

Comparison of Earthquake Location by Using One- and Three- Dimensional Velocity Structures in the Taiwan Area

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ABSTRACT

Many approaches for locating earthquakes attempt to solve a nonlinear inverse system in a one-dimensional velocity model. To ensure precise earthquake locations in geologically complex areas, however, a three-dimensional velocity model has to be considered. In this study, the authors have applied an alternative approximate method based on the dynamic ray theory with a 3-D velocity model to relocate 374 events from 1980 to 1989 recorded by the Taiwan Telemetered Seismographic Network (TTSN). The solutions to locating earthquakes using 1-D and 3-D velocity models are compared. These results show that the root mean square (RMS) of travel time residuals for the 3-D model are much lower than those for the 1-D velocity model. The discrepancies between the 1-D and 3-D solutions reflect the importance of lateral velocity variations in locating earthquakes in the Taiwan area. These discrepancies are larger in focal depths than in epicentral determinations. From the examination of seismicity along the Chaochou fault with both 1-D and 3-D velocity models, the results here show that the hypocenter determinations from a 1-D model may even lead to an absurd interpretation in seismicity. The presence of the lateral heterogeneity of seismic velocity in Taiwan makes the necessity of locating earthquakes with a three-dimensional velocity model. The increases in computation time in using a 3-D velocity model to locate earthquakes can be minimized by applying the dynamic ray tracing technique due to its fast computation capacity and high level of accuracy.

(Key words: Earthquake location, Velocity structure, TTSN)

1. INTRODUCTION

Accurate earthquake locations are crucial in the interpretation of tectonic and other geophysical problems (e.g., Lee and Lahr, 1975; Bullen and Bolt, 1985). Therefore, the

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earthquake location problem is still a subject of perennial interest. Many approaches for locating earthquakes attempt to solve a nonlinear inverse system with a one-dimensional velocity model. However, in geologically complex areas, a three-dimensional velocity model must be considered to ensure the accuracy of earthquake locations (Virieux *et al.*, 1988). The trade-off for applying 3-D earthquake location is the increase in computation time. This shortcoming can be minimized by adapting an accurate and fast ray tracing method. Most standard ray tracing techniques are either too slow or inaccurate for routine use in earthquake location. An alternative approximate method based on the dynamic ray tracing theory (Virieux *et al.*, 1988) can calculate fast and still provide accurate travel times of rays propagating in an arbitrary velocity distribution of a earth model. In this study, the authors applied this method and a 3-D velocity model deduced by Roecker *et al.* (1987) to relocate 374 events (Figure 1) from 1980 to 1989 recorded by the Taiwan Telemetered Seismographic Network (TTSN). In order to unravel the relationship between earthquake locations and geological structures, the relocated results are compared to the TTSN solutions that were obtained by using a 1-D velocity model and the HYPO71 location routine (Lee and Lahr, 1975). The authors have derived the general trend of the discrepancies between 1-D and 3-D earthquake locations in the whole Taiwan area. With the same analysis, the study area has been subdivided into subregions based on geological considerations in order to understand the local characteristics of lateral heterogeneity. In addition, examples of seismicity profiles taken along and across fault zones are given in this study in order to demonstrate the superiority of earthquake locations obtained from a 3-D model in structure interpretation. All these discussions make

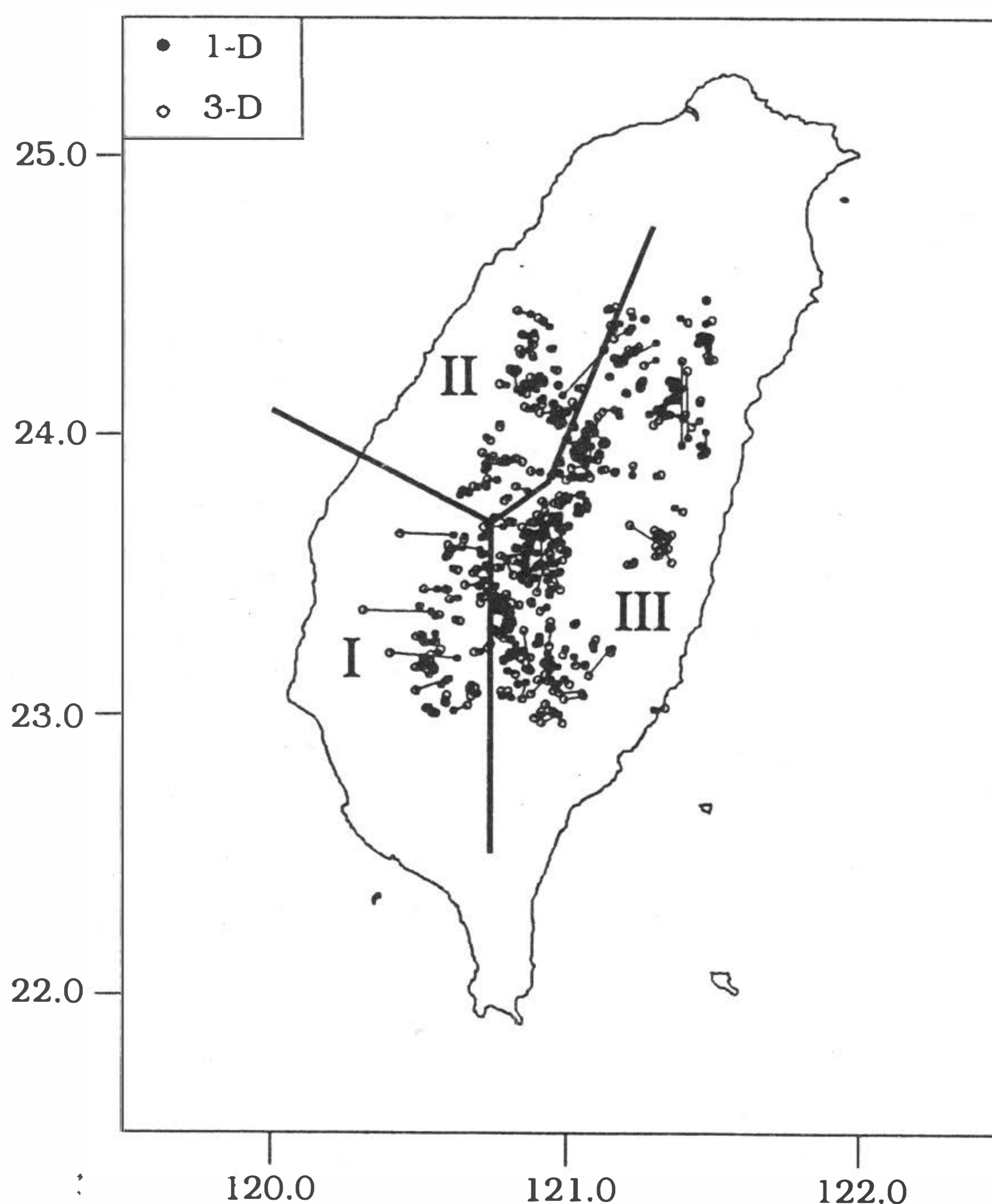


Fig. 1. Epicenter distribution. Solid and open circles represent 1-D and 3-D solutions respectively. Three sub-regions (I,II,III) were divided according to geological structures for further individual statistic analyses.

apparent the necessity of routine earthquake location using a 3-D velocity model in Taiwan. The efficiency and potential of the computer program used in this study was also tested for routine earthquake locations.

2. THREE-DIMENSIONAL EARTHQUAKE LOCATION

A dynamic ray tracing method has been successfully applied to 3-D earthquake location (e.g., Vireux *et al.*, 1988; Vireux, 1991). A previous study shows that ray tracing in elastic media does not differ substantially from that in acoustics (Cerveny *et al.*, 1977); thus, we only the scalar wave equation is discussed as follows:

$$\nabla^2 \phi(x, t) - \frac{1}{v^2(x)} \frac{\partial^2 \phi(x, t)}{\partial t^2} = 0 \quad (1)$$

where $\phi(x, t)$ is the wave field. When the velocity $v(x)$ slowly changes inside the medium, an asymptotic solution can be cast in the following form:

$$\phi(x, t) = s(\varpi) A(x) e^{ix[t - \theta(x)]} \quad (2)$$

This is the approximation of geometrical optics. In (2), $A(x)$ is the amplitude, $\theta(x)$ is the travel time function, ϖ is the frequency and $s(\varpi)$ is the source time function. Inserting (2) into (1) and collecting terms of the same order of ϖ yields :

$$(\nabla \phi)^2 = u^2 = v^{-2} \quad (3)$$

which is known as the eikonal equation (the u is slowness).

$$\text{Let } p = \nabla \theta = u \frac{dx}{ds} \quad (4)$$

to be the slowness vector (x is the position vector, s is arc length along the ray path) and using Hamilton's canonical equations, yields the ray tracing system

$$\begin{aligned} \frac{dx}{d\tau} &= p \\ \frac{dp}{d\tau} &= u \nabla_x u \end{aligned} \quad (5)$$

where ∇_x denotes the gradient with respect to vector x , and τ is the ray parameter defined by the relationship of $u d\tau = ds$. Supposing a ray that has been traced according to equation (5) is called the central ray, other rays can be traced from this already traced one by the paraxial approximation (Cerveny *et al.*, 1982). This approximation provides the travel time of the points in the vicinity of the central ray, i.e.,

$$\theta(x, \tau) = \theta(x_c) + p_c \delta x + \frac{1}{2} \delta x^T M(\tau) \delta x \quad (6)$$

where x_c and p_c are the position and slowness vectors of the central ray respectively. M is a 3 by 3 matrix composed of the second derivatives of the travel time field with respect to the coordinate system.

In a medium that is divided into a set of finite elements with simple velocity distribution, it holds that for each element :

$$u^2 = u_o^2 + \gamma \cdot x = u_o^2 + \gamma_i x_i, \quad (7)$$

where u_o is the reference slowness and γ is the velocity gradient of that element. In such a situation, this gives the simplest analytical solutions of the ray tracing system (5) and the paraxial approximation as

$$p = \frac{1}{2}\gamma\tau + p_o,$$

$$x = \frac{1}{4}\gamma\tau^2 + p_o\tau + x_o$$

and

$$\theta = p_o^2\tau + \frac{1}{2}\gamma p_o\tau^2 + \frac{1}{12}\gamma^3\tau^3 \quad (8)$$

From (8), rays can be traced and travel times of points in the neighborhood of the central ray can be efficiently. This algorithm also provides a way to do the forward calculation of theoretical travel time in source parameter inversions.

3. DATA AND VELOCITY MODEL

In this study, P and S wave arrival times have been collected from 374 events recorded by the TTSN from 1980 to 1989 (Figure 1). These events were selected by the following three criteria. First, each event had to have been recorded by 10 or more stations. Thereby preventing the quality of the hypocenter inversion from being affected by fewer readings of arrival time. Second, the epicenters determined by the TTSN are within the network, which also ensures that the solutions are not significantly affected by the geometrical distribution of the stations. Third, the locating quality of the earthquake is A or B (Lee and Lahr, 1975). Under these three conditions, the differences in locating an earthquake from 1-D and 3-D velocity models result from velocity heterogeneity.

The 1-D velocity model used in this study is from P-wave travel time inversion derived by Yeh and Tsai (1981). Although this model does not fully represent the complicated subsurface structures of Taiwan, it has shown itself to be acceptable and has been applied to earthquake locations by the TTSN and the Central Weather Bureau Seismic Network (CWBSN) since 1983. Besides, HYPO71 software (Lee and Lahr, 1975) used for the routine earthquake location by the two networks can only adapt a 1-D velocity model.

The 3-D velocity structure selected for earthquake relocation is from Roecker *et al.* (1987). This velocity model which was derived from P and S wave travel time inversion has been confirmed by several studies of 2-D forward ray tracing in northern Taiwan (Yeh *et al.*, 1988) and in eastern and southern Taiwan (Chen, 1991). The velocity model indicates that

the thickness of the broad-scale distribution of recent sediments on the island Taiwan results in the seismic velocity zonation of highs in the eastern part and lows in the western part of the island for the upper 10 km crust. It also shows that the P and S wave velocities (at depth 5-15 km) south of latitude 24°N are divided into lows and highs along northeast-southwest trends, while north of latitude 24°N various P- and S-wave velocity trends integrate into a very complicated pattern. Below 15 km, broad-scale structures become evident. Between the depths of 15 and 25 km, there is a general zonation of lows in the center and highs in the northwestern and southwestern parts of the island. The lows are concentrated in the middle part of the island between 25 and 30 km. Obviously, the crustal velocity structure is so complicated with strong heterogeneity that a 1-D velocity model for earthquake location is inadequate.

4. RESULTS AND DISCUSSION

The relocated results are compared with the 1-D solutions to determine the general trend of the differences. This analysis has been applied not only to the whole island in order to obtain the general trend but also to several geologically distinct subregions to correlate the discrepancies between 1-D and 3-D models with geological structures. Finally, based on comparison of the results of the 1-D and 3-D models around the Chaochou fault area, it is demonstrated that earthquake locations from a 3-D model are much better in revealing geologic structures than those from a 1-D model.

4.1 General Comparison

More than 85% of the relocated events have RMS (root mean square) values of travel time residuals of less than 0.1 second. In contrast, most of the travel time residuals from the 1-D model have larger RMS values ranging between 0.1 and 0.3 second as shown in Figure 2. This implies that the accuracy of earthquake location using a 3-D velocity model is substantially improved. Moreover, the computation time used to relocate the total of 374 earthquakes in a 3-D velocity model is only about 1.6 times that in a 1-D velocity model. This indicates that the computation time of earthquake location using 3-D velocity model is not as slow as first thought. It also confirms that the dynamic ray tracing method has the advantage of being able to quickly calculate travel time (Vireux *et al.*, 1988; Vireux, 1991) because the travel time can be more accurately estimated by an analytic function than by a numerical method adapted by the complicated two-point ray tracing.

The relocated epicenters are shown in Figure 1 (open circles in the figure) for comparison with the origin locations (solid circles). The spatial differences (3-D solutions minus 1-D solutions) in longitude and latitude of the epicenters are plotted in Figures 3a and 3b. The distributions are concentrated around the mean values of -0.1 km and 0.33 km with standard deviations of 2.92 km and 2.77 km respectively. This implies that, except for a few of them, epicenters are not strongly affected by velocity models. However, the frequency distribution of the differences in focal depths (Figure 3c) has a mean at -1.0 km with a large standard deviation of 6.12 km. The large standard deviation indicates that the determination of the focal depth is strongly sensitive to the 3-D velocity structure. The comparison above shows that the hypocenter locations given by a 1-D model might be offset at a distance much larger than the estimated error when lateral velocity anomalies exist. This conclusion can also be confirmed from numerical testing (Vireux *et al.*, 1988).

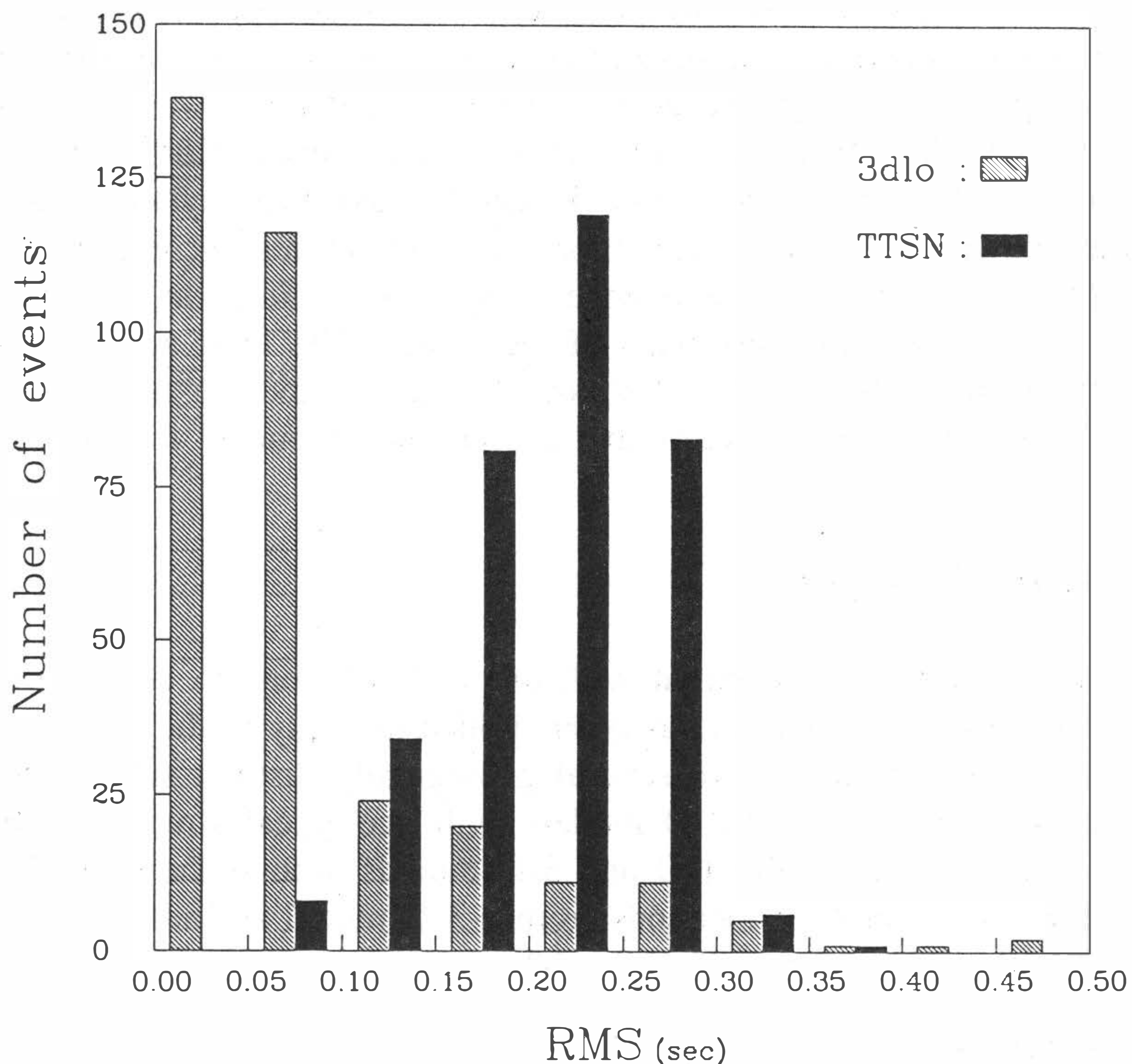


Fig. 2. Frequency distribution of root mean square (RMS) values of earthquake locations using 1-D and 3-D velocity models.

4.2 Comparison in Sub-regions

In this study, to examine the effect of employing the 3-D model for earthquake locations in different geological regions of Taiwan, the whole region was divided into three parts (I, II and III as shown in Figure 1) and the hypocenter locations derived from 3-D and 1-D velocity models respectively in each sub-region were compared.

In sub-region I, the southwestern part of Taiwan, the epicentral differences (as defined before) in longitude and latitude are shown in Figures 4a and 4b. For latitude, the differences have an average of 0.78 km with a standard deviation of 2.27 km, while for longitude, the differences have an average of 0.77 km with a standard deviation of 3.94 km. It should be noted that the longitudinal distribution scatters in a wider range (from 0 to 20 km) than the latitudinal one. Geologically, in sub-region I, not only does the intensity of deformation decrease from the eastern foothills toward the west, but also the rock types change significantly in the same direction (Ho, 1975). Here, it is inferred that the presence of a strong change in the surficial geological environment in the E-W direction makes for a larger difference in longitude than in latitude between the 1-D and 3-D solutions of shallow earthquakes. The frequency analysis of focal depths (Figure 4c) shows that the average difference deviates from zero to a negative value, indicating that the focal depth obtained from the 3-D velocity model is shallower than that obtained from the 1-D model. This may be a result of the absence of low velocity sediments near surface in the 1-D velocity model. Because the events within this sub-region have shallow focal depths, the thickness of low velocity surficial sediments is an important factor in earthquake location.

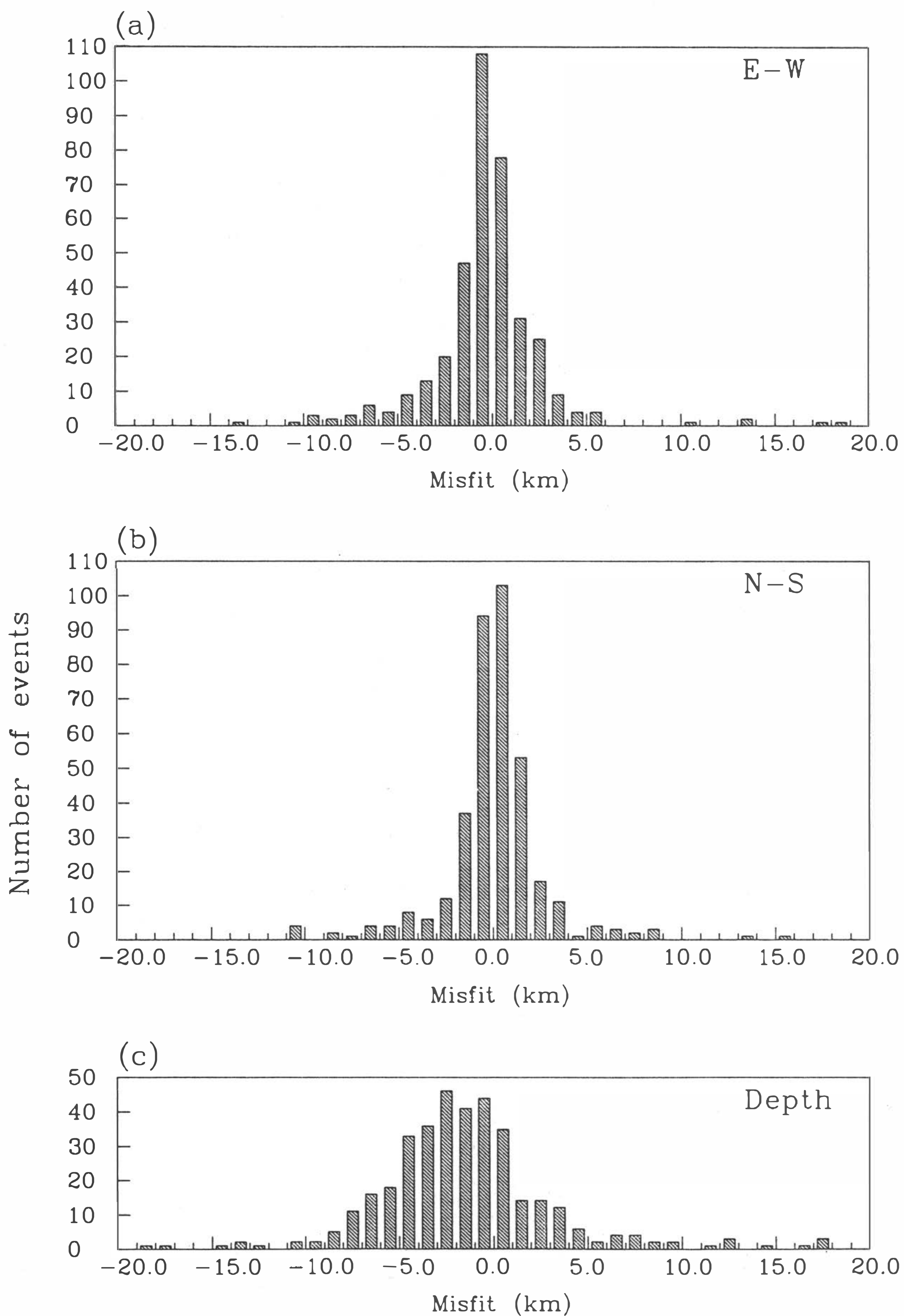


Fig. 3. Frequency distribution of epicentral differences between 1-D and 3-D solutions in the (a) E-W direction, (b) N-S direction and (c) focal depth of 374 events. A positive difference shows that the 3-D solution is offset east, north, and downward relative to the 1-D solution respectively, and negative for west, south and upward.

In sub-region II, the western central part of Taiwan, the frequency analysis (Figure 5) indicates that the solutions obtained from 1-D and 3-D velocity models do not differ significantly. Because the 1-D velocity model adapted in this study was originally derived from this area (Yeh and Tsai, 1981), it is not a surprise that the 1-D solution can give accurate source parameters.

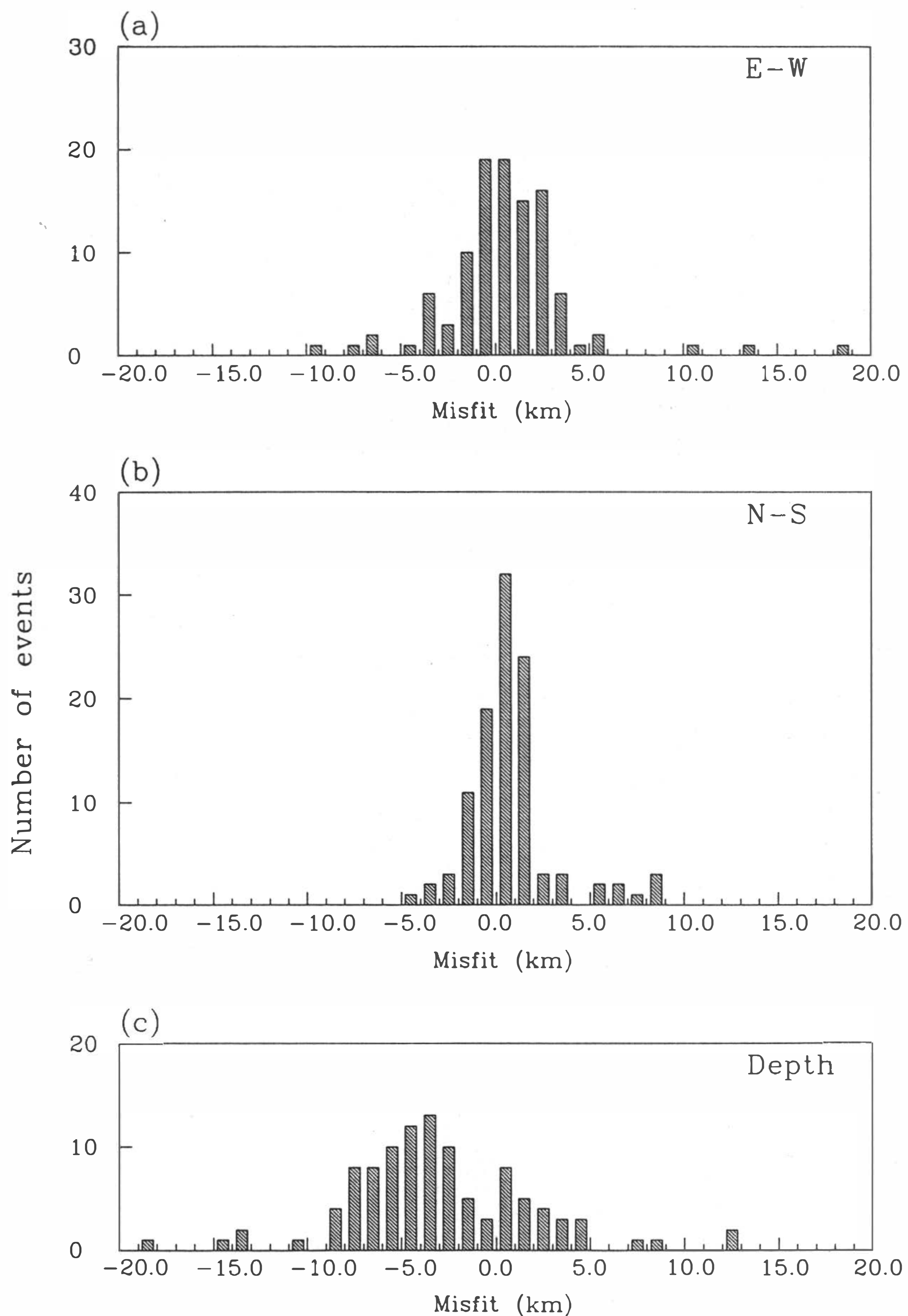


Fig. 4. Frequency distribution of epicentral differences of sub-region (I) between the 1-D and 3-D solutions in the (a) E-W direction (b) N-S direction and (c) focal depth. The positive difference shows that the 3-D solution is offset (a) east (b) north, and (c) downward relative to the 1-D solution, and negative for (a) west, (b) south and (c) downward.

In sub-region III, the eastern central and eastern parts of Taiwan, the epicenters obtained from 1-D and 3-D models show some linear trends emerging in the overall pattern in the 3-D solutions. Although the average differences both in longitude and in latitude between 1-D and 3-D solutions (Figures 6a and 6b) are small, the standard deviation in latitude is the largest among the three sub-regions. In the 3-D velocity model, the velocity distribution is

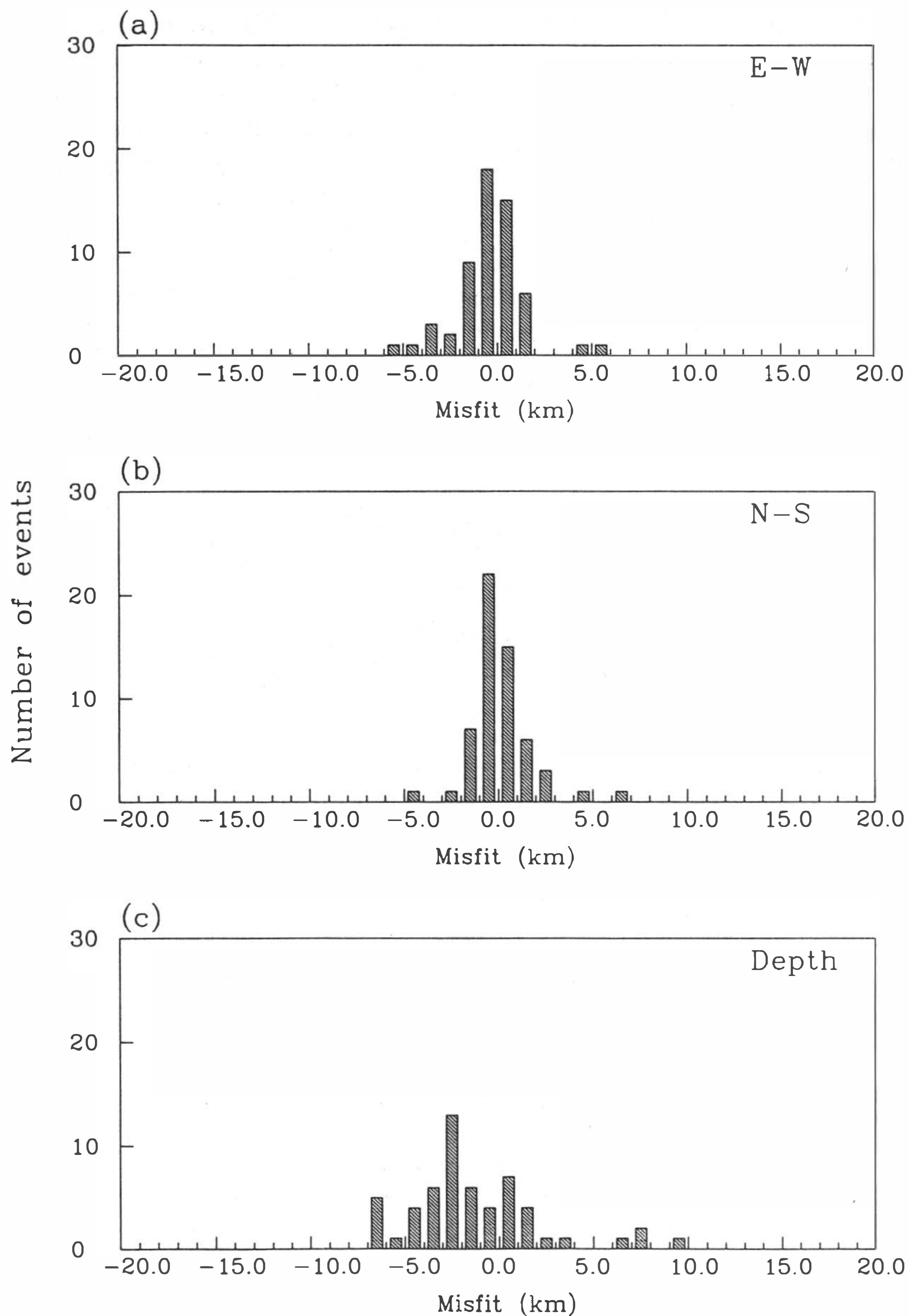


Fig. 5. Frequency distribution of epicentral differences of sub-region (II) between the 1-D and 3-D solutions in the (a) E-W direction (b) N-S direction and (c) focal depth. The positive difference shows that 3-D solution is offset (a) east (b) north, and (c) downward relative to the 1-D solution, and negative for (a) west, (b) south, and (c) downward.

very complicated in the eastern central and the eastern parts of Taiwan. The P- and S-wave velocities divide into lows and highs which indicate the NNE direction trends between the depths of 10 to 15 km (Roecker *et al.*, 1987). This strong velocity heterogeneity causes a larger discrepancy between the 1-D and 3-D solutions in latitude than in longitude. Figure

6c shows the distribution of the differences in focal depths. The average difference is -0.56 km with a large standard deviation of 8.06 km. The large standard deviations in both latitude and focal depth indicate that the effect of the heterogeneous velocity structure cannot be ignored in earthquake location in this region. In other words, earthquake location using a 3-D velocity model is crucial in eastern Taiwan due to the strong lateral velocity variation.

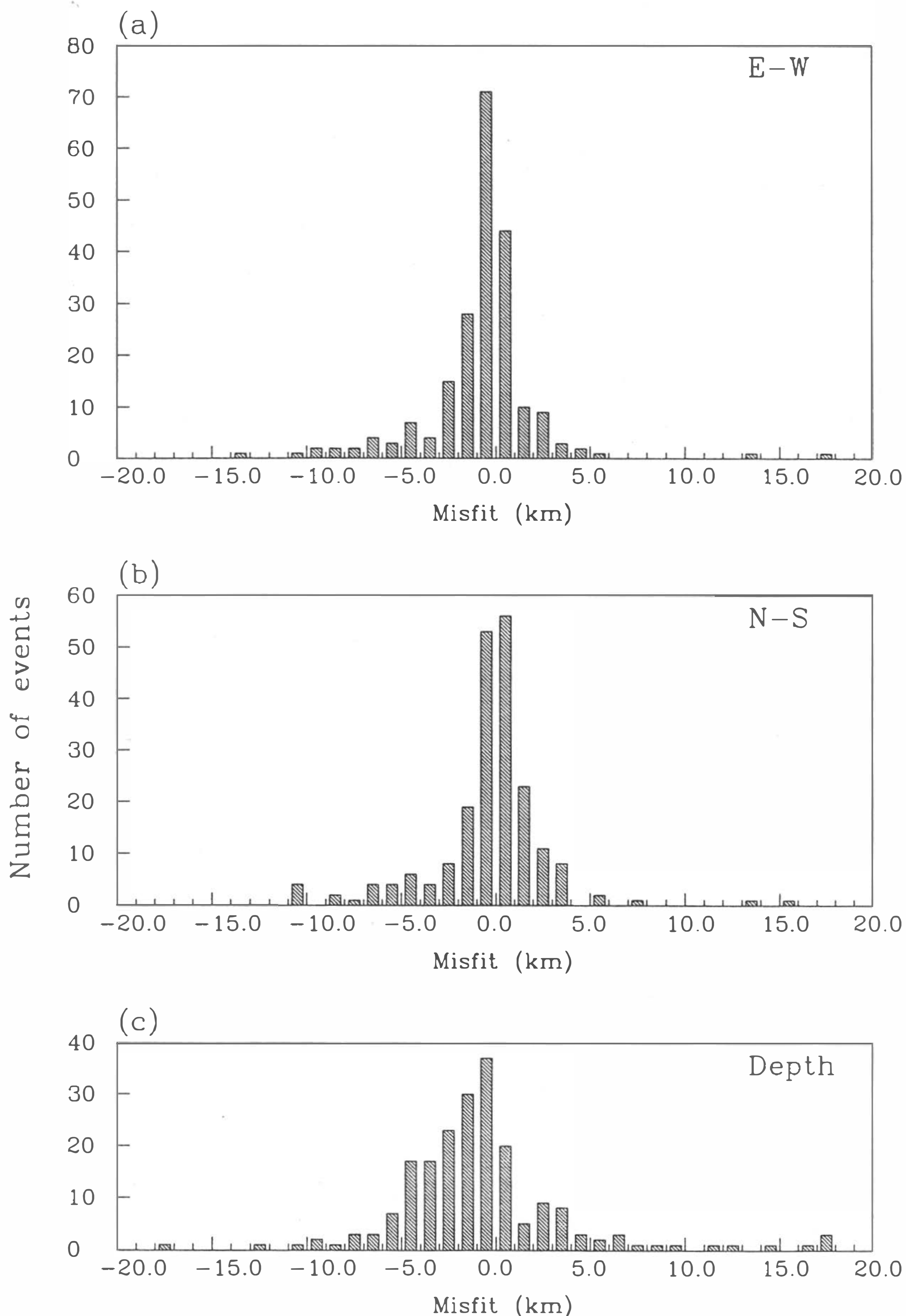


Fig. 6. Frequency distribution of epicentral differences of sub-region (III) between the 1-D and 3-D solutions in the (a) E-W direction (b) N-S direction and (c) focal depth. The positive difference shows that 3-D solution is offset (a) east (b) north, and (c) downward relative to the 1-D solution, and negative for (a) west, (b) south, and (c) downward.

4.3 Relocation of Aftershocks

The distribution of aftershocks is often used to identify the attitude of a fault which means so the accuracy of the earthquake location is very important in revealing geological structures. To explore the relationship between the fault and the seismicity (Figure 7), a mainshock occurred near the Chaochou fault and its aftershocks were chosen in this study. The mainshock, which occurred on June 6, 1976, had a magnitude (ML) of 4.8. Although the identification of the aftershocks is somewhat arbitrary, it follows general rules such as those based on the rate of aftershock occurrence and the distance of hypocenter distribution from the main shock. In this study, the aftershocks selected occurred within 3 days after the mainshock and were distributed in an area with a distance of less than 10 km from the mainshock. These events show no connection with the Chaochou fault system based on 1-D earthquake location. It is suspected that overlooking lateral heterogeneity has led to unexpected finding.

In order to examine the possibility that these events are indeed strongly connected to the Chaochou fault system, the focal mechanism of these events has been analyzed. One of the reasons for choosing these events and not those earthquakes used in the previous sections is because the latter are too small in magnitude to obtain the focal mechanism from P-wave first motion. The composed fault plane solution (Figure 8) of the main shock and aftershocks is derived from the first motions of direct P-waves by the joint inversion technique (Udias *et al.*, 1988). The fault plane solution implies a thrust-type focal mechanism with the compression in an almost axis nearly E-W direction. The nodal plane, with a strike in an almost N-S direction and a dip to the east, is similar to the attitude of the Chaochou fault according to geological observations (Ho, 1986).

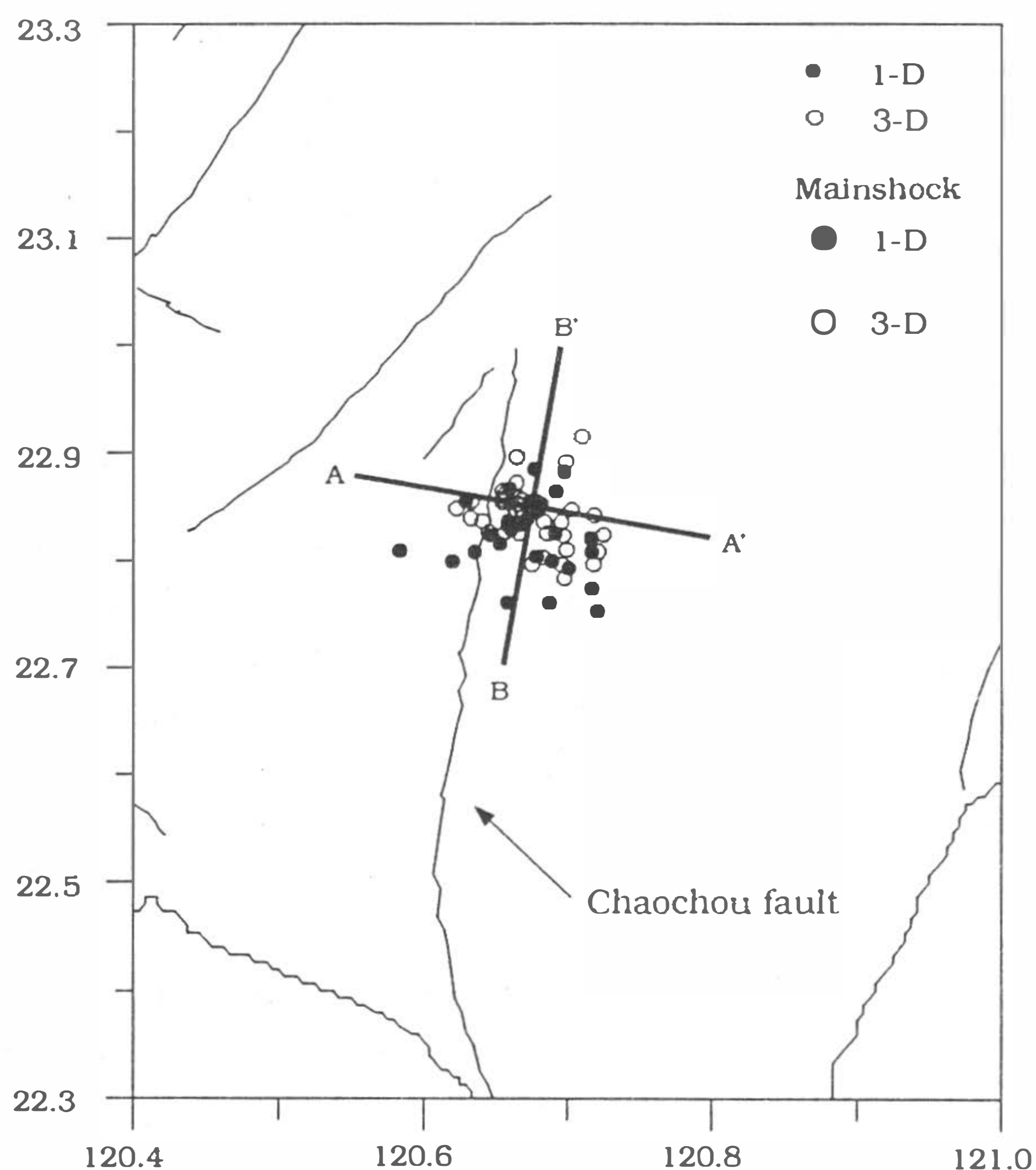


Fig. 7. Epicenter distribution of mainshock (star) and aftershocks near the Chaochou fault as determined from the 1-D (solid circles) and 3-D (open circles) velocity models.

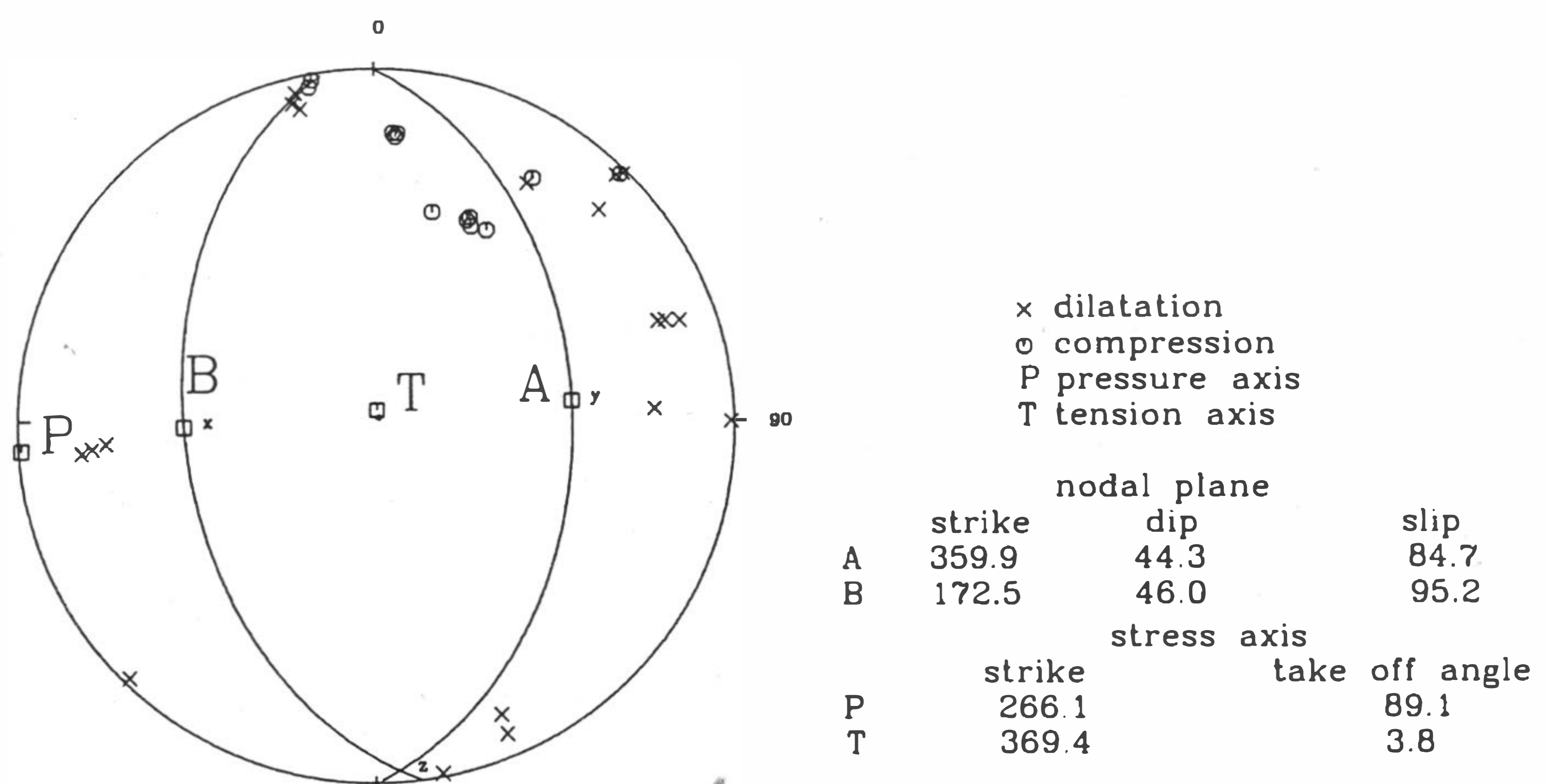


Fig. 8. Composite fault plane solution of mainshock and aftershocks. A and B are nodal planes, and P and T are the compression axis and tension axis respectively. First motions of the P-waves are depicted by squares (compression) and crosses (dilatation).

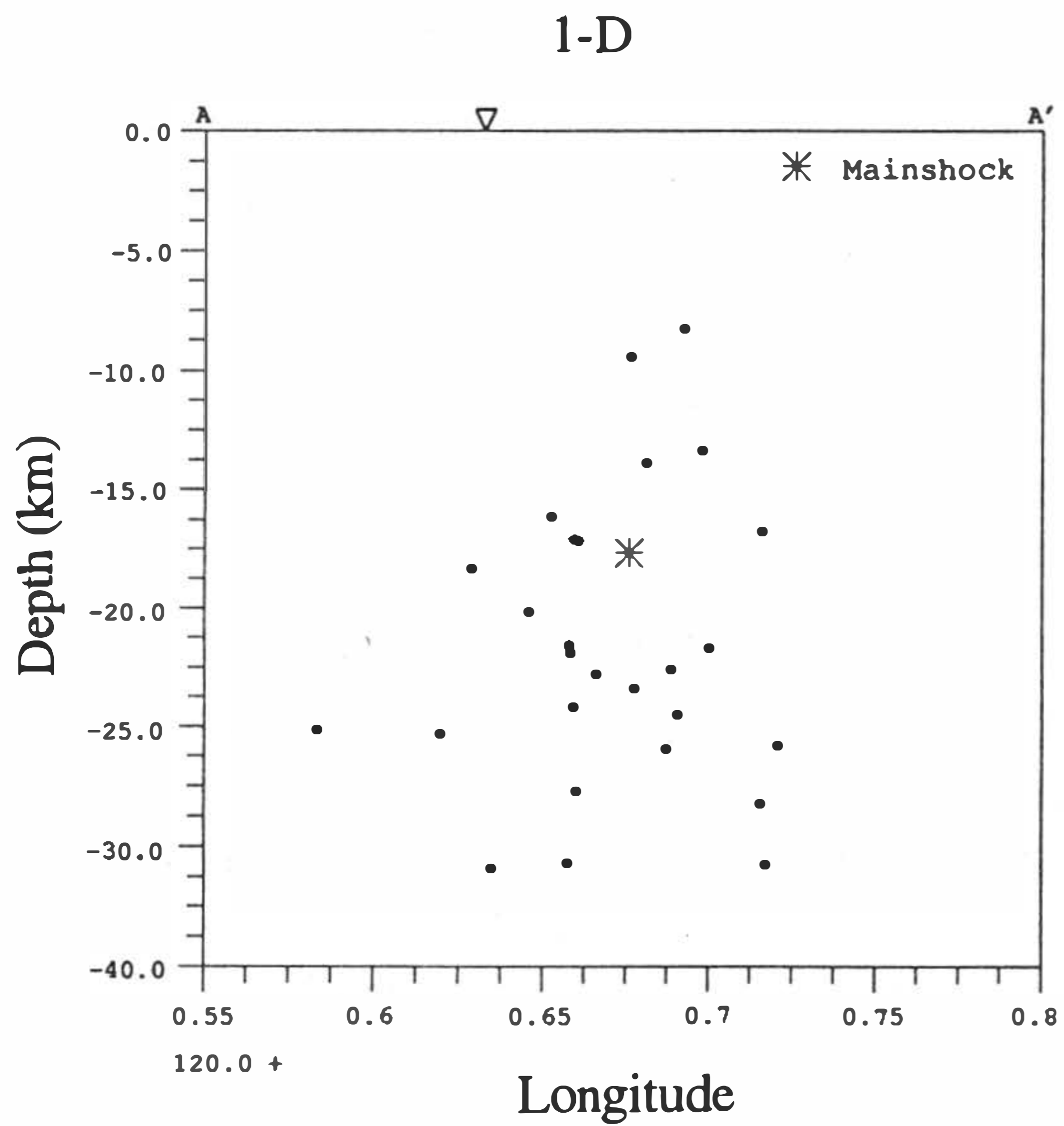
Although the composed focal mechanism shows the thrust plane with strike in a N-S direction, the seismicity derived from 1-D velocity model shows a different fault plane attitude. In the 1-D solutions, the hypocenter distribution exhibits a trend dipping to the south in the N-S direction profile (A-A') (Figure 9a), which is obviously contradictory to the focal mechanism. In addition, it shows no linear pattern in the E-W direction. On the other hand, the hypocenters determined by the 3-D model display an eastward dipping plane in the across strike profile but no particular features in the along strike profile (B-B') (Figure 9b). The dipping plane marked by the 3-D solution agrees well with both the fault attitude constrained from the field geology and the focal mechanism. This suggests that the seismicity data from the 3-D model are much better than those from the 1-D model at delineating a fault and seismotectonic interpretation.

5. CONCLUSIONS

The solutions to earthquake locations using 1-D and 3-D velocity models are compared in this study. The complex velocity structure causes errors in 1-D hypocenter determination, especially in the focal depth. In the eastern central and eastern parts of Taiwan, remarkable discrepancies are shown, implying a strong lateral velocity variation in this area. The errors derived from the adaptation of a 1-D velocity model may also yield an error in the interpretation of the seismicity and seismic structure. The results here show that it is necessary to use a three-dimensional velocity model for earthquake location due to the heterogeneous of velocity distribution in Taiwan.

The use of dynamic ray tracing in earthquake locations in this research reveals that the root mean square values of travel time residuals can be remarkably reduced by employing a 3-D model. The computation time is only about 1.6 times longer than that required by the HYPO71. Three-dimensional earthquake location needs fast and accurate seismic travel time algorithm for routine work. The dynamic ray tracing technique with the advantages of fast computation and high accuracy can be applied to locate earthquakes in a three-dimensional model for routine use.

(a)



(b)

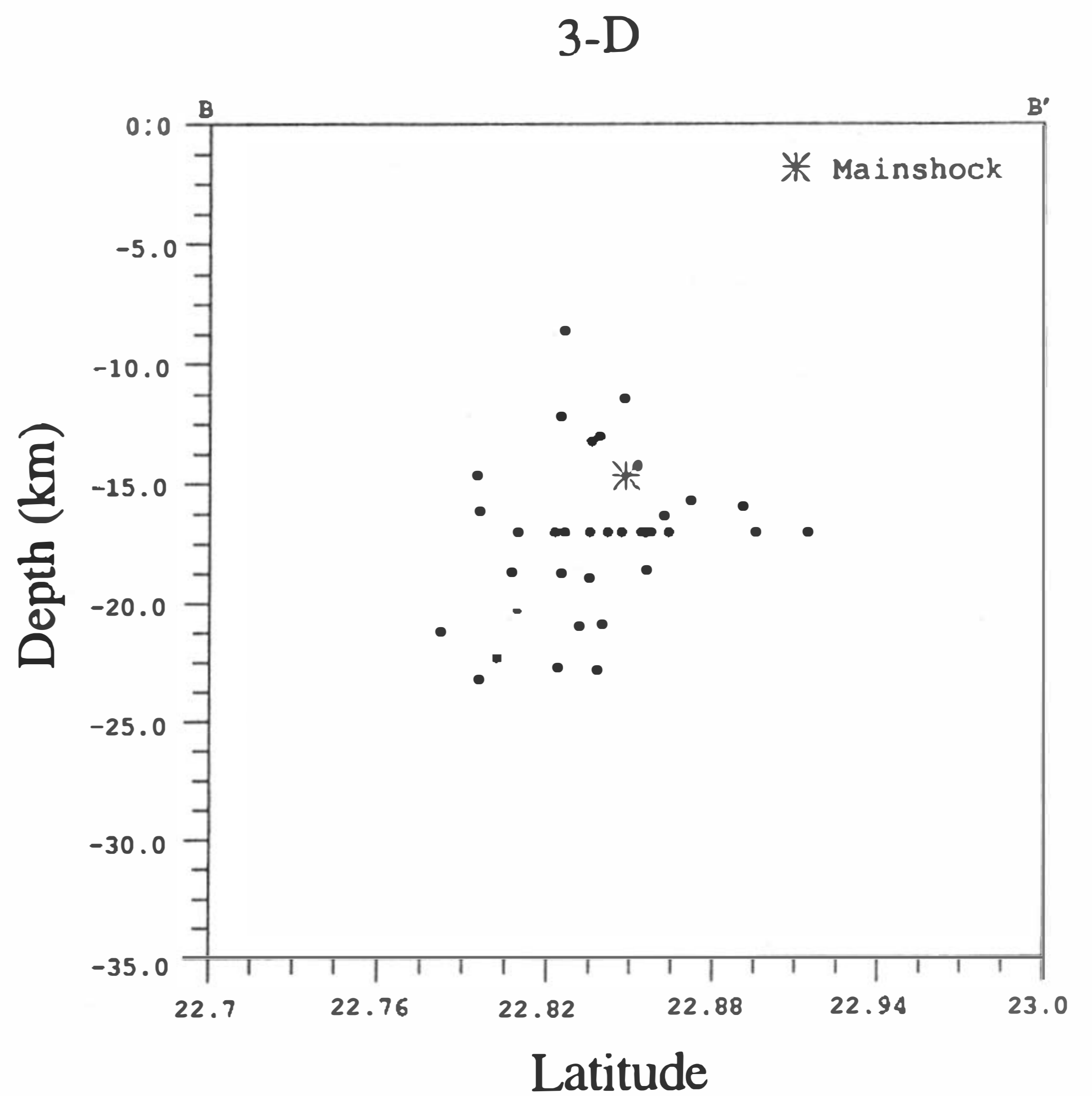
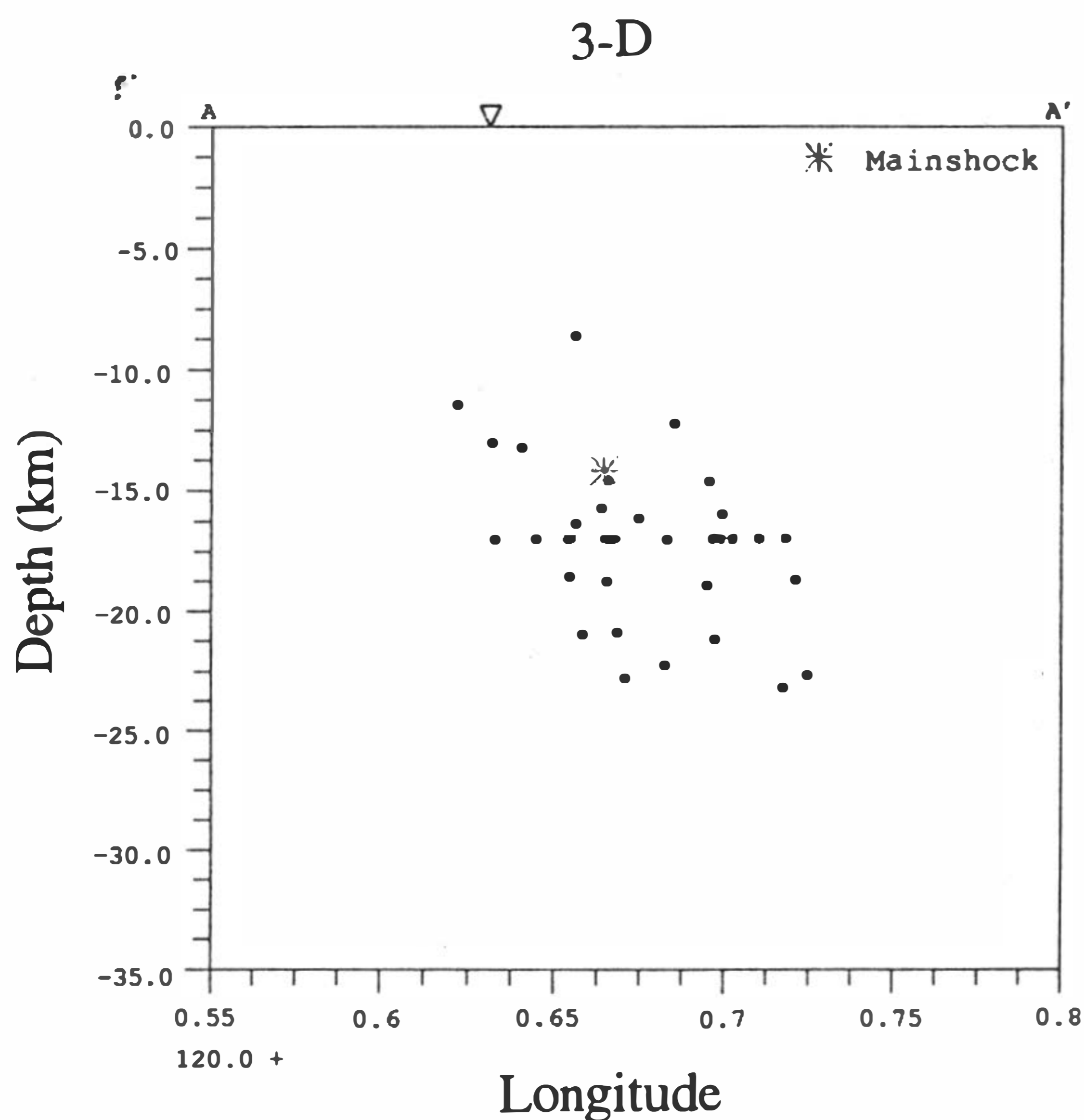
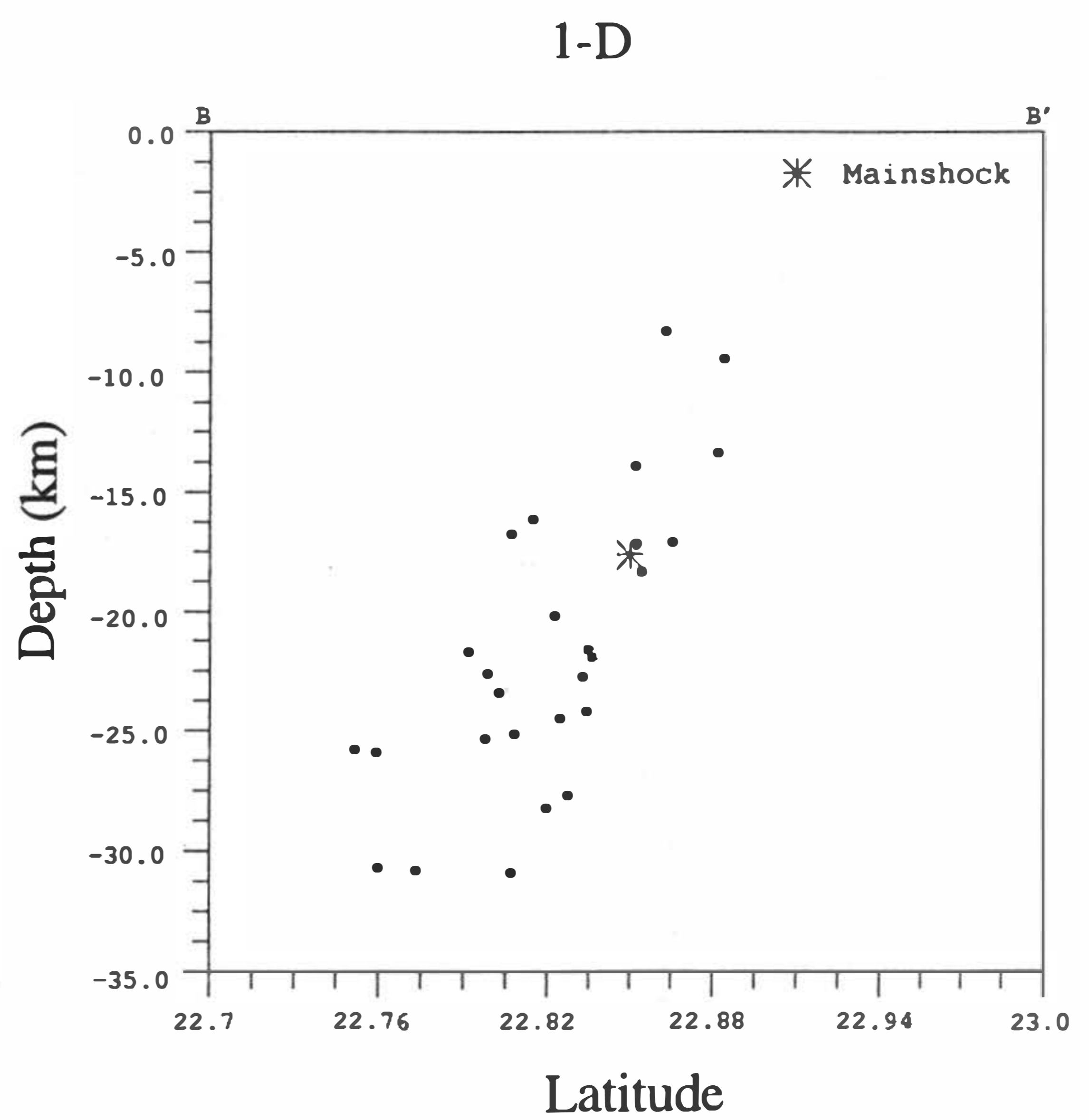


Fig. 9. Hypocenter profiles along the A-A' and B-B' directions (shown in Figure 7) which are perpendicular and parallel to the Chaoahou fault. (a)1-D solutions. (b)3-D solutions.

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