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Crustal Structure of the Korean Peninsula By Travel Time Inversion of Local Earthquakes

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ABSTRACT

Simultaneous inversion of first-arrivals of local earthquakes recorded by the Korea Meteorological Administration(KMA) seismograph network from 1991 to 1998 is made to derive 1D crustal velocity structure of the Korean peninsula. Twenty-nine events with 178 observations are used in the inversion. Average crustal P-wave velocity turns out to be about 6.3 km/sec, and crustal thickness and upper mantle P-wave velocity are estimated as 33 km and 7.9 km/sec, respectively. Results of inversion indicate the possibility of the low velocity layer in the lower crust. Joint inversion is applied to estimate hypocenters, station delays, and velocities simultaneously. Relative station corrections for 11 stations range from zero to about 1.2 sec. Analysis of the synthetic data shows that estimates of hypocenter locations and station corrections as well as averaged crustal structure are reliable for the given data set.

Key words: Korean peninsula, Crustal structure, Simultaneous inversion, Station correction, Low velocity layer

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요약: 한반도의 일차원 지각구조모델 결정을 위하여 1991년부터 1998년까지 한국 기상청 지진관측망에 기록된 국지지진의 P-파의 도달시각자료에 대해 동시역산방법을 적용하였다. 역산에는 29 개 지진의 178 개 관측자료가 이용되었다. 한반도의 지각과 상부맨틀의 평균속도는 각각 6.3 km/sec, 7.9 km/sec 이며, 평균 지각 두께는 약 33 km로 나타났다. 또한, 하부지각에 저속도층의 가능성을 보여주었다. 동시역산 방법은 진원요소, 관측소 보정치, 속도구조를 동시에 결정하기 위해 적용된다. 11 개 관측소에 대한 관측소 보정치는 0 ~ 1.2 sec 정도의 차이를 보인다. Synthetic data의 분석은 평균 지각 속도구조 뿐만 아니라, 진앙의 위치, 관측소 보정치가 신뢰할 만하다는 것을 보여준다.

주요어: 한반도, 지각 구조, 동시 역산, 관측소 보정, 저속도층

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1. Introduction

The Korean peninsula is located in the eastern part of the Eurasian plate and its seismicity shows the typical characteristics of the intraplate seismic activity, irregular strain release both in space and time(Lee, 1987). About 20 ~ 30 earthquakes of magnitude 2.0 ~ 4.0 have been annually observed by the KMA(Korea Meteorological Administration) seismograph network in the vicinity of the Korean peninsula since the KMA network was significantly augmented in 1991. Figure 1 shows the locations of the earthquakes observed by the KMA seismic network from 1991 to 1998 and the spatial distribution of the 13 stations operated during the period. Only 29 earthquakes in Figure 1 were used in this study and they are not distinguished from other events in Figure 1.

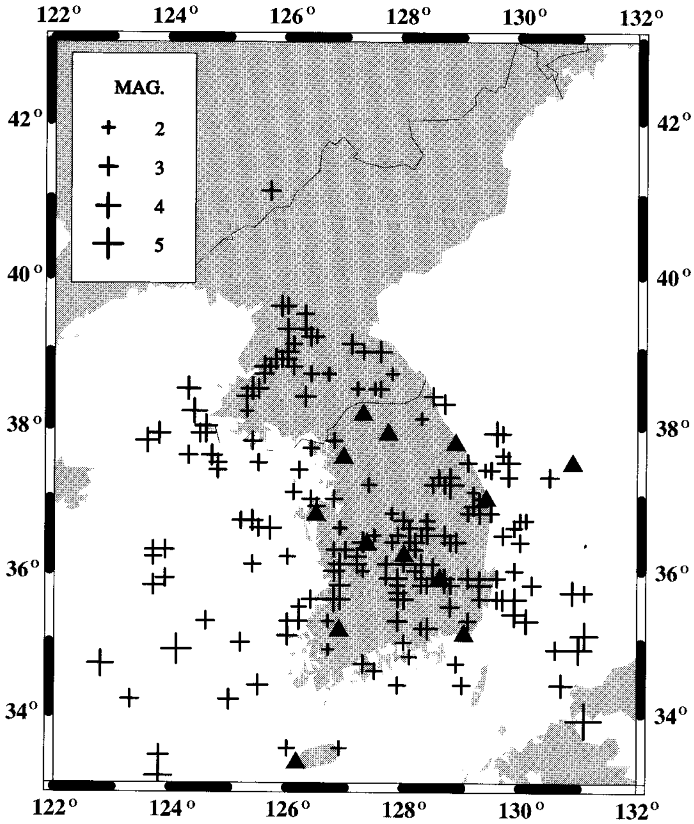

Fig. 1. Epicenters of earthquakes observed by the KMA seismograph network in vicinity of the Korean peninsula from 1991 to 1998. Local magnitudes of earthquakes mostly range from 2.0 to 4.0. Crosses and triangles indicate epicenters and stations, respectively.

It is important to obtain accurate velocity information on the crust and upper mantle of the earth for a variety of studies, such as seismicity, composition of the crust, and crustal generation and evolution(Crosson, 1976a). In particular, accurate determination of earthquake location is imperative in understanding seismicity of the Korean peninsula showing a very irregular pattern. Since Lee(1979) first investigated the crustal structure of the Korean peninsula, a few studies on the same problem have been made using seismic and gravity data(Kim and Kim, 1983; Kim and Jung, 1985; Kim, 1995; Kwon and Yang, 1985; Choi and Shin, 1996). Based on the travel time data of the Ssanggyesa earthquake of July 4, 1936, occurred in the southern part of the peninsula, Lee(1979) made the following observations on the crustal structure of the peninsula: 1). A well refined Moho-discontinuity of Pn- velocity of about 7.7 km/sec exists, 2). The crustal thickness is about 35 km, 3) Upper crustal P- and S-velocities are about 5.8 km/sec and 3.5 km/sec, respectively. 4). It is not clear if the crust is single layered or multi-layered. Subsequent studies have failed to reveal any concrete evidence on the layering of the crust of the Korean peninsula because of the paucity of reliable seismic data. For instance, Kim and Kim(1983) proposed a two-layered crustal model of the peninsula without providing seismic phases resulting from the velocity discontinuity between upper crust and lower one. The three-layered model of Kim(1995) which has a thin top layer of low velocity in addition to upper crust and lower one also have not provided seismic phases indicating discontinuities in the crust. Three crustal models of the Korean peninsula proposed by Lee(1979), Kim and Kim(1983) and Kim(1995) are shown in Figure 2.

In this study, joint inversions of first arrival times of KMA local earthquakes from 1991 to 1998 are made to determine the crustal structure of the Korean peninsula as well as earthquake locations and station corrections simultaneously.

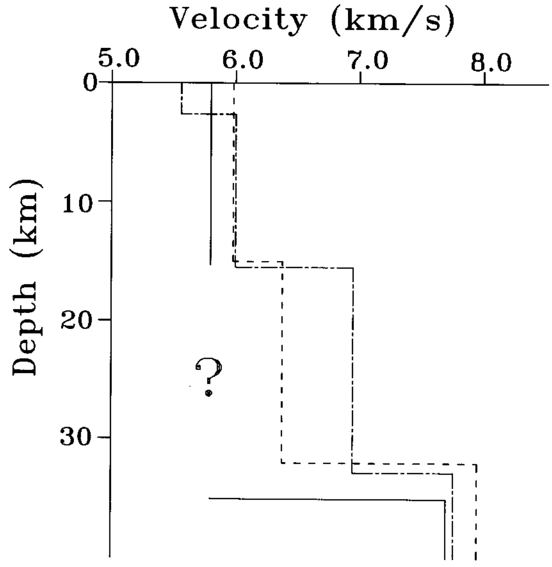

Fig. 2. Previous studies of the P-wave velocity structure of the Korean peninsula(Solid line - Lee, 1979; dashed line - Kim and Kim, 1983; dashed-dot line - Kim, 1995).

2. Data

We used first arrival times from local earthquakes recorded at 11 short-period, vertical-component stations operated by KMA during the period from 1991 to 1998. S-phase information provides strong constraint on the determination of hypocentral parameters, especially the origin time and focal depth (Gomberg *et al.*, 1990). However, only P-wave arrival times were used in this study since it is difficult to read S-wave arrival times accurately on vertical component records. Approximately 200 earthquakes were observed in the vicinity of the Korean peninsula during the period with the magnitude 2.0 to 5.0. We selected 33 events from them based on the criteria that events are located within the array and recorded at 5 or more stations. Among 33 events originally selected, 29 events having small residuals were chosen for the inversion. The observations for these 29 events amount to 178. Table 1 lists the final data set along with the hypocenter solutions obtained by the final model of this study. Examples of waveform data used in this study are shown in Figure 3. Analog waveform records were scanned and first P-arrivals were read on the scanned seismic traces.

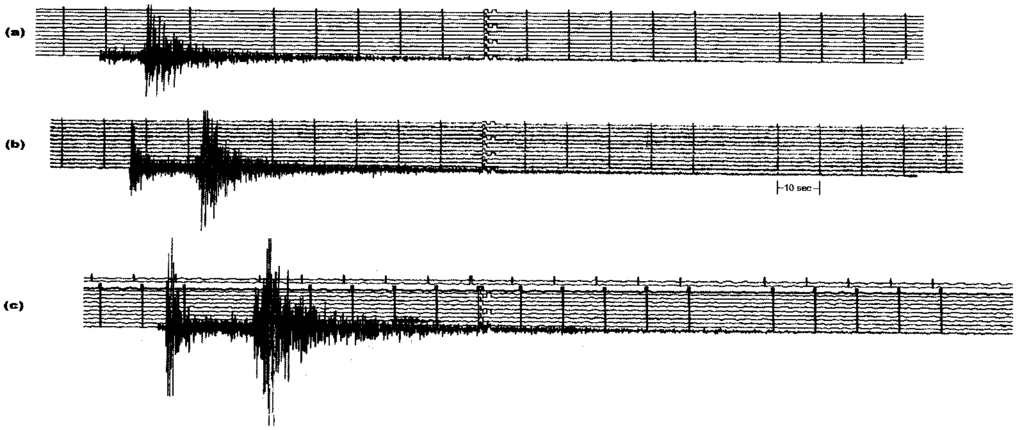

Fig. 3. Vertical-component analog waveforms of the 12 February 1994 earthquake recorded at the station SOS(a), SEO(b), CHL(c), respectively, of the KMA seismograph network(see Table 1). The local magnitude of the earthquake is 3.5 and epicentral distances are 85, 136, and 197 km, respectively, from top to bottom. Vertical scale is not normalized.

Table 1. Earthquake Data Used in the Inversion.

No.	Date (Y/M/D)	Time (H:M:S)	Lat. (deg.)	Lon. (deg.)	Depth (km)	Mag.	Gap (deg.)	RMS (sec)	Station P Arrivals*										
									CHL	CHP	CHU	KAN	KWA	PUS	SEO	SOS	TAG	TEJ	ULC
1	91/03/28	03:31:32.7	37.06	126.54	16.4	2.7	223	0.01			57.0		66.4		45.5		68.0	51.0	72.0
2	91/04/14	01:48:48.0	36.38	128.64	4.5	3.1	120	0.12			78.1	73.2		71.4	79.8		57.2	65.8	63.9
3	91/05/13	01:25:57.3	35.84	128.40	0.6	2.2	98	0.14					82.2	73.2			60.2	74.0	82.4
4	91/07/23	23:08:49.1	35.78	128.02	4.8	3.1	108	0.19			85.0		69.5	68.0	83.5		58.4	62.9	79.3
5	93/04/09	02:28:40.1	36.61	126.88	15.5	2.2	120	0.02			66.7		66.6		58.3	48.5		49.2	
6	93/07/08	11:11:06.7	35.07	128.22	13.6	3.6	295	0.12	61.9		57.4					49.4	27.7	37.5	47.8
7	93/08/26	00:07:15.8	35.78	127.88	0.2	2.9	109	0.11			53.0		34.7	37.2		43.6	27.0		47.1
8	94/02/12	11:58:13.9	36.37	127.31	12.5	3.5	105	0.24	43.8		41.8	45.5	36.6	46.9	36.2	28.7	35.0		44.7
9	94/02/26	04:52:46.5	35.58	127.93	0.2	2.5	128	0.24					64.5	64.9			58.4	62.5	79.7
10	94/03/25	06:03:24.9	36.29	128.17	6.5	2.3	82	0.06			54.3		52.7	49.6	53.9	51.5	35.0	36.3	47.1
11	94/09/21	03:35:47.6	36.46	128.84	15.8	3.2	158	0.01	82.4			71.3	82.2				59.0		61.0
12	96/03/02	21:42:04.5	36.41	127.75	16.1	2.2	94	0.03					30.0		28.3		20.5	10.4	30.5
13	96/03/20	04:54:13.2	36.62	128.19	18.6	2.5	96	0.10				36.1			37.1		27.9	25.7	32.1
14	96/04/14	05:22:11.8	35.87	127.88	8.8	3.1	102	0.06			46.0		31.1	33.5	44.0	38.3	22.6	23.1	
15	96/04/19	02:39:50.9	36.23	127.01	8.2	2.8	138	0.08			82.1		70.6		75.0	64.3	75.1	57.0	
16	96/06/21	01:04:07.7	36.03	126.88	5.5	2.8	159	0.14					23.8		35.6	22.9	33.1	16.9	
17	96/08/14	18:10:03.4	36.63	127.99	1.6	3.0	78	0.05				27.4	34.1	34.6	25.8			13.2	25.1
18	96/12/13	13:10:16.1	37.27	128.75	20.7	4.5	104	0.04			35.6	26.5	58.0	52.3		48.8			28.5
19	96/12/13	13:27:06.5	37.29	128.76	12.4	3.0	112	0.11			25.5	16.1			33.0			32.5	18.2
20	96/12/14	15:17:51.5	37.27	128.74	10.7	2.7	103	0.06				61.9			78.7		76.5	77.6	63.8
21	96/12/15	16:20:39.6	37.28	128.75	11.8	2.5	105	0.03				49.4			66.4		65.3	65.4	51.5
22	97/05/10	00:56:44.5	37.28	128.76	9.9	2.5	106	0.04		65.9	63.0	53.6						69.8	55.6
23	97/05/22	07:52:36.0	36.05	127.11	20.1	3.5	134	0.03	70.7		68.0		53.3		62.8	53.3		43.8	71.0
24	97/06/26	03:50:21.9	35.82	129.30	20.2	4.2	193	0.13	66.5	42.0	60.7	54.4	56.0	35.8				50.0	43.3
25	97/06/30	23:48:44.8	36.03	127.86	5.3	2.8	89	0.02		48.7	77.5		66.0	68.7				54.0	73.1
26	97/08/05	04:47:32.5	37.28	128.75	0.9	2.3	106	0.08	58.5	54.5	51.0	41.5		70.9	58.8	66.3		57.8	43.7
27	97/10/18	19:35:31.2	37.27	128.75	2.6	3.0	104	0.06		52.8		40.5			57.0	65.1		56.3	43.4
28	98/09/13	00:42:12.8	36.15	126.99	16.7	3.6	142	0.06	46.3		44.0		31.2		38.1	27.2	36.9	20.0	48.0
29	98/09/30	22:29:02.0	35.76	126.76	0.2	3.3	179	0.11					13.8		35.0	21.7	28.5	16.4	

*Hours and minutes of the arrivals are the same as those of the origin times

Each reading was assigned a reading quality of A, B and C with A denoting a very sharp impulsive arrival, C an emergent one, and B intermediate. This reading quality was used as weighting factor in the inversion process.

3. Analysis

Arrival times from local earthquakes contain information on the velocity structure of the area as well as the hypocentral parameters(origin time, epicenter coordinates, and focal depth) of the events. Thus, hypocentral parameters for each event and crustal velocity structure can be estimated jointly by simultaneous inversion of local earthquake arrival time data(Crosson, 1976a). Furthermore, the accuracy of the locations, particularly the focal depths, can be improved to some extent as the velocity model improves. This simultaneous inversion has been applied to a large number of regions in order to obtain better earthquake locations and velocity structures of the laterally homogeneous earth (Crosson, 1976b; Steppe and Crosson, 1978; Crosson and Koyanagi, 1979; Hileman, 1979) as well as heterogeneous earth(Aki and Lee, 1976; Roecker, 1982; Thurber, 1983; Roecker *et al.*, 1987; Protti *et al.*, 1996; Kaufmann and Long, 1996; Ghose and Hamburger, 1998). However, such a simultaneous inversion is computationally inefficient because the size of the matrices involved is very large for a large number of earthquakes. Fortunately, this problem was overcome by techniques developed by Pavlis and Booker(1980) and Spencer and Gubbins(1980).

The program VELEST used in this study carries out the simultaneous inversion for 1-D layer model (Kissling *et al.*, 1994). Kissling *et al.*(1994) defined a minimum 1-D model as the least squares solution to the coupled hypocenter-velocity problem, which can be successfully used as initial reference model for 3-D seismic tomography.

3.1. Preliminary Inversions

The events were initially relocated using the single event location routine, HYPO71(Lee and Lahr, 1975) with the one-dimensional velocity model of Kim and Kim(1983) in order to obtain initial hypocenter solutions for the inversion process. Figure 4 shows the reduced travel time curve of 178 first arrivals used in the study with a reduction velocity of 6.3 km/sec. There is a clear discontinuity in the slope of travel time curve indicating the existence of the crust-upper mantle boundary(Moho-discontinuity). It is, however, difficult to resolve the details of the crustal structure from the curve. The crustal P phases are readily observed to be first arrivals from 20 to 150 km. The Pn-phase becomes first arrival from about 150 km and continues to the end of the profile. Average P-wave velocities of the crust and upper mantle roughly estimated from the travel time curve are 6.3 km/sec, 8.0 km/sec, respectively. The thickness of the crust is estimated as 35 km.

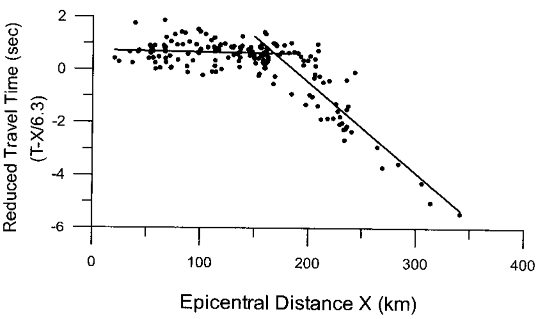

Fig. 4. Reduced travel-time curve of 178 first arrivals used in this study with a reduction velocity of 6.3 km/sec. Two lines correspond to velocities 6.3 km/sec and 8.0 km/sec, respectively.

Preliminary inversions were made using the selected 178 observations and the initial hypocenter locations obtained above with a large number of starting models having different velocities and thicknesses based on the previous studies and travel time curve of the area(see Fig. 4). Since VELEST does not automatically adjust layer thickness, the appropriate layering of the model is to be found by trial and error. Much attention has been paid to the effect of layering of the model throughout the whole inversion process. Preliminary inversions revealed several features. Final hypocenter locations and station corrections turn out to converge to almost the same solution, irrespective of various starting models used. However, the inverted velocity structures depend on initial velocities and thicknesses of the layers. Actually, the selected 29 events with a total of 178 observations are not sufficient enough to resolve the details of the crustal structure because many observations of simply overdetermined system do not provide independent unique information. So, a sequence of numerical tests on synthetic data was undertaken to study the effects of parameterization of the velocity model for the given data set before deriving a final velocity model.

3.2. Analysis of Synthetic Data

Synthetic arrival times to KMA stations were generated for various velocity models using the hypocenter locations of the selected 29 events. Only the arrival times for the stations that recorded the events were used in the analysis to make the synthetic data set as similar to the actual ones of this study as possible. Normally distributed reading errors were added to the calculated arrival times to allow for the errors in measuring the arrival times. The locations of the events arbitrarily shifted 5 km in average from their original locations were used as initial estimates in the inversion process. Therefore, the analysis of the synthetic data may check the validity of the results from analysis of the real data. Some interesting points observed from a large number of cases examined will be discussed below.

Figure 5 shows a test that illustrates the correlation of the upper mantle velocity with the Moho depth. The data were generated for a simple two-layer model

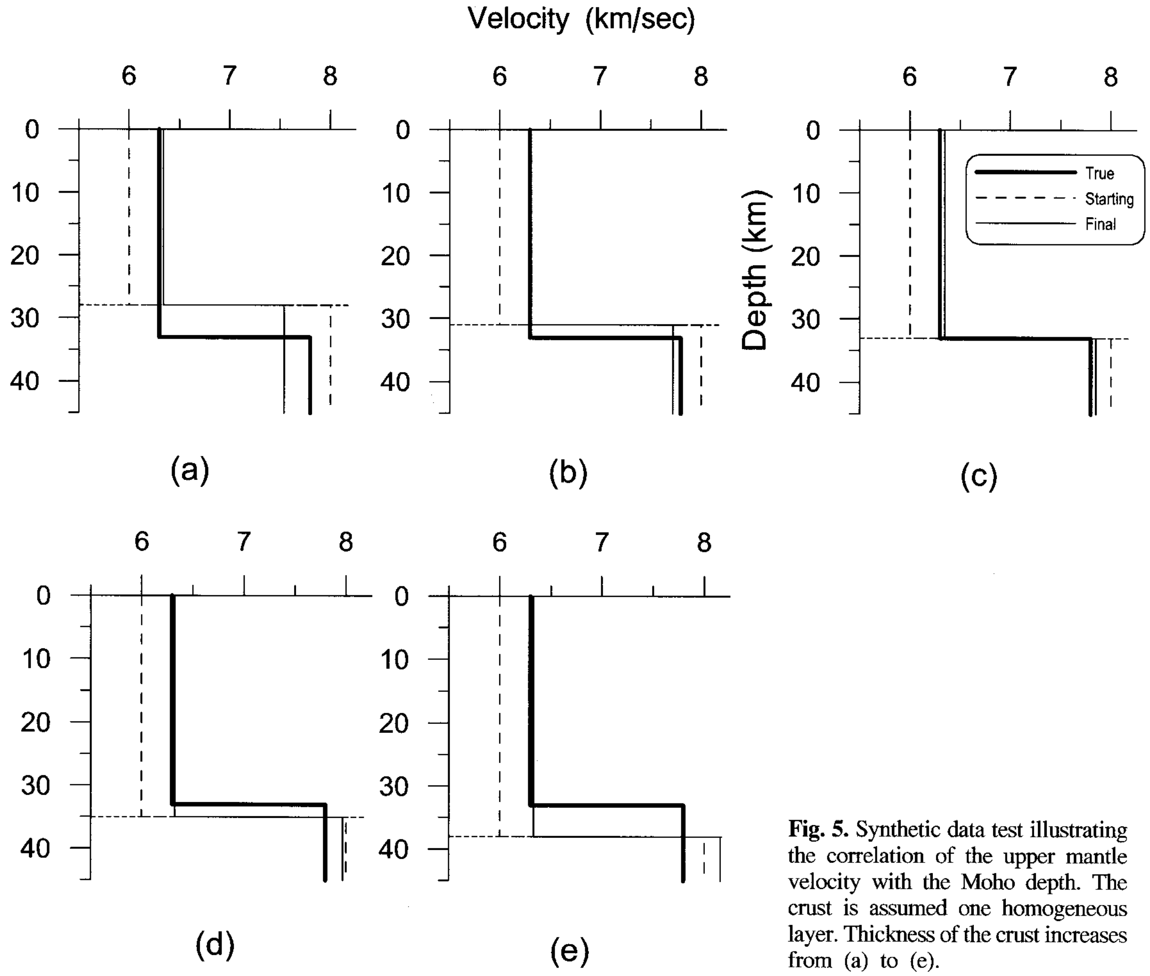

Fig. 5. Synthetic data test illustrating the correlation of the upper mantle velocity with the Moho depth. The crust is assumed one homogeneous layer. Thickness of the crust increases from (a) to (e).

and inverted with the starting models having the first layer of the same velocity but varying thickness. Inversion shows the velocity of the second layer increases as the thickness of the first layer increases while the velocity of the first layer remains almost constant without significant variation of RMS residuals. However, the velocity of the second layer is accurately estimated when the position of the layer boundary is correct(Figure 5(c)). It indicates that the correct layer velocities can be obtained in the two-layer model if the layer boundary is estimated accurately.

Figure 6 shows tests for a three-layer model in which two crustal layers overlie the mantle. The data were inverted with varying layer boundaries in the crust. The velocity of the upper mantle is relatively accurately estimated, but the crustal structure varies with positions of layer boundaries of the starting model. It turns out that the structure of the upper-layer depends more on the position of the layer boundary with its velocity generally overestimated. Crosson (1976b) noted that most ray paths of deep events pass almost vertically through the top subsurface layer and a strong correlation between origin times and top layer velocity is thus produced. Steppe and Crosson(1978) also pointed out a trade off between velocities in the top layer of the crust and the absolute level of the station delays. Thus, reliable a priori information is required to resolve the details of the structure of the upper crust.

Structure with monotonically increasing velocity with depth down to the Moho discontinuity is specified in Figure 7. For a single layer crust, the inversion yields about the average velocity of the crust. When the crust consists of two layers, the estimated velocities are larger than the average velocities of the corresponding layers. For the crust having the same layer boundaries with the true model, estimated velocities follow the general trend of the true model although a little bit overestimated in the upper part as shown in Figure 7(c).

Figure 8 illustrates cases for structures with a low velocity layer(LVZ). For the crust of two layers with correct layer boundary, LVL of rather accurate velocity is detected(Figure 8(a-1)). Although the position of the layer boundary is not correct, the low velocity layer is detected(Figure 8(a-2)). However, the LVZ is not detectable when the crust consists of three layers with the LVZ as the bottom layer(Figure 8(b)).

Accurate epicenter locations of the events were obtained from the inversion irrespective of a variety of starting models when compared to the true locations. Inclusion of station corrections in the tests

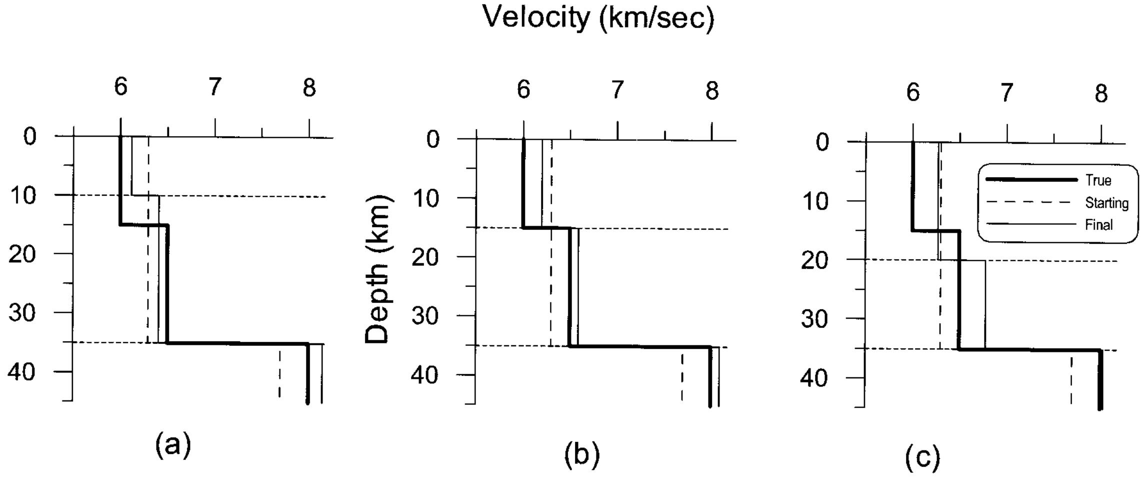

Fig. 6. Synthetic data test for a two-layer crust model. Dashed horizontal lines denote the layer boundaries of the starting model. Thickness of the upper crust increases from (a) to (c).

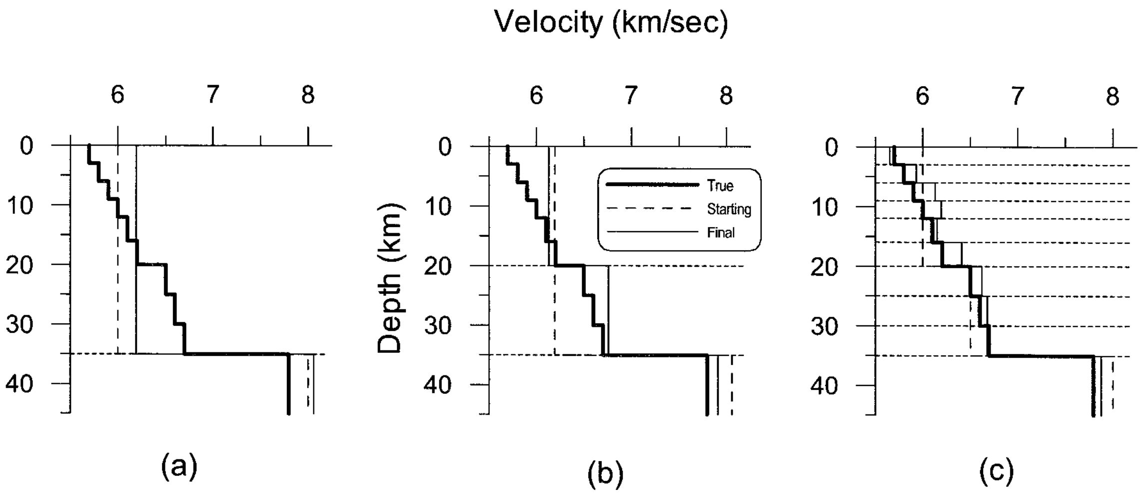

Fig. 7. Synthetic data test for the crust having velocity increasing monotonically with depth. Dashed horizontal lines denote the layer boundaries of the starting model((a) one-layer model; (b) two-layer model; (c) model with the same layer boundaries as the true model).

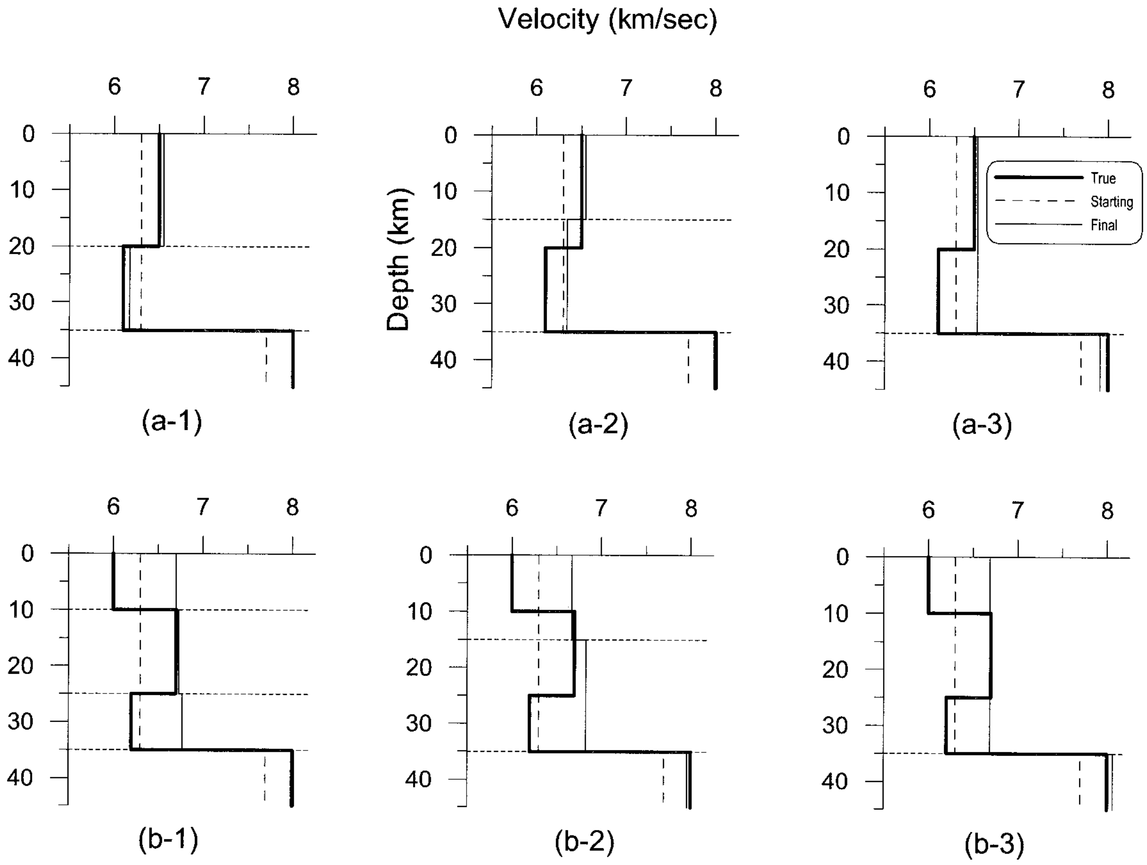

Fig. 8. Synthetic data test for the crust having a low-velocity layer in the lower crust((a)three-layer model, (b)four-layer model). Dashed horizontal lines denote the layer boundaries of the starting model.

yielded the same results. The results of synthetic data analysis in this study may be summarized as follows: 1) Average crustal and upper mantle velocities can be estimated accurately with the correct crustal thickness. 2) The details of the upper crust cannot be resolved without some reliable a priori information. 3) The LVL can be detected for the two-layer crust.

3.3. Velocity Inversion

As demonstrated in the preceding section, correct interface depths are very important in estimating an accurate velocity structure since the VELEST used in this study holds the depths of interfaces constant. In this regard, an accurate crustal thickness is required to estimate the accurate upper mantle velocity of the study area. Crustal thickness of the Korean peninsula has been reported to range from 29 to 35 km(Lee, 1979; Kim and Kim, 1983; Kim and Jung, 1985; Kim, 1995; Kwon and Yang, 1985; Choi and Shin, 1996). It is similar to that of eastern China(Li and Mooney, 1998), which is tectonically connected with the Korean peninsula, and this region is referred to as the Sino-Korean plaform collectively. This crustal thickness also compares well with the global average for extended continental crust (Christensen and Mooney, 1995).

Shedlock and Roecker(1985) successfully determined the depth to the Moho discontinuity based on some statistical parameters like RMS residual and data variance. We assumed one layer crust overlying a half space in order to simplify the situation because the number of the observations in this study is not considered sufficient enough for more detailed structure. Then, we moved the interface up and down by 1km step within the depth range from 29 to 35 km and checked the inversion results such as velocities of the two layers and the statistical parameters. The result turns out to be very similar to that of the numerical test in Figure 5. As the Moho depth varies, the velocity of the upper mantle varies while average crustal velocity remains constant. Interestingly, the RMS travel time residual and data variance converge simultaneously to the smallest values as the Moho depth approaches 33 km(Figure 9). Thus, the best estimate of the Moho depth in the Korean peninsula appears to be 33 km. With the crustal thickness of 33 km, average crustal and upper mantle velocity are estimated to be 6.3 and 7.9 km/sec, respectively.

It is difficult to explore more detailed crustal structure of the study area with the present data since marked velocity discontinuity is not observed except for the Moho discontinuity and analysis of only first arrivals cannot eliminate a masked layer problem. One solution to this problem is to select a large number of thin layers in an attempt to approximate an arbitrary continuous velocity distribution (Crosson, 1976a). However, the present data is not sufficient enough to work with a large number of unknowns. We tested several combinations of two and three layers over a half-space, adjusting the layer boundaries under the fixed crustal thickness of 33 km in order to investigate general trends of velocity variation with depth in the crust. Figure 10 shows examples of the inverted results when the crust is split into two layers. The velocity of the lower layer turns out to be slightly lower than that of the upper layer, irrespective of the location of the interface. The result indicates the existence of a low velocity layer(LVL). However, when the crust is divided into three or more layers for greater resolution, the results become unstable even though the LVL persists. The three-layer model including the mantle is considered

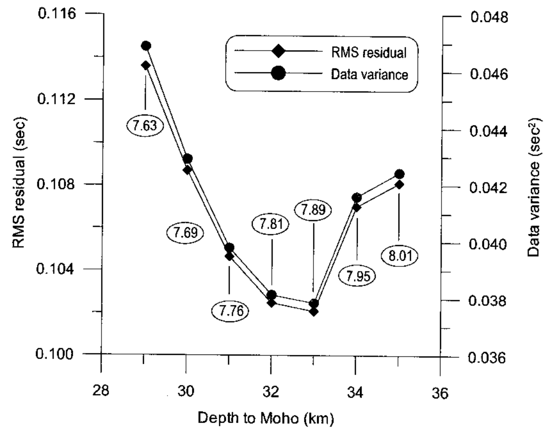

Fig. 9. RMS residual and data variance versus depth to Moho discontinuity. Number in the ellipse denotes the estimate of the upper mantle velocity.

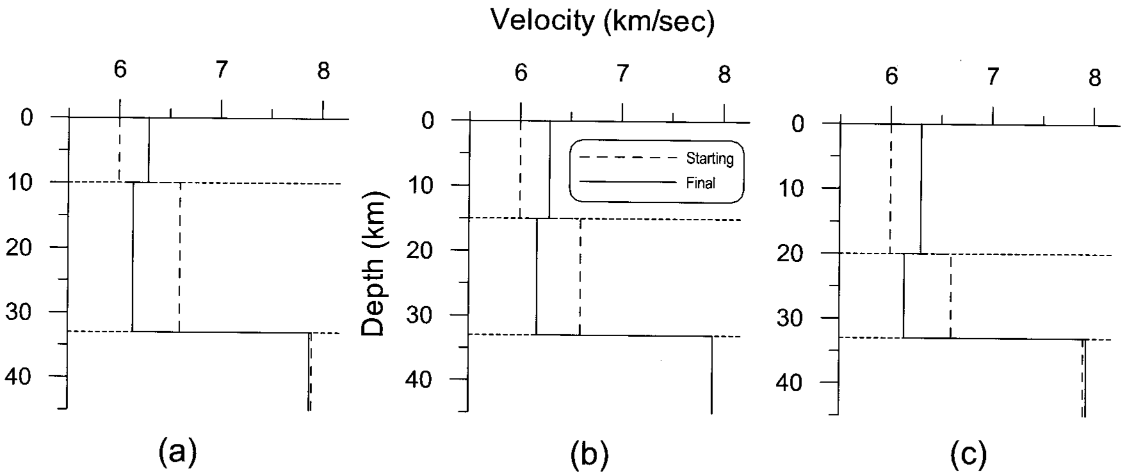

Fig. 10. Velocity inversions for two layer crusts. The depths to the interface are 10, 15, and 20 km for models (a), (b), and (c), respectively. Dashed horizontal lines denote the layer boundaries of the starting model.

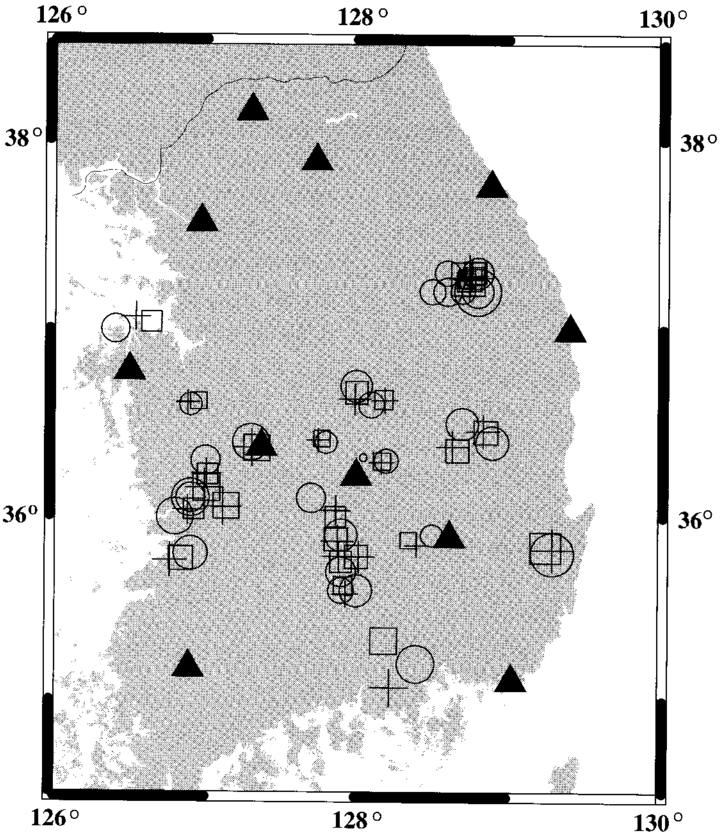

Fig. 11. Comparison of three different sets of epicenters of the 29 events used in this study. Circles, squares, and crosses denote epicenters obtained from the KMA list, the single event location routine(HYPO71), and the simultaneous inversion, respectively. Stations are indicated by solid triangles. The size of the symbol is proportional to the magnitude.

to be about the limit of stability for the present data set. We conclude that greater resolution for the crust with the exact nature of the LVL is difficult to obtain from the present data set. Thus, the homogeneous 33 km thick crust with average P-wave velocity of 6.3 km/sec overlying a mantle of Pn velocity 7.9 km/sec is chosen as the final model in this study.

Relocated epicenters by inversion are stable, irrespective of a variety of starting velocity models. Figure 11 shows three sets of locations obtained from the KMA list, the single event location program (HYPO71), and the simultaneous inversion process, respectively. Although the benefit of station corrections in the 3D velocity inversion is still questionable(Protti *et al.*, 1996), they provide a convenient method of introducing a pseudo lateral inhomogeneity in the 1D velocity inversion. This approximation to lateral inhomogeneity is obviously reasonable if the velocity anomalies are confined to restricted regions near the individual stations. Station corrections can be easily correlated with origin times unless an additional constraint is imposed because they are simply additive adjustments to all arrival times(Pujol, 1988). In VELEST, one of the station corrections is set to some fixed value, say zero, and all other station corrections are estimated relative to this fixed value. The reference station is selected based on its location and number of arrivals. Taejon(TEJ) station was chosen as the reference station because it is located near the center of the array with the most arrivals. Station corrections resulting from the simultaneous inversion turn out to hardly depend on the starting models; the same pattern of spatial variation persisted with little change in absolute values. The station corrections obtained through the inversion using the final velocity model are listed in Table 2. The range of the delays is about 1.2 sec.

4. Conclusion

First arrival time data from a short-period seismic network of the Korea Meteorological Administration were used to resolve the crustal velocity structure in the southern Korean peninsula. Average crustal P-wave velocity of the Korean peninsula turns out to be 6.3 km/sec and transition to an upper mantle velocity of 7.9 km/sec appears at about 33 km depth. Although we failed to obtain the detailed structure

Table 2. Station locations and station corrections for the KMA seismograph network used in this study.

Station	Lat. (deg.)	Lon. (deg.)	Elev. (m)	Sta. Corr. (sec)	No. of Obs.
CHE	33.2833	126.1667	73.2		
CHL	38.1500	127.3000	155.7	0.25	7
CHP	36.2167	128.0000	248.6	0.15	5
CHU	37.8904	127.7308	125.0	0.63	18
KAN	37.7523	128.8907	26.0	0.61	13
KWA	35.1731	126.8909	71.0	0.83	20
PUS	35.1048	129.0319	70.0	0.52	13
SEO	37.5667	126.9667	87.0	0.60	20
SOS	36.7770	126.4942	26.0	1.13	14
TAG	35.8849	128.6188	58.0	0.38	19
TEJ	36.3727	127.3708	68.0	0.00	25
ULC	36.9918	129.4133	49.0	0.61	24
ULL	37.4814	130.8989	221.0		

* Data of station CHE and ULL were not used in this study because of the lack of arrivals.

of the crust, the result of this study is more significant than those of the previous studies because more and better seismic data were used. The existence of the low velocity layer is suggested in the lower crust. More accurate hypocenter locations are obtained by the inversion method to estimate hypocenters, station delays, and velocities simultaneously. Relative station corrections for 11 stations range up to about 1.2 sec.

Seismic velocities usually increase with depth in the crust even though the possibility of the LVL in the crust has been reported(Crosson, 1976b; Crosson and Koyanagi, 1979). However, it is difficult to detect low velocity layers in the crust with insufficient local earthquake data. Maurer and Kradolfer(1996) excluded the possibility of the LVL throughout their inversion process to keep the inversion stable. Nevertheless, the LVL persists in all crustal models of this study which consist of two or more layers. A variety of possible layer configurations may be required in order to resolve characteristics of the LVL precisely. However, with the very limited present data, determination of detailed crustal structure with LVZ is impossible. This problem may be solved when more data are accumulated. Future studies on the LVL are expected to yield important information on the tectonics in the Korean peninsula.

Roecker(1982) noted that velocity estimate of a layer is principally controlled by the data from events in the layer. Thus, it is important to have reliable estimates of focal depths for reasonable evaluation on inversion results. The distance from the epicenter to the nearest station should be less than the focal depth to obtain reliable focal depths(Lee, 1979). Unfortunately, the average station spacing of the KMA network used in the study is approximately 100 km, relatively sparse seismic coverage, while focal depths of the events range from near surface to about 20 km. A denser seismic network is required to obtain detailed and realistic crustal structure of the Korean peninsula.

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