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Application of Moment Tensor Inversion to Small Local Earthquakes in the Korean Peninsula
한반도의 소규모지진 모멘트 텐서 역산의 응용

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요 지

모멘트 텐서 역산의 응용 목적은 지진 메커니즘, 지진 모멘트, 한반도에서 국지적으로 발생하는 규모 5.5 이하의 소규모 지진의 진원깊이 등의 진원인자를 결정하는 것이다. 이와 같이 광범위한 지형에서 발생하는 지진들은 어느 지역에서의 활동적인 지체구조를 밝혀내는 실마리를 제공해 준다. 더욱이 소규모 지진의 지진 메커니즘 연구를 위해서는 반드시 필요하다. 본 논문에서는 한반도에서 최근에 발생한 규모3.3 - 4.8의 14개 지진을 모멘트 역산방법 (TDMT_INV)을 이용하여 지진 메커니즘 분석 결과를 소개하고 있다. 단층들의 주향은 북동-남서, 북서-남동 방향으로 주향이동 또는 소규모 역단층의 주향이동 단층을 보이고 있다. 응력장의 압축방향은 몇몇 단층을 제외하고는 동-서 또는 동북동-서남서 방향이 우세한 것으로 나타났다. 그리고 영남 육괴와 원산 지역에 분포하는 지진들은 남-북 또는 북북서-남남동 방향이 우세한 것으로 나타났다.

핵심용어 : 모멘트 텐서 역산, Green 함수, 모멘트 규모

Abstract

The purpose of application of moment tensor inversion method is to determine source parameters, such as, focal mechanism, seismic moment and source depth. This paper presents results of focal mechanism solutions of 14 recent events with magnitudes ranging from M3.3 to M4.8 by using moment tensor inversion method called TDMT_INV. The strike of faults is in the direction of NE-SW and NW-SE with the movement of strike-slip or strike-slip of minor reverse component. The compressional axis of the stress field is predominantly E -W or ENE-WSW except for some faults, which are distributed at Ryongnam Massif and Wonsan, they have a compressional axis of N-S or NNW-SSE.

Keywords : moment tensor inversion, focal mechanism, Green's function, moment magnitude.

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1. Introduction

The Korean Peninsula is not in a high seismicity zone. According to the catalogue of the Korean Meteorological Administration (KMA), most of earthquake magnitudes in and near the Korean Peninsula are less than 4.0. Earthquakes of this type have a widespread geographic occurrence, and in some cases provide the only clue to the active tectonics of a region. Therefore, it is necessary to study the focal mechanism of small earthquakes. The obtained information will be useful for grater understanding of the tectonic process in and near the Korean Peninsula. During the last decade the Inchon station, which belongs to the global IRIS (Incorporated Research Institutions for Seismology) seismographic network and two local networks, KMA and KIGAM (Korea Institute of Geology and Mineral Resources) were installed in Korea. This allows us to solve various problems of seismology on a qualitatively higher level than was possible before.

The determination of source parameters from long-period teleseismic body waves has become routine for events whose magnitudes are greater than about 5.5 (*Dziewonski et al., 1981*). For smaller magnitude events, regional waveforms at shorter periods offer better signal-to-noise (S/N) ratios. Regional inversion techniques have been developed using surface waves (*Patton, 1988; Jimener et al., 1989*), body waves (*Fan and Wallace, 1991; Dreger and Helmberger, 1991*), and both body and surface waves (*Dreger and Helmberger, 1993; Walter, 1993*).

In particular, new prospects are appearing in the research of source mechanisms of shallow, moderate size earthquakes whose magnitudes are too small to be well recorded teleseismically. In this case, regional waveforms must be used to determine the source parameters.

In this paper we attempted to use the moment tensor inversion routine TDMT_INV (*Dreger and Langston, 1995*) developed recently for regional distance. This program is a time domain inverse code designed to invert regional long-period waveform data incorporating body wave with surface waves and can provide good constraint of focal parameters using data of a single station, but surer and 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 modelled 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 modelled 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. The studies obtained from Pasyanos et al. (*1996*) demonstrate that body and surface waves are effective when models are calibrated. Therefore the most labour- 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.

For this investigation we had chosen fourteen recent South Korean earthquakes with local magnitudes range from 3.3 to 4.8. The focal mechanism solutions of these earthquakes are very important to the study of the tectonic processes on the Korean Peninsula.

2. Basic Methodology and Program Assumptions

2.1 Basic Methodology

The general representation of seismic sources is simplified by considering both a spatial and temporal point-source:

$$U_n(x,t) = M_{ij} \cdot G_{ni,j}(x,z,t) \qquad (1)$$

U_n is the observed n^{th} component of displacement, G_{nij} is the n^{th} component Green's function for specific force-couple orientations, M_{ij} is the scalar seismic moment tensor, which describes the strength of the force-couples.

The general force-couples for a deviatoric moment tensor may be represented by three fundamental-faults, namely a vertical strike-slip, a vertical dip-slip, and a 45^0 dip-slip.

The temporal behavior is carried in the Green's function, x represents the source-station distance, and z is the source depth. The indices i and j refer to geographical directions. The above equation is solved using linear least squares for a given source depth. The inversion yields the M_{ij}, which is decomposed into the scalar seismic moment, a double-couple moment tensor and a compensated linear vector dipole moment tensor. The double-couple is further represented in terms of the strike, rake and dip of the two nodal planes. The basic methodology and the decomposition of the seismic moment tensor are described in Jost and Herrmann (*1989*).

The source depth is found iteratively by finding the solution that yields the largest variance reduction (VR),

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

Where d_i is the discrete data, s_i is Green's function time series. The summation is performed for all stations and components. A variance reduction value of 100 means the full coincidence of data and synthetics in given frequency bands.

The Green's functions were computed using the FKRPROG software developed by Saikia et al (*1994*).

2.2 Program Assumptions

First, it is assumed that the event location is well represented by the high frequency hypocentral location. A low frequency centroid location is not determined.

Second, the simplified representation above assumes that the source time history is synchronous for all of the moment tensor elements and that it may be approximated by a delta function. These assumptions are generally reasonable for M_w<7.5 events since long period waves (>10-20s) are used. It is noted, however, that for larger events these point-source assumptions break down for the period range employed and alternative finite fault approaches (*Dreger and Kaverina, 2000*) are defined or longer period waves and larger source-station distances (*Fukuyama and Dreger, 1999*).

Third, it is assumed that the crustal model is sufficiently well known to explain low frequency wave propagation. Crustal velocity models that are sufficient for moment tensor analysis may be derived from models used to locate earthquakes, or by modeling of the broadband seismograms (*Dreger and Helmberger, 1990 and 1993; Dreger and Romanowicz, 1994; Rodgers et al., 1999; Zhao and Helmberger, 1991; Song et al., 1996*). Two- and three-dimensional models may be used provided that the codes used to synthesize the Green functions produce the full complement of fundamental-fault responses.

3. Background and data analysis

From 1998 to 2000 there are several seismologists who applied the moment tensor inversion for single-station data to determine source parameter from regional earthquakes with magnitude Mb > 4.5, such as, December 13, 1996, Youngwol earthquake, June 25, 1997, Kyongju Earthquake in Korea and Kobe, Neftegorsk earthquakes and their aftershocks in the Far East Asia (*Kim and Kraeva, 1998; Kim et al., 2000*). These results were in well agreement with information obtained from both other methods and the tectonic situation in the studied region.

In this work, we will present results obtained from applying this method to recent events with local magnitudes from 3.3 to 5.5 and for trying to

Table 1. Earthquake parameters

No	Earthquake Name	Date mm/dd/yy	O.T h:m:s (UTC)	LAT (E)	LONG. (N)	M	Dist. (Km)	Azi.	Station
1	Waegwan	10/15/1996	20:45:32.3	36.1	128.3	3.3	214	316	INCN[1]
2	1996 Kyokryolbiyol-do	11/10/1996	12:33:21.0	36.7	125.4	3.5	140	51	INCN[1]
3	Wonsan	11/16/1996	23:49:15.1	39.0	127.6	3.6	188	207	INCN[1]
4	Youngwol	12/13/1996	04:10:16.5	37.1	128.7	4.8	193	282	INCN[1]
5	Kyongju	06/25/1997	18:50:21.1	35.8	129.2	4.7	294	308	INCN[1]
6	Namcheon	04/15/1998	18:58:10.1	38.4	126.3	3.5	106	164	INCN[1]
7	SW of Nampo	06/08/1998	02:45:09.5	38.5	124.3	3.7	234	118	INCN[1]
8	1998 Kyokryolbiyol-do	09/03/1998	07:52:47.8	36.6	125.7	3.8	129	40	INCN[1]
9	Uljin	01/23/1999	16:01:52.1	37.0	128.8	3.3	146	242	TJN[2]
10	Tokchok-do	02/23/1999	17:14:32.2	37.3	126.0	3.5	159	130	TJN[2]
11	Taebaek san	04/07/1999	14:43:19.1	37.2	128.9	3.3	129	307	CHU[3]
12	Pohang	06/02/1999	09:12:23.3	35.9	129.3	3.4	261	328	CHU[3]
13	2000 Kyokryolbiyol-do	04/12/2000	19:44:01.4	36.9	125.3	3.5	194	107	TJN[2]
14	West of Kunsan	04/28/2000	23:53:26.8	35.8	125.7	3.3	205	24	INCN[1]

[1] belongs to IRIS network; [2] belongs to KIGAM network; [3] belongs to KMA network.

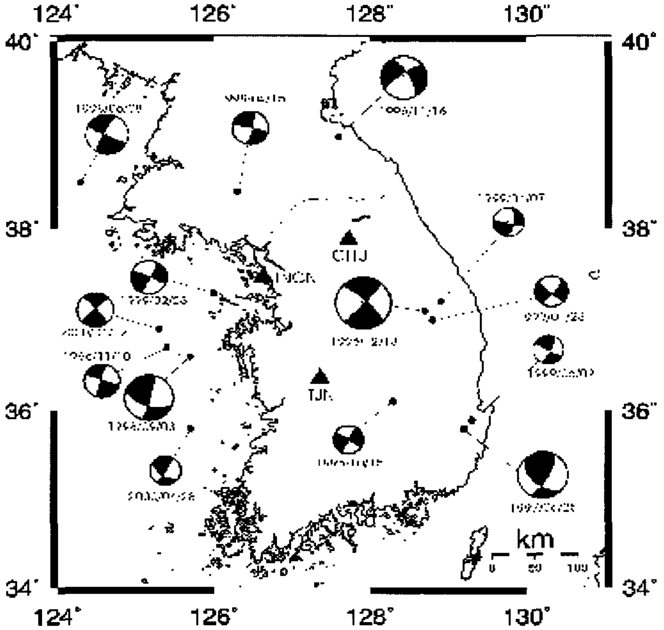

Fig 1. Location of earthquakes and stations used for focal mechanism solution results in this study. Closed circles and triangles indicate epicenters and stations; Closed and opened quadrants correspond to compression and dilatation.

study focal mechanism of small earthquakes, which are very common in the Korean Peninsula.

We select 14 recent earthquakes in the studied region. The focal mechanisms of all these earthquakes will show important information to help us understand more about the local tectonic process in the Korean Peninsula

Table 1 shows a list of events, which were calculated in this study. Stations used for the inverse calculation are Inchon Station belonging to IRIS, Chuncheon station belonging to KMA, Taejon station belonging to KIGAM in Korea (see Fig 1).

4. Focal Mechanism Results

Based on the spatial distribution of these events in the tectonic divisions, they can be classified into 5 groups as follows:

- Group 1: includes 6 events distributed at the sea of Western Korean Peninsula: The November 10, 1996, M3.5, Kyokryolbiyol-do Earthquake, The September 3, 1998, M3.8, The April 12, 2000, M3.5, Kyokryolbiyol-do Earthquake, The June 7, 1998, M3.7, SW of Nampo Earthquake, The February 23, 1999, M3.5, Tokchok-do Earthquake and The April 29, 2000, M3.3, west of Kunsan Earthquake, which occurred at the tectonic region called as the Kyonggi Massif in the central part of the Korean Peninsula..
- Group 2: includes 2 events distributed at the North of the South Korea: The November 16, 1996, M3.6, Wonsan Earthquake and The April 15, 1998, M3.5, Namcheon Earthquake, which occurred at the Pyongnam basin.
- Group 3: includes 3 events distributed at the Southeastern central region of the South Korea: The October 15, 1996, M3.3, Waegwan Earthquake, The January 23, 1999, M3.3, Uljin Earthquake, The April 7, 1999, M3.3, Taebaek-san Earthquake, which occurred at the tectonic region called as Yongnam Massif.
- Group 4: includes 2 events distributed at the Southeast of Korea: The June 02, 1999, M3.4, Pohang Earthquake, The June 25, 1997, M4.7, Kyongju Earthquake, which occurred at the Yonil Basin to the east of the Kyongsang Basin.
- Group 5: had the biggest magnitude - The December 13, 1996, M4.8, Youngwol Earthquake in the Okchon Neogeosynclinal zone.

In each group, the focal mechanism solutions of these events will be expounded in decreasing order of magnitude.

In calibrating the Green function, we tested several crustal models to evaluate the appropriateness of Green's functions (Table 2-5, Fig 2). The main criterion of a suitable model is maximum value of variance reduction (Equation 2).

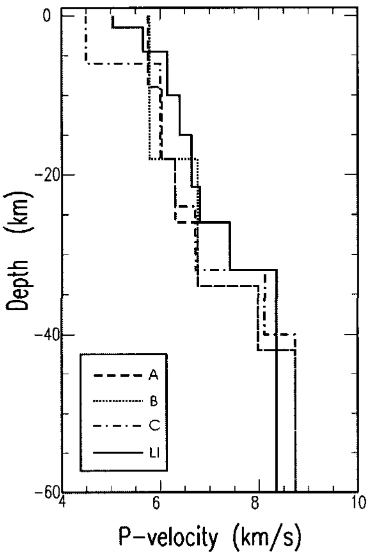

Fig 2. Crust velocity models of the Korean peninsula (their names signed by letters A, B, C and LI are corresponding to Table 2-5).

To choose an optimal model from the four above models, we carried out calculations for these models with several source depths. Figure 3 shows the variance reduction results from model

LI and A for the September 3, 1998, M3.8, Kyokryolbiyol-do Earthquake. The shape of curve of the variance reduction of model LI is narrower and the maximum value is higher, so this model is more sensitive to changes in depth and the results obtained from this model are in better fit with the data than does the simple two-player model A. The best-fit found model is LI received from results of modern South Korean tomography investigations (Kim and Li, 1998). This model is average cross-section of the crust along latitude 37° N from 127.5° E up to 129.5° E.

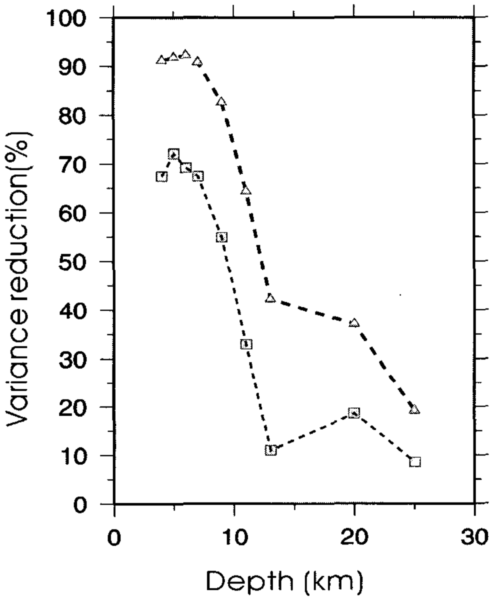

Fig 3. The variance reduction of the September 3, 1998, M3.8, Kyokryolbiyol-do earthquake using Green's functions computed at the different source depths for the crust model A and LI. Symbols triangles and squares correspond to model A and LI

The moment tensor solutions for the September 3, 1998, M3.8, Kyokryolbiyol-do Earthquake received from different models are shown in Figure 4 and Table 6.

The variance reduction has the maximum for depth of 6 km for LI model and it is the highest among four models, so this model gives better approximation of seismogram.

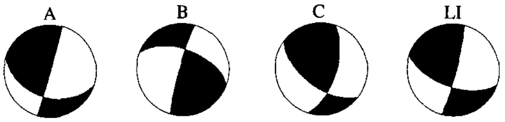

Fig 4. Focal mechanism solutions of the September 3, 1998, M3.8, Kyokryolbiyol-do earthquake at four crust models A,B,C and LI. Closed and opened quadrants correspond to compression and dilatation.

Table 2. Model A of the Korean Peninsula

Depth km	Thickness km	Vp km/s	Vs km/s	ρ g/cm^3	Qp	Qs
18	18	5.78	3.44	2.62	200	100
34	16	6.75	3.90	2.93	600	300
42	8	7.98	4.61	3.32	1000	500
102	60	8.73	5.04	3.56	1450	725

From Kim(1994)

Table 3. Model B for the East Part of South Korea

Depth km	Thickness km	Vp km/s	Vs km/s	ρ g/cm^3	Qp	Qs
9	9	5.75	3.42	2.61	100	50
18	9	6.03	3.59	2.70	200	100
26	8	6.30	3.64	2.79	600	300
34	8	6.75	3.90	2.93	600	300
42	8	7.98	4.61	3.32	1000	500
102	60	8.73	5.04	3.56	1450	725

From Kim and Lee(1996)

Table 4. Model C for all South Korea

Depth km	Thickness km	Vp km/s	Vs km/s	ρ g/cm^3	Qp	Qs
6	6	4.50	2.56	2.10	70	40
18	12	6.00	3.41	2.80	200	90
24	6	6.30	3.58	2.90	600	267
32	8	6.70	3.81	3.10	1000	450
40	8	8.11	4.65	3.30	1000	450
100	60	8.73	5.05	3.37	1450	725

From Kim and Lee(1994)

Table 5. Model LI received from Tomography Data

Depth km	Thickness km	Vp km/s	Vs km/s	ρ g/cm^3	Qp	Qs
1.5	1.5	5.04	2.91	2.38	100	50
4.5	3	5.65	3.26	2.58	100	50
10	5.5	6.14	3.54	2.74	200	100
15	5	6.39	3.69	2.82	400	200
21.5	6.5	6.63	3.83	2.89	600	300
26	4.5	6.80	3.92	2.95	600	300
32	6	7.40	4.28	3.14	1000	500
102	60	8.35	4.82	3.44	1450	725

From Kim and Li, 1998

Table 6. Focal mechanism solutions of the Kyokryolbiyol-do 1998 earthquake for different crust models.

Model	Strike	Rake	Dip	VR %	DC %
A	16;107	132;8	89;48	69.2	36
B	196;291	144;8	84;54	82.7	55
C	18;127	143;33	63;58	84.5	38
LI	15;108	149;7	84;59	92.2	70

4.1. Focal mechanism solutions of Earthquakes in the group 1

The September 3, 1998, M3.8, Kyokryolbiyol-do Earthquake: occurred at the South of the Kyokryolbilyol-do (Fig 1). According to KMA origin time, epicenter are determined as 07:52:47.800 (UTC) with latitude 36.6(N, longitude 125.7°E and local magnitude, at epicenter distance 129km from very broadband Inchon station, azimuth to epicenter is 40°.

The final results of tensor moment inversion are represented in Fig 1 and Table 7. The mean of variance reduction showing deviation of observed and theoretical data is high enough - 92.2% at a depth of 6 km. More exact information about the crust structure of the Korean peninsula will possibly allow us to improve the accuracy of this result. The focal mechanism solution from data of Inchon station is the strike-slip along a right-lateral fault plane with a dip of 84° and a strike of 15° (NNE). The choice of fault plane from two nodal planes is conditioned by the geology and tectonics of a given region. Fig 5a shows the comparison of observed

Table 7. The focal mechanism solutions of 14 events in this.

No	Earthquake Name	Date mm/dd/yy	O.T h:m:s(UTC)	Strike	Rake	Dip	Mo Dyne-cm	Mw	H km	VR %	DC %	Station
1	Waegwan	10/15/1996	20:45:32.3	301.31	179,0	90, 89	8.41e+20	3.3	10	84.4	89	INCN[1]
2	1996 Kyokryolbiyol-do	11/10/1996	12:33:21.0	288.198	6,176	86, 84	3.29e+21	3.6	7	88.2	85	INCN[1]
3	Wonsan	11/16/1996	23:49:15.1	234,329	-20,-166	77, 70	1.73e_22	4.1	11	89.3	96	INCN[1]
4	Youngwol	12/13/1996	04:10:16.5	43,312	-168, -5	86, 78	1.70e+23	4.8	9	90.0	72	INCN[1]
5	Kyongju	06/25/1997	18:50:21.1	28,135	139, 25	70, 52	1.75e+22	4.1	7	92.0	98	INCN[1]
6	Namcheon	04/15/1998	18:58:10.1	282,13	-11, -175	85, 79	1.24e+21	3.4	8	87.7	93	INCN[1]
7	SW of Nampo	0/08/1998	02:45:09.5	117,207	-15, -117	87, 75	9.68e+21	4.0	12	97.0	84	INCN[1]
8	1998 Kyokryolbiyol-do	09/03/1998	07:52:47.8	15,108	149, 7	84, 59	7.11e+21	3.9	6	92.2	70	INCN[1]
9	Uljin	01/23/1999	16:01:52.1	132,40	-168, -8	82, 79	1.84e+21	3.5	11	86.2	76	TJN[2]
10	Tokchok-do	02/23/1999	17:14:32.2	295,26	170, 2	88, 80	2.1e+21	3.5	12	91.6	84	TJN[2]
11	Taebaek san	04/07/1999	14:43:19.1	104,8	-147, -12	80, 58	3.18e+21	3.6	5	90.7	94	CHU[3]
12	Pohang	06/02/1999	09:12:23.3	118,27	13, 174	84, 77	3.69e+21	3.7	10	84.8	90	CHU[3]
13	2000 Kyokryolbiyol-do	04/12/2000	19:44:01.4	228,319	172, 3	87, 82	1.29e+21	3.43	10	76.8	89	TJN[2]
14	West of Kunsan	04/28/2000	23:53:26.8	32,125	149, 6	85, 59	1.39e+21	4	6	84.0	94	INCN[1]

1 belongs to IRIS network; 2 belongs to KIGAM network; 3 belongs to KMA network

(solid line) and theoretical (dotted line) seismograms for this event.

The June 7, 1998, M3.7, SW of Nampo Earthquake: occurred at 02:45:09.500 (UTC) with latitude 38.5°N, longitude 124.3°E, (according to KMA) at epicenter distance 234 km from very broadband Inchon station, azimuth to epicenter is 118°(Fig 1).

The analysis of dependence of variance reduction from depth shows that the optimal depth for model LI is 12 km. Fig 5a shows the comparison of observed (solid line) and theoretical (dotted line) seismograms for this event. The inversion result for this event is presented in Fig 1 and Table 7. It shows that the solution is a left-lateral strike-slip normal faulting with a dip of 87° and a strike of 117°. The choice of the active fault plane was based on the regional tectonic evidence.

The November 10, 1996, M3.5, Kyokryolbiyol-do Earthquake: occurred at 03:33:21.0 (UTC) with latitude 36.7°N, longitude 125.4°E (according to KMA) at epicenter distance 140 km from very broadband Inchon station, azimuth to epicenter is 51° (Fig 1).

Green's function calculations using each of the velocity models show that the best model for this earthquake is LI (Fig 2, Table 5). The analysis of dependence of variance reduction on depths shows that the optimal depth for model LI is 7km. The final results of a moment tensor inversion for this event are presented in Fig 1 and Table 7.

So our focal mechanism solution using data from broadband Inchon station is a pure strike slip along right-lateral fault in a nearly vertical plane and striking at 198(with a minor reverse component. The comparison of observed (solid

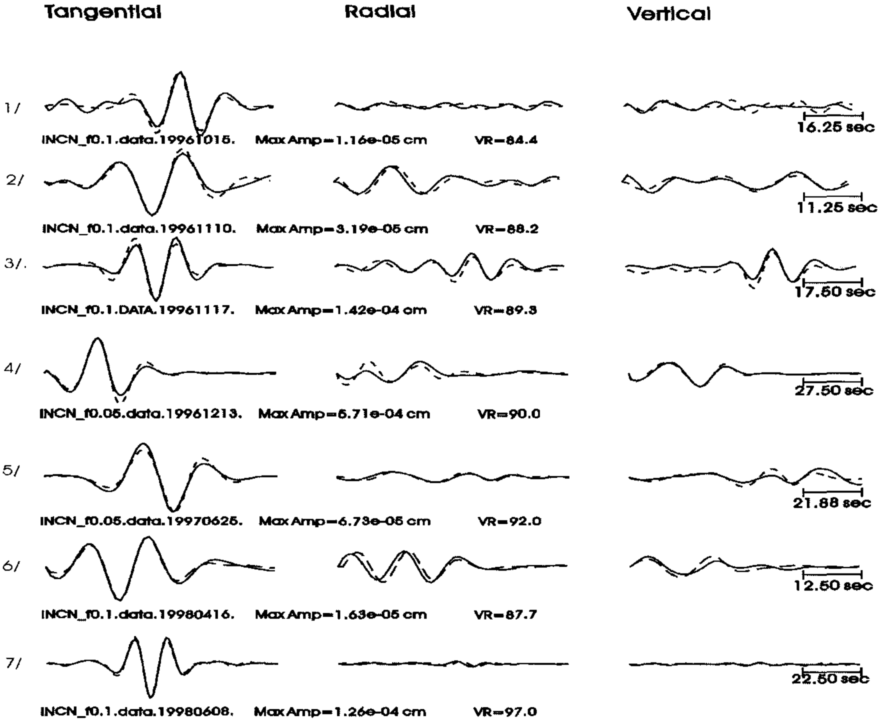

Fig 5a. Comparison of data and theoretical seismograms for 14 earthquakes in the Korean Peninsula. Solid lines correspond to observed seismograms and dashed lines to synthetics; (from the event 1 to event 7).

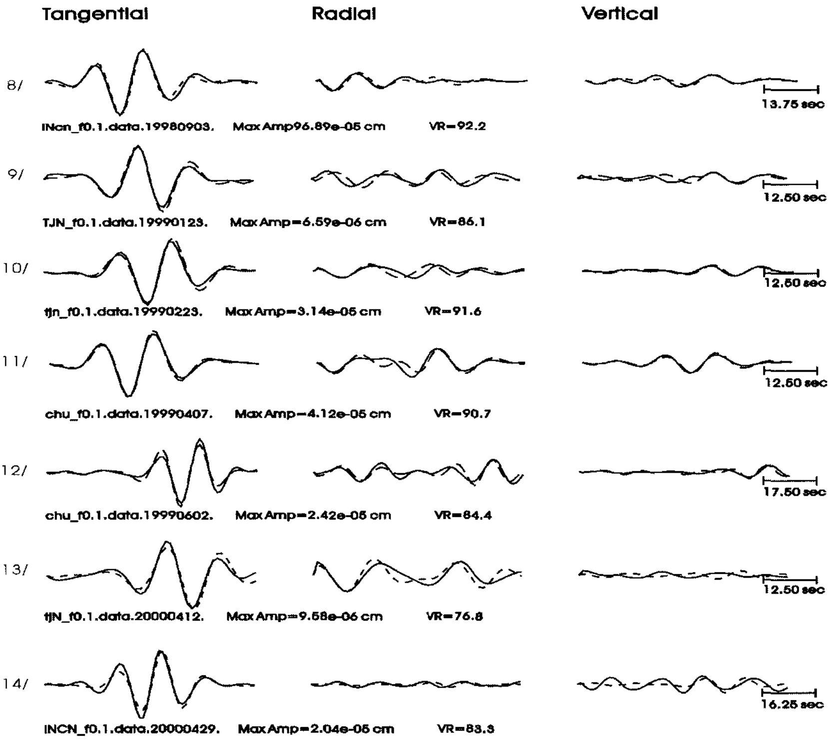

Fig 5b. Comparison of data and theoretical seismograms for 14 earthquakes in the Korean Peninsula. Solid lines correspond to observed seismograms and dashed lines to synthetics;(from the event 8 to event 14).

line) and theoretical (dotted line) seismograms for this event is shown in Fig 5a.

The April 12, 2000, M3.5, Kyokryolbiyol-do Earthquake: occurred at 19:44:01.4 (UTC) with latitude 36.9°N, longitude 125.3°E (according to KMA) at epicenter distance 194 km from very broadband Inchon station, azimuth to epicenter is 107°. Fig 5b shows the comparison of observed (solid line) and theoretical (dotted line) seismograms for this event. The inversion result for this event is presented in Figure 1 and Table 7. It shows that the solution is a right-lateral strike slip reverse fault in a plane dipping at 87° and striking at 228°. The choice of the active fault plane was based on the regional tectonic evidence.

The February 23, 1999, M3.5, Tokchok-do Earthquake: occurred, at 17:14:32.200 (UTC) with latitude 37.3°N, longitude 126.0°E, according to KMA at epicenter distance 159 km from very broadband Taejon station, azimuth to epicenter is 130° (Fig 1). The variance reduction has a maximum - 91.6% for depth of 12 km. The comparison of observed (solid line) and theoretical (dotted line) seismograms for this event is shown in Fig 5b.

The final result of moment tensor inversion of this event is presented in Fig 1 and Table 7. The focal mechanism solution is a left-lateral pure strike slip reverse fault in a plane dipping at 80° and striking at 26°(NE). The choice of fault plane from two nodal planes is conditioned by geology and tectonics information of this region.

The April 29, 2000, M3.3, West of Kunsan

Earthquake: occurred at 22:53:26.800 (UTC) with latitude 35.8°N, longitude 125.7°E, according to KMA at epicenter distance 205 km from very broadband Inchon station, azimuth to epicenter is 24° (Fig 1). The variance reduction has a maximum - 84% for depth of 6 km. The comparison of observed (solid line) and theoretical (dotted line) seismograms for this event is shown in Figure 5b.

The final result of moment tensor inversion of this event is presented in Fig 1 and Table 7. The focal mechanism solution is the right-lateral strike-slip reverse fault in a plane dipping at 8 5° and striking at 32°(NE). The choice of fault plane from two nodal planes is conditioned by geology and tectonics information of this region.

4.2. Focal mechanism solutions of Earthquakes in the group 2

The November 16, 1996, M3.6, Wonsan Earthquake: occurred at 23:49:15.100 (UTC). According to information from KMA epicenter is determined as with latitude 39.0°N, longitude 127.6°E at epicenter distance 188 km from very broadband Inchon station, azimuth to epicenter is 207°(Fig 1).

The analysis of dependence of variance reduction on depths shows that the optimal depth for model LI is 11km. Fig 5a shows the comparison of observed (solid line) and theoretical (dotted line) seismograms for this event. The inversion result for this event was presented in Fig 1 and Table 7. It shows a left-lateral strike-slip normal fault with a dip of 77° and a strike of 234°. The choice of this active fault plane was based on the regional tectonic evidence.

The April 15, 1998, M3.5, Namcheon Earthquake: occurred at 18:58:10.100 (UTC) with latitude 38.4°N, longitude 126.3°E (according to KMA) at epicenter distance 106 km from very broadband Incho station, azimuth to epicenter is 164°(Fig 1).

Green's function calculations for different models show that the model LI is the best crustal model (Fig 2, Table 5). The variance reduction has a maximum value (87.7%) at a depth of 8 km. The final result of the moment tensor inversion is presented in Fig 1 and Table 7. The comparison of observed (solid line) and theoretical (dotted line) seismograms for this event is shown in Fig 5a.

The focal mechanism solution is a pure strike-slip along right-lateral fault plane with a dip of 79° and azimuth of 13°(NE). The choice of fault plane from two nodal planes is conditioned by geology and tectonics information of this region.

4.3. Focal mechanism solutions of Earthquakes in the group 3

The October 15, 1996, M3.3, Waegwan Earthquake: occurred at 20:45:32.300 (UTC) with latitude 36.1°N, longitude 128.3°E, according to KMA at epicenter distance 214 km from very broadband Taejon station, azimuth to epicenter is 316°(Fig 1). The variance reduction has a maximum value (84.4%) at a depth of 10 km. The comparison of observed (solid line) and theoretical (dotted line) seismograms is shown in Fig 5a.

The final result of moment tensor inversion is presented in Fig 1 and Table 7. The focal mechanism solution is a strike slip along left-lateral fault plane with a dip of 89(to the SE and azimuth of 31°(NE). The choice of active fault plane from two nodal planes was based on the regional geology and tectonics evidence.

The January 23, 1999, M3.3, Uljin Earthquake: occurred at 16:01:52.100 (UTC) with latitude 37.0°N, longitude 128.8°E, according to KMA at epicenter distance 146 km from very broadband KIGAM station TJN, azimuth to epicenter is 242° (Fig 1). The variance reduction has a maximum value (86.1%) at a depth of 11 km. The comparison of observed (solid line) and theoretical (dotted line) seismograms is shown in Figure 5b.

The final result of moment tensor inversion of this event is presented in Fig 1 and Table 7. The focal mechanism solution is a pure strike slip along left-lateral fault plane with a dip of 79° to the SE and azimuth of 40((NE). The choice of active fault plane from two nodal was based on the regional geology and tectonics evidence.

The April 7, 1999, M3.3, Taebaek-san Earthquake: occurred at 14:43:19.100 (UTC) with latitude 37.2°N, longitude 128.9(E, according to KMA at epicenter distance 129 km from very broadband Chuncheon station, azimuth to epicenter is 307° (Fig 1). The variance reduction has a maximum value 90.7% at a depth of 6 km. The comparison of observed (solid line) and theoretical (dotted line) seismograms for this event is shown in Fig 5b.

The final result of moment tensor inversion of this event is presented in Fig 1 and Table 7. The focal mechanism solution is a left-lateral oblique-slip fault in a plane dipping SE at 58° and striking at 8°(NE). The choice of fault plane from two nodal is conditioned by geology and tectonics information of this region.

4.4. Focal mechanism solutions of Earthquakes in the group 4

The June 25, 1997, M4.7, Kyongju Earthquake: occurred at 18:50:21.100 (UTC) with latitude 35.8°N, longitude 129.2(E, according to IRIS at epicenter distance 294 km from very broadband Inchon station, azimuth to epicenter is 308°(Fig 1). Inversions with various source depths gave a maximum value 92.0% of coincidence between observed and synthetic seismograms at the depth of 7 km. The comparison of observed (solid line) and theoretical (dotted line) seismograms of this event is shown in Fig 5a. The final result of moment tensor inversion is presented in Fig 1 and Table 7. The focal mechanism solution is a left-lateral oblique-slip reverse fault in plane dipping SW at 52° and striking at 135°SE, which is consistent with the signs of first arrivals recorded at 14 stations of the Korea, Japanese local network (according to data of the Korea Seismological Institute, South Korea) and data of Kim and Kraeva (1998). The choice of active fault plane was based on the regional tectonics evidence.

The June 02, 1999, M3.4, Pohang Earthquake: occurred at 09:12:23.300 (UTC) with latitude 35.9°N, longitude 129.3(E, according to KMA at epicenter distance 261 km from very broadband Chuncheon station, azimuth to epicenter is 328°(Fig 1). The variance reduction has a maximum value 84.8% at the depth of 10 km. The comparison of observed (solid line) and theoretical (dotted line) seismograms of this event is shown in Fig 5b.

The final result of moment tensor inversion is presented in Fig 1 and Table 7. The focal mechanism solution is a left-lateral strike-slip reverse faulting with a dip of 84° and strike of 118°(SE). The choice of fault plane from two nodal planes is conditioned by geology and tectonics information of this region.

4.5. Focal mechanism solution of Earthquake in the group 5

The December 13, 1996, M4.8, Youngwol Earthquake: occurred at 04:10:16.500 (UTC) with latitude 37.1°N, longitude 128.7°E, according to IRIS at epicenter distance 193 km from very broadband Inchon station, azimuth to epicenter is 282°(Fig 1). Inversions with various source depths gave a maximum value 90.0% of coincidence between observed and synthetic seismograms at the depth of 9 km. The comparison of observed (solid line) and theoretical (dotted line) seismograms for this event is shown in Fig 5a. The final result of moment tensor inversion of this event is presented in Table 7 and Fig 1.

The focal mechanism solution is a pure right-lateral fault in plane dipping SE at 86° and striking at 43°NE. This result is confirmed by data from Baag et al. (1997) on the focal mechanism derived from the signs of P wave first arrivals recorded by 29 short-period KIGAM, KSRS (Korea Seismic Research System) and stations in Japan and it is mainly in agreement with data of Kim et al. (1999, 2000) except the maximum value of the variance reduction in this study is higher at the depth of 9km. The choice of active fault plane from two nodal planes was based on the regional tectonics evidence.

5. Discussion and conclusions

We may describe the focal mechanism solutions here in terms of the regional tectonics. At the Kyonggi Massif, the strike of the faults is mainly in the direction of NE-SW with a movement of right-lateral or left-lateral strike-slip. The fault in SW Nampo is an exception, which had a strike in the direction of NW-SE; the compressional axis of the stress field at the Kyonggi Massif is dominantly ENE-WSW. At the Yongnam Massif, the strike of the faults is nearly in the direction of NE-SW with the movement of left-lateral strike-slip; the compressional axis of the stress field is dominantly N-S. At the Yonil Basin, the strike of the faults is nearly in the direction of NW-SE with the movement of a left -lateral strike-slip or strike-slip with reverse component; the compressional axis of the stress field is dominantly ENE-WSW. At the Pyongnam Basin, the strike of the faults is in the direction of NE-SW with the movement of left-lateral or right-lateral strike-slip in a plane dipping less than 80(; the compressional axis of the stress field is dominantly N-S or NE-SW. At the Okchon Neogeosynclinal zone, the strike of the faults in the direction of ENE-WSW with the movement of right-lateral strike-slip; the compressional axis of the stress field is dominantly ENE-WSW.

The focal mechanism solutions obtained from this research are in good agreement with the previous geological and geophysical information from other works. Further, they also confirmed the previous information.

Through the focal mechanism solutions obtained by using Moment Tensor Inversion (Dreger and Langston, 1995) for 5 groups of earthquakes including the 14 studied events occurred on the Korean Peninsula, this method once again demonstrated the applicability of it that uses body and surface waveforms recorded at one broadband stations to reconstruct the parameters of a slip-type source.

In this work we tried to use data requested from the global seismographic network IRIS and local network KMA and KIGAM. Most of them (9/14) had a magnitude not larger than 3.5. For events with magnitudes less than 4.0, the bandpass filter frequencies are 0.05-0.1 hz.

The important limitation of the given method is the plain-layered approach of the crust structure. The focal mechanism solution for the October 15, 1996, M3.3, Waegwan Earthquake is found to be a left-lateral strike slip fault with a NE strike; The November 10, 1996, M3.5, Kyokryolbiyol-do Earthquake is found to be a pure right-lateral strike slip reverse fault with a strike to the NE; The November 16, 1996, M3.6, Wonsan Earthquake is found to be a normal fault with left-lateral slip in NE direction; The December 13, 1996, M4.8, Youngwol Earthquake is found to be a pure right-lateral strike-slip in NE direction; The June 25, 1997, M4.7, Kyoungju Earthquake is found to be a left-lateral oblique-slip reverse fault with a strike to the SE; The April 15, 1998, M3.5, Namcheon Earthquake is found to be a right-lateral pure strike-slip fault with a NE strike; The June 7, 1998, M3.7, SW of Nampo Earthquake is found to be a left-lateral strike slip normal fault with a strike to the SE; The September 3, 1998, M3.8, Kyokryolbiyol-do

Earthquake is found to be a right-lateral strike-slip reverse fault with a strike to the NNE; The January 23, 1999, M3.3, Uljin Earthquake is found to be a left-lateral pure strike slip in NE direction. The February 23, 1999, M3.5, Tokchok-do Earthquake is found to be a left-lateral strike slip reverse fault in NE direction. The April 7, 1999, M3.3, Taebeak San Earthquake is found to be a left-lateral pure strike slip fault with a strike to the NNE; The June 02, 1999, M3.4, Pohang earthquake is found to be a thrust fault with left-lateral strike slip in SE direction; The April 12, 2000, M3.5, Kyokryolbiyol-do Earthquake is found to be a right-lateral pure strike-slip with minor reverse component in NE direction; The April 29, 2000, M3.3, West of Kunsan Earthquake is found to be a right-lateral oblique-slip reverse fault in NE direction.

Most of the focal mechanisms for the Korean earthquakes seem to be strike-slip motions, which are consistent with those of SW Japan and Bo Hai, China area earthquakes.

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