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Re-examination of the Epicenter of the 16 September 1994 Taiwan Strait Earthquake Using the Beam-forming Method

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ABSTRACT

The source location of the 16 September 1994 Taiwan Strait earthquake was relocated based on the beam-forming method using joint seismic observations from regional seismic networks in Taiwan and Fujian and the International Seismological Center Bulletin. The revised epicenter is located at latitude 22.37° N (±0.03°) and longitude 118.63° E (±0.03°). Results of this study showed that the location uncertainty has been significantly reduced using this approach. Decomposition tests of this study showed that the epicenters of Taiwan Strait events can be determined by the beam-forming method using data from densely distributed seismic stations in Taiwan. However, source depths of Taiwan Strait events can not be determined unambiguously using the first P-arrivals only. Seismic waveform data should be carefully re-examined using this method to investigate earthquake source properties and seismicity of the Taiwan Strait region.

(Key words: Taiwan Strait, Beam-forming, Seismic array, Relocation)

1. INTRODUCTION

The Taiwan Strait is situated on the continental shelf off the southeast China coast between the East China Sea and the South China Sea with an average water depth of less than 100 m. Its dimensions are 380 km and 190 km in the north-south and east-west directions, respectively. Regional stresses of the Taiwan Strait area are controlled by two tectonic forces, i.e., the compressional stress related to the arc-continent collision between the Philippine Sea plate and Eurasian continent and the extensional stress related to the opening of the South China Sea in the south. From a tectonic perspective, the Taiwan Strait is sandwiched between the arc-continental collision zone of Taiwan and the stable Eurasian continental regions. Geological and geophysical investigations in this region may provide strong constraints for the geotectonic evolution processes of the Taiwan Strait and the arc-continental collision evolution of the Taiwan island. From a seismological point of view, seismicity in the Taiwan Strait

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is much lower than that beneath Taiwan and it's eastern offshore region. However, several large historical (M > 6) earthquakes were reported to have occurred in the Taiwan Strait. The largest event was the 1604 Quanzhou earthquake with a magnitude near 8 (Lee et al., 1976, 1978; Kuo and Ma, 1988). This event induced extensive damage in the coastal region of Fujian province (Jia, 1994). However, due to incomplete documentation, it is difficult to re-examine source properties of large historical events in the Taiwan Strait in detail. The latest damaging event in the Taiwan Strait occurred on 16 September 1994. Earthquake damage was reported on the coastal area of Fujian (Peng and Lin, 1995). The epicenter was located offshore of southwestern Taiwan with a magnitude (M_s) of nearly 6.5 (Figure 1). This event was well recorded by the Global Seismic Network (GSN) and its source properties have been studied using global seismic data (Kao and Wu, 1996; Zheng et al., 1998), which provided, for the first time, important information on seismogenic conditions of intraplate earthquakes and present-day tectonic stress of the Taiwan Strait region. However, limited by the network resolution of the GSN, the exact location of this event and its aftershock distribution are still unknown. This event and its aftershocks were also poorly determined by the Central Weather Bureau Seismic

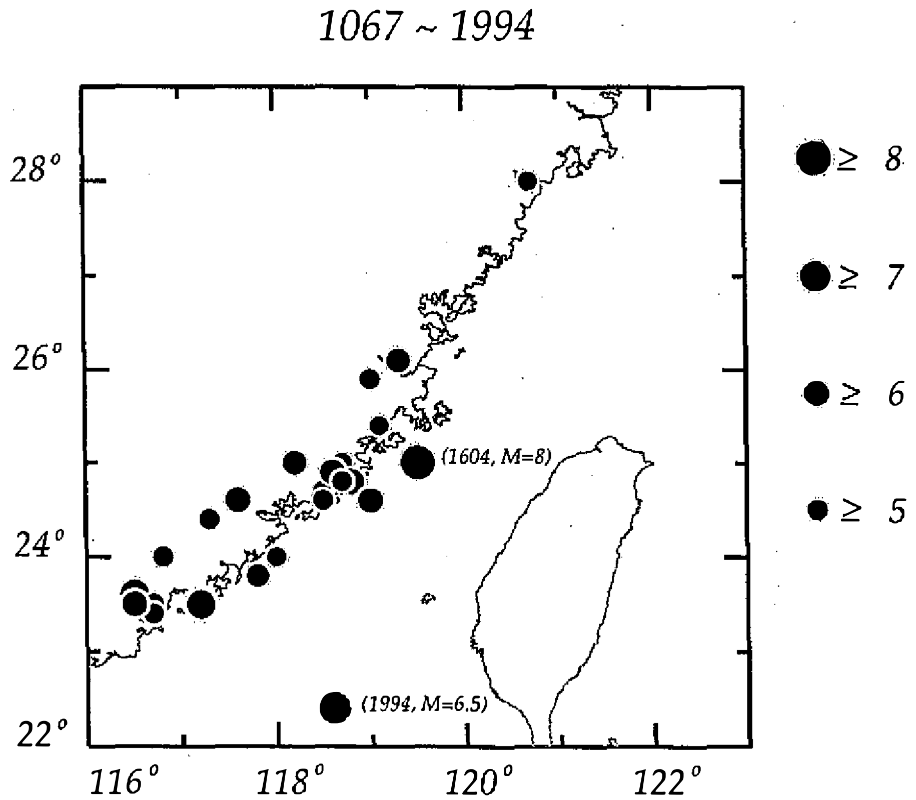


Fig. 1. Seismicity of major earthquakes of Quanzhou-Shantou and Taiwan Strait regions from 1067 to 1994 (Kuo and Ma, 1988). Two large earthquakes (1604 and 1994) are marked with their magnitude given.

Network (CWBSN) because the source area was located outside the CWBSN. This same situation occurs to those events analysed by the seismic network in Fujian.

Detailed analysis of source properties of the 16 September 1994 Taiwan Strait earthquake and reliable earthquake location for its aftershocks may provide key information to estimate earthquake risk and to reduce hazards in its surrounding area. In this study, regional seismic observations of the 16 September 1994 earthquake on both sides of the strait and nearby individual seismic observations reported by the International Seismological Center (ISC) bulletin were integrated to relocate this event utilizing the beam-forming method (Capon, 1973). The aim of this study is to discuss the uncertainties of earthquake locations associated with different data and methods and to suggest possible solutions to improve the epicenter location of Taiwan Strait earthquakes.

2. METHOD

Routine earthquake location is usually calculated by a computer program (e.g., HYPO71, HYPOELLIPSE) based on a one dimensional earth model (e.g., Lee and Lahr, 1975; Lahr, 1989). Generally, earthquake locations can be well determined if they occur inside a seismic network. However, for an event at a regional distance from a network, pinpointing its location can be very poor due to the uncertainties of the earth model, the insufficiency of the locating scheme and the distribution of distant seismic stations. It is equally difficult to determine a reliable location for the 16 September 1994 Taiwan Strait earthquake and its aftershocks using Taiwan and Fujian seismic data alone. Several methods have been proposed to improve the accuracy of earthquake location. Among them, Manchee and Weichert (1968) stacked seismic signals from the Yellowknife seismic array to determine incident phase velocity and azimuth of seismic waves across the array to locate earthquakes between 26° to 90°. Mykkeltveit and Ringdal (1981) located earthquakes at a regional distance based on frequency-wave number spectra computations using small-aperture seismic array. Chiu et al., (1998) determined regional earthquakes located outside of a network using groups of seismic station from a dense seismic network. Jih (1999) relocated the epicenter of an earthquake through triangulation using backazimuths derived from two skew large-aperture subnetworks or array. In this study, a beam-forming method (Capon, 1973) is proposed to locate earthquake epicenters at regional distances from a seismic network.

The beam-forming method has been used in seismic array data analysis to improve the signal-noise ratio (SNR) and to focus the high resolution properties of earthquake source and earth structure. In beam-forming, a delay τ_j is inserted into a time series $u_j(t)$. The time shifted signals are then averaged over all stations to increase the SNR. The averaged signal is called the beam and is given by

$$B(t) = \frac{1}{N}\sum_{j=1}^{N} u_j(t+\tau_j) \tag{1}$$

where N is the number of stations. According to this approach, the uncorrelated noise can be reduced to $1/N$ of the original signals. To locate earthquakes using the beam-forming method, we employ the concept shown in equation (1) and define the beam value $B(x,y)$ for any point with location coordinate (x, y) as

$$B(x,y) = \sum_i \left[\sum_{j=1}^{N} H_j A_{j,i+tj(x,y)} \right] \tag{2}$$

where N is the number of stations to be used, i is the time interval to be stacked, j is the station index and $tj(x,y)$ is the P-wave arrival time from a source with location coordinate (x,y) to station j. $A_{j,i+tj}$ is the amplitude of signal observed at station j during time period i which begins from time tj. H_j is the weighting factor of station j which is usually assumed to have a value between 0 and 1. Herein, the P-wave arrival time $tj(x,y)$ (travel time to be shifted) is calculated from point (x,y) to station j using a selected one dimensional earth model. To use equation (2) to locate earthquakes, we need to calculate the beam value B of all grid points of the source area according to seismograms recorded by each station. B will reach its maximum value at the true source location. By examining the B values of a source area, the earthquake location can be determined and its uncertainty can be estimated according to the distribution of B values.

In this study, we developed a program based on the beam-forming method [equation (2)] to locate earthquakes. Using this approach, no initial guess of the hypocenter is necessary and travel times from different station groups can be calculated according to their associated earth models. However, extensive computation is necessary for waveform stacking to obtain the B image and the computation time of the beam-forming method is longer than that using other traditional earthquake location algorithms, e.g., HYPO71.

3. DATA

Three sets of seismic readings were used in this study. The first was P-wave arrival times from the CWBSN. The P-wave arrivals can be unambiguously picked from seismograms recorded on CWBSN stations (Figure 2). After carefully examining recorded seismograms, 54 P-wave arrivals with clear initial phases were selected. These P-wave arrivals can be viewed as seismic wavefronts propagating over Taiwan island as shown in Figure 3. The wavefronts are relatively smooth with small azimuthal perturbations reflecting the complicated lateral crustal and upper mantle structure variations beneath Taiwan. Since most seismograms were off-scale immediately after the first P-wave arrivals as shown in Figure 2, no S-wave arrivals can be identified from the 3-component CWBSN data and only P-wave data are used for earthquake location. The second data set was P-wave arrival times reported by the Fujian seismic network, which were tabulated by Yeh (1995). However, no seismic waveforms are available to verify the data quality. Since the stations in Fujian have similar epicentral distances as those in CWBSN, we believe that those P-wave arrivals are reliable. The S-wave arrivals have also been compiled by Yeh (1995). However, as noted by the author, S-waves were off-scale for all seismograms that the S-wave arrivals were estimated according to the frequency change on seismic waveforms. Therefore, S-wave arrivals from seismic stations in the Fujian area are not used in this study. The third type of data were P-wave arrival times recorded by seismic stations in the Philippines which were reported in the ISC bulletin. Five

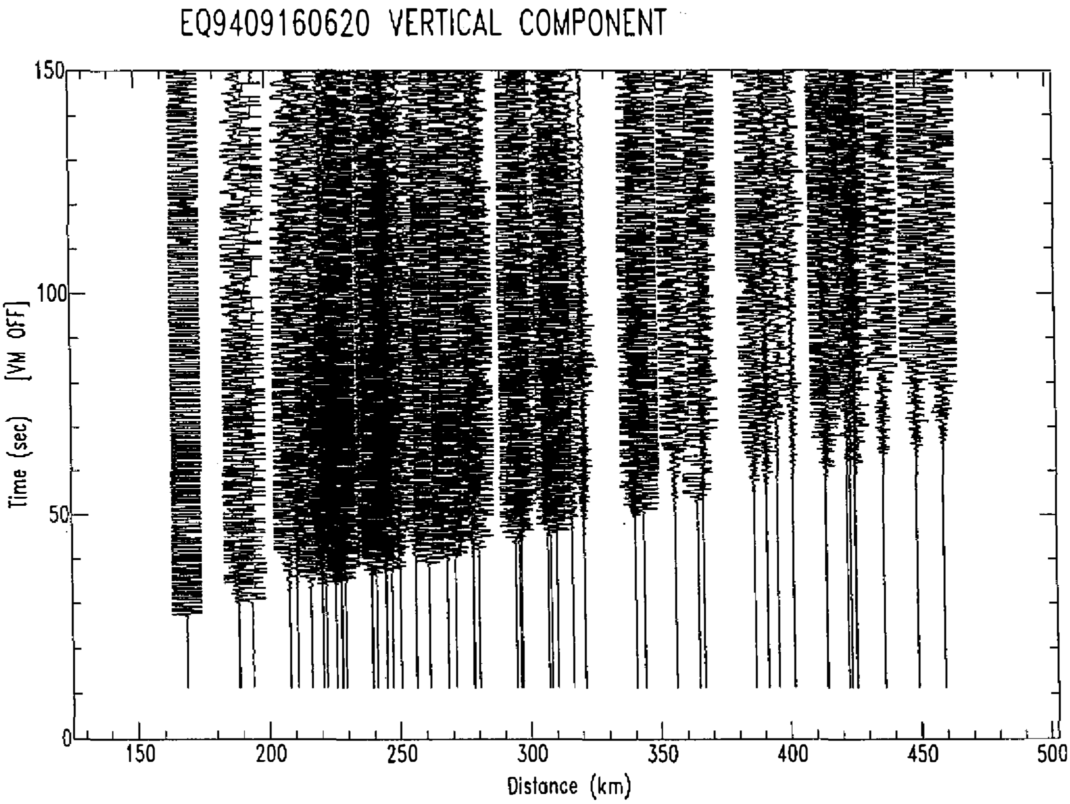


Fig. 2. Vertical Seismic profile of the 16 September 1994 Taiwan Strait earthquake recorded by the Central Weather Bureau Seismic Network. Each seismogram is over scale within a short time after the first P-arrival.

seismic readings with epicentral distances less than one thousand kilometers were selected for this relocation process.

In general, seismic data of the 16 September 1994 Taiwan Strait earthquake collected from CWBSN, Fujian seismic network and ISC bulletin have raypaths along different geological provinces. Seismic data recorded by CWBSN have long raypaths beneath Taiwan island. All seismic waves from the source to the Fujian area traveled mainly along continental paths. Seismic data reported in the ISC bulletin were observed in the Philippine islands. Their raypaths are mainly along oceanic plates. To ensure a reliable epicenter relocation using beamforming, different earth models have been used to compute seismic travel times for stations on different geological provinces. The seismic travel times for CWBSN stations were computed based on the crustal model of Yeh and Tsai (1981) which was determined using 1-D travel time inversion. Since most of the P-arrivals recorded by the CWBSN stations are Pn phases, the upper mantle velocity of Yeh and Tsai's model has been replaced by the Taiwan Strait model of Huang et al., (1998). The travel times of stations in Fujian were computed based on an earth model of Liao et al., (1988) which was determined from seismic explosion studies in the southeastern China area. The travel times for Philippine stations were computed based on the regional oceanic earth model of Yao et al., (1994).

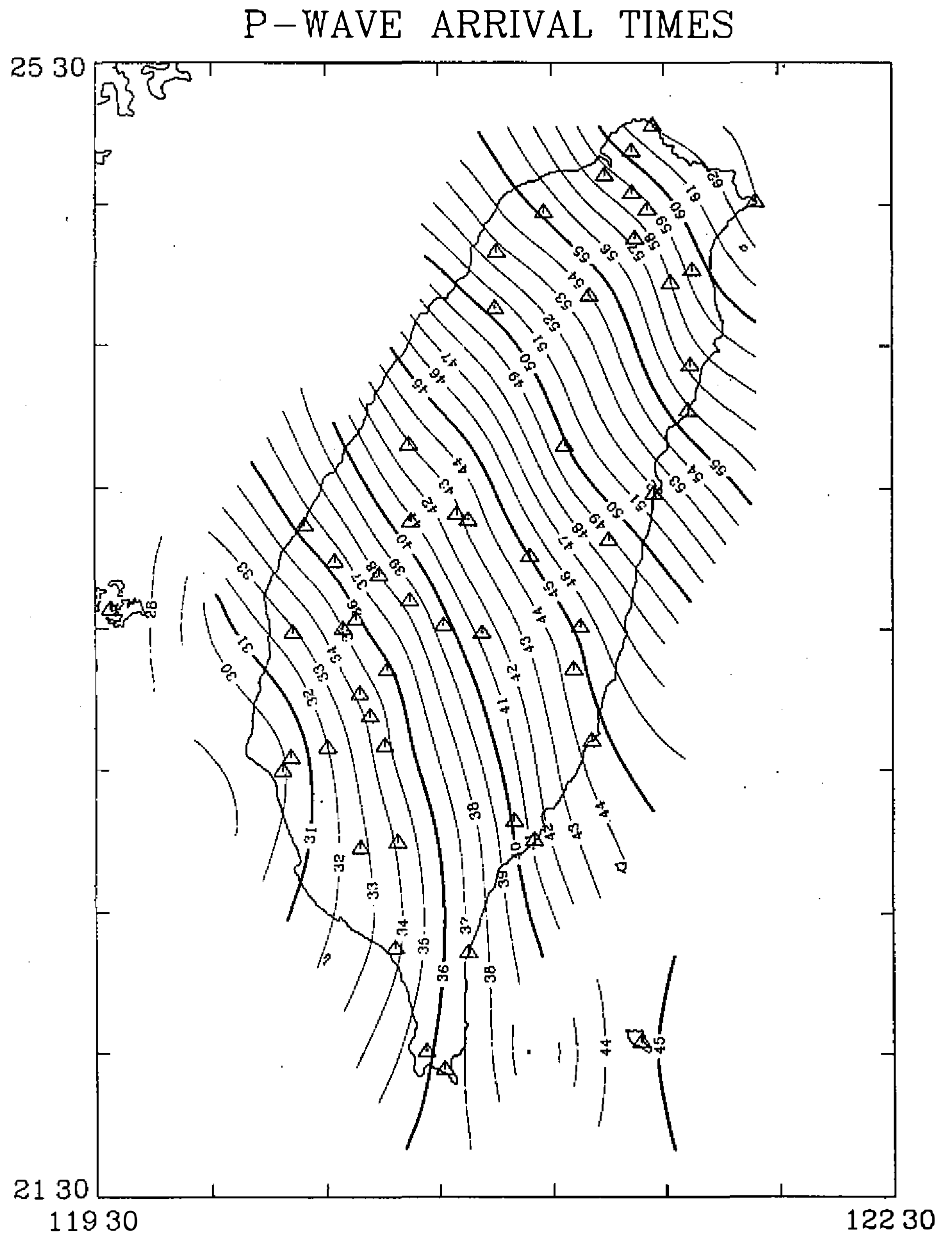


Fig. 3. P-wave wavefronts of the 16 September 1994 Taiwan Strait earthquake propagating over Taiwan area.

4. ANALYSIS AND RESULTS

To locate earthquakes using seismic data from different seismic networks, it is important to evaluate the fundamental differences among the networks, especially with regards to the reference timing system. However, in practice, it is difficult to examine the differences between the seismic networks of Taiwan and Fujian. Fortunately, station KNM (24.42° N, 118.43° E) of the CWBSN is very close to station SHM (24.44° N, 118.10° E) in the Fujian network. Relative time differences between KNM and SHM can be used to estimate the timing difference between the two networks. Using the epicenter previously determined by CWBSN or ISC, the epicentral distances of the above two stations are separated by about 13 km, which will account for an arrival time difference of about 1.6 sec calculated from the given Pn velocity in this region. However, the observed Pn arrival at station KNM was only 0.75 sec faster than that at station SHM. Thus, a travel time correction of 0.85 sec has been added to all stations in the Fujian area. Since seismic arrivals reported in the ISC bulletin were based on individual clocks in each station, no correction was possible for those stations.

Using the beam-forming method and accounting for all possible systematic travel time corrections, the epicenter of the 16 September 1994 Taiwan Strait earthquake was determined at latitude 22.37° $\pm$ 0.03°N and longitude 118.63° $\pm$ 0.03°E (Figure 4). As a formal error is difficult to specify with the beam-forming method, we use the region with beam values greater than 90% and pick beam amplitude as a conservative estimate of uncertainty. For comparison, epicenters of this event reported by different earthquake catalogues are listed in Table 1. It is found that the maximum location uncertainties from different catalogues are 0.29° and 0.28° for longitude and latitude, respectively. The aftershock region of this event determined by the CWBSN is within this location uncertainly (see Figure 5 of Kao and Wu, 1996). It is risky to attempt to integrate aftershock information from different earthquake catalogues to discuss seismicity of the Taiwan Strait region. Furthermore, the error estimations for earthquake locations are incomplete and not consistent among those catalogues. It is difficult to evaluate the location accuracy of Taiwan Strait earthquakes. As shown in Figure 4, the beam-forming method can provide estimates of uncertainty in the relocation process. Using the seismic data from CWBSN and the Fujian seismic network independently, the potential source regions are elongated away from the network and mostly probably the intersection of the two elongated potential source regions is the actual epicenter (Figure 5). Since there was only one observation (station BBP, $\Delta = 3.64°$, Batan islands, Philippines) with similar epicentral distance comparable to that from Taiwan and Fujian regions, seismic data from the ISC bulletin have been assigned a very low weight, which will only slightly affect the determination of the epicenter.

5. DISCUSSION AND CONCLUSION

Comparing Figure 4 and 5, we show that joining network data from Taiwan and Fujian can significantly reduce the uncertainties of earthquake epicenter location in the Taiwan Strait. We have also noticed that a reasonable earthquake location in the Taiwan Strait can be achieved for a routine earthquake location using CWBSN alone, even though the uncertainties may be

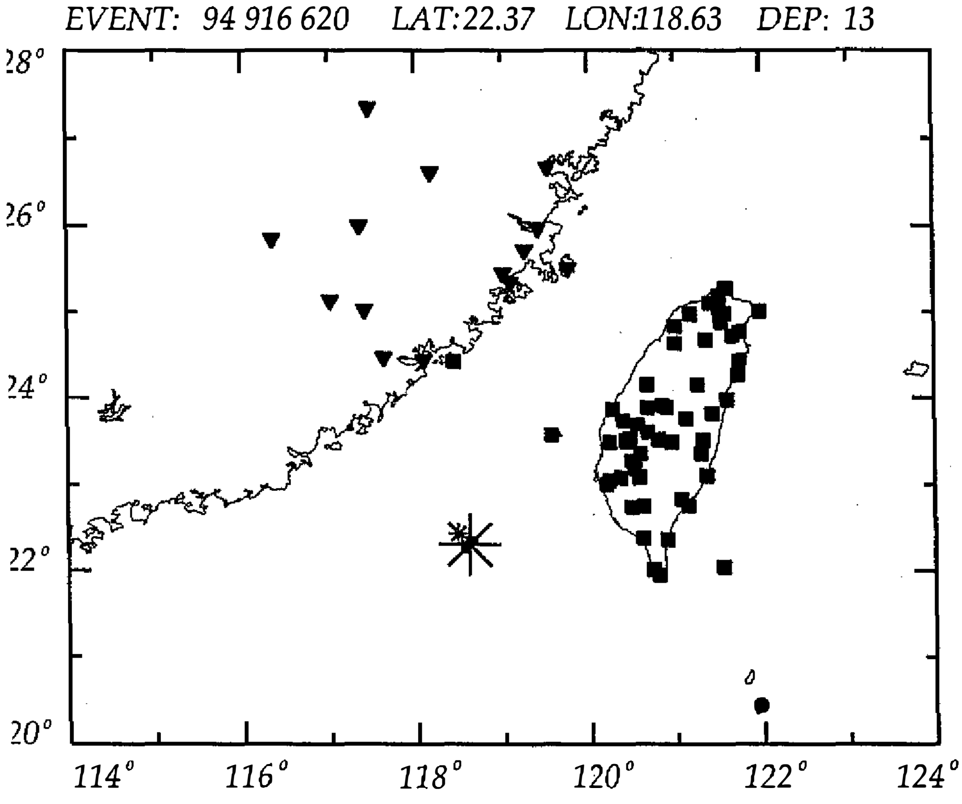


Fig. 4. Relocation of the 16 September 1994 Taiwan Strait earthquake using the beam-forming method using seismic data from CWBSN (solid square), Fujian Seismic network (Solid triangular) and ISC bulletin (solid circle). The determined epicenters are shown as large and small stars for this study and CWBSN, respectively. The small blocks nearby the epicenter represent the uncertainty area of the epicenter determined using beam-forming analysis.

relatively large (see Figure 4 and 5). This is likely due to the high station density in Taiwan. Because only data from a limited number of seismic stations in the Fujian network are available, it is difficult to evaluate the location capability of the Fujian seismic network for earthquakes in the Taiwan Strait. Since the beam-forming method is capable of locating regional earthquakes far from the seismic arrays, aftershocks of the 16 September 1994 event can be relocated to investigate their spatial distribution and tectonic implications. The beam-forming method has advantages of global searching, (no initial guess of hypocenter is needed) and flexible model selection (travel times at different station groups can be calculated using different earth models). Our efforts in this study have already stimulated other efforts to relocate other major events at regional distances from the CWBSN.

Table 1. Hypocenter locations from different earthquake catalogues.

	Latitude (deg)	Longitude (deg)	Depth (km)
This study	22.37 (±0.03)	118.63 (±0.03)	13[1]
CWBSN	22.43	118.47	19
Fujian	22.66	118.75	—[2]
ISC	22.52	118.75	19
NEIC	22.53	118.71	13

1. Source depth determined by Kao and Wu (1996) from waveform modeling.

2. Source depth was not reported by Fujian seismic network.

Since the 16 September 1994 Taiwan Strait earthquake was located at a regional distance from any CWBSN station (epicentral distance more than 170 km) and this event has been verified to be a shallow event inside the earth's crust (Kao and Wu, 1996), the first arrival should be a Pn-wave. The beam-forming method has poor resolution for determination of source depth because a trade off between source depth and origin time exists. Therefore, we adapted the source depth of Kao and Wu (1996) where surface reflection phases (e.g., pP, sP) of P-wave at teleseismic distances were used to determine the depth. It is, however, not as easy to determine the source depths of aftershocks as it is to determine the source depth of the mainshock.

The source location of the 16 September 1994 Taiwan Strait earthquake is near the northern boundary of the Tainan Basin as shown in Figure 6. Tainan basin is one of the Tertiary basins along the southeastern Chinese continental margin (Sun, 1985). This basin is characterized by extensional normal faults which trend mainly in NE/SW and E/W directions (Yang et al., 1991). These normal faults are considered directly related to the opening of the South China Sea and continental rifting during the Early Oligocene to Middle Miocene (Yu, 1990). After the Late Miocene, the spreading of the South China Sea ceased and substantial thermal basin subsidence occurred.

The source mechanism of this event consistently shows a pure normal faulting with two nodal planes striking approximately E/W as shown in Figure 7 (Dziwonski et al., 1995; Kao and Wu, 1996; Zheng et al., 1998). Kao and Wu (1996) and Zheng et al., (1998) also indicated anomalous high stress drop for this event. The N/S extension may be considered as a representation of regional stress in the source area. It also indicates that, in the deep crust, normal faulting processes are active in the historically subsiding Tainan basin. However, the N/S

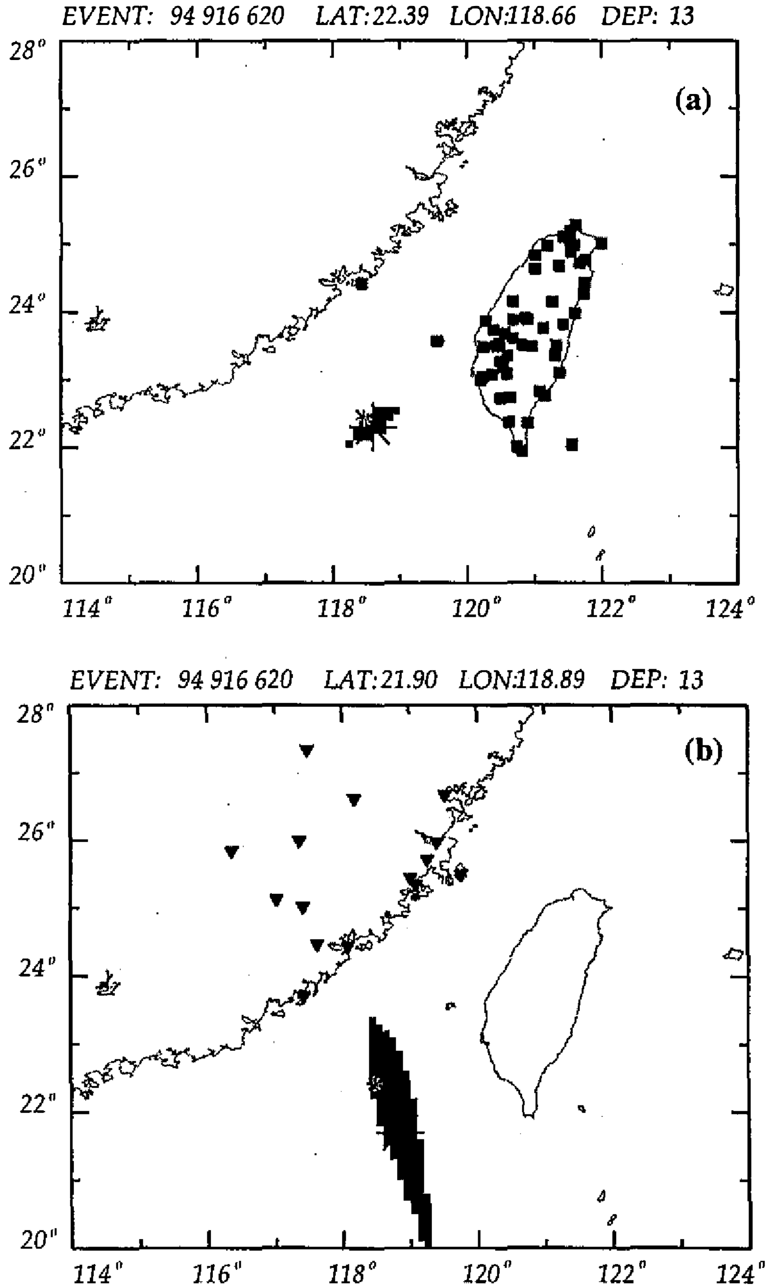


Fig. 5. (a). Earthquake relocation by the beam-forming method using CWBSN data alone. (b). Earthquake relocation by the beam-forming method using data from the Fujian Seismic Network alone. The definitions of symbols are the same as in Figure 4.

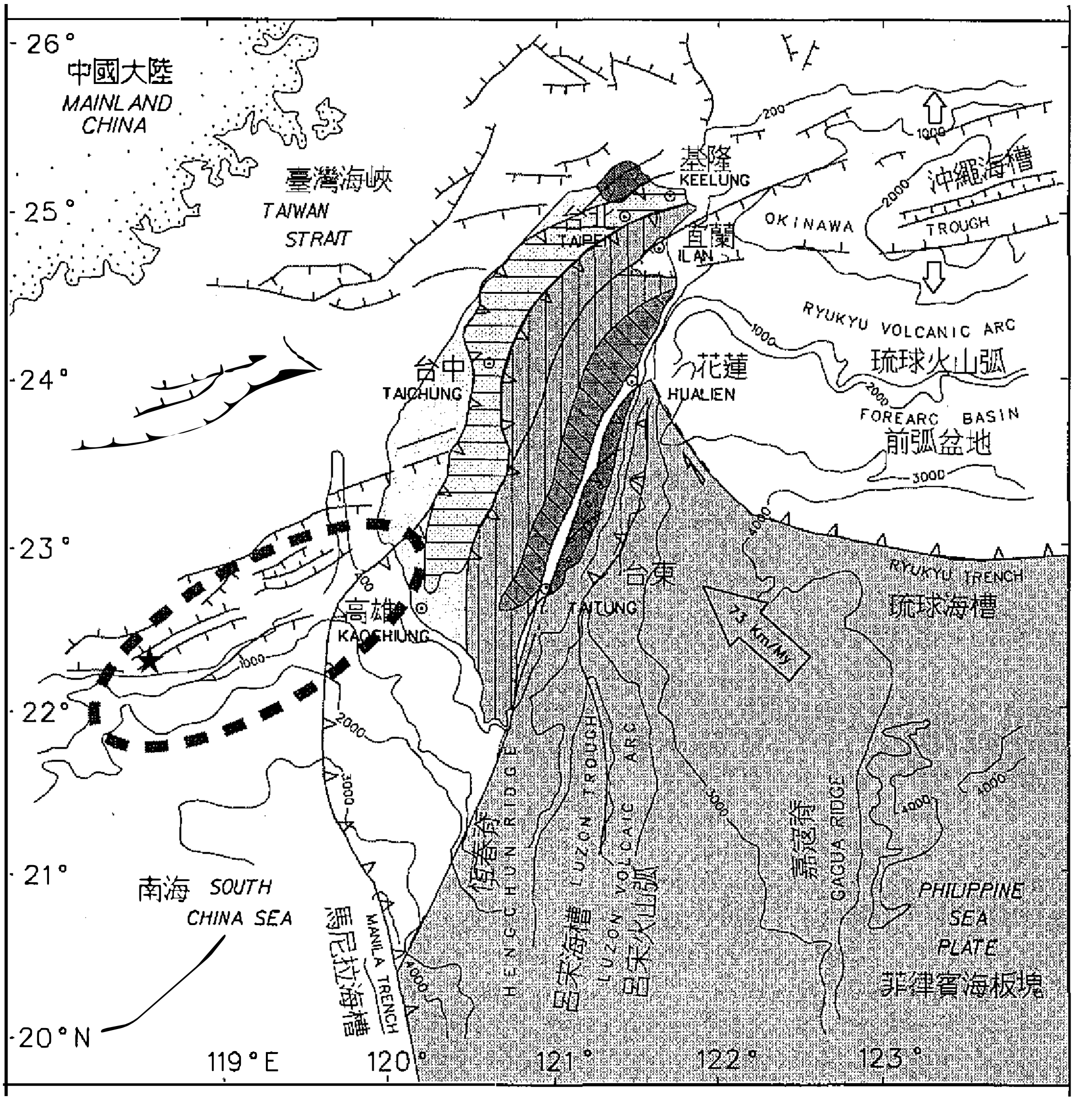
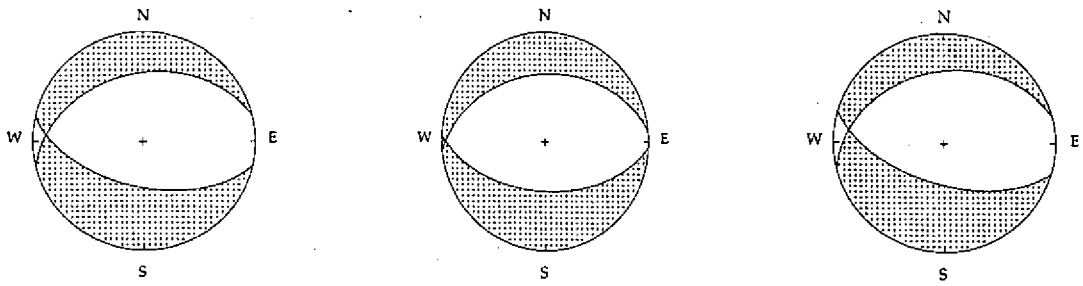


Fig. 6. Map showing the geological and tectonic settings near Taiwan (modified from Lee et al., 1997). The 16 September 1994 earthquake (symbol star) was located in the northern boundary of the Tainan basin (simplified as dashed ellipsoid).

regional extensional stress is difficult to explain from our current knowledge of tectonic process near the source region. Kao and Wu (1996) proposed a model with an N/S mantle flow under the crust of the Taiwan Strait to help explain this discrepancy. Further study of aftershocks from this event and other seismic activities in the region will provide important information for our understanding of seismogenic mechanisms in the Taiwan Strait. Actually, the



(a) (b) (c)

Fig. 7. The best double couple fault plane solutions of the 16 September 1994 Taiwan Strait earthquake determined by different groups. (a) Kao and Wu (1996), (b) Zheng et al. (1998) and (c) The Harvard solution (Dziwonski et al., 1995).

aftershock distributions which were independently determined by CWBSN and Fujian seismic networks, were previously employed to explain the regional tectonic stress of the source region. Based on the poorly constrained aftershock distributions of the 16 September Taiwan Strait earthquake, Kao and Wu (1996) and Zheng et al., (1998) explain this event and its tectonic implications as being related to different nodal planes.

There are two solutions to improve the earthquake locations for Taiwan Strait events. First, joint seismic data from the Taiwan and Fujian seismic networks can significantly improve the accuracy of epicenter locations in the Taiwan Strait. Secondly, the routine earthquake locations of the CWBSN can provide a reasonable location for the Taiwan Strait events. The capability of the CWBSN for locating Taiwan Strait events can be significantly improved if additional seismic stations can be installed on an island at regional distances from southwestern Taiwan or a few ocean-bottom seismometers can be deployed in the Taiwan Strait. In addition, a detailed analysis of crustal structure of the Taiwan Strait from marine seismic profiles using explosions or large airguns could also improve the capability of the CWBSN for earthquake location in the Taiwan Strait.

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