earthquake monitoring is still relatively short compared with the characteristic earthquake cycle, studies of the historic record provide important information about the seismicity and seismic hazards of the Korean Peninsula. Studies of historic earthquakes in the Korean Peninsula have found evidence that the Gyeongju area experienced more than 100 "felt" earthquakes between A.D. 2 and 1902 (Fig. 2), of which at least 11 are believed to have MMI ≥ VIII (e.g., Lee and Jin, 1991; Chiu and Kim, 2004; Kyung et al., 2010). Among others, a notable MMI VIII earthquake is documented in Samguksagi, the history of the three kingdoms, which reports more than 100 fatalities. Lee and Jin (1991) estimated that the magnitude of this event was greater than 6.7, making it the largest known earthquake in the Korean Peninsula during the last 2000 yrs, although magnitude estimates vary (e.g., Lee and Jin, 1991; Chiu and Kim, 2004; Kyung et al., 2010). Another example of a large regional earthquake is reported in Goryeosa, the history of the Goryeo Dynasty: in 1036, an estimated $M_{\rm L}$ 6.4 (MMI VII) earthquake was felt across the Korean Peninsula (Kyung et al., 2010). The record states that aftershocks continued for three days in Gyeongju and caused major structural damage.

Lee and Na (1983) initially proposed that the Yangsan fault system is active because it fits the criteria of an active fault, including historic seismicity and microearthquake activity observed by a temporary regional seismic network in 1982. Lee and Jin (1991) further divided the fault system into northern, central, and southern segments based on either seis-



Figure 2. Historic earthquake epicenters in Korea, A.D. 2–1904 (Kyung *et al.*, 2010). Approximate locations of major historic earthquakes in A.D. 779 and 1036 (discussed in the Geologic Setting and Seismicity section) are indicated by gray and black stars, respectively, and labeled with their respective years. Location of 12 September 2016 earthquake is also shown by a gray star for reference.

micity (historic and instrumental) or surface expression. Their study showed a high slip rate (~4.4 mm/yr) and frequent seismic activity in the central segment based on 2000 yrs of historic records, much more so than the northern and southern segments. The postulated segmentations further yielded characteristic earthquakes with intensities VII, IX, and VIII for the northern, central, and southern segments, respectively. It is noteworthy that the central segment is expected to host the largest characteristic earthquake along the Yangsan fault.

Despite Korean historic records that indicate several episodes of large earthquakes in the Gyeongju area, including an estimated **M** 6.7 earthquake in A.D. 779 and an **M** 6.4 event in A.D. 1306, seismicity during the modern instrumental observation period (since 1978) has been relatively very low. An M_L 4.2 earthquake in 1997 was the largest in the area before 12 September 2016.

The Gyeongju earthquake sequence started with an $M_{\rm L}$ 5.1 foreshock at 10:44:32 UTC, 12 September 2016.



Figure 3. Earthquakes are plotted as vertical bars against their occurrence date in September 2016, with lengths proportional to local magnitudes (left vertical axis). $M_{\rm L} \ge 2.0$ earthquakes that occurred during the first 10 days of the $M_{\rm L}$ 5.8 Gyeongju earthquake sequence are shown. The cumulative number of earthquakes is plotted as a solid red line (right vertical axis). Most earthquakes occurred in the first 1.5 days. The largest aftershock ($M_{\rm L}$ 4.5) occurred on 19 September.

Approximately 1 hr later, at 11:32:55, the mainshock $(M_L 5.8)$ occurred. A large aftershock $(M_L 4.5)$ occurred at 11:33:58 UTC, 19 September 2016. During the first 10 days following the mainshock, the Korea Meteorological Administration (KMA) announced more than 120 earthquakes with $M_L \ge 2.0$ in the epicentral region (Fig. 3). The three largest earthquakes in the sequence occur during the first 10 days and are included in the scope of this study.

Data and Methods

Immediately after the M_L 5.1 foreshock, a group of seismologists was dispatched to establish temporary seismic stations in the source region. Institutions in the aftershock monitoring group include Pukyong National University, Pusan National University, Seoul National University, and the Korea Polar Research Institute (hereafter, the Gyeongju earthquake aftershock research group). Approximately 1 hr after the mainshock, the first temporary seismic station was established, 1.5 km east of the epicenter. A total of 27 threecomponent stand-alone seismic stations were installed in the epicentral region, covering an area of $\sim 40 \times 30$ km, in the following three days. Each temporary station is equipped with a Trillium compact broadband seismometer and either a Nanometrics Taurus or a Nanometrics Centaur digitizer. Station spacing is 2-4 km in the mainshock region and 6-7 km in the periphery. Readers are referred to K.-H. Kim et al. (2016) for further details of the temporary seismic network.



Figure 4. Earthquake locations of the Gyeongju earthquake sequence. (a) Earthquake epicenters determined from *P*- and *S*-wave arrivals using HYPOELLIPSE and the 1D velocity model proposed by Kim (1999). (b,c) Cross-sectional views of the initial earthquake locations along A–A' and B–B', respectively. (d) Earthquake epicenters determined by hypoDD. (e,f) Cross-sectional views of the relocated earthquake hypocenters along A–A' and B–B', respectively. The foreshock (M_L 5.1), the mainshock (M_L 5.8), and the largest aftershock (M_L 4.5) are represented by green, red, and cyan stars, respectively. (a–c) Modified from K.-H. Kim *et al.* (2016).

The epicentral region of the M_L 5.8 Gyeongju earthquake has been an area of special interest, due to well-known historic seismicity and critical infrastructure. The region is monitored by many permanent seismic stations operated by either the KMA or the Korea Institute of Geosciences and Mineral Resources (KIGAM). Because the area is well covered by seismic stations and the primary purpose of this study is to obtain high-precision locations of early aftershocks in the Gyeongju earthquake sequence, we collected and analyzed the first 10 days of continuous data (12–21 September 2016) from five permanent seismic stations and five temporary seismic stations installed by the Gyeongju earthquake aftershock research group immediately after the M_L 5.8 mainshock (Fig. 1b).

The continuous data were reviewed to identify clear *P*- and *S*-wave arrivals. Initially, 803 earthquakes were identified; the use of data from temporary stations almost doubled the catalog reported by KMA, which included only 413 earthquakes of $M_L \ge 1.5$ during the same period. Earthquake locations were initially determined using HYPOELLIPSE (Lahr, 1999) employing a 1D velocity model proposed by Kim (1999).

To determine relative locations with high precision, we used the double-difference algorithm (hypoDD; e.g., Waldhauser, 2001; Waldhauser and Ellsworth, 2002), which takes advantage of the fact that if two earthquakes are separated by

a small distance, the ray paths between their sources and a given receiver are similar. Thus, the difference in travel times or waveforms is very small and can be attributed to the small spatial offset between the pair. This technique has been widely applied to data from a range of tectonic settings (e.g., Waldhauser and Ellsworth, 2002; Kim and Park, 2010; Kim *et al.*, 2010; Kim and Kim, 2014).

Focal mechanism solutions for select earthquakes with $M_{\rm L} \geq 3.0$ are determined by the program HASH using *P*-wave first motions; this code is especially suited for generating acceptable mechanisms under various sources of uncertainties, including imperfect knowledge of the seismic velocity structure (e.g., Hardebeck and Shearer, 2002, 2003; Kilb and Hardebeck, 2006). To improve the accuracy of the focal mechanism solutions, we used additional *P*-wave polarities from permanent seismic stations operated by KMA or KIGAM (not shown in Fig. 1b), thereby enlarging the effective array aperture, plus data from all temporary seismic stations.

Results and Discussions

Epicenters of larger events (e.g., the $M_{\rm L}$ 5.1 foreshock, the $M_{\rm L}$ 5.8 mainshock, and the $M_{\rm L}$ 4.5 aftershock) seem to migrate southward through time (Fig. 4a–c). The aftershock distribution delineates a broader north-northeast–south-southwest-trending, steeply east-southeast-dipping structure that extends about 7 km between the Yangsan fault and an unnamed fault, which run parallel to and west of the Yangsan fault. Hypocentral depths are always between 11 and 16 km, with the highest concentration between 13 and 14 km.

Relocated earthquake hypocenters are clearly more clustered to delineate a system of subsurface faults whose geometries can be inferred from the spatial distribution of seismicity (Fig. 4d–f). The spread in aftershock seismicity along A–A' reveals that the size of the mainshock rupture area was $\sim 3 \times 3 \text{ km}^2$. The other cross-sectional view along B–B' indicates that the fault which ruptured during the seismic sequence dips steeply to the east-southeast at a dip of $\sim 79^\circ$.

Fault planes are confidently distinguished from auxiliary planes by making comparisons with well-constrained seismicity. The strikes of the selected fault planes are generally in agreement with the trend of relocated epicenters in map view. Most of the focal mechanisms show predominantly strike-slip motion, with the maximum compressive stress direction (P axis) in the east-northeast–west-southwest direction (Fig. 5).



Figure 5. Focal mechanism solutions of selected events from the Gyeongju earthquake sequence. Focal mechanisms of the foreshock (M_L 5.1), mainshock (M_L 5.8), and largest aftershock (M_L 4.5) are represented by green, red, and cyan stars, respectively. Focal mechanisms of smaller earthquakes at the northern and southern tips of the area, showing slightly different strikes, are represented in yellow. Inset shows a potential generating mechanism with a geometry similar to the orientation of faults in the area. YSF, Yangsan fault.

One of the greatest unknowns following the Gyeongju earthquake is the fault responsible for the earthquake sequence. If the earthquake had ruptured the surface, this would have been easier to determine; however, the Gyeongju earthquake produced no apparent surface features and the KIGAM report published after field inspections did not show any fault scarps or surface ruptures related to the earthquake (KIGAM, 2017). Relocated earthquake hypocenters are also limited to depths between 12 and 15 km. Because of the limited depth distribution of earthquakes and the absence of earthquake foci above this depth range, it is difficult to associate events in the sequence with any known fault at the surface.

Although earthquake hypocenters recorded in a relatively short time window do not usually provide enough information to fully describe a sequence, because only limited segments of a fault system are seismically active during the observation period, reliably constrained earthquake locations may reveal the geometries of active subsurface faults without surface expressions. The relocated seismicity in the present study is not diffuse but forms densely populated planar features in vertical profiles and meaningful structures in surface view (Fig. 4d–f). A strike-slip duplex is a zone of steep imbricate faults that are developed typically between two parallel master faults with bend or stepover geometries (e.g., Woodcock and Fischer, 1986; David and Reynolds, 1996; Kim *et al.*, 2004). The duplex structure may also form between two bounding faults that are interconnected or softly linked by subsidiary minor faults such as Riedel shears (Tchalenko, 1970). Each connecting fault is thus linked with at least one master fault at depth. The geometry observed in Figure 5 is similar to that of connecting faults within a strike-slip duplex.

The general trend of relocated seismicity slightly differs from the general trend of mapped faults in the area, with an angular difference of $\sim 15^{\circ}$ (Fig. 5). Most of the focal mechanisms, including those of the three most energetic earthquakes, have nodal planes oriented approximately north-northeast-south-southwest, which agrees with the trend of relocated earthquake epicenters. Discernible variations are also observed in the trends of relocated seismicity at the northern and southern ends of the earthquake cluster, which appears to show a Z-shaped sigmoidal distribution. The strikes of focal mechanisms obtained from small earthquakes in the north and south (Fig. 5, yellow focal mechanism plots) also differ from those in the central portion: earthquakes at the northern and southern ends strike N8° E-N15°E, whereas the major earthquakes near the center strike N25°E-N32°E.

Laboratory experiments (e.g., Tchalenko, 1970; Wilcox *et al.*, 1973) and the cartoon showing the simplest scenario (Fig. 5, inset) also predict a slight bend in the direction of strike at the tip where the subsidiary fault bifurcates from the main fault. Thus, we consider the reactivation of a preexisting weak zone in a strike-slip duplex that formed from subsidiary Riedel shears between two master faults to be the most likely scenario.

Conclusions

Because there have been few earthquakes on the Korean Peninsula since the beginning of instrumental monitoring, the ability of the Yangsan fault to generate major earthquakes was unclear. Because of the very low seismicity rate, it was assumed that seismicity and seismic hazard on the Korean Peninsula were always very low; for this reason, few of the general public saw the need to evaluate negative scenarios related to seismic hazard assessment. These assumptions were proven wrong by the 12 September 2016 Gyeongju earthquake, which was unprecedented in the instrumental period of seismic observations in Korea. Key stakeholders had already understood the issue of seismic risk well before the Gyeongju event, and now the general public's perception of seismic hazard in Korea has completely changed. In addition, Korean society has been reminded that regional earthquakes are repeatedly mentioned in historic documents, with estimated magnitudes greater than 6. New information from the Gyeongju earthquake sequence should be incorporated into seismic hazard and risk assessment in Korea.

We obtained reliable relative earthquake locations of the 2016 Gyeongju earthquake sequence using doubledifference relocation. We also determined focal mechanism solutions for selected events. These provide critical information that illuminates seismically active structures at depth and their faulting behavior. This study identified an active structure responsible for the early Gyeongju earthquake sequence that strikes \sim N26°E and dips to the east-southeast at \sim 78°. No shallow seismicity (< 12 km) during the study period has been observed, so it cannot be associated with any specific known surface fault. The strike of the rupture plane, as defined by relocated seismicity, is slightly oblique to the general trend of the mapped surface faults. The geometry of the rupture plane, as delineated by the focal mechanisms of the most energetic earthquakes in the sequence, is also consistent with that obtained from relocated seismicity. We propose a pre-existing sigmoidal R-shear fault in the offset between two parallel master faults was the causative fault of the Gyeongju earthquake sequence.

Data and Resources

Earthquake catalog and waveform data are acquired from the Korea Meteorological Administration (KMA; http ://www.kma.go.kr/weather/earthquake_volcano/domesticlist .jsp, last accessed March 2017) and the Korea Institute of Geosciences and Mineral Resources (KIGAM, http:// quake.kigam.re.kr/, last accessed March 2017). Continuous data may be obtained from corresponding parties upon request. Some figures were prepared using Generic Mapping Tools (GMT; Wessel and Smith, 1991). Earthquakes were initially located using HYPOELLIPSE program (Lahr, 1999) and relocated using the hypoDD program (e.g., Waldhauser, 2001; Waldhauser and Ellsworth, 2002). Focal mechanisms were determined using the HASH program (Hardebeck and Shearer, 2002).

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