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The offshore Uljin, Korea, earthquake sequence of April 2006: seismogenesis in the western margin of the Ulleung Basin

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ABSTRACT: An unusual earthquake sequence comprising 11 events with magnitude range of M_L 2.0 to 3.2 occurred off the eastern coast of the southern Korean Peninsula in April 2006. Since there is no obvious mainshock in this sequence unlike a typical mainshock-aftershock sequence, the seismicity pattern shows the characteristics of swarm behavior. Focal mechanism of the largest event (M_L 3.2) on the 29 of April is normal to strike-slip faulting. Hypocenter relocations of nine events improve the epicenter locations that fall within an area with a radius of about 0.7 km while depths are less well constrained with ranges of 1.6 km to 13.0 km. We propose that a swarm behavior of the sequence is closely related to the marginal geometry of the Ulleung Basin and the regional stress regime. The fact that epicenters of the April 2006 sequence are at the same transitional zone of continental to rifted continental crust as that of the 29 May 2004, M_w 5.1, earthquake indicates that the Ulleung Fault is seismically active.

Key words: earthquake sequence, swarm behavior, Ulleung Basin, Ulleung Fault

1. INTRODUCTION

In April 2006, an earthquake sequence comprising 11 events occurred at a distance of about 60 km to the northeast of Uljin in the East Sea (Japan Sea). Korea Institute of Geoscience and Mineral Resources (KIGAM) catalog lists 10 events of the sequence with the magnitude range of M_L 2.0 to 3.2 (http://quake.kigam.re.kr). Korea Meteorological Administration (KMA) assigned the magnitude range of M_L 2.1 to 3.5 for the sequence (http://kmaneis.go.kr). In that the first event at 09:35 local time on 19 April has a magnitude of M_L 2.2 (KIGAM), the earthquake sequence has a cluster type of pattern not showing a large mainshock preceding a series of small aftershocks.

The cluster of the April 2006 earthquake sequence occurred at the transitional zone from continental to rifted continental crust in the East Sea (Fig. 1). Major tectonic elements in the zone are the N-S to NNE-SSW oriented faults represented by the Ulleung Fault along the western margin of the Ulleung Basin (Chough et al., 2000). Chough et al. also maintains that regional tectonic regime of the East Sea is compressional since about 10 to 7 Ma. The seismicity along the zone is relatively high compared to that in the inland of the Korean Peninsula. On 29 May 2004, a moderate earthquake of M_w 5.1 occurred at about 50 km to the south of the April 2006 sequence (Fig. 1; Kang and Baag, 2004; Park and Mori, 2005). The in-depth analysis of the May 2004 earthquake by Kang and Baag (2004) has suggested the possibility that an eastward-dipping thrust fault on a north-south trend is governed by the compressional tectonic regime in the East Sea and is directly related to the Ulleung Fault.

There is, however, still no definite evidence to distinguish whether faulting related to the May 2004 earthquake was on the eastward or westward dipping plane. The April 2006 sequence offers a good opportunity that may give a constraint on the dual ambiguity of the fault planes responsible for the May 2004 earthquake. In this paper, we analyzed the April 2006 sequence with the goal to better understand the seismogenic structures that caused the recent seismic activity in the offshore area of the eastern margin of the Korean Peninsula.

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2. DATA SET

The April 2006 earthquake sequence was well recorded on the short-period and broadband stations within the monitoring networks operated by KMA, KIGAM, Korea Electric Power Research Institute (KEPRI), Korea Institute of Nuclear Safety (KINS), and Universities. About 50 stations produced digital seismogram data with the sampling rate of 100 Hz. Information on the station distribution is given in Kang and Baag (2004). However, because the earthquake sequence occurred off the eastern coast of the Korean Peninsula, the station coverage is confined to the left side of the sequence except for the station ULL (the Ulleung Island).

The waveform data utilized in this study consist of records of 11 earthquakes: six small (M_L 2.0–2.8) events on the 19 April 2006 and five events of M_L 2.4–3.2 occurred between 28 and 30 April 2006 (Table 1). Although the M_L 2.0 event at 09:49:25.46 on 19 April 2006 is not shown in both the KMA and KIGAM catalogs, a close lookup of the seismograms for the M_L 2.8 event at 09:49:34.31 on the same day reveals that a pair of phases in the seismograms corresponds to two separate events that occurred at times about 9 seconds apart (Fig. 2). Here we use magnitudes presented

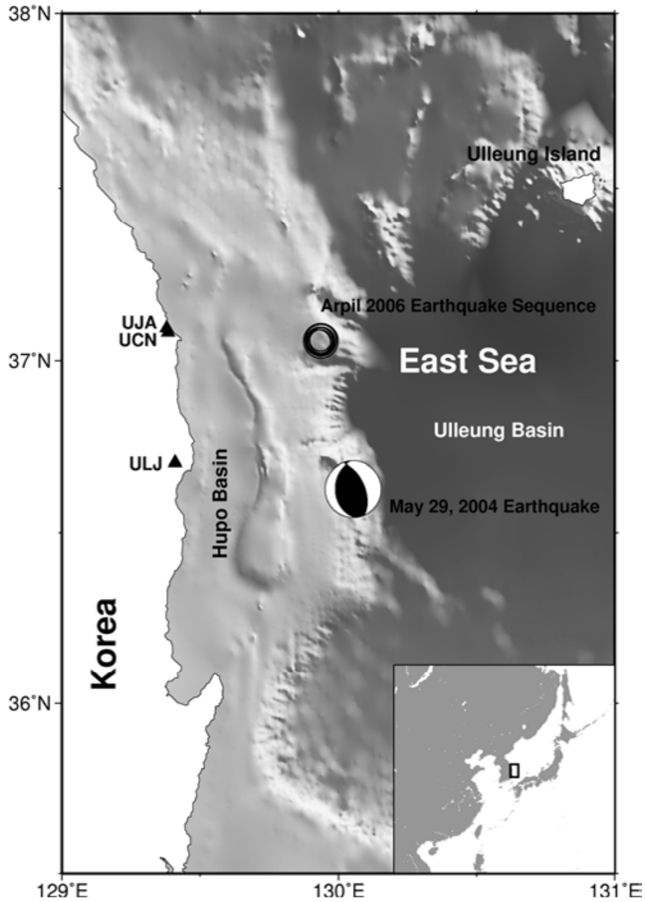

Fig. 1. Epicentral locations (open circles) of the April 2006 earthquake sequence on a topographic relief map of the East Sea. Beachball shows the epicenter and lower hemisphere focal mechanism of the 29 May 2004, M_w 5.1, earthquake. Solid triangles indicate the closest three stations to the April 2006 sequence, and waveforms recorded at the stations are used to measure differential travel times for the hypocenter relocation of the sequence.

in the KIGAM catalog if it is not mentioned specifically. The closest station to the event cluster is UCN (KINS) at an epicentral distance of about 50 km from the centroid of the sequence cluster.

Figure 3 shows the vertical-component seismograms from the station UCN for all the events listed in Table 1. The seismograms are quite complicated implying the effects of severe heterogeneous crustal structure. Among the seismograms the waveform similarity is weak but arrival times of *P* and *S* phases are similar to each other, suggesting that their epicenters are located close together but their focal depths may vary.

3. FOCAL MECHANISM

Only the M_L 3.2 event at 11:01:13.05 on 29 April 2006 of the sequence provided sufficient data for a well-constrained focal solution. For the event, a total of 13 polarities of the first motions were read from seismograms of the networks. Eight polarities were from short-period vertical-component waveforms, and five were from broadband waveforms. Because the station coverage is incomplete, we cannot obtain a reliable fault-plane solution using polarity information only. Thus we add *SH*-wave polarities and amplitude ratios of *SH* to *P* waves at three stations closest to the epicenter. All the data prepared for focal mechanism analysis are listed in Table 2. This dataset is inverted for the focal mechanism using the grid search algorithm (FOCMEC) of Snoke et al. (1984). Thus we find a well-constrained focal mechanism showing a combination of normal and strike-slip faulting along either a focal plane of strike 16°, dip 40° and rake 209°, or a plane of strike 263°, dip 72° and rake 306° (Fig. 4).

The normal sense is rather unusual compared to the regional tectonic environments of the Korean Peninsula

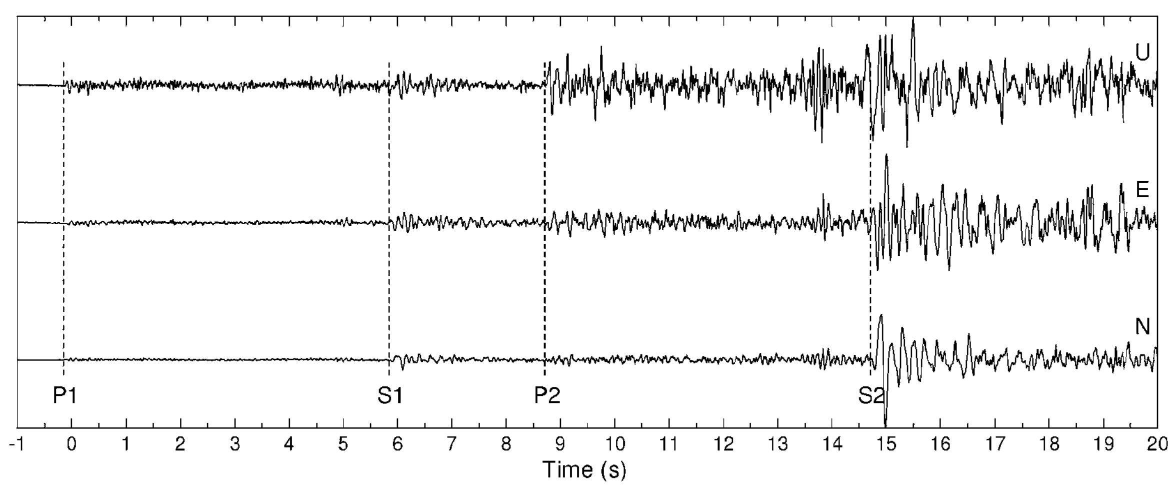

Fig. 2. Doublet observed on seismograms at the station UCN for the event 09:49:34.31 on 19 April 2006. Arrivals of *P* and *S* waves for the preceding event (09:49:25.46) are indicated by P1 and S1, respectively, while P2 and S2 correspond to the following event (09:49:34.31). The marks U, E, and N denote the vertical, east-west, and north-south components, respectively. The origin of time scale is aligned with the origin time of the second event 09:49:34.31. All the traces are normalized to the same scale.

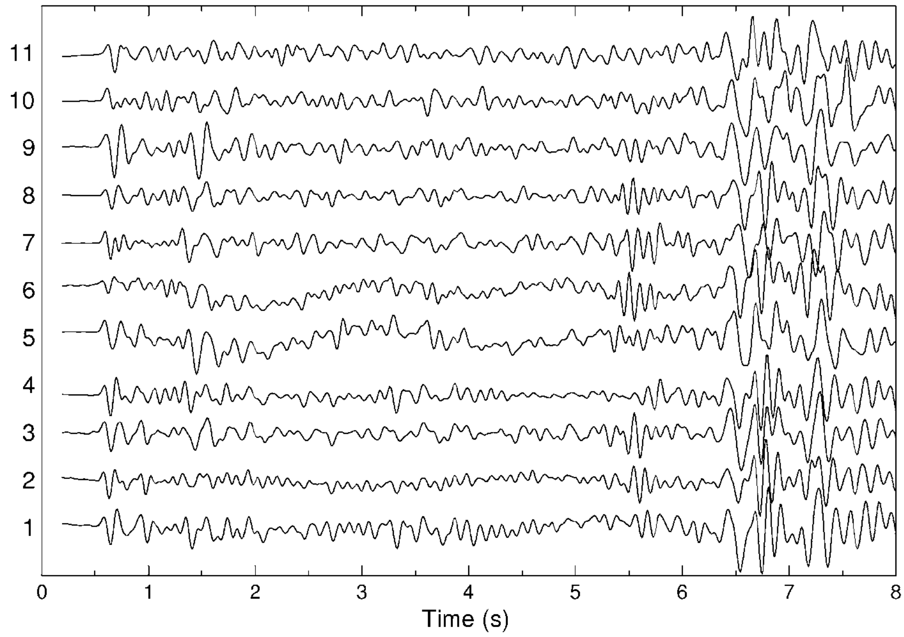

Fig. 3. Vertical component seismograms recorded at the station UCN for all the events of the April 2006 sequence listed in Table 1. The seismograms are aligned on the direct P arrivals and bandpass filtered between 0.1 and 10 Hz. The numbers on the left side denote the event number assigned in Table 1. All the traces are normalized to the same scale.

Table 1. List of events in the April 2006 earthquake sequence, offshore Uljin, Korea. These are compiled from catalog of the Korea Institute of Geoscience and Mineral Resources (KIGAM, http://quake.kigam.re.kr).

Event Number	Origin Time (local time: GMT+9hr)	Magnitude (M_L)
1	2006/04/19-09:35:10.54	2.2
2	2006/04/19-09:49:25.46*	2.0
3	2006/04/19-09:49:34.31	2.8
4	2006/04/19-10:57:55.88	2.4
5	2006/04/19-16:01:32.48	2.3
6	2006/04/19-16:18:11.93	2.0
7	2006/04/28-23:47:55.32	2.9
8	2006/04/28-23:54:57.64	2.5
9	2006/04/29-01:01:00.72	2.4
10	2006/04/29-11:01:13.05	3.2
11	2006/04/30-09:50:02.43	2.4

*This event is not reported in the KIGAM and KMA catalogs.

under the ENE-WSW compressional regime. Thus we try to find focal solutions repeatedly without information on the amplitude ratios, considering a possibility of measurement errors. Because the motions of *SH* waves picked on the tangential components of the three stations (UCN, UJA, and ULJ) are clear, we include the polarities of *SH* waves in addition to those of *P* waves in the focal mechanism inversion to constrain the focal solution. The results are identical to the case of including the amplitude ratios. The pressure axis is oblique and oriented to the southwest with an azimuthal trend of 213° and a plunge of 50°. The trend is comparable to an approximate azimuthal trend (256° or 76°) of the 29 May 2004 earthquake with near-horizontal plunge implying consistency with the regional tectonic regime in and around the Korean Peninsula.

The other events considered in this study are all too small for well-constrained focal solutions. However, we pay attention to the fact that all of the first motions that can be read for those small events (specifically, on the seismograms of the closest stations UCN, UJA, and ULJ) are consistent with the first motions of the M_L 3.2 event at 11:01:13.05 on 29 April 2006. This may suggest similar focal mechanisms for those smaller events.

4. HYPOCENTER RELOCATION

Accurate hypocenter locations of the cluster events are important to obtain information on geometry of the causative fault and identification of the active fault plane of such a cluster. Accuracy of the locations depends on minimization of errors in arrival-time measurements and errors arising from unmodeled velocity structure. If sources of events are collocated so that the effects of heterogeneous velocity structure along the ray path are negligible, we may skip the consideration on the unmodeled velocity structure. Then the cluster events on a fault may produce similar waveforms at a common station. In this case, a double-difference location algorithm using waveform cross-correlation can be effectively applied to high-precision relative hypocenter locations (Waldhauser and Ellsworth, 2000).

However, in the case of the April 2006 sequence, waveform similarity between events is not so good (Fig. 3) and thus measurements of relative *P*- and *S*-wave arrival times using waveform cross-correlation can be unstable. For this reason, we choose to use a manual picking instead of cross-correlation method to measure the differential travel times

Table 2. Input data used in focal mechanism analysis for the event 2006/04/29 with origin time 11:01:13.05.

Station	Azimuth (°)	Take-off angle (°)	*P*-Polarity	*SH*-Polarity	log(*SH*/*P*) ratio
UCN	273.29	97.57	Up	Up	0.7082
UJA	274.79	97.50	Up	Up	0.5518
ULJ	230.24	95.90	Down	Down	-0.0632
YOD	218.84	94.26	Down	-	-
ULL	061.33	64.96	Down	-	-
PHA	208.00	64.96	Down	-	-
YOW	276.05	49.93	Down	-	-
HDB	198.24	49.93	Down	-	-
DGY	302.52	49.93	Up	-	-
KMC	236.87	48.54	Down	-	-
KRB	198.23	48.54	Down	-	-
SKC	318.05	48.54	Up	-	-
WJU	283.50	48.54	Up	-	-

Table 3. Velocity model (Chang and Baag, 2006) used for relocation of events in this study.

Depth (km)	*P*-Velocity (km/s)	*S*-Velocity (km/s)
0.0	5.67	3.27
5.1	6.05	3.49
16.7	6.67	3.85
29.9	7.88	4.55

between events. The seismograms recorded at the stations UCN, UJA, and ULJ show clear arrivals of *P* wave in the vertical component and *SH* waves in the tangential component. Thus arrival times of *P* and *SH* waves could usually be picked within about 0.02 and 0.05 seconds, respectively, for those stations. The catalog from the KIGAM for the April 2006 earthquake sequence is used as an input data of initial event locations for the double-difference relocation (Waldhauser and Ellsworth, 2000). The differential travel times between events at the three stations mentioned earlier are equally weighted as unity for both *P* and *S* waves.

The events with origin times 09:35:10.54 and 16:18:11.93 on 19 April have phase arrivals at the station UCN only. Thus nine events among a total of 11 events listed in Table 1 have a sufficient number of arrivals of at least five phases for relocations. We solve the forward problem for relocations using this data set with a 1D layered *P*-wave velocity model (Table 3) assuming a Poisson's solid. The velocity model is based on a joint analysis of regional broadband waveforms and travel times in southern Korea (Chang and Baag, 2006). Following receiver function studies of Chang and Baag (2005), depth to the Moho discontinuity under the station ULC (the old name of the station ULJ) is measured as 29.9 km. Thus we substitute this Moho depth for that of the original velocity model.

The relocated hypocenters are listed in Table 4, being compared with those from the original catalog of KIGAM. Figure 5 also shows the location of hypocenters in both map and cross-sectional view. We note that the relocation of the nine events greatly improves the epicenter locations that fall within an area with a radius of about 0.7 km. It seems that depths are less well constrained with ranges of

Table 4. Relocated hypocenters in comparison with hypocenters from the KIGAM catalog.

Origin Time	KIGAM Catalog			Hypocenter Relocation		
	Latitude (°)	Longitude (°)	Depth (km)	Latitude (°)	Longitude (°)	Depth (km)
2006/04/19-09:49:25.46*	-	-	-	37.059379	129.935319	10.119
2006/04/19-09:49:34.31	37.0685	129.9337	7.6	37.060205	129.936043	11.146
2006/04/19-10:57:55.88	37.0634	129.9308	2.9	37.058403	129.930908	2.985
2006/04/19-16:01:32.48	37.0583	129.9234	2.2	37.053743	129.926937	1.597
2006/04/28-23:47:55.32	37.0559	129.9354	12.3	37.060177	129.936882	13.017
2006/04/28-23:54:57.64	37.0542	129.9318	11.3	37.058057	129.934383	12.603
2006/04/29-01:01:00.72	37.0505	129.9401	10.6	37.058492	129.939372	10.081
2006/04/29-11:01:13.05	37.0540	129.9351	7.8	37.057332	129.936906	9.586
2006/04/30-09:50:02.43	37.0478	129.9476	9.0	37.057682	129.935343	4.837

*Initial location of the event 2006/04/19-09:49:25.46 for the relocation procedure is set to be the same as that of the event 2006/04/19-09:49:34.31.

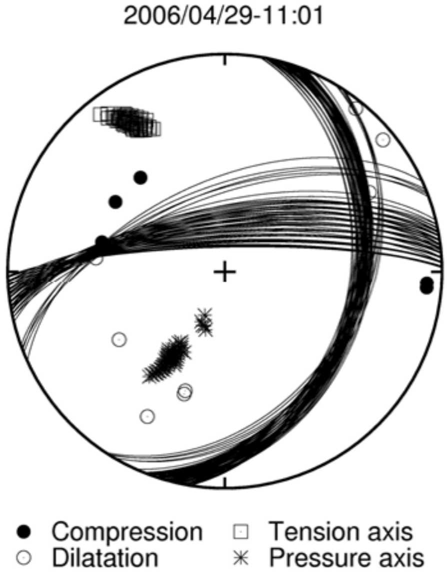

Fig. 4. Focal mechanism (lower hemisphere projection) obtained by inversion of *P* and *SH* polarities and *SH*/*P* amplitude ratios for the event 11:01:13.05 on 29 April 2006 (M_L 3.2).

1.6 km to 13.0 km. However, as mentioned earlier, weak similarity of waveforms among events as shown in Figure 3 explains that rays from the sources at depths of a wide range sample responses of the Earth's structure differently.

In spite of taking uncertainty of depth distribution into consideration to some extent, the relocated nine events can be grouped in two sets according to depths: three events with range of 1.6 to 4.8 km, and six events with range of 9.6 to 13.0 km. This implies that the April 2006 sequence was triggered along the two subfault patches with diameters of 3.2–3.4 km which can be considered to be in maximum scales. Because the horizontal extent of epicenters is small compared to the vertical extent of depths, it is hard to deduce a horizontal trend (strike direction) of the fault patches. On the other hand, epicenters of the April 2006 sequence appear to be located on the northern end of the Ulleung Fault mapped by Chough et al. (2000) in the northwestern margin of the Ulleung Basin. We refer to Figure 12 in Kang and Baag (2004) on details of tectonic structures off the eastern coast of southern Korea.

We cannot make an inference on the question which one of the two focal planes of the event, M_L 3.2, with origin time 11:01:13.05 on 29 April 2006 (Fig. 4) is a representative of the fault patches, because such a small-sized earthquake is mainly related to a posture of the existing microfault. However, the trend of the Ulleung Fault running to NNE direction at the northern end corresponds to the fault plane of strike 16°, dip 40° and rake 209° for the M_L 3.2 event at 11:01:13.05 on 29 April 2006.

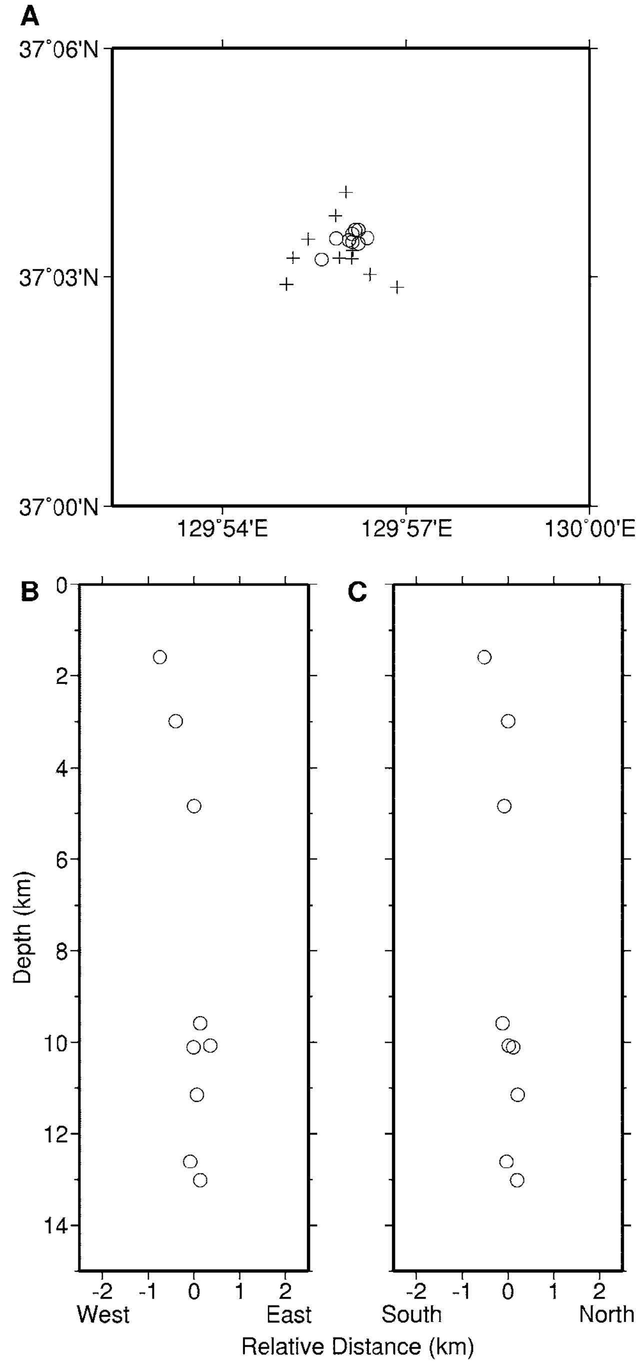

Fig. 5. Relocated hypocenters for the nine events of the April 2006 sequence. (A) epicenter map, (B) vertical cross-section along the east-west direction, and (C) vertical cross-section along the north-south direction. In (A), the relocated epicenters marked by open circles are compared to the epicenters (cross) from catalog presented by the Korea Institute of Geoscience and Mineral Resources (http://quake.kigam.re.kr).

5. DISCUSSIONS AND CONCLUSIONS

Unlike a typical mainshock-aftershock sequence, there is no obvious mainshock in the April 2006 earthquake sequence.

This series of events started on 19 April at 19:35 with an M_L 2.2 earthquake. It was followed by five events with magnitude range of M_L 2.0–2.8 on the same day. After nine days from the time, five earthquakes (M_L 2.4–3.2) started to occur again over three days (April 28th to 30th). As of 29 April, the largest M_L 3.2 event occurred nearly 11 hours after the second subsequence began. Thus the seismicity pattern shows the characteristics of swarm behavior, rather than mainshock-aftershock sequence.

It is known that most earthquake swarms are associated with volcanic regions with a few exceptions, their occurrence has often been related to the movement of magma, and the focal mechanisms of swarms are typically normal slip or occasionally strike-slip (Lay and Wallace, 1995). In that the focal mechanism of the M_L 3.2 event at the origin time 11:01:13.05 on 29 April 2006 is normal to strike-slip faulting (Fig. 4), these superficial characteristics of the April 2006 sequence seem to be similar to those of earthquake sequence related to an igneous activity. However, in the present state, there is no obvious evidence related to the magma flow in the region, although there is an argument that the ancient tectonics associated with the opening of the East Sea were governed by magma movement (Cho et al., 2004).

An alternative explanation is also possible in the viewpoint of the marginal geometry of the Ulleung Basin and the regional stress regime. The northern and western edges in the northwestern margin of the Ulleung Basin form an approximately right angle (Fig. 1). And also pressure axis of NE-SW to ENE-WSW directions is aligned obliquely to the Ulleung Fault at the western margin of the Ulleung Basin. Then tension forces the faults in NE-SW direction to be normal slip including strike-slip component on the northern end of the Ulleung Fault at the northwestern margin of the Ulleung Basin. Faults trending NE-SW direction are not large or continuous under this stress regime. Thus magnitude expected for a given earthquake is small. As shown in Figure 12 of Kang and Baag (2004), development of some small-sized normal faults in the continental region off the northwest of the Ulleung Basin supports these hypotheses strongly.

Cohesive microfaults accommodating strain accumulation can be developed into larger fault. The expected maximum sizes (3.2–3.4 km) of fault patches related to the April 2006 sequence indicate that a moderate-sized earthquake comparable to the 29 May 2004, M_w 5.1, earthquake may be expected to occur in this area sometime in the future. The time depends on the rate of stress build-up on the causative fault. We are unable to determine if this sequence will reactivate and/or will trigger a large earthquake on the Ulleung Fault. However, the fact that the occurrence of the April 2006 sequence is at the same transitional zone of continental to rifted continental crust as that of the 29 May 2004 earthquake indicates that the Ulleung Fault is seismically active.

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