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LETTER

The 12 September 2016 Gyeongju earthquakes: 1. Observation and remaining questions

YoungHee Kim *School of Earth and Environmental System Science, Seoul National University, Seoul 08826, Republic of Korea*
Junkee Rhie
Tae-Seob Kang* *Division of Earth Environmental System Science, Pukyong National University, Busan 48513, Republic of Korea*
Kwang-Hee Kim *Department of Geological Science, Pusan National University, Busan 46241, Republic of Korea*
Minook Kim *Division of Earth Environmental System Science, Pukyong National University, Busan 48513, Republic of Korea*
Sang-Jun Lee *School of Earth and Environmental Sciences, Seoul National University, Seoul 08826, Republic of Korea*

ABSTRACT: Two earthquakes (M_L 5.1 and 5.8) ruptured branches of the Yangsan Fault System in Gyeongju, S. Korea on September 12, 2016. After the M_L 5.8 earthquake, aftershock earthquakes continued to occur, including two notable earthquakes (M_L 4.3 and 4.5) on September 12 and 19, 2016. This paper details the early reports of the Yangsan Fault System in the Gyeongsang Basin from various geological and geophysical/seismological perspectives. Based on a review and an initial seismological analysis of the results of the three earthquakes (M_L 5.1, 5.8, and 4.5), we present and discuss the following topics: (1) the tectonic setting and the geophysical/seismic structure of the Yangsan Fault System, (2) historical seismicity and inferred seismic hazard from historical (literature) data, and (3) source mechanisms of the three earthquakes. In the end, we highlight some of the outstanding issues with regard to earthquakes and future research topics.

Key words: Gyeongju earthquake, earthquake source mechanism, Yangsan Fault System, Gyeongsang Basin, historical seismicity

1. INTRODUCTION

At 10:44:32 UTC (19:44:32 Korea Standard Time; GMT + 9 hours) and 11:32:55 UTC (20:32:54 Korea Standard Time) on 12 September 2016, M_L 5.1 and 5.8 earthquakes occurred approximately one hour apart in the historic city of Gyeongju (Fig. 1). Immediately followed by these two events, an M_L 4.3 earthquake (considered to be an aftershock) occurred in the source region. Aftershocks, including a notable M_L 4.5 earthquake on September 19 at 11:33:58 UTC (20:33:58 Korea Standard Time), were clustered around the epicenters of the first two events (Fig. 1). No surface ruptures were reported for the events. Parts of the city suffered small to moderate damages in building structures, but no fatalities due to the sudden ground shaking were reported. The 2016 Gyeongju earthquakes have now become forceful reminders that such events have occurred in the past and can hit the region any time.

The M_L 5.8 earthquake is considered as the largest earthquake in terms of magnitude in South Korea to have occurred during the modern instrumental recording period (since 1978). The earthquake occurred at the Yangsan Fault System in the Gyeongsang Basin (GB; Fig. 1, inset), which is considered as a massif filled with 6–9 km thick non-marine deposits and igneous rock (Jeon and Sohn, 2003). Here, we denote the Yangsan Fault System as an inter-related system of the NNE-SSW trending Yangsan Fault and its splay faults. From A.D. 2 to 1989, more than 500 events occurred in the Gyeongsang Basin, with at least 126 earthquakes in close proximity to the Yangsan Fault System (Lee and Jin, 1991). Among the 126 events, at least ten earthquakes of $MMI \geq VIII$ are considered to have occurred in Gyeongju, presumably related to the activity of the Yangsan Fault System, based on historic documents (Lee and Jin, 1991). A notable (and possibly the event with the largest magnitude in the region over past 2000 years; Lee and Jin, 1991) earthquake occurred in 779, taking the lives of at least 100 people, according to 'Samguksagi', the oldest surviving chronicle of Korean history. Another event in the instrumental period was the M_L 4.2 earthquake on 26 June 1997 (Fig. 1; Kyung and Lee, 1998; Chung and Kim, 2000).

Written descriptions of historical earthquakes have become critical for assessments of seismic hazards in Korea, as the geological record of permanent earthquake deformation preserved at the surface is limited and because the earthquake cycle in an intraplate setting is typically far beyond any instrumental earthquake catalog time span. This paper will thus revisit some of the notable historical earthquake record data in addition to seismic activities along the Yangsan Fault System, including the 2016 September events. The paper will also emphasize a careful reevaluation of such historical records for a better assessment of seismic hazards within a probabilistic framework by reducing the large uncertainties in inferred historical earthquake source parameters and incorporating paleoseismic data in the assessment. In addition, we present the source parameters of the three 2016 earth-

*Corresponding author: tskang@pknu.ac.kr

quakes and discuss the relevance of these events with reference to activities pertaining to the Yangsan Fault System.

2. TECTONIC SETTING AND SEISMIC STRUCTURE OF THE YANGSAN FAULT SYSTEM

Major crustal faults associated with large historical earthquakes on the Korean Peninsula are formed by Mesozoic tectonic activities which severely disrupted the upper crust (Lee and Yang, 2006, and references therein). Among them, the Yangsan Fault System is the most prominent, inter-related fault system in the southeastern part of the Korean Peninsula (Fig. 1), and it has been examined by those in different disciplines of the geological sciences. The NNE-trending Yangsan Fault System is a dominantly right-lateral strike-slip fault with a continuous trace approximately 200 km long (Kyung and Lee, 2006, and references therein). There are also another locally prominent lineament features in the WNW direction which dissect the NNE-trending Yangsan Fault at several places (Um et al., 1993). Both the northern and southern portions of the Yangsan Fault System have been suggested to have been active during the late Quaternary period based on fault-trench data (Kyung and Lee, 2006, and references therein).

Lee and Jin (1991) report based on historic documents at least 126 historical earthquakes in the period between A.D. 2 and 1905 within a 40-km-wide fault zone centered on the Yangsan Fault, including ten destructive events of *MMI* ≥ *VIII*. In particular, earthquakes with such intensities exceeding a *MMI* level of *VIII* have the potential to produce surface ruptures (Michetti et al., 2005). Although these historical earthquake data motivate paleoseismic investigations of the Yangsan Fault System, difficulties related to the identification of fault-related deformation features over the past 2000 years arise, particularly in active zones where surface deformation due to fault slip competes with erosional processes (Jeong and

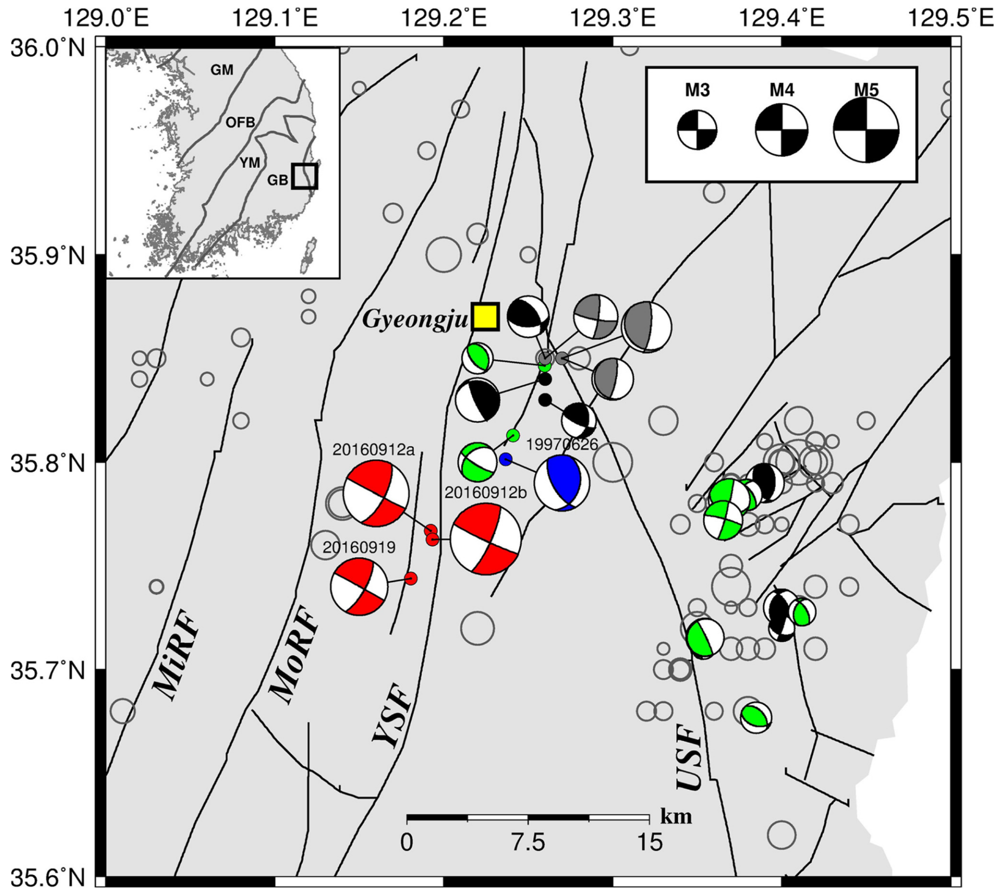

Fig. 1. Regional tectonic setting of the 2016 Gyeongju earthquakes. Thin black lines denote the lineaments and faults, with abbreviations (YSF, Yangsan Fault; MoRF, Moryang Fault; MiRF, Miryang Fault; USF, Ulsan Fault). The city of Gyeongju is highlighted as a yellow square. Previous seismicity occurred between 2000 and 2016 is shown as gray circles. Red beach balls with the date labeled show the source mechanisms of the 2016 Gyeongju events (‘20160912a’ for M_L 5.1 earthquake, ‘20160912b’ for M_L 5.8 earthquake, and ‘20160919’ for M_L 4.5 earthquake). Other colored beach balls show past earthquakes in the region (blue, Chung and Kim, 2000; green, Chang et al., 2010; black, Park et al., 2007; gray, Jo and Baag, 2003). The M_L 4.2 earthquake on 26 June 1997 is shown as the blue beach ball. Inset in the upper left corner illustrates tectonic framework of S. Korea with abbreviations (GB, Gyeongsang Basin; YM, Yeongnam Massif; OFB, Okcheon Belt; GM, Gyeonggi Massif).

Cheong, 2005). Despite such difficulties, here we briefly highlight a few examples of evidence based on paleoseismology, field-based structural geology, mineralogy, and several geophysical/seismological properties of the Yangsan Fault System.

Based on field data, the Yangsan Fault has undergone predominant right-lateral strike-slip (at least three times) and dip-slip motions (twice) since the Eocene (Chae and Chang, 1994). The right-lateral displacement of the Yangsan Fault is suggested to be 25 km in the middle region of the fault system (Choi et al., 1980; Um et al., 1983) and 35 km in the northern region (Chang et al., 1990) by examining correlations between sedimentary rock features, and 21–22 km through correlations of granitic rocks (Hwang et al., 2004, 2007a, 2007b). Jeong and Cheong (2005) suggested multiple faulting events in the late Quaternary after examining a weathering profile in the Yangsan Fault System on the microscale. The authors emphasized the importance of mineralogical and micromorphological analyses for the detection of fault zone activities by noting that observed multiple faulting events cannot be easily recognized during field investigations.

In the absence of evident fault zone deformation features on the surface, geophysical methods can be used to determine subsurface fault zone properties. Lee et al. (1986) observed lower resistivity that may be associated with fault zone fractures from geomagnetic survey data in the northern part of the Yangsan Fault System. Several authors investigated whether any useful information about the structure of faults and/or the geophysical properties can be retrieved from seismic waves transmitted across a fault zone. Kim et al. (1999, 2000) constructed a seismic attenuation (Q_p) model of the Gyeongsang Basin based on local P-wave phase and showed higher attenuation levels (Q_p of ~500) across NNE trending fault systems compared to the direction parallel to the strike of the fault system (Q_p of ~833). A low crustal Q_p within the fault zone may be related to distributed microfractures (Eberhart-Phillips et al., 2014). Kim et al. (1998) reported higher SH-wave anisotropy (0.355) and relatively small P-wave anisotropy (0.054), resulting in a fracture density of 0.284 at the fault zone and thus suggesting well-developed north-south trending fractures.

3. HISTORICAL SEISMICITY AND INFERRED SEISMIC HAZARD FROM HISTORICAL DATA

The historical record can provide a longer time history than instrumental data can offer. The importance of historical earthquake data is thus now largely recognized both by seismologists and engineers, who use such data in a wide range of applications. Korea has maintained relatively long historical earthquake records; consequently, with such records, the earthquake catalog time span covers nearly 2000 years (Lee and Jin, 1991). Nevertheless, the reliability of such a record is often questioned due to human input when interpreting the literature. Furthermore, spatial and temporal variations in the historical seismicity of the Yangsan Fault System have not been fully verified with geological field data.

Based on the historical seismicity data, Lee and Yang (2006) note unusually high seismicity from the fifteenth to eighteenth centuries. Lee and Jin (1991) show the 70-km-long central segment of the Yangsan Fault System has generated the highest level of seismicity over the past 2000 years based on cumulative seismic moments and the frequency of earthquakes. The historical data includes several devastating events mostly concentrated on the movement of the Yangsan Fault System, which we briefly summarize in chronological order in this section.

'Samguksagi', the oldest chronicle of Korean history, reports an earthquake in 779 in Gyeongju which caused severe structural damage and more than 100 fatalities. 'Goryeosa', the history of the Goryeo Dynasty, reports an earthquake in 1036, which was felt throughout a wide area of the peninsula, for instance from Gyeongju to Kaesong (currently in N. Korea; roughly 500 km away from Gyeongju). The record also states that earthquakes (inferred as aftershocks) continued for three days in Gyeongju and thus caused major structural damage. Based on this report, the epicenters of such earthquakes are assumed to have been located in Gyeongju. This earthquake is also mentioned in a document preserved inside Bulguksa Seokgatap (the three-storied stone pagoda of the Bulguksa temple), which reports that the stone pagoda was rebuilt twice due to the devastating earthquake activities which took place in Gyeongju during the period of the Goryeo Dynasty. 'Joseon Wangjo Sillok' (the Annals of the Joseon Dynasty) notes that King Sejong was particularly concerned about the frequent seismic activities in the region that includes the southern part of the Gyeongsang Basin during his 14th year in power.

These lines of evidence in the historical literature are most likely in accordance with recent seismic activities in Gyeongju and can offer new insight into fault zone activities together with instrumental data. Aftershock events that continue in the region after a large event, as also noted in the historical literature, can reflect the tectonic stress condition and its temporal variation within the crust. An hour immediately after the 2016 M_L 5.8 event, a temporary seismic array (with a total of 27 broadband sensors) was constructed to record aftershock earthquakes (of magnitudes down to 1.0), and the initial analysis results of the aftershocks were presented in a companion paper by Kim et al. (2016).

4. SOURCE MECHANISMS OF THE 2016 GYEONGJU EARTHQUAKES

Determination of accurate source parameters for the 2016 September events is of the utmost importance for understanding local seismic risks and associated tectonic activities. Before the 2016 Gyeongju earthquakes, an M_L 4.2 earthquake (the largest earthquake in the Gyeongsang Basin prior to the 2016 events) occurred on 26 June 1997 in a nearby source region (the blue beach ball in Fig. 1), and its focal mechanism was determined using P-wave first motions (Chung and Kim, 2000). Figure 1 also includes several focal mechanisms in this region based on P-wave first motions and SH/P amplitude ratios (denoted as black beach balls by Park et al., 2007, as green beach balls by Chang et al., 2010, and as gray beach balls by Jo and Baag, 2003).

The focal mechanisms of the 2016 Gyeongju events are represented as red beach balls (Fig. 1), as determined by a time domain waveform inversion technique (Dreger and Helmberger, 1993; Pasyanos et al., 1996; Rhie and Kim, 2010). Using this method, we report that the main M_L 5.8 event ('20160912b' in Fig. 1) ruptured the fault plane with a strike of 115° (or 24°), a dip of 86° (or 78°), and a rake of 12° (or 176°) (Table 1). In the calculation of the moment tensor, we fix the focal depth, as shown in Table 1. The hypocentral parameters employed in the inversion are readily determined using the *velellipse* location algorithm, a combination of the *hypoellipse* package (Lahr, 1999) and an algorithm which searches iteratively for an optimum velocity model minimizing the travel-time residuals (Kim et al., 2014). The moment tensor solutions show that all three events involve strike-slip mechanisms (Fig. 2; Table 1).

5. CONCLUDING REMARKS: FUTURE RESEARCH TOPICS

The 2016 Gyeongju events have now become forceful reminders that earthquakes have occurred in the past and can hit the region again at any time. These earthquakes provide an opportunity to reaffirm aspects already known based on evidence from both historical (literature) and seismological data. Moreover, the occurrence of the 2016 Gyeongju earthquakes has motivated more detailed studies of the Yangsan Fault System and a reexamination of the previously held consensus regarding the fault system. Rapid advances in our seismological knowledge of the region have raised several outstanding issues that require more attention in future research. We discuss these issues below.

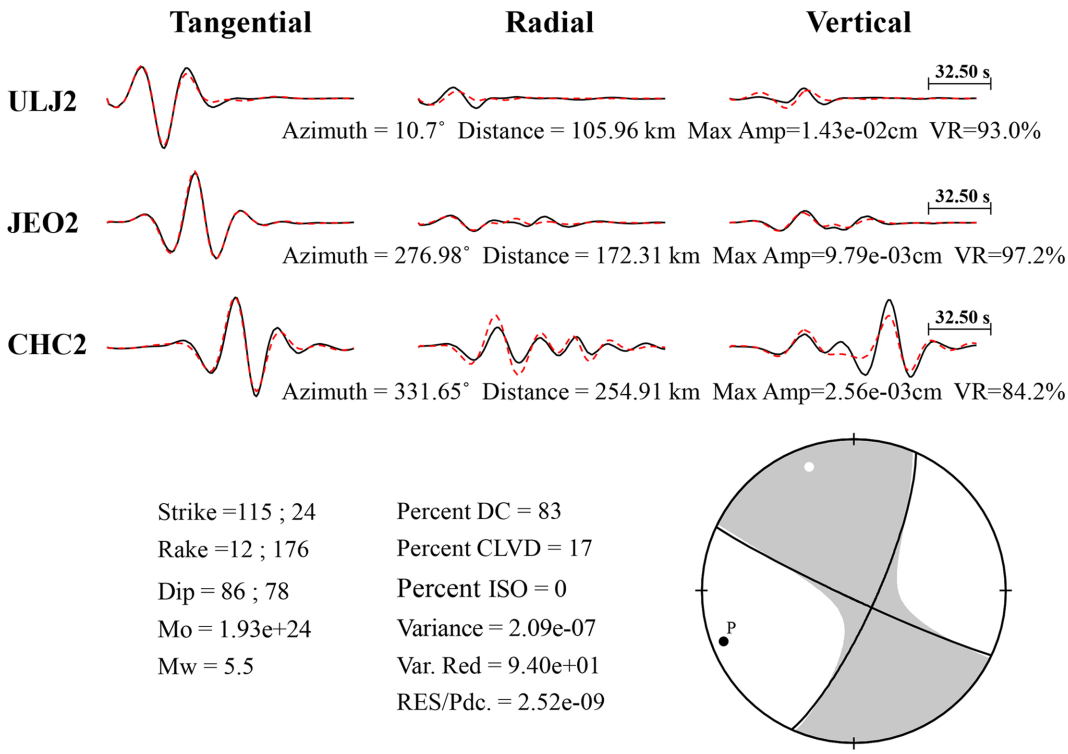

Fig. 2. Example of moment tensor inversion of event '20150912b' (the event location shown in Fig. 1). The black solid and red dashed traces indicate the observed and synthetic waveforms calculated from the determined moment tensor solution, respectively (see also Table 1).

Table 1. Fault parameters of the 2016 September Gyeongju earthquakes

Event ID (yymmdd)	Origin Time (UTC)	Lon. (°E)	Lat. (°N)	Depth (km)	M_W	Strike (°)	Dip (°)	Rake (°)
20160912a	10:44:33.30	129.1923	35.7670	14.0	5.1	118; 27	89; 68	22; 179
20160912b	11:32:54.80	129.1932	35.7628	13.6	5.5	115; 24	86; 78	12; 176
20160919	11:33:59.26	129.1806	35.7440	14.2	4.4	299; 29	89; 73	–17; –179

5.1. Recurrence Interval of Major Earthquakes across the Yangsan Fault System

A complete earthquake cycle may not be embedded within the earthquake catalogs based on instrumental seismicity because the deformation rates in a typical intraplate setting are usually small (<1 cm/yr). A statistical treatment of the earthquake recurrence time usually carries large uncertainties. Owing to the longer time interval of major earthquake occurrences in intraplate settings, we require historical seismicity data together with paleoseismic evidence to expand the limited time frame of our existing earthquake record. In addition to the recurrence time, paleoseismology provides fault parameters and the sizes of past seismic events, which can be critical when assessing seismic hazards. These factors should be investigated in conjunction with the study of the structure, stratigraphy, geochronology, and geomorphology of the fault zones. Jeong and Cheong (2005) highlight the critical role of mineralogical and micromorphological investigations of fault gouges in reconstructions of the movement history of faults in the Gyeongsang Basin.

5.2. Evolution of Static Coulomb Stresses induced by Earthquakes

Detailed studies of the coseismic slip distribution associated with the 2016 Gyeongju events are fundamental for a clearer understanding of repeated tectonic movement along the Yangsan Fault System. Coseismic fault slip causes changes to the surrounding crustal stress field that may influence the state of neighboring faults, possibly causing advances or delays in the timing of future events (King et al., 1994). An updated geometry and slip distribution of the 2016 events can be retrieved from the most precise aftershock locations, which are available in a companion paper by Kim et al. (2016). In particular, the fault rupture depth is of vital importance for assessing the static stress changes and the aftershock hazard in the surrounding fault regions, and for understanding the fault evolution characteristics.

5.3. High-resolution Fault Zone Imaging in the Gyeongsang Basin

Damaged fault zone rocks with high crack density levels are expected to produce several indicative signals in seismic wavefields. These include scattering, intrinsic attenuation, anisotropy from cracks or fault zone properties, reflections associated with impedance contrasts, and fault-zone-guided head and trapped waves. Recent breakthroughs in theory and data processing allow every byte of continuous seismic data to be used for imaging the complexities of earthquake sources and fault zone structures. The high-resolution imaging of the subsurface structures of the fault zone can be used to track the possible temporal evolution of the fault zone materials. For this work, a dense seismic array (either with broadband or high-frequency sensors) is required across the fault system.

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