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Fault Plane Solutions of the Recent Earthquakes in the Northern Part of the Korean Peninsula

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Abstract: Fault plane solutions in North Korea and the northern part of the Yellow Sea (37.5°N-40.5°N, 124.5°E-128.5°E) was studied for the earthquakes that occurred from November, 2008 to May, 2013. The analysis was based on the data collected from seismic networks in Korea and China. Fault plane solutions were obtained from P and SH wave polarities and SH/P amplitude ratioes. Most earthquakes exhibited predominantly strike-slip fault characteristics with NNE-SSW or WNW-ESE nodal planes. The P-axes trends are mainly NE-SW or ENE-WSW direction in the northern part of the Yellow Sea and inland area of North Korea except some areas in the Hwanghae province. Fault plane solutions and main axis of stress field in the study region were similar to those observed in the southern part of the Korean Peninsula.

Keywords: fault plane solutions, North Korea, northern part of the Yellow Sea, strike-slip fault, P-axes

Introduction

The tectonic forces from relative movements among plates are transmitted into the continental crust. It controls the crustal deformation and creates a seismogenic stress field in the intraplate region such as the Korean peninsula. The seismogenic stress field in and around the Korean peninsula may be formed under the common tectonic conditions of the regional tectonic forces originated from the collision between the Indo-Australian and the Eurasian plates in the west and the combined effects of subduction of the Pacific and Philippine plates around the Izu and Tokai area in the east (e.g., Kyung et al., 1996).

Over the last two thousand years, the Korean peninsula had been rather quiet in seismicity, except for a period of abnormally high seismicity from the fifteenth to eighteenth centuries (Lee, 1987). The seismic activity of the Korean Peninsula has been studied by several authors (e.g., Kyung, 1989; Lee and Yang, 2006; Lee et al., 2003).

Recently seismic networks in the southern part of the Korean peninsula have been expanded to almost ninety stations. Some institutions such as Korea Meteorological Adminstration (KMA) and Korea Institute of Geology and Mineral Resources (KIGAM) have been operating their own networks. KIGAM has been operating the seismic stations not only in Korea but also in China.

Based on the Korean event records from Chinese stations of KIGAM network, our study calculated the fault plane solutions of recent earthquakes in the northern part of the Yellow sea and inland area of North Korea.

Earthquake Data

The earthquake data were collected from the stations of KMA and KIGAM networks in Korea and China. Among Chinese stations of KIGAM network we used the data from the following stations: DHN (Donha), YNB (Yeonbyun), YNG (Yeonggu), RCN

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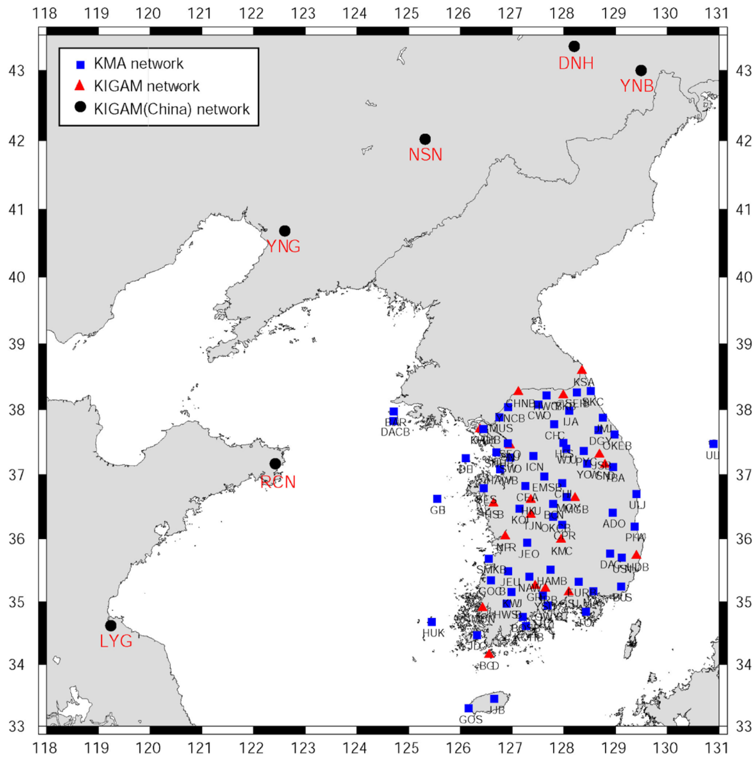

Fig. 1. Location of seismic stations used in this study. They include the networks of KMA in Korea and KIGAM in Korea and China. The names of five stations in China are as follows: DHN (Donha), YNB (Yeonbyun), YNG (Yeonggu), RCN (Yeongseong), and LYG (Yeonunhang).

(Yeongseong), and LYG (Yeonunhang). The short-period and broadband vertical-component wave forms were analyzed for this study. In case the station coverage is incomplete for polarity study only, we added SH-wave polarities and amplitude ratioes of SH to P waves.

Fig. 1 shows the location of seismic observations of KMA and KIGAM networks in Korea and China. This study only used the data of the recent earthquakes which occurred from November, 2008 to May, 2013.

The epicenter of each event was relocated by the program Hypoinverse-2000 (Klein, 2002). The seismic parameters such as origin time, epicenter, and focal depth were recalculated from the program using the 1-D crustal velocity model (Table 1) (Chang and Baag, 2006) and P wave first arrival time.

Our analysis used mainly observations within a hypocentral distance of 100 km including a hypocentral distance extended to 150 km.

Table 1. Crustal velocity model used in this study (Chang and Baag, 2006)

Depth (km)	P-Velocity (km s^{-1})	S-Velocity (km s^{-1})
0.0	5.67	3.27
5.1	6.05	3.49
16.7	6.67	3.85
31.9	7.88	4.55

The epicenters from KIGAM's catalog and relocated ones by this study are shown in Fig. 2. Epicentral differences for the same event are mostly within 0.05° except two events (No. 2 and 6) less than 0.18°. The uncertainty may be related to location of stations. The larger uncertainties were observed for farther epicenters from the stations in South Korea. Table 2 shows the earthquake parameters of each event.

Fault Plane Solution

Fault plane solution for the Korean peninsula was

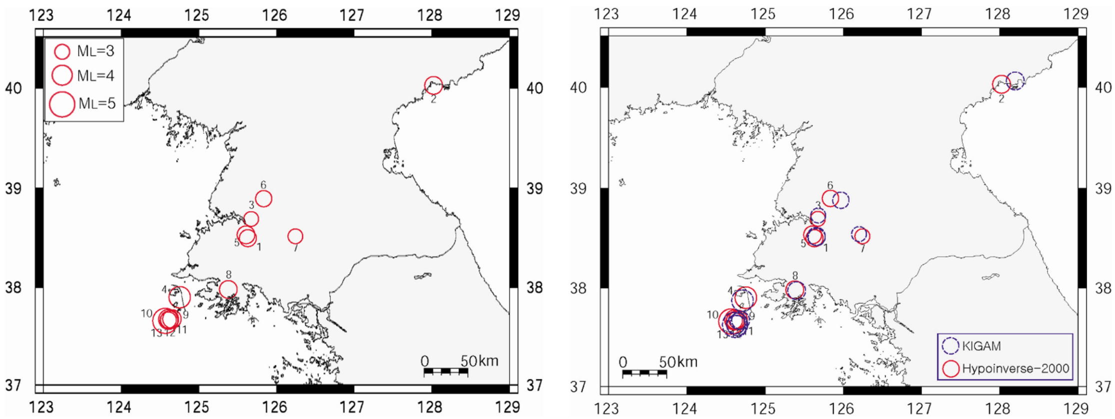

Fig. 2. Comparision of epicenters relocated by this study (solid circle on the left) and those by KIGAM (dashed circle on the right) for the recent earthquakes greater than magnitude 2.6.

done by numerous researchers (e.g., Jun, 1990, 1991; Kim, 1991; Baag et al., 1998; Lee and Chung, 1999; Chung and Kim , 2000; Kyung et al., 2001; Kang and Baag, 2004; Kang and Shin, 2006; Park et al., 2007; Hoe and Kyung, 2008; Back et al., 2011).

This study used the FOCMEC (FoCal MEChanism determination) program (Snoke, 2000, 2003), excuting the grid search not only for the trend and plunge of B axis (vertical to main compressional P axis and main dilatational T axis) in the range of 0^o-360^o and 0^o-180^o, respectively, but also for the A axis (vertical to B axis) in the range of 0^o-180^o. The best fit nodal surface which satisfies both the polarity of the first P motion and SH/P amplitude ratio was determined. The focal depth was preliminary presumed to be 10km in the Korean Peninsula. The magnitude of the earthquakes (by KIGAM) ranges from 2.7 to 4.9.

The results are presented by equal area and lower hemisphere projections, as shown in Fig. 3. Table 3 shows the parameters of fault plane solutions for the thirteen earthquakes. The number of wave form data used for each event ranges from nine to fifty five. Among thirteen earthquakes, fault plane solutions of eleven earthquakes were obtained from only P-wave polarity. Fault plane solution of two earthquakes (No. 9 and 11 in Table 3) were obtained from P- and SH-wave polarities with SH/P amplitude ratios.

Table 2. Earthquake parameters for the earthquakes used in this study. The shaded numbers indicate the parameters of earthquakes occurred in Yellow sea

No.	Origin time (KST)		Epicenter		Magnitude	Depth
	yyyy/mm/dd	hh:mm:ss	Latitude (N)	Longitude (E)	(KMA)	(km)
1	2008/11/11	21:20:54	38.5026	125.6302	3.0	3.73
2	2010/11/07	20:11:41	40.0301	128.0215	2.9	4.94
3	2011/03/06	11:04:40	38.6947	125.6741	2.9	9.95
4	2011/06/17	16:38:33	37.9043	124.7534	4.0	13.39
5	2011/08/15	06:10:40	38.5371	125.6077	3.2	11.76
6	2011/09/08	01:56:40	38.9050	125.8341	3.2	10.00
7	2012/01/19	15:43:00	38.5196	126.2451	2.7	2.77
8	2012/07/26	19:24:58	37.9833	125.3830	3.4	8.48
9	2013/05/18	03:00:59	37.6742	124.6220	3.5	4.51
10	2013/05/18	07:02:24	37.6618	124.5723	4.9	3.02
11	2013/05/18	07:26:10	37.6694	124.6081	3.3	2.12
12	2013/05/18	11:45:15	37.6766	124.6140	3.9	4.07
13	2013/05/18	16:17:53	37.6806	124.6542	3.7	5.11

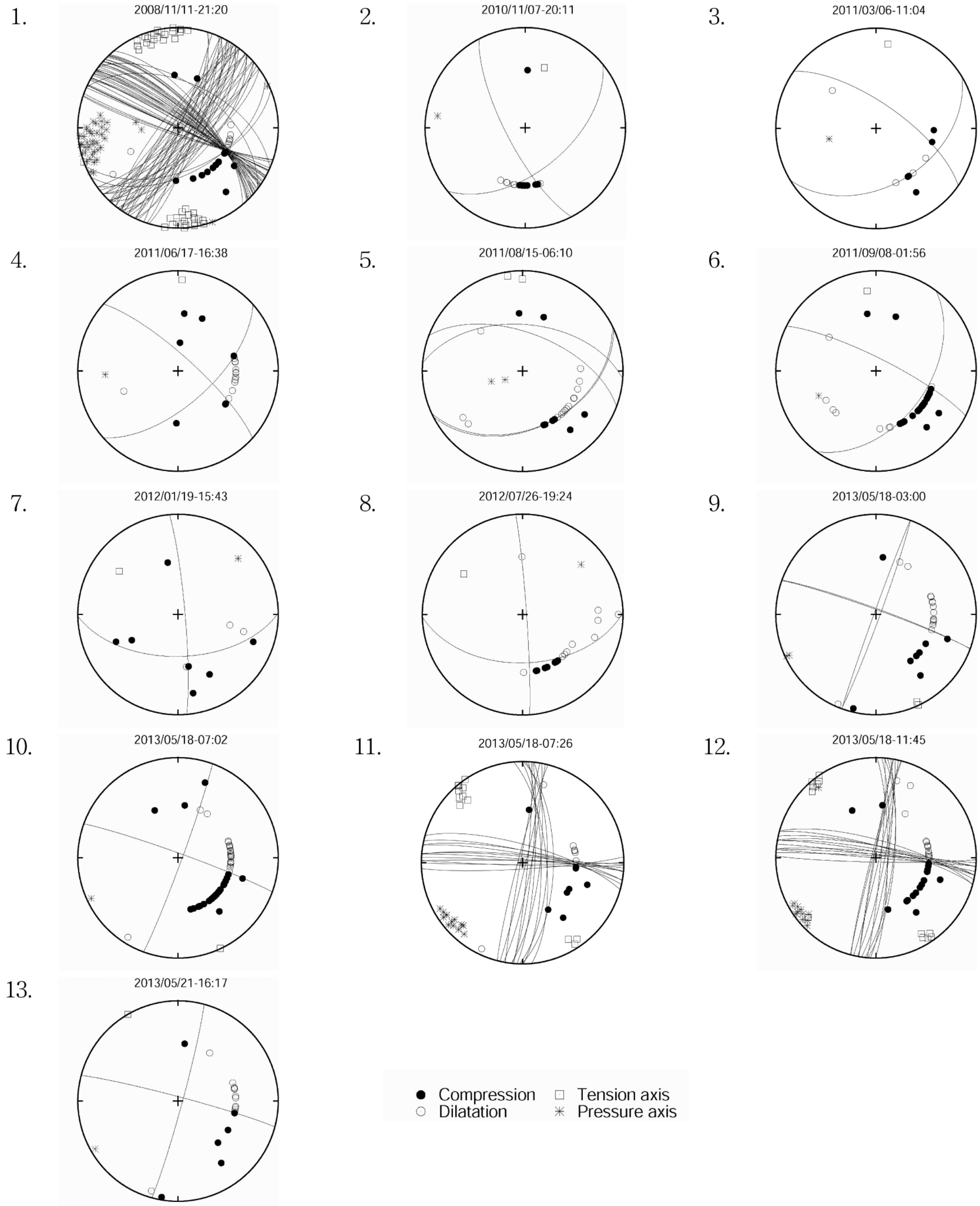

Fig. 3. Fault plane solution of 13 earthquakes obtained from P-wave polarities of first motion and SH/P amplitude ratioes.

Results

Fig. 4 shows the epicentral distribution and focal mechanism solutions of the earthquakes. The median values were selected when the range of the fault plane solutions is wide. The directions of maximum amplitude in the compressional and dilatational fields define the T-axis and P-axis, respectively (Lowrie, 1997). Geometrically, The P- and T-axis are the bisectors of the angles between the fault plane and auxiliary plane.

Near the Paekryong island the earthquakes with M>3.4 occurred five times (No. 9, 10, 11, 12, 13 in

Table 3. Parameters of fault plane solutions for the 13 earthquakes in the northern part of the Korean peninsula

No.	Plane 1			Plane 2			P-axis		T-axis		Data	
	Strike	dip	rake	Strike	dip	rake	azimuth	dip	azimuth	dip	P	SH
1	304.81	78.56	-9.77	36.76	80.42	-168.40	260.96	14.96	170.62	1.29	22	-
2	152.52	74.24	37.25	50.84	54.37	160.47	277.75	12.70	17.59	37.16	11	-
3	304.80	69.75	-52.31	58.94	42.06	-148.89	257.43	50.33	8.04	16.27	9	-
4	311.99	77.80	-27.62	48.30	63.05	-166.29	267.20	28.02	2.50	9.85	18	-
5	290.64	58.68	-60.35	63.04	42.06	-129.11	251.51	63.19	359.89	9.05	21	-
6	296.61	79.45	-44.01	36.64	46.92	-165.49	246.65	37.76	353.67	20.70	26	-
7	88.98	55.61	6.93	355.05	84.28	145.41	46.99	19.21	306.31	28.02	10	-
8	88.69	50.18	4.18	356.01	86.79	140.11	49.44	24.40	304.57	29.50	15	-
9	290.07	85.30	1.71	199.93	88.29	175.30	245.08	2.11	154.92	4.53	24	1
10	289.89	86.17	-3.22	20.11	86.79	-176.17	245.02	4.98	154.98	0.44	55	-
11	279.95	82.95	-7.11	10.82	82.95	-172.89	235.38	10.00	325.38	0.00	16	-
12	282.47	80.34	-2.61	12.91	87.42	-170.33	238.07	8.65	147.31	4.98	27	1
13	284.89	86.47	-3.54	15.11	86.47	-176.46	240.00	5.00	330.00	0.00	18	-

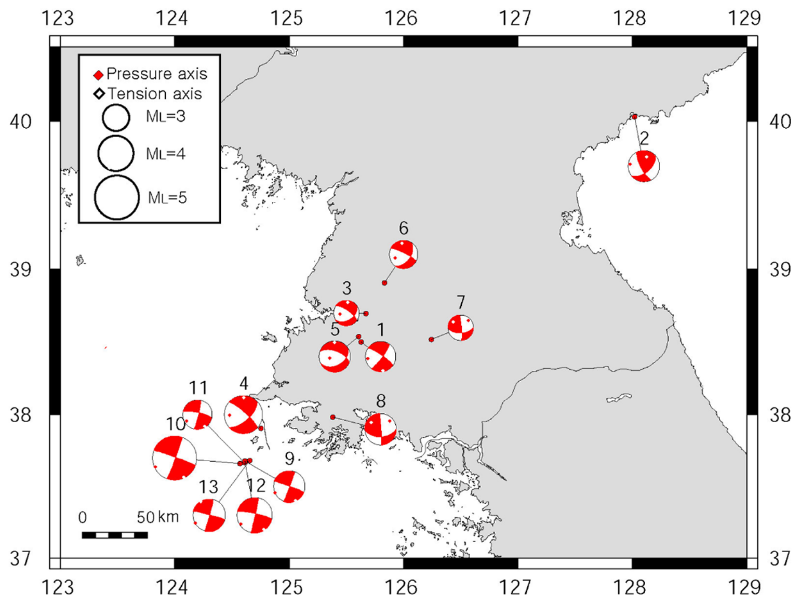

Fig. 4. Epicentral distribution and fault plane solutions of the earthquakes in this study.

Fig. 4) in May 18 to 21, 2013, consecutively. Their fault plane solutions show almost the same strike-slip faultings with the P- and T-axes of ENE-WSW and NNW-SSE, respectively. The directions of nodal planes are NNE-SSW or WNW-ESE. The fault plane solutions are almost the same as those of the inland area of the southern Korean Peninsula. Another earthquake (No. 4 in Fig. 4) near the Paekryong earthquakes, shows similar fault plane solution.

In inland area of the northwestern part of the Korean peninsula, some earthquakes show almost the same fault plane solutions with strike-slip faulting (No. 1, 7, and 8 in Fig. 4) with P-axis direction of ENE-WSW or NE-SW. The directions of nodal planes are NNE-SSW or WNW-ESE.

However, Sariwon earthquake (No. 5 in Fig. 4) shows normal faulting with T-axis of N-S direction. Songrim earthquake (No. 3 in Fig. 4) and Pyeongyang earthquake (No. 6 in Fig. 4) show strike-slip faulting with normal component. Sinpo earthquake (No. 2 in Fig. 4) in the northeastern coastal area shows strike-slip faulting with reverse component.

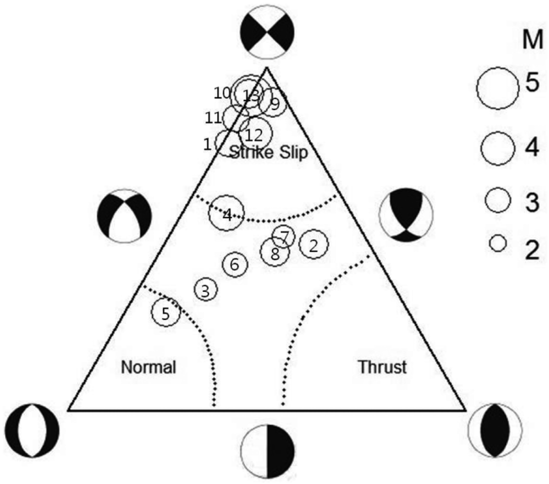

Fig. 5. Ternary plot of focal mechanism solutions. The size of the circle is proportional to the local magnitude of the earthquakes.

Fig. 5 shows the ternary plot of the focal mechanism solution by Frohlich (2001) for thirteen earthquakes: Six earthquakes show strike-slip faultings (No. 1, 9, 10, 11, 12, and 13), one normal faulting (No. 5), and five strike-slip with oblique components (No. 2, 3, 6, 7, and 8).

Fig. 6 shows the principle pressure axis determined from focal mechanism solutions. Although not the exact principal stress directions, the P- or T-axes of focal mechanisms are useful first-order approximations to the tectonic stress regime (Zoback, 1992). The compressional stresses in the study area range from E-W to NE-SW. However, the predominant trend is ENE-WSW, which agree well with the previous studies in the southern Korean Peninsula (e.g., Baag et al., 1998; Chung and Kim, 2000; Kang and Baag, 2004; Kim, 2011). As one exception, event of Hwanghae Provine shows normal faulting with N-S tensional axis (No. 5 in Fig. 6), which coincides well the previous result by Jun and Jeon (2010) in the Hwanghae Province.

The trend of the regional stress field for east Asia including north-eastern China, the Korean Peninsula, and the inner zone of southwest Japan exhibits mainly ENE-WSW or E-W compression and NNW-SSE extension with strike-slip faulting (e.g., Shiono, 1977; Tsukahara and Kobayashi, 1991; Xu, 1994).

Conclusion

Fault plane solutions in North Korea and the northern part of the Yellow Sea (37.5°N-40.5°N, 124.5°E-128.5°E) were obtained for the recent earthquakes. Out of thirteen earthquakes larger than magnitude 2.8, seven events occurred in inland area of

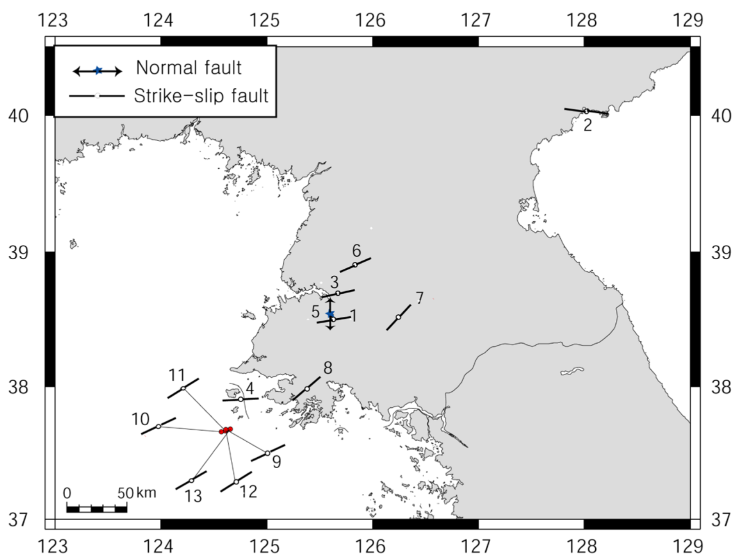

Fig. 6. Directions of maximum stress axis determined from focal mechanism solutions.

North Korea while six in the northern parts of the Yellow Sea.

1. The fault plane solutions are obtained by applying FOCMEC program (Snoke, 2000). The result shows that strike-slip faulting events predominate in the northern part of Yellow Sea and inland area of North Korea. The directions of nodal planes are mainly NNE-SSW or WNW-ESE. It indicates the fault plane solutions are almost the same as those in the southern part of the Korean Peninsula.

2. However, some events show normal faulting or strike-slip faulting with normal component in Hwanghae Province of North Korea.

3. The orientation of the compressional stresses from P-axes in the northern part of Yellow Sea and the northern part of the Korean Peninsula range from E-W to NE-SW. However, the predominant trend is ENE-WSW, which coincide well with the previous studies in the southern part of the Korean peninsula.

More precise fault plane solutions require to analyze Chinese data to cover the full region of North Korea.

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