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# P-wave velocity structure of upper crust in the vicinity of the Yangsan Fault region

Woohan Kim *Department of Earth and Environmental Science, Gyeongsang National University, Jinju 660-701, Korea (e-mail:wookim@nongae.gsnu.ac.kr)*

**Abstract: This study presents the P-wave velocity structure of the upper crust in the vicinity of the Yangsan Fault region based on travel-time inversion of thirty-five digital secmic records obtained by the Korea Institute of Geology, Mining and Materials (KIGAM). The present model consists of 8 horizontal layers with constant velocity in the subsurface depth of 18 km. Two-point ray tracing is applied for travel-time inversion and determination of hypocenteral parameters of the earthquakes to reduce errors resulting from ray path. The computational results of travel-time inversion show that (1) a velocity gradient with depth is nearly constant in the subsurface depth of 8 km, (2) a low-velocity zone exists in the depth between 10 and 15 km, and (3) a relatively large velocity discontinuity appears at about 15 km.**

**Key words:** velocity structure, travel-time inversion, two-point ray tracing, hypocenteral parameters

## 1. INTRODUCTION

Although travel-time inversion using earthquake data in one dimensional layered media is one of the classical methods to determine velocity structure in earthquake and explosion seismology. It has not been well studied compared to the $\tau-p$ inversion method (Johnson and Gilbert, 1972; Bessonova et al., 1974; Kennet, 1976; Diebold and Stoffa, 1981). The $\tau-p$ inversion method requires a large number of data and may have problems to pick up secondary arrival phases reflected from multi-layers. It is actually difficult to apply two-point ray tracing to travel-time inversion. If two-point ray tracing does not apply to travel-time inversion in one dimensional layered media and the ray paths between the source and the receivers are assumed as straight lines, the seismic records for the same event are treated as one record because all ray paths are dependent on each other.

This study introduces the travel-time inversion in horizontally layered media using local earthquake data assuming that the velocity of each layer is constant. This method requires smaller set of data and gives high accuracy compared with the $\tau-p$ inversion method. This method also reduces ambiguity of picking the phases by using only the first arrival phases of transmitted waves for an earthquake. In this study, two-point ray tracing introduced by Kim and Baag (1998) is applied for both travel-time inversion and determination of hypocenteral parameters to reduce errors resulting from ray path. The hypocenteral parameters are longitude, latitude, depth, and origin time of an earthquake. The two-point ray tracing provides high accuracy and rapid convergency. The location error of station between the true and the calculated value by the two-point ray tracing is less than $10^{-5}$ km or $10^{-10}$ km in single precision or in double precision within 4 iterations. The travel-time inversion algorithm developed by Ham and Kim (1998) is used in this study.

The crust beneath the Korean peninsula has been considered as either one layer (Lee, 1979), two layers (Kim, 1983; Kim and Lee, 1996) or three layers (Kim and Jung, 1985; Kim, 1995). The velocity of each layer was estimated from the analysis of travel-time curves and/or surface wave dispersion data (Fig. 1). In this study, the velocity structure of the upper crust in the vicinity of the Yangsan Fault region is calculated by using travel-time inversion. The model has 8 layers, and provides more detailed velocity structure. Each layer is 2 or 3 km thick and the total depth of the model is considered to be 18 km. Thirty five records provided by the Korea Institute of Geology, Mining and Materials (KIGAM) digital seismic network are used in this study for 8 earthquakes. To limit the study area in the vicinity of the Yangsan Fault region and to increase the accuracy for the determination of hypocentral parameters, the data are selected to satisfy such conditions that the epicenter of the earthquake is present in the vicinity of the Yangsan Fault region and the earthquake is recorded at more than 4 stations. Figure 2 shows location map of the epcenters of 8 earthquakes and KIGAM Seismic Stations.

The Kim's velocity model (1995) is employed to calculate hypocentral parameters of 8 earthquakes as a starting model. The model (8 layers) estimates velocities by travel-time inversion using the data calculated by Kim's velocity structure (1995). The hypocenteral parameters are recalculated according to the velocity structure resulting from travel-time inversion. The iterations of travel-time inversion and the determination of hypocenteral

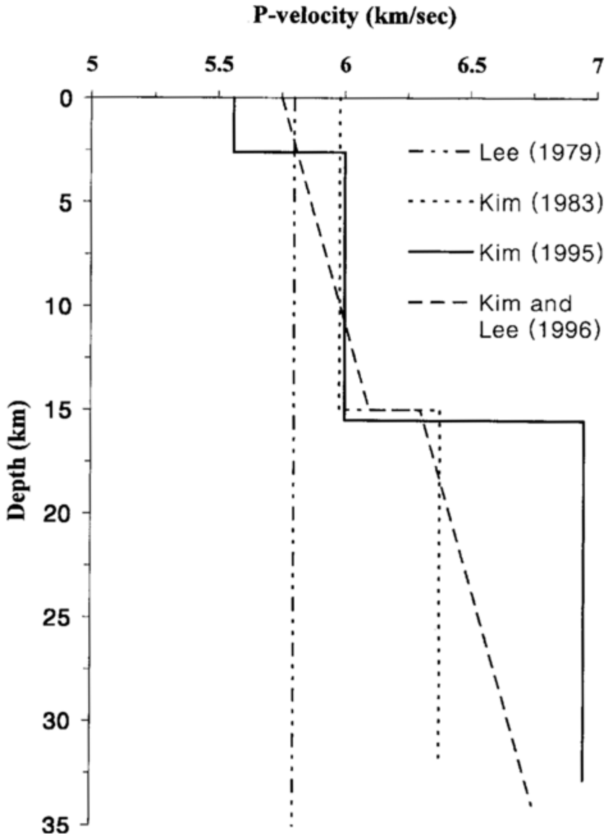


**Fig. 1.** P-wave velocity structure of the crust beneath the Korean peninsula estimated by the previous studies. Lee (1979) considered the whole crust as one layer. Kim (1983) and Kim and Lee (1996) divided the crust into two layers. Kim (1995) divided the crust into three layers.

parameters are continued until the variations of epicentral distance, depth, and origin time of each earthquake are less than 0.01 km, 0.05 km, and 0.002 second, respectively. This study uses only direct P-waves ($P_g$) which are recorded as the first arrival phase. However, the direct P-waves and S-waves ($S_g$) are used to determine the hypocenters and the origin times. The direct P-wave is recorded as the first arrival phase when the epicentral distance is less than 50 km, if the depth of an earthquake is between 10 and 17 km. The computational results of travel-time inversion show some characteristics in that the velocity gradient with depth is nearly constant, up to 8 km, and a low velocity zone exists between 10 and 15 km subsurface depth, and relatively large velocity discontinuity appears at about 15 km depth.

## 2. METHOD

The travel-time inversion for horizontal layered media is one of the basic tools for the determination of preliminary one-dimensional velocity structure using relatively small amount of data. This method can be made possible by applying two-point ray tracing. All ray paths between a source and receivers are dependent on each other for the same event if the ray paths are assumed as straight lines. This problem can be solved by applying two-point ray tracing. The two-point ray tracing for horizontally layered media was introduced by Kim and Baag (1998). They derived a two-point ray tracing equation by describing the horizontal distance between the source and the receiver with respect to the take-off angle at a source and by approximating the equation of the horizontal distance with respect to the initial value of the take-off angle by using Taylor's expansion up to second order. In this study, the two-point ray tracing is applied to travel-time inversion and determination of hypocenteral parameters of the earthquakes. The two-point ray tracing can be applied to the travel-time inversion method although the medium has low-velocity layers. The location error of the station between the true and the calculated value is less than $10^{-5}$ or $10^{-10}$ km in single precision or in double precision within 4 iterations.

In this study, the travel-time inversion algorithm developed by Ham and Kim (1998) is used. The travel time $T_i$ for the $i$-th ray can be described as follows by using Snell's law:

$$T_i = \sum_{j=1}^{n} \frac{h_j}{v_j \sqrt{1 - v_j^2 p_i^2}}, \tag{1}$$

where slowness for the $i$-th ray $p_i = \frac{\sin\delta_j}{v_j}$ is constant, and parameters $h_j$, $v_j$, and $\delta_j$ are thickness, velocity, and take-off angle at $j$-th layer, respectively. Equation 1 can be linearlized by using Taylor's expansion with respect to velocity difference $\Delta v$ between true velocity ($v_t$) and estimated velocity ($v_e$). The travel time $T_i$ will be approximated as a linear form by applying Taylor's expansion to Equation 1 up to the first order:

$$T_i = T_{ei} + \sum_{j=1}^{n} \left( \frac{\partial T_i}{\partial v_j} + \frac{\partial T_i}{\partial p_i} \frac{\partial p_i}{\partial v_j} \right) \Delta v_j, \tag{2}$$

where $T_{ei}$ is travel-time for $i$-th ray for the estimated velocity and $\Delta v_j = v_{tj} - v_{ej}$ is the velocity difference between the true velocity ($v_{tj}$) and the estimated velocity ($v_{ej}$) in $j$-th layer. The partial derivative terms in right hand side of Equation 2 can be obtained by using Equation 1 and the definition of slowness, $p_i = \frac{\sin\delta_j}{v_j}$:

$$\frac{\partial T_i}{\partial v_j} = \sum_{j=1}^{n} \frac{h_j (2v_j^2 p_i^2 - 1)}{v_j^2 (1 - v_j^2 p_i^2)^{3/2}}$$

$$\frac{\partial T_i}{\partial p_i} = \sum_{j=1}^{n} \frac{h_j v_j p_i}{(1 - v_j^2 p_i^2)^{3/2}}$$

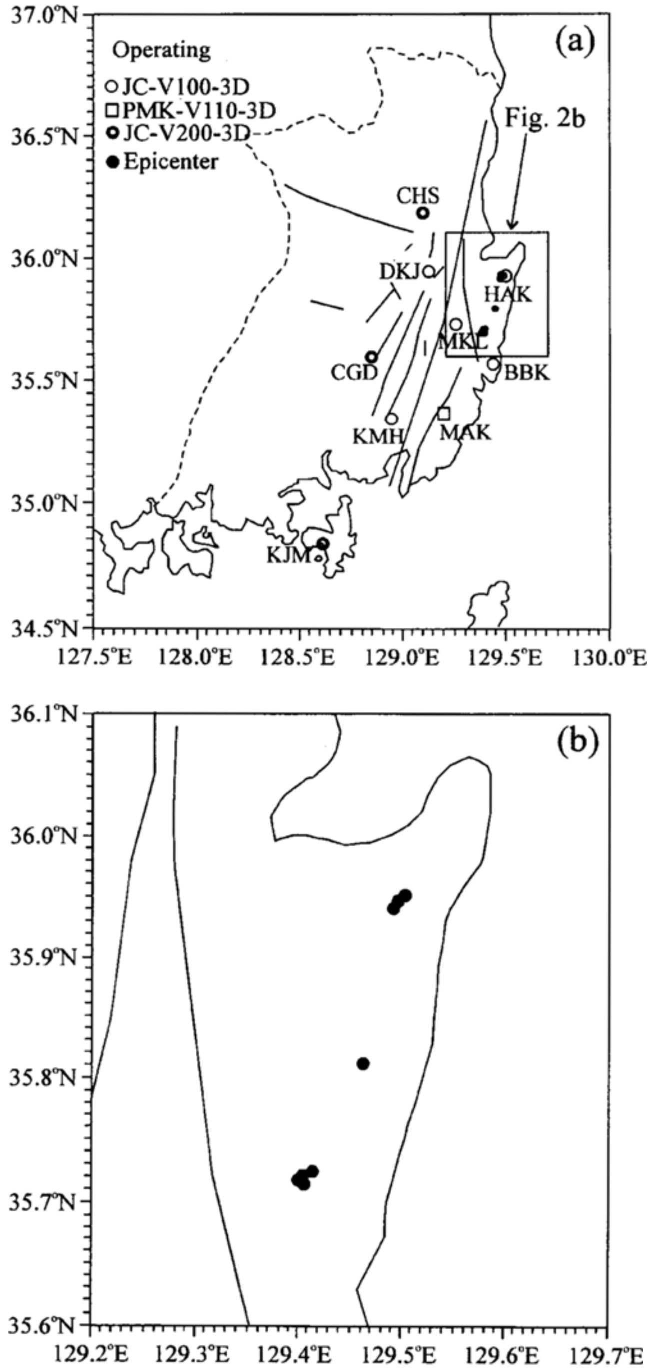


**Fig. 2.** (**a**) The location map of the epicenters for 8 earthquakes and KIGAM Seismic Stations around the Yangsan Fault. The symbol of circle or rectangle represents seismic stations and the solid circle represents the epicenters. The dotted line deontes the boundary of the Kyongsang Basin and the solid lines denote the faults around the study area. (**b**) The enlarged location map of the epicenters for 8 earthquakes.

$$\frac{\partial p_i}{\partial v_j} = -\sum_{j=1}^{n} \frac{p_i}{v_j} .$$

The effects of the second partial derivative terms in right hand side of Equation 2 are generally smaller than those of the first partial derivative, but it may play an important role for an increase in accuracy and convergence rate of the travel-time inversion (Ham and Kim, 1998). Equation 2 will be rewritten as a matrix form as follows:

$$\Delta T_i = T_i - T_{oi} \simeq \sum_{j=1}^{n} \left( \frac{\partial T_i}{\partial v_j} + \frac{\partial T_i}{\partial p_i} \frac{\partial p_i}{\partial v_j} \right) \Delta v_j = G_{ij} \Delta v_j^{est} \quad (3)$$

If subscript $i$ varies from 1 to $m$, where the number of data is $m$, $G$ will be $m \times n$ matrix. If $m$ is larger than $n$ (over determined case) and data have errors, the damped least square solution $\Delta v^{est}$ in Equation 3 is given by

$$\Delta v^{est} = (G^T G + \lambda I)^{-1} G^T \Delta T , \quad (4)$$

where $\lambda$ is a weighting factor (or Lagrangian multiplier), $G^T$ is a transpose matrix of $G$, and $I$ is an $n \times n$ identity matrix.

## 3. COMPUTATIONAL RESULTS AND DISCUSSION

The travel-time inversion is carried out to estimate velocity structure of the upper crust in the vicinity of the Yansang Fault region. Thirty-five records for 8 local earthquakes are used for this study provided by the KIGAM Seismic Network. The KIGAM Seismic Network has digital recording system with 0.01 second sampling interval. The data are selected to satisfy conditions in that the epicenter of earthquake was recorded in the vicinity of the Yangsan Fault region and an earthquake was recorded at more than 4 stations. These conditions are limited in the vicinity of the Yangsan Fault region and may reduce errors of the hypocenter and origin time for the local earthquakes. Only the direct P-wave ($P_g$), which is recorded as a first arrival phase, is used in travel-time inversion to reduce reading errors. Both phases $P_g$ and $S_g$ (direct S-wave) are used to determine hypocenters and origin times of the earthquakes, respectively. The epicentral distances of 35 data points are less than 50 km, where $P_g$ is recorded as the first arrival phase. The location map of 8 earthquakes and of KIGAM Seismic Stations is shown in Figure 2. The list of the 8 earthquakes is shown in Table 1. The quality of earthquake records is relatively good. Figure 3 shows the seismic records of one earthquake among 8 earthquakes, in which the origin time is on 96/02/02 03:35:02.27, the epicenter is 35.7240N and 129.4122E, and the depth is 13.71 km. The quality of other qarthquake records is similar to that shown in Figure 3.

The present model has 8 layers which are 2 km thick for the layers between from surface to 12 km depth, and 3 km thick from 12 to 18 km, respectively. The estimated velocity structure by Kim (1955) is used as an initial velocity for calculating the hypocenteral parameters of the earthquakes. As shown in Figure 1, his model has 3 layers whose depths of the interface are at 0, 2, 15.5, 34 km, and whose velocities are 5.56, 6.00, 6.92 km/s, respectively. A program for calculating the hypocenter and the origin time was provided by S.K. Kim (personal communication) and subsequently modified for two-point ray tracing. The travel-time inversion for 8 layers is calculated based on the hypocenters and origin times obtained from the Kim's (1995) velocity structure as a starting model. The hypocenters and the origin times of 8 earthquakes are recalculated using the results of travel-time inversion. The iterations of travel-time inversion and the determination of hypocentral parameters are continued until the differences of the epicentral distances, depth, and origin time of the earthquakes between the present and the previous calculations are less than 0.01 km, 0.05 km, and 0.002 second, respectively. Two-point ray tracing is applied to every step of travel-time inversion and the determination of hypocenteral parameters to reduce errors resulting from the ray paths. The location error between the true and the calculated by two-point ray tracing is less than $10^{-5}$ km in single precision within 4 iterations. Two-point ray tracings for 4 earthquakes among 8 earthquakes (Fig. 4) are based on the velocity structure (Fig. 5). The depths of 4 earthquakes are 11.33, 10.64, 13.71, and 16.22 km, respectively. The weighting factor $\lambda$ in Equation (4) is given as 0.0001.

The computational results of travel-time inversion in the vicinity of the Yangsan Fault show that P-wave velocities of 8 layers are 5.56, 5.72, 5.87, 6.02, 6.12, 6.04, 5.94, and 6.34 km/s from top to bottom layer after 13 iterations (Fig. 5). This velocity structure shows the following characteristics. Firstly, the velocity gradient

**Table 1.** List of 8 earthquakes used in travel time inversion. The epicentral distances of 35 data are less than 50 km, where $P_g$ is recorded as the first arrival phase.

| Origin time (Y/M/D) (h:m:s) | Latitude (degree) | Longitude (degree) | Depth (km) | Station | Epicentral distance (km) | Arrival time (m:s) $P_g$ | $S_g$ |
|---|---|---|---|---|---|---|---|
| 96/02/02 03:35:02.27 | 35.7240N | 129.4122E | 13.71 | MKL | 15.03 | 35:05.72 | 35:08.14 |
| | | | | BBK | 16.56 | 35:05.91 | 35:08.47 |
| | | | | HAK | 23.92 | 35:06.94 | 35:10.05 |
| | | | | DKJ | 36.55 | 35:08.87 | 35:13.45 |
| | | | | MAK | 44.89 | 35:10.20 | 35:15.71 |
| 96/02/04 20:47:13.83 | 35.7194N | 129.4012E | 13.99 | MKL | 14.05 | 47:17.12 | 47:19.54 |
| | | | | BBK | 16.22 | 47:17.40 | 47:19.94 |
| | | | | HAK | 24.75 | 47:18.60 | 47:22.06 |
| | | | | DKJ | 36.16 | 47:20.26 | 47:24.92 |
| 95/02/05 06:01:13.70 | 35.7216N | 129.4037E | 14.06 | MKL | 14.26 | 01:17.10 | 01:19.52 |
| | | | | BBK | 16.42 | 01:17.37 | 01:19.91 |
| | | | | HAK | 24.44 | 01:18.48 | 01:31.91 |
| | | | | DKJ | 36.16 | 01:20.27 | 01:24.84 |
| 96/02/27 04:39:33.78 | 35.9521N | 129.5039E | 11.33 | HAK | 2.84 | 39:35.76 | 39:37.10 |
| | | | | MKL | 33.94 | 39:39.84 | 39:44.08 |
| | | | | DKJ | 35.42 | 39:40.07 | 39:44.45 |
| | | | | BBK | 42.14 | 39:41.15 | 39:46.39 |
| | | | | CHS | 44.89 | 39:41.60 | 39:47.06 |
| 96/02/28 07:07:21.77 | 35.9498N | 129.4989E | 11.10 | HAK | 2.61 | 07:23.71 | 07:25.05 |
| | | | | MKL | 33.44 | 07:27.74 | 07:31.98 |
| | | | | DKJ | 34.96 | 07:27.99 | 07:32.33 |
| | | | | BBK | 41.82 | 07:29.09 | 07:34.33 |
| | | | | CHS | 44.67 | 07:29.55 | 07:34.99 |
| 96/02/28 13:23:56.87 | 35.9455N | 129.4957E | 10.64 | HAK | 2.21 | 23:58.73 | 23:59.97 |
| | | | | MKL | 32.90 | 24:02.74 | 24:06.92 |
| | | | | DKJ | 34.67 | 24:03.03 | 24:07.37 |
| | | | | BBK | 41.32 | 24:04.10 | 24:09.30 |
| 96/03/18 22:30:33.85 | 35.7172N | 129.4042E | 16.22 | MKL | 14.35 | 30:37.51 | 30:39.95 |
| | | | | BBK | 15.92 | 30:37.69 | 30:40.23 |
| | | | | HAK | 24.89 | 30:38.86 | 30:42.32 |
| | | | | DKJ | 36.53 | 30:40.58 | 30:45.17 |
| 96/05/05 02:50:49.14 | 35.8134N | 129.4615E | 10.89 | HAK | 13.10 | 50:52.04 | 50:53.82 |
| | | | | MKL | 21.57 | 50:53.25 | 50:56.09 |
| | | | | BBK | 26.40 | 50:53.99 | 50:57.46 |
| | | | | DKJ | 34.79 | 50:55.32 | 50:59.68 |

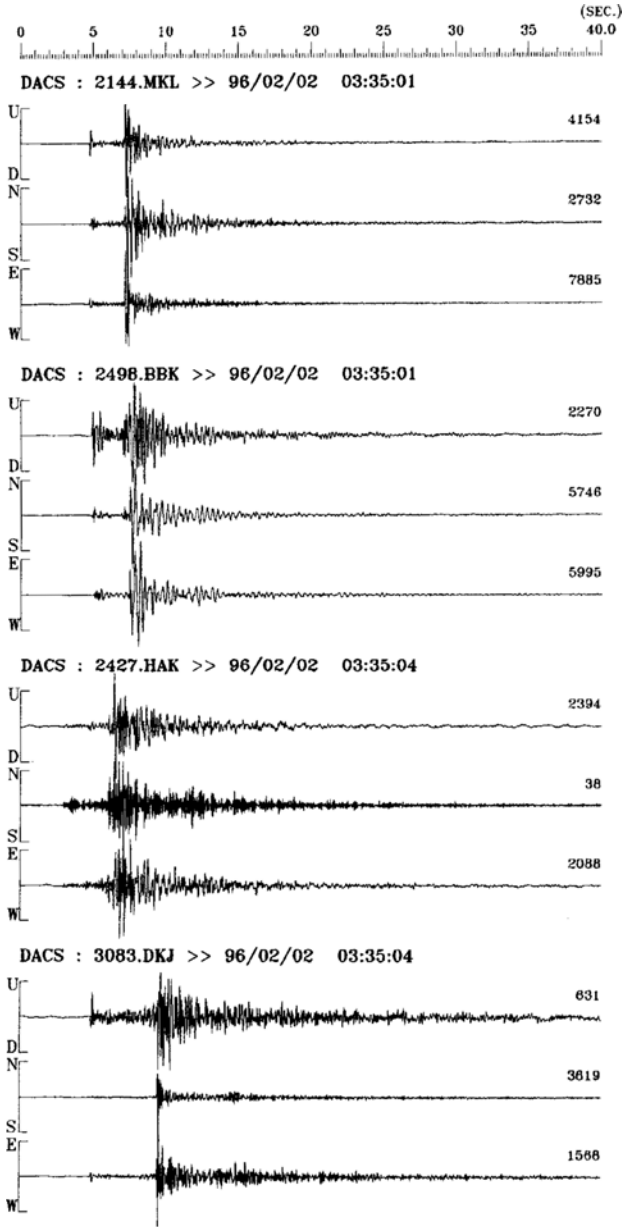


**Fig. 3.** One example of earthquake records, whose origin time is on 96/02/02 03:35:02.27, and epicenter is 35.7240N and 129.4122E, and depth is 13.71 km. The quality of other 7 earthquake records is nearly same as these records.

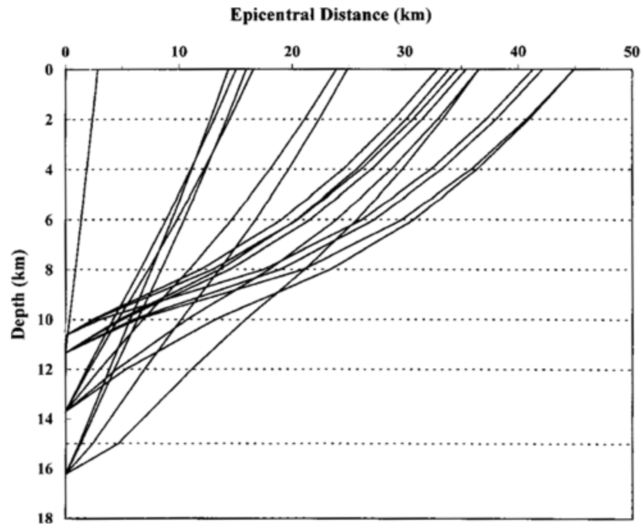


**Fig. 4.** Two-point ray tracing between the hypocenters and receivers for 4 earthquakes among 8 earthquakes. The distance errors from the hypocenters to stations between the true and the calculated distance are less than $10^{-5}$ km in single precision.

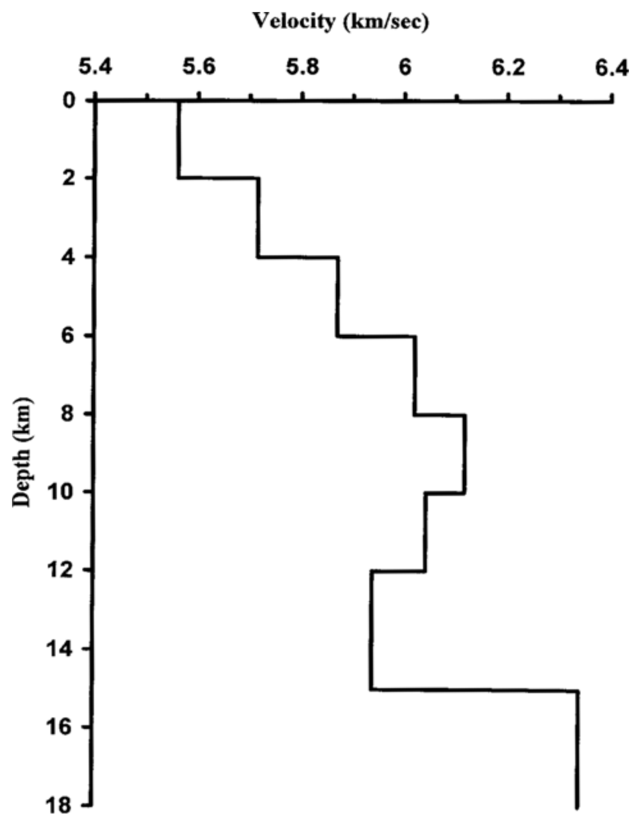


**Fig. 5.** P-wave velocity structure of upper crust around the Yangsan Fault. The model used in this study has 8 layers whose thicknesses are 2 km from surface to 12 km, and 3 km from 12 to 18 km. The computational results of travel time inversion show that the P-wave velocities of 8 layers are 5.56, 5.72, 5.87, 6.02, 6.12, 6.04, 5.94, and 6.34 km/s from top to bottom layer after 13 iterations.

with depth is nearly constant (about 0.075) from the surface to 8 km subsurface depth. This phenomenon may be related to the thickness of the Kyongsang Basin in the vicinity of the Yangsan Fault region. Secondly, there is a low velocity zone between 10 to 15 km subsurface depth, although this phenomenon is unusual compared with the velocity structure in the previous studies. The low velocity zone beneath the Yangsan Fault region may be due to the higher heat-flow values than in the other area (Lim, 1995; Han and Keehm, 1996; Lim and Kim, 1997). Thirdly, there is a relatively large velocity discontinuity at about 15 km depth, which may indicate an existence of the Conrad discontinuity in the Yangsan Fault region.

## 4. CONCLUSIONS

The travel-time inversion method is one of the basic tools to estimate preliminary velocity structure. It requires minimum data points, but provides relatively accurate results if two-point ray tracing is applied. The accuracy and convergence rate of the two-point ray tracing are adquate for travel-time inversion and determination of hypocenteral parameters of an earthquake. The computational results of travel-time inversion in the vicinity of the Yangsan Fault show following characteristics.

1. The velocity gradient with depth is nearly constant (about 0.075) from the surface to 8 km depth, which may be related with the depth of the Kyongsang Basin in the vicinity of the Yangsan Fault region.
2. There is a low-velocity zone between 10 to 15 km subsurface depth. The low-velocity zone beneath the Yangsan Fault may be related to the high heat flow.
3. There is a relatively large velocity discontinuity at about 15 km depth, which may indicate the existence of the Conrad discontinuity beneath the Yangsan Fault.

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## REFERENCES

Bessonova, E.N., Fishman, V.M., Ryaboi, V.Z. and Sitnikova, G.A., 1974, The tau method for inversion travel time—deep seismic sounding data. Geophysical Journal of Royal Astronomical Society, 36, 377–398.

Diebold, J.B. and Stoffa, P.L., 1981, The travel time equation, tau-p mapping, and inversion of common midpoint data. Geophysics, 46, 238–254.

Han, U. and Keehm, Y., 1996, A study on the heat flow distribution in the Korean Peninsula and its vicinity. Journal of the Geological Society of Korea, 32, 267–275.

Ham, I.K. and Kim, W., 1999, Travel time inversion using two point ray tracing in the layered media with constant or linearly varying velocity function. (in preparation)

Johson, L. and Gilbert, F., 1972, A new datum for use in body wave travel time inversion problem. Geophysical Journal of Royal Astronomical Society, 30, 373–380.

Kennet, B.L.N., 1976, A comparison of travel time inversion. Geophysical Journal of Royal Astronomical Society, 44, 517.

Kim, S.G. and Lee, S.K., 1996, Seismic velocity structure in the central Korean Peninsula using the artificial explosions. Bulletin Seismological Association of the Far East, 1, 4–17.

Kim, S.J., 1983, A Study on the Crustal Structure of South Korea Using Seismic Waves. M.S. thesis, Hanyang University, Seoul. (in Korean with English abstract)

Kim, S.K. and Jung, B.H., 1985, The crustal structure of the southern part of the Korean Peninsula. Journal of Korcan Institute of Mining Geology 18, 151–157. (in Korean with English abstract)

Kim, S.K., 1995, A study on the crustal structure of the Korean Peninsula. Joururnal of Geological Society of Korea, 31, 393–403. (in Korean with English abstract)

Kim, W. and Baag, C.-E., 1999, Rapid and accurate two point ray tracing in the layered media with constant or linearly varying velocity function. (in preparation)

Lee, K., 1979, On the crustal structure of the Korean Peninsula. Journal of Geological Society of Korea, 15, 134–150.

Lim, J.U., 1995, Geothermal potential in the Republic of Korea. In: Gupta, M.L. and Yamano, M. (eds.), Terrestrial Heat Flow and Geothermal Energy in Asia. Oxford and IBH Publishing Company, New Delhi, p. 435–467.

Lim, J.U. and Kim, H.C., 1997, Heat flow in south Korea. Coordinating Committe for Coastal and Offshore Geoscience Programs in East and South East Asia (C.C.O.P) Technical Bulletin, 26, 85–91.

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