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LETTER

The 12 September 2016 Gyeongju earthquakes: 2. Temporary seismic network for monitoring aftershocks

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ABSTRACT: The M_L 5.8 earthquake in Gyeongju, southeastern Korea, on September 12, 2016 11:32:54 (UTC) was the largest earthquake on the Korean Peninsula since instrumental monitoring began in 1978. It was preceded by an M_L 5.1 foreshock and is being followed by numerous aftershocks. Within an hour of the mainshock, the first temporary seismic station to monitor aftershocks was installed at about 1.5 km east of the announced epicenter. The current temporary seismic network consists of 27 stations equipped with broadband sensors covering an area of ~38 × 32 km in the mainshock region. This is the first high-density aftershock monitoring array in the Korean Peninsula. Initial results, using data from both the regional seismic networks and the aftershock monitoring array, indicate that earthquakes during the first 10 days following the mainshock are related to the Yangsan Fault System. Establishment of an official rapid-response team to monitor aftershocks of major earthquakes is advised.

Key words: Gyeongju earthquake, aftershock monitoring network, Yangsan Fault System, rapid earthquake response

1. INTRODUCTION

On September 12, 2016, at 11:32:54 UTC (20:32:54 Korea Standard Time; GMT + 9 hours), a moderate earthquake (M_L 5.8) occurred in Gyeongju, southeastern Korea. The earthquake was preceded by an M_L 5.1 foreshock at 10:44:32 UTC and followed by numerous aftershocks, including 17 events with local magnitude larger than 3.0 during the rest of the month. The largest aftershock, M_L 4.5, occurred on 19 September 2016, at 11:33:58 UTC. In a companion paper to this study (Kim et al., 2016), the source parameters of the main events are discussed in detail. Immediately after the M_L 5.1 foreshock, teams for aftershock monitoring were dispatched from Busan to Gyeongju. Approximately one hour after the main earthquake, the first temporary seismic station to record aftershocks in the epicentral area began recording continuous seismic data at a sampling frequency of 200 Hz. Three additional seismographs were installed in the epicentral area by midnight on the day of the main earthquake.

There has been a long academic dispute concerning the seismic activity of the Yangsan Fault System, including the potential for reactivation (e.g., Kyung et al., 1999, 2010). Although seismic activity is documented in historic records, events during the instrumental recording period have been ignored due to the very low seismicity rate (Chiu and Kim, 2004; Lee and Yang, 2006; Kyung et al., 2010). The M_L 5.8 Gyeongju earthquake and its aftershocks have settled the debate.

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This study describes the seismic monitoring response and initial results following the September 12 earthquake in Gyeongju, which include the rapid deployment of temporary seismic stations in the field, coordination of further instrumental installations, data archiving and release plans. We also make suggestions for future aftershock monitoring deployments.

2. VOLUNTARY RAPID RESPONSE TO THE GYEONGJU EARTHQUAKE SEQUENCE

On the evening of September 12, 2016, an M_L 5.1 earthquake jolted the entire southern Korean Peninsula. In less than an hour, the country was surprised by another even larger event, a record M_L 5.8 earthquake in the same region. Initial earthquake reports by the Korea Meteorological Administration (KMA) indicated both shocks nucleated ~9 km SSW of the town center of Gyeongju. The mainshock was the largest and most widely felt earthquake since the beginning of modern instrumental earthquake monitoring in Korea in 1978. Immediately after the earthquakes, volunteer aftershock monitoring teams were deployed by Pukyong National University and Pusan National University, approximately 60 km south of the epicenter. The first standalone station was established at Naenam Elementary School, 1.5 km east of the initial KMA earthquake epicenter (Fig. 1). Recording began at 12:38 UTC, 12 September 2016 (21:38 local time; UTC + 9 hours), less than an hour after the main event. A representative example of an earthquake signal recorded during the first hour is shown in Figure 2. By midnight local time, four sets of seismographs had been established in the source area. The nearest temporary seismic station, located at Naenam Elementary School, hosted two sets of seismographs to ensure uninter-

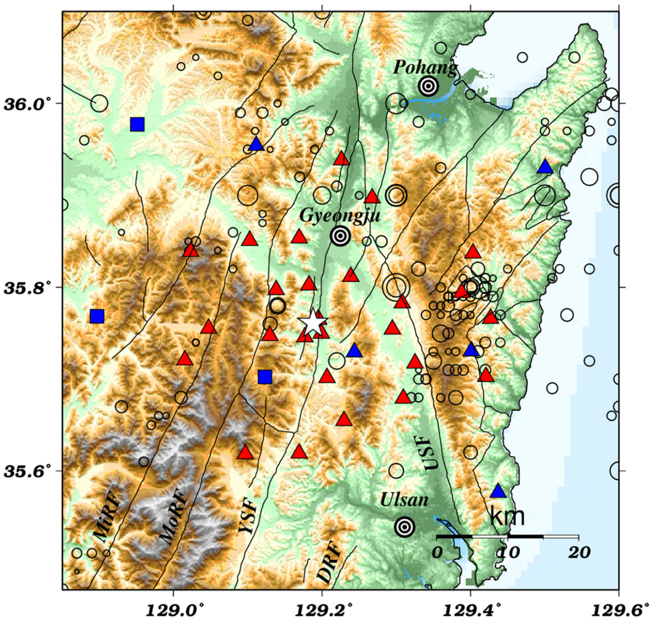

Fig. 1. Distribution of temporary seismic stations (red triangles) to monitor aftershocks following the 12 September 2016, M_L 5.8, Gyeongju earthquake. Seismic stations of the Korea National Seismograph Network (KNSN), administered by the Korea Meteorological Administration (KMA), and stations operated by the Earthquake Research Center of the Korean Institute of Geoscience and Mineral Resources (KIGAM) are indicated by blue squares and triangles, respectively. Epicenters of the M_L 5.8 Gyeongju earthquake and background seismicity in the area since 1978 are indicated by a white star and open circles, respectively. Centers of major cities in the area, including Gyeongju, Pohang, and Ulsan, are shown. Major faults in the area include USF = Ulsan Fault, DRF = Dongrae Fault, YSF = Yangsan Fault, MoRF = Moryang Fault, and MiRF = Miryang Fault.

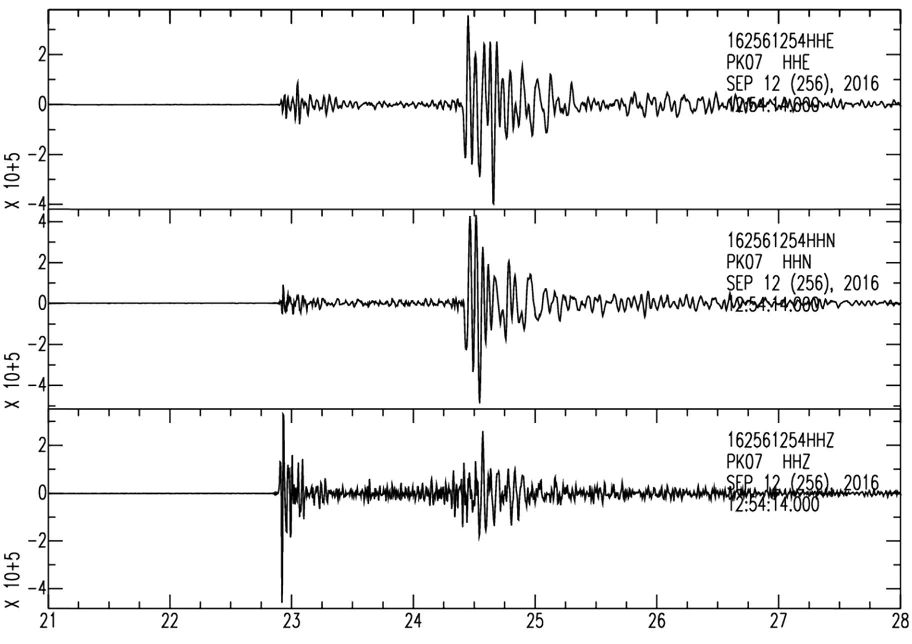

Fig. 2. Typical example of 3-component earthquake waveforms recorded by the temporary seismic array, showing an M_L 2.2 earthquake that occurred at 12:54:34 UTC, 12 September 2016. The data shown in this example were recorded by the first temporary standalone seismic station deployed in the source area, located at Naenam Elementary School.

Table 1. List of temporary seismic stations for aftershock monitoring and permanent seismic stations of KMA and KIGAM located in the source area (Fig. 1)

Network	Station code	Latitude (°N)	Longitude (°E)	Elevation (m)
Temporary Array	GJ01	35.7551	129.0473	202
	GJ03	35.7211	129.0156	213
	GJ06	35.8531	129.1692	82
	GJ12	35.6191	129.1695	93
	GJ15	35.7945	129.3875	121
	PK03	35.6548	129.2294	174
	PK05	35.8509	129.1024	82
	PK06	35.7973	129.1384	86
	PK08	35.6791	129.3095	59
	SS02	35.8390	129.0230	394
	SS03	35.7475	129.1298	115
	SS04	35.7460	129.1769	76
	SS05	35.7500	129.1990	61
	SS06	35.7175	129.3252	99
	SS07	35.7652	129.1951	59
	SS08	35.7664	129.4276	48
	SS12	35.8380	129.4023	144
	SS13	35.7652	129.1951	59
	TP02	35.7830	129.3079	112
	TP03	35.7543	129.2947	88
	TP05	35.8117	129.2387	63
	TP06	35.7028	129.4204	55
	TP07	35.8972	129.2674	43
	TP09	35.6184	129.0683	200
	TP12	35.8024	129.1826	61
	TP13	35.9385	129.2261	17
	TP14	35.7016	129.2067	91
KMA	DAG2	35.7685	128.8970	262
	USN	35.7024	129.1232	241
	YOCB	35.9772	128.9511	143
KIGAM	BBK	35.5797	129.4355	45
	DKJ	35.9467	129.1089	173
	HAK	35.9295	129.5003	16
	HDB	35.7336	129.3990	146
	MKL	35.7295	129.2435	121

rupted continuous recording of seismic data from aftershocks.

During the next three days, staff from Seoul National University and the Korea Polar Research Institute volunteered to install additional portable seismographs. The dense seismic array, with 27 stations covering an area of ~38 × 32 km in the mainshock region, was fully established by 15 September 2016 (Table 1). Each standalone station was equipped with a Trillium compact broadband seismometer and either a Nanometrics Taurus or a Nanometrics Centaur digitizer. Seismographs were installed at ground level in small- to medium-sized buildings (i.e., schools, museums, churches, temples, private or public institutions, and houses). Most sites provided a steady, continuous power supply, although instruments are always equipped with an auxiliary power source. The relative instrument spacing is 2–4 km in the mainshock area and 6–7 km in the periphery of the temporary network. The largest aftershock, an M_L 4.5 event on 19 September 2016, was well-observed by all 27 stations in the array (Fig. 3).

Aftershock activity, in terms of both magnitude and rate, decreases rapidly with time. Pukyong National University, Pusan National University, Seoul National University, and

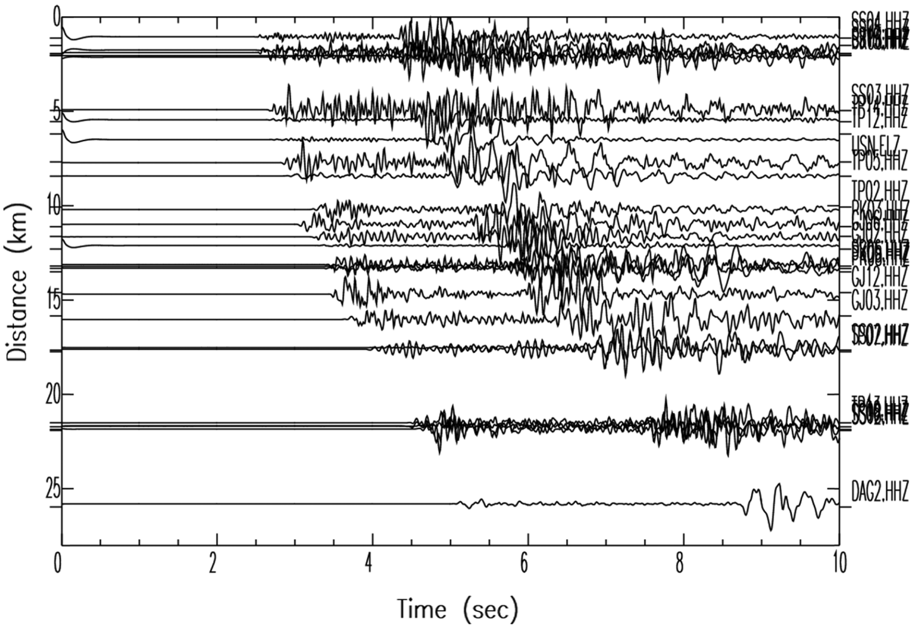

Fig. 3. Vertical-component seismic waveforms of the largest aftershock (M_L 4.5, 19 September 19, 2016, 11:33:58 UTC). All 27 temporary seismic stations recorded the event. Seismic records from two permanent KMA seismic stations (USN and DAG2) are also shown. Waveforms are bandpass filtered between 2 and 15 Hz.

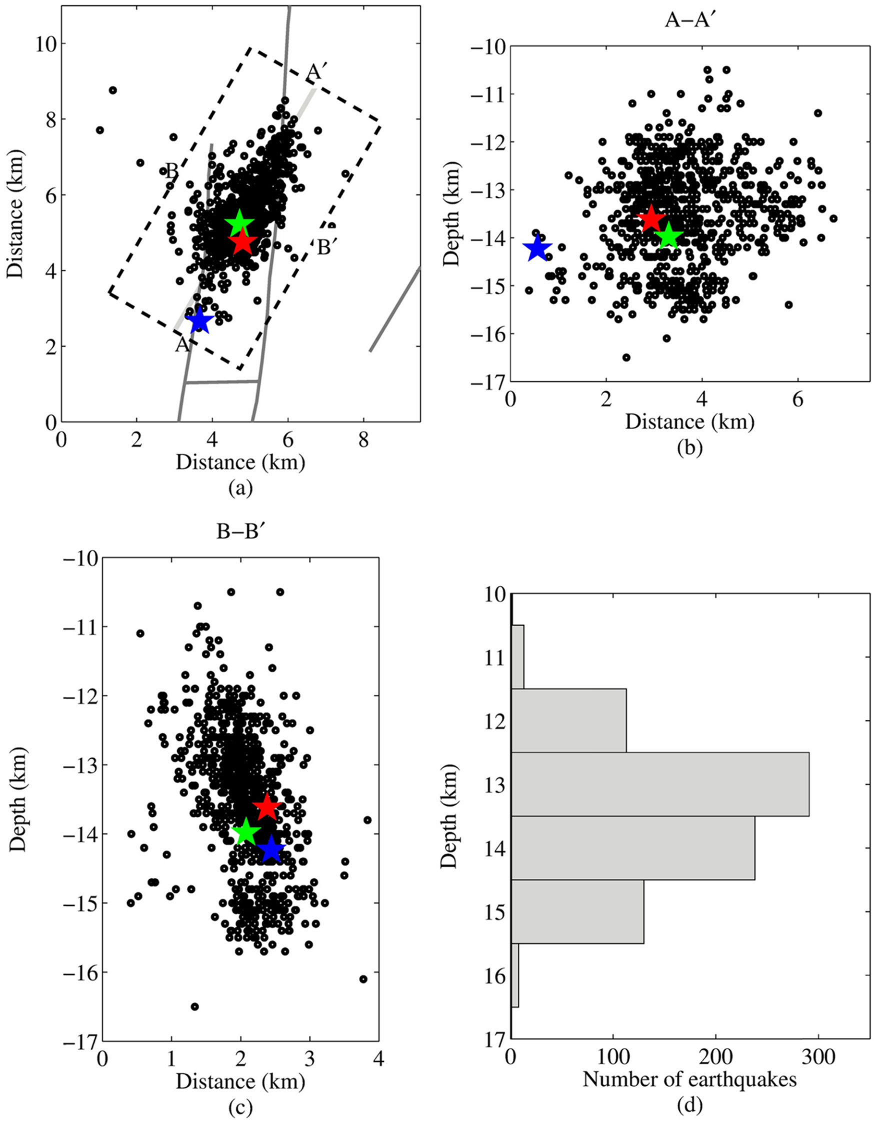

Fig. 4. Distribution of 803 earthquake epicenters for the first 10 days after the M_L 5.8 Gyeongju earthquake. (a) The distribution is represented on the projected coordinate systems in accordance with the geographic coordinates of (129.14°E, 35.72°N) in the lower left and (129.24°E, 35.82°N) in the upper right corners, respectively. Epicenters of the largest foreshock (M_L 5.1), the mainshock (M_L 5.8) and the largest aftershock (M_L 4.5) are indicated by green, red, and blue stars, respectively. The Yangsan Fault (YSF) and other unnamed faults are indicated by solid lines. (b, c) Depth distribution of the events along the profiles A-A′ and B-B′ respectively. (d) Depth dependency of the events.

the Korea Polar Research Institute (hereafter called the working group) plan to maintain the temporary seismic array in the source region as long as significant aftershock activity continues. The working group visits field sites on a regular basis (once every three or four weeks) to collect data. The working group also plans to archive the continuous data from all temporary stations and make them available to scientists under general conditions for research. Parties or persons interested in the dataset are encouraged to contact the working group for further details.

3. CLOUD OF AFTERSHOCKS

The first 10 days of continuous data were collected during routine maintenance visits on 23–24 September 2016. KMA provided source parameters (locations, times, and magnitudes) of 413 earthquakes that occurred within 10 days of the mainshock (12–21 September 2016). Experienced staff briefly reviewed the continuous data and were able to identify 803 earthquakes including those already located by KMA. All earthquakes exhibit clear P- and S-wave arrivals, and can be reliably located using the *hypoellipse* earthquake location package (Lahr, 1999) with a local seismic velocity model proposed by Kim (1999). The distributions of earthquake epicenters are mostly limited to two mapped faults running parallel to each other, striking nearly north-south direction in the source area (Fig. 4). Both are part of the Yangsan Fault System possibly linked with each other in the subsurface.

4. DISCUSSION AND CONCLUSIONS

The primary purpose of the aftershock monitoring array is to locate seismic events with higher precision than permanent seismic networks can achieve. This is no different from the purpose of regional or global seismic networks. The data could be used to investigate many problems, including, but not limited to, seismic source studies; studies of Earth's interior on local, regional, and global scales; relationships between faults and earthquakes observed during the aftershock sequence; and interactions between faults in and near the source area, due to stress perturbations after large earthquakes.

For the first time in Korea, a high-density temporary seismic array has been installed to monitor aftershock activity in response to the M_L 5.8 Gyeongju earthquake. The first seismic station was installed in the source area approximately 1 hour after the mainshock. Within 5 hours, 4 seismic stations were installed. Within three days of the main event, the number of temporary seismic stations increased to 27. The distributions of the initial locations of 803 earthquakes indicate that the Yangsan Fault System is responsible for the aftershock seismicity.

The most frequently asked questions during the Gyeongju earthquake crisis are as follows. Are there any active faults in the source area? Which faults are responsible for the mainshock–aftershock sequence? Is the Yangsan fault active? Is it possible to release information regarding impending earthquake activity? How long will the aftershocks continue? Decision makers were frequently embarrassed by unexpected questions. Improved decision making should be possible with better seismic monitoring. Many questions could have been answered with confidence if real-time data from a high-density seismic network were available.

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