Source Parameter Determination of Local Earthquakes in Korea Using Moment Tensor Inversion of Single Station Data

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Source Parameter Determination of Local Earthquakes in Korea Using Moment Tensor Inversion of Single Station Data

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Abstract The purpose of this investigation is to determine source parameters such as focal mechanism, seismic moment, moment magnitude, and source depth from recent small earthquakes in the Korean Peninsula using broadband records of three-component single station. It is very important and worthwhile to use a three-component single station in Korea because for most Korean earthquakes it is not possible to read enough first motions of *P*-wave arrivals because of the poor coverage of the seismic network and the small size (M_L 5.0 or less) of the events. Furthermore the recent installation of the very broadband seismic stations in Korea and use of a 3D tomography technique can enhance moment tensor inversion to determine the source parameters of small earthquakes (M_L 5.0 or less) that occur at near-regional distances ($\Delta \leq 500$ km).

The focal solution for the Youngwol earthquake of 13 December 1996 is found to be a right-lateral strike slip event with a NE strike, and the Kyongju earthquake of 25 June 1997 is found to be an oblique reverse fault with a slight component of left-lateral slip in the SE direction.

Introduction

It is well known that focal mechanism solutions are well determined using the first motion readings of *P* waves. This method, however, does not work properly for an uneven distribution of seismic stations and/or for the case of seismic events located outside the seismic network. Furthermore it is very difficult to determine the focal mechanism of small events in the Korean Peninsula because there is no seismological data exchange between South and North Korea.

The recent installation of a very broadband seismic station makes it possible to recover the seismic parameters of small earthquakes ($2.5 \leq M_L \leq 5.0$) that occur at local and regional distances. Therefore if we know the gross crustal structure, it is possible to use the *P*, *SV*, and *SH* displacement waveforms from a single three-component station to determine the seismic moment tensor (Dreger and Helmberger, 1993; Fan and Wallace, 1991; Walter, 1993). The body waveform modeling in this study is described by Dreger and Helmberger (1993). In regions where the propagation paths are well calibrated, a three-component single station of the broadband records is sufficient. The models are improved by forward modeling of the broadband displacement waveforms. The Korean institutes and universities are planning to install more broadband stations ($\geq$10) within a few years. These efforts are being extended to establish a robust automated system to determine seismic source parameters including focal mechanism solutions of small earthquakes in Korea.

Dreger and Helmberger (1993) proposed a method to invert regional body and surface waves recorded by IRIS broadband seismographs and to provide good constraints on the focal parameters using data from just a single station (e.g., Fan and Wallace, 1991; Dreger and Helmberger, 1993). More robust results are obtained using multiple stations. Although the regional waveforms are complicated, the long-period body waves are relatively stable; they change slowly with distance (Dreger and Helmberger, 1993) and can often be modeled with sufficiently simple plane-layered velocity models derived independently from travel-time studies. Surface waves are more sensitive to velocity gradients in the crust and can be well modeled only in the case of accurate knowledge of average velocities and Q on the ray path (Walter, 1993), especially in the case of a single station. Pasyanos *et al.* (1996) demonstrate that body and surface waves are effective when models are calibrated. Therefore the most labor-consuming aspect of this technique is Green's function calibration using plane-layered crustal models and independent determinations of source mechanisms of one or more events from the same region.

Source depth is not inverted for but is determined iteratively by performing inversions with Green's functions computed for several source depths. The best-fitting source depth may be determined from the variance reduction,

$$VR = \left[1 - \frac{\sum(d_i - s_i)^2}{\sum(d_i)^2}\right] \cdot 100, \qquad (1)$$

where d_i = data and s_i = synthetic seismogram.

In this study, we used moment tensor inversion software written by Douglas Dreger of the University of California, Berkeley, and distributed by IRIS.

Focal Mechanism Results

South Korean Earthquake near Youngwol

This earthquake (Figs. 1 and 2) occurred on 13 December 1996, and according to the IRIS Data Center, origin time, epicenter, and magnitude were determined as 04 hr 10 min 16.5 sec (UTC) with latitude 37.141° N, longitude 128.764° E and magnitude m_b = 4.8, respectively, at an epicentral distance of 192 km from the very broadband IRIS INCN station (azimuth to epicenter is 101°). Original and instrument-corrected, integrated, and filtrated (0.02–0.05 Hz) LP-channel seismograms are shown in Figure 1.

We tested several crustal models to evaluate the appropriateness of Green's functions (Tables 1–5, Figures 3–5). The model LE is mainly associated with the path and structure between the two sources and the station, and therefore it is the best-fit model derived from results of modern South Korean tomographic investigations (Kim and Li, 1998). Model LE is an average cross section of the crust along latitude 37° N from 127.5° up to 129.5°. Figure 5 shows

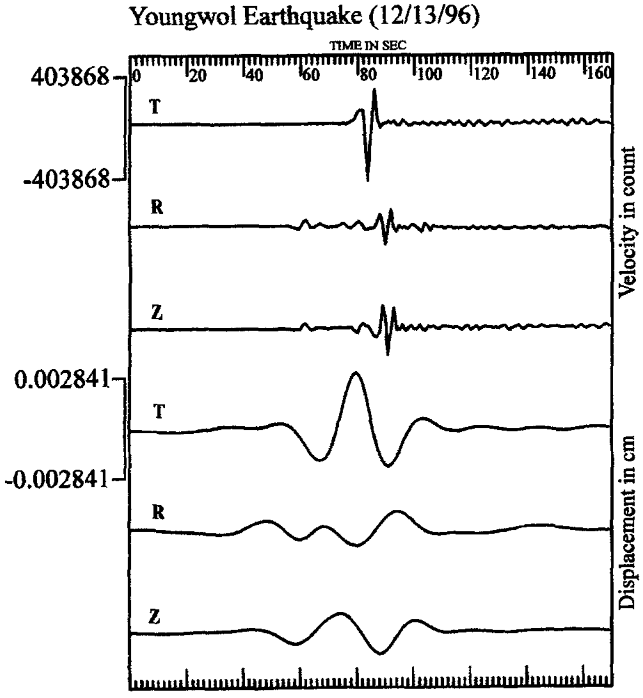

Figure 1. LP-channel seismograms registered at Inchon station (IRIS) from Youngwol earthquake. Raw data (the upper three) and instrument-corrected integrated and bandpass (0.02–0.05 Hz) filtered data (the lower three).

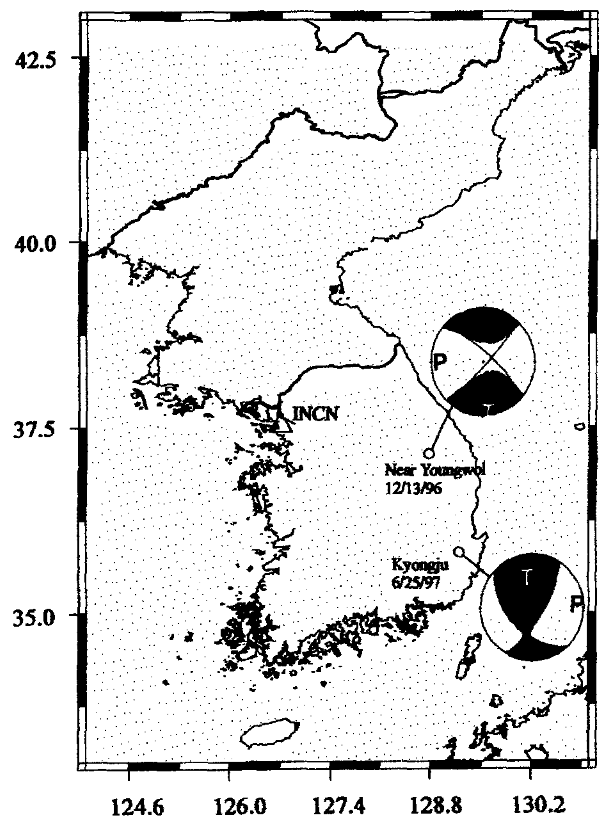

Figure 2. Map of the Korean peninsula showing locations of INCN stations and epicenters of Youngwol and Kyongju earthquakes. Also, fault plane solutions are represented here. Gray and open quadrants correspond to compression and dilatation. P and T represent the orientation of pressure and tension stress axes, respectively.

Table 1
Model A of the Korean Peninsula

Depth (km)	Thickness (km)	V_P (km/sec)	V_S (km/sec)	Density (g/cm³)	Q_P	Q_S
0	18	5.78	3.44	2.62	200	100
18	16	6.75	3.90	2.93	600	300
34	8	7.98	4.61	3.32	1000	500
42	60	8.73	5.04	3.56	1450	725

From Kim (1994).

Table 2
Model B for the East Part of South Korea

Depth (km)	Thickness (km)	V_P (km/sec)	V_S (km/sec)	Density (g/cm³)	Q_P	Q_S
0	9	5.75	3.42	2.61	100	50
9	9	6.03	3.59	2.70	200	100
18	8	6.30	3.64	2.79	600	300
26	8	6.75	3.90	2.93	600	300
34	8	7.98	4.61	3.32	1000	500
42	60	8.73	5.04	3.56	1450	725

From Kim and Lee (1996).

Table 3
Model C for All of South Korea

Depth (km)	Thickness (km)	V_P (km/sec)	V_S (km/sec)	Density (g/cm^3)	Q_P	Q_S
0	6	4.50	2.56	2.10	70	40
6	12	6.00	3.41	2.80	200	90
18	6	6.30	3.58	2.90	600	267
24	8	6.70	3.81	3.10	1000	450
32	8	8.11	4.65	3.30	1000	450
40	60	8.73	5.05	3.37	1450	725

From Kim and Lee (1994).

Table 4
Model LE Received from Tomography Data

Depth (km)	Thickness (km)	V_P (km/sec)	V_S (km/sec)	Density (g/cm^3)	Q_P	Q_S
0	1.5	5.04	2.91	2.38	100	50
1.5	3	5.65	3.26	2.58	100	50
4.5	5.5	6.14	3.54	2.74	200	100
10	5	6.39	3.69	2.82	400	200
15	6.5	6.63	3.83	2.89	600	300
21.5	4.5	6.80	3.92	2.95	600	300
26	6	7.40	4.28	3.14	1000	500
32	60	8.35	4.82	3.44	1450	725

From Kim and Li (1998).

Table 5
Tensor Moment Inversion of the Youngwol Earthquake for the Different Crust Models

Model	Strike	Rake	Dip	*VR* (%)	*DC* (%)
A	301, 209	5, 157	67, 86	85.6	34
B	310, 42	−19, −172	83, 71	85.3	68
C	311, 45	148, 6	85, 58	85.8	97
LE	311, 43	−6, −167	77, 84	89.1	70

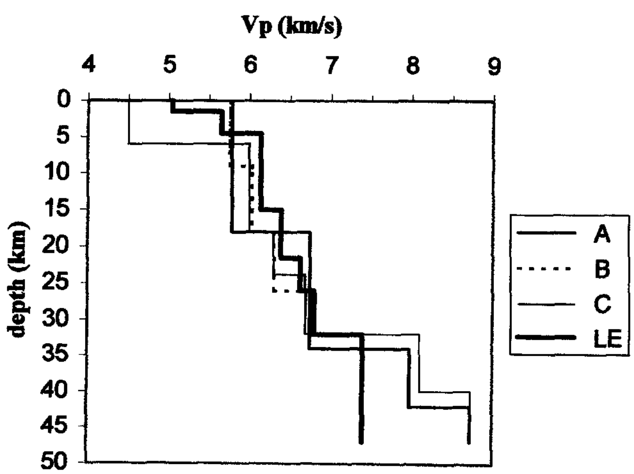

Figure 3. Crust velocity models of the Korean Peninsula (designated by A, B, C, and LE, corresponding to Tables 1–4).

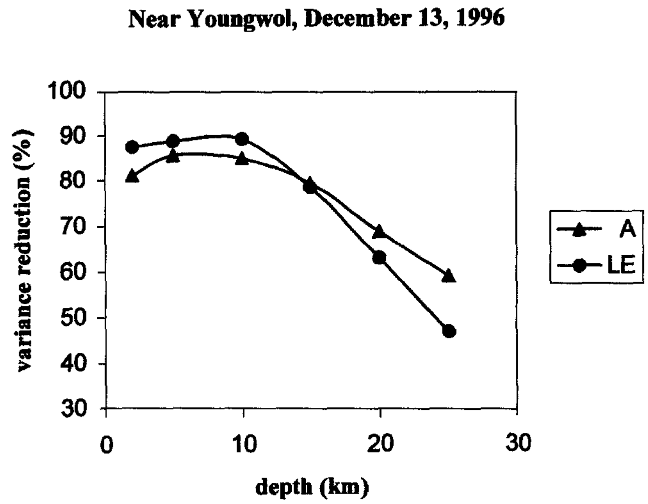

Figure 4. Plot showing the variance reduction for INCN single-station inversion for the Youngwol earthquake using Green's functions computed for different source depths (for crust models A and LE).

moment tensor results using each of the velocity models. The moment tensor solutions are coincident with models A, B, and LE; however, model C, which shows the opposite solution due to the change of pressure and tension axes. The main criterion of a suitable model is in terms of the maximum value of variance reduction.

To search for an optimal source depth using the LE model, inversions were performed for several source depths. Results of these calculations are represented in Figure 4. For comparison the similar results obtained using a simple two-layer model A are shown. The variance reduction has a maximum value at a depth of 10 km for model LE and at 5 km for model A. The maximum value of model LE is narrower and higher, so model LE is more sensitive to changes in depth and results in a better fit with the data than does the simple two-layer model A.

The final results of the moment tensor inversion are represented in Table 6 and Figure 2. The mean of the variance reduction showing deviation of observed and theoretical data is sufficient at 89%. More exact information about the crustal structure of the Korean Peninsula will possibly improve this result. Our focal mechanism solution using data of only one INCN station is pure strike slip along the right-lateral fault plane, with a dip at 84° to the NE and azimuth of 43° (NE). The choice of fault plane from the two nodal planes is based on the geology and tectonics of the given region. Figure 6 compares observed (solid line) and theoretical (dotted line) seismograms for this event.

The results in general are in accordance with the study of Baag *et al.* (1997) about fault-plane solutions obtained from the *P*-wave first motion recorded at the KIGAM, KSRS, and JAPAN stations.

South Korean Kyongju Earthquake

According to the IRIS Data Center catalog, the South Korean Kyongju earthquake (Figure 2) occurred 25 June

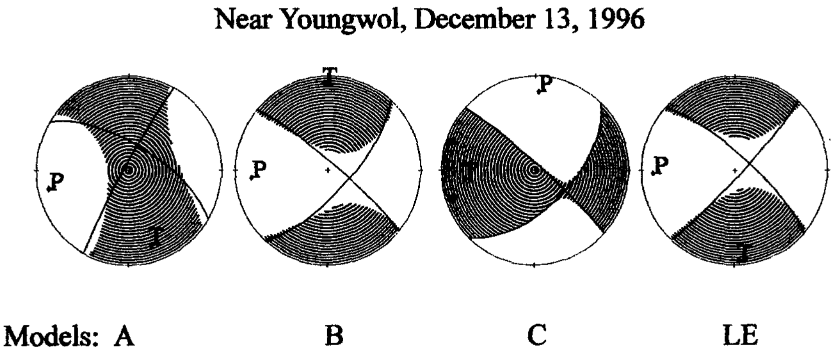

Figure 5. Moment tensor solution for the Youngwol earthquake obtained using different models.

Table 6
Results of the Tensor Moment Inversion for Two Korean Earthquakes

Name of earthquake	Stat Chan.	Δ (km)	Az	Strike	Rake	Dip	Moe + 23 (d-cm)	M_w	*VR* (%)	*DC* (%)
Youngwol, South Korea	INCN LP	192	101	311, 43	−6, −167	77, 84	7.1	5.2	89.1	70
Kyongju, South Korea	INCN VBB	294	128	135, 31	22, 140	52, 72	1.7	4.8	91.6	99

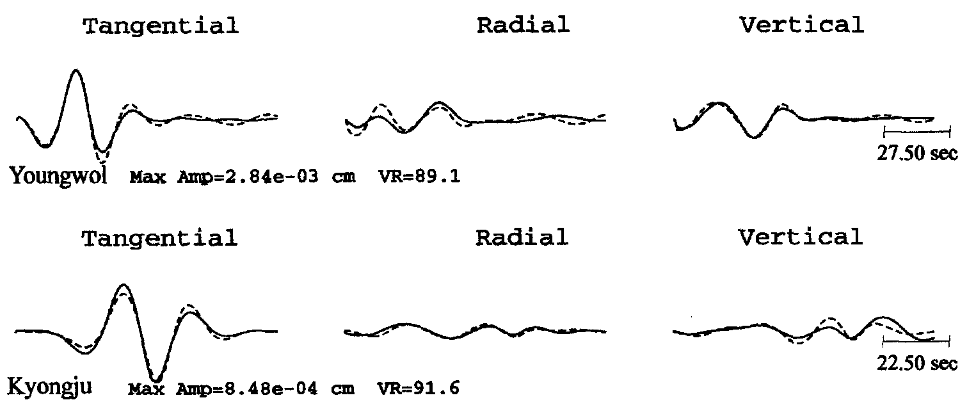

Figure 6. Comparison of data and theoretical seismograms for the two Korean earthquakes. Synthetics computed using model LE. VR is variance reduction.

1997 at 18 hr 50 min 21 sec, with latitude 35.820° N, longitude 129.189° E, and magnitude m_b 4.7 at an epicentral distance of 294 km from the INCN station (azimuth to epicenter is 128°). Original and instrument-corrected values for integrated and filtrated (0.02–0.05 Hz) VBB channel seismograms are presented in Figure 7.

Green's function calculations for different models show that the best crust model for this earthquake is again LE (Table 4 and Fig. 3). The analysis of dependence of variance reduction from depth shows that in this case, using model LE, the optimal depth is 7 km.

The final inversion results for Kyongju earthquake are presented in Figures 2, 7, and 8 and in Table 6 and show the left-lateral oblique reverse fault obtained for this event. From Figure 9, we see that the first motions of the Kyongju earthquake are well matched with the focal mechanism from the moment tensor inversion (Kim, 1998a, 1998b). The fault-plane solution for the nodal line observation is tested using the low-velocity model C for the low-velocity deposit of the Kyongsang Basin because the focal mechanism of model C is quite different from others. To determine the orientation of the nodal plane it is important to select the lower variance reduction for the correct solution. The fault-plane solution of this model is very close to that of model LE. From field investigations in the nearby nuclear power plant sites (KIGAM, 1998), most of this area's surface faults have been found to be thrust types. Using 3D tomography studies, Kim and Li (1998) also found low-velocity structure and faults of reverse type on the vertical profiles at a depth of 10 km near Kyongju area. The tomography studies show the hypocenter and the rough fault system of the Kyongju earthquake. In the case of the Youngwol earthquake, the choice of a right-lateral strike-slip with a NE strike as the fault plane was inferred from the tectonics of the region. As a result,

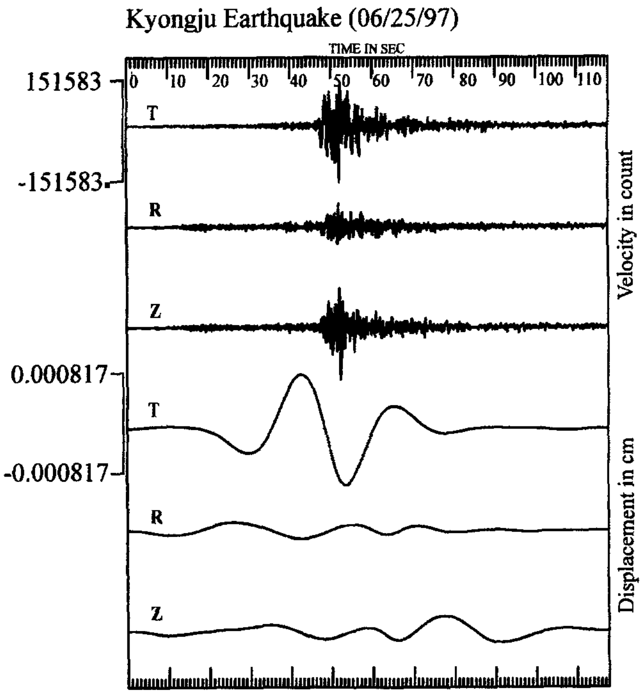

Figure 7. VBB-channel seismograms registered at Kyongju earthquake. Raw data (the upper three) and instrument-corrected integrated and bandpass (0.02–0.05 Hz) filtered data (the lower three).

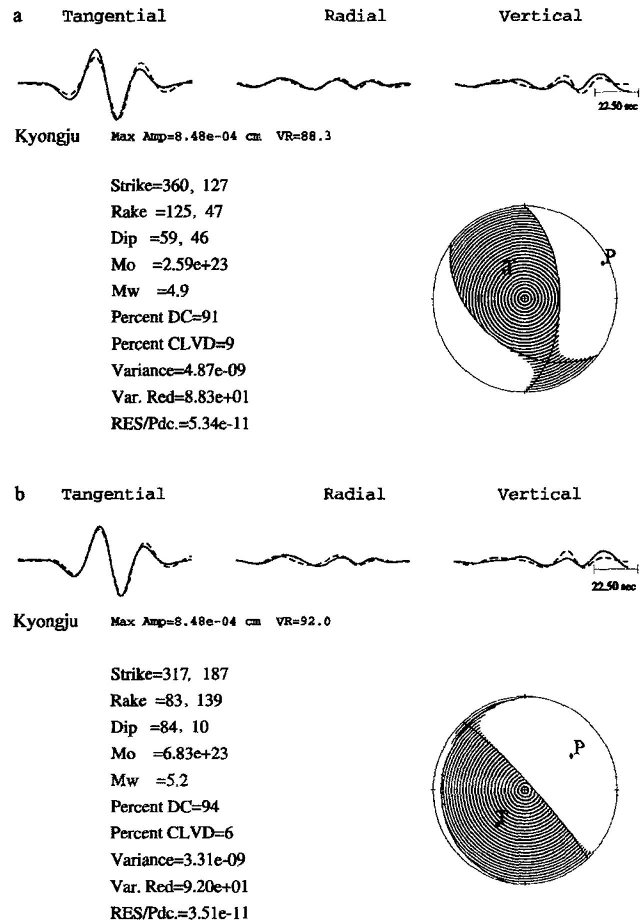

Figure 8. Two-mechanism solutions of the Kyongju earthquake (for model C). The solution in (a) (correct) is computed for zero offset = 6, the solution in (b) (incorrect) is computed for zero offset = 1, which implies the best-fitting source depth estimation. These zero offset values correspond to two close maximums of VR. Solid lines correspond to observed seismograms, dotted lines correspond to theoretical ones.

the source determination by moment tensor inversion is critically dependent on the orientation of the nodal planes from the station as well as the velocity model of the ray path. More observations or additional constraining information such as first motions is needed.

Discussion and Conclusions

In this paper we determined source parameters for the Youngwol earthquake of 13 December 1996 and the Kyongju earthquake of 25 June 1997, using the three-component IRIS station (INCN). Most parameters are coincident with other data and information (e.g., Baag *et al.* 1997). The Youngwol earthquake focal mechanism shows a right-lateral strike-slip with a NE strike, whereas the Kyongju earthquake seems to be a reverse fault with slight left-lateral strike-slip in the SE direction. These findings correspond with the present fault systems of these regions.

The variance reduction is calculated by equation (1), which holds general sums of three components of earthquake records. It normally works when components have similar amplitudes. But when a station is near a nodal plane, the tangential component begins to dominate the sum. In Figure 6 one can see that vertical and radial theoretical seismograms correspond more accurately to data in cases with more values of *VR* that are low, so these solutions are correct and must be chosen.

As pointed out in Dreger and Helmberger (1993) and Walter (1993), inexact crust models may be compensated for by changing the source depth or distance. They also remark that small changes in the epicenter location do not strongly change the best-fit solution, but changes in focal mechanism introduced by using an oversimplified velocity model are more significant. Their results indicate that reasonable knowledge of the velocity structure is the most important *a priori* information when using complete waveforms. We can have true source depth only when we use well calibrated Green's functions, that is, when we have an exact crust model given by results confirmed by other data.

Acknowledgments

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Table 7
First Motions of the Kyongju Earthquake

Station	Location	Azimuth (degrees)	Take-off angle (degrees)	Polarity	Remarks
MKL	35.73N 129.24E	182	152	Up	KIGAM* stations, digital record
CHS	36.17N 129.09E	343	96	Up	
DKJ	35.94N 129.11E	329	104	Up	
HAK	35.92N 129.50E	52	100	Down	
BBK	35.57N 129.43E	140	101	Up	
MAK	35.36N 129.18E	188	96	Up	
KMH	35.34N 128.92E	204	74	Down	
INCN	37.48N 126.63E	309	47	Up	IRIS†
Kwangju	35.17N 126.88E	253	47	Down	KMA stations, digital record
Pusan	35.10N 129.03E	195	74	(?)	
Uljin	35.98N 129.42E	6	47	(?)	
Kangneung	37.75N 128.90E	352	47	Up	
Chupoongnyung	37.88N 127.73E	294	47	Down	
Cholwon	38.15N 127.30E	327	47	Up	
Chunchon	37.88N 127.73E	330	47	Up	
SIHY‡	35.73N 129.24E	187	153	Down	Seismol Inst. station, digital record

*KIGAM, Korea Institute of Geology, Mining, and Materials.
†KMA, Korea Meteorological Administration.
‡SIHY, Seismological Institute, Hanyang University.

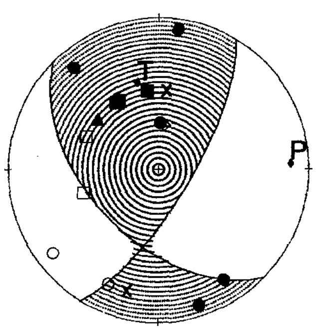

Figure 9. The first motions correspond to the focal plane solution of the Kyongju earthquake of 25 June 1997. Circles, squares, triangles, and diamonds represent the stations of KIGAM (Korea Institute, Mining and Materials), KMA (Korea Meteorological Administration), IRIS (Inchon), and SIHY (Seismological Institute of Hanyang University), respectively. Closed and open symbols, and x's indicate compression, dilatation, and unknowns, respectively.

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