

## Aftershock Observations of the 1999 Chi-Chi, Taiwan Earthquake

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### Abstract

We conducted aftershock observations of 20 September, 1999 Chi-Chi, Taiwan Earthquake beginning 15 days after the main shock. We deployed 20 seismographs twice in a 100 km by 100 km area around the focal area of the main shock. Each observation period lasted one month. Two months of observations yielded about 80 GB of continuously recorded aftershock data, from which a large number of aftershocks are identified. Among these we located 736 aftershocks from a four-day record. Taking lateral heterogeneity in the crustal structure into account, we have a clear distribution of the aftershocks. There are three particular trends in the east-west cross-section: an east-dipping plane, a nearly flat plane distribution, and a deeper cluster. These trends correspond to the fault plane of the main shock, the hypothesized decollement between the accretionary wedge, and the upper boundary of the Eurasian Plate, and intra-plate activity respectively.

**Key words:** Chi-Chi Taiwan earthquake, aftershock distribution, temporary observation, decollement

### 1. Introduction

On September 20, 1999 UT (September 21 Local time), an earthquake with a local magnitude of ( $M_L$ ) 7.3 ( $M_s=7.7$ ) occurred in central Taiwan. The Island of Taiwan is located on the boundary between the Eurasian and Philippine Sea plates; the two plates either collide with each other or one plate is being subducted (Fig. 1). The Eurasian Plate is subducting eastward beneath the Philippine Sea Plate in southern Taiwan. In northern Taiwan, the Philippine Sea Plate is subducting northward beneath the Eurasian Plate at the Ryukyu Trench. In central of Taiwan, there is a collision boundary between the two plates (Seno, 1994). The location of the boundary in middle Taiwan is not well defined: one possibility is that the boundary lies in western Taiwan, eastern bounds of the foothill plain, and the other is that the Longitudinal Valley in eastern Taiwan is the plate boundary. The convergence rate of 7.1 cm/y between the two plates (Seno *et al*, 1993) is rapid and the central mountain range of Taiwan has a high erosion rate of 5.5 cm/y (Li, 1975).

The earthquake, named for the nearby town of Chi-Chi, was followed by numer-

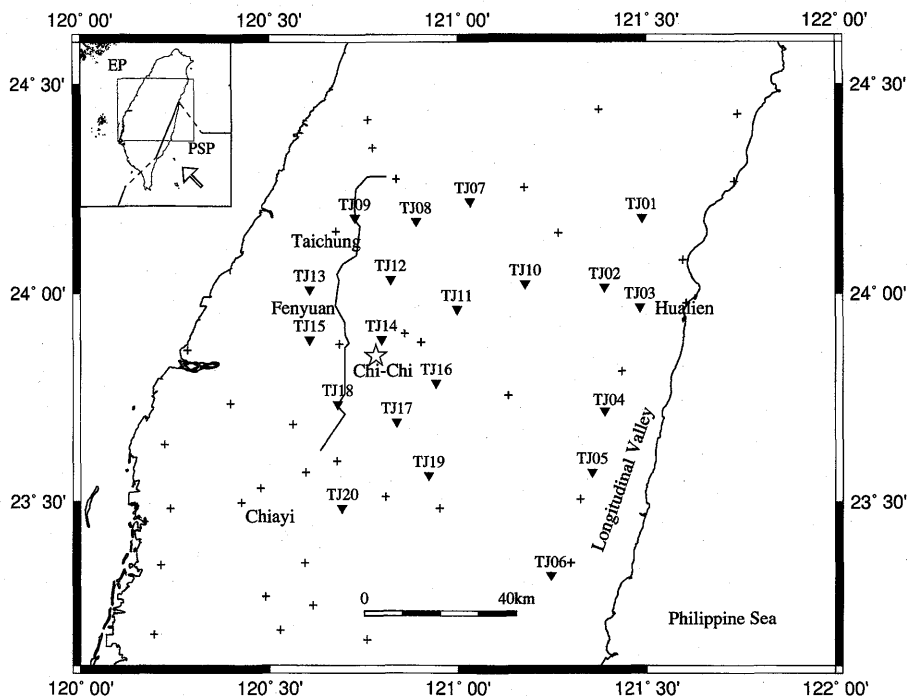


Fig. 1. Temporary seismic stations deployed for this study (▼) and permanent seismic stations operated by the CWB (+). Surface rupture is shown by a solid line. Inset shows the location of this study on a simplified tectonic map of Taiwan (EP, Eurasian Plate; PSP, Philippine Sea Plate).

ous aftershocks including five large aftershocks with a local magnitude ( $M_L$ ) of 6.0 or more in one week. Through November 8, eight large aftershocks ( $M_L \geq 6$ ) occurred in and around the focal area, including the November 2, 1999, earthquake ( $M_L = 6.9$ ) southeast off Hualien city. The aftershock area extends about 100 km in both the north-south and east-west directions (Fig. 2). The aftershock activity seems to coincide with the area of active background seismicity of central Taiwan. The eastern limit of the aftershocks lies at the boundary between the seismically active and the inactive areas beneath the central mountains.

In Taiwan, 75 telemetered seismic stations are operated by the Central Weather Bureau (CWB) (Wu *et al.*, 1997). Although the station spacing of this seismic network is sufficient to monitor felt earthquakes, detailed spatial distributions of the aftershock activity are not well constrained by the CWB data. Ten stations are located in the vicinity of the focal area, but some of them were damaged by the main shock, and were not available for the aftershock study. To understand the detailed aftershock distribution in space and time, we deployed 20 temporary seismic stations in the 100 km by 100 km focal area beginning 15 days after the main shock.

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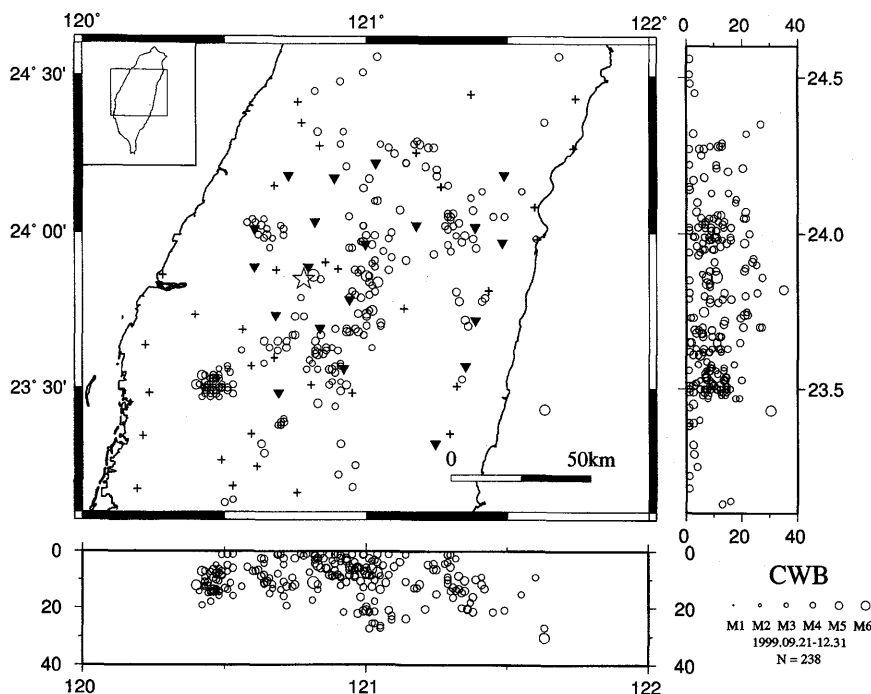


Fig. 2. Aftershock distribution from September 21 to December 31, 1999 reported by the Taiwan Central Weather Bureau. Data are from a web page of the CWB (<http://www.cwb.gov.tw/>). The star indicates the location of the mainshock.

## 2. Observation

We started to deploy 20 temporary seismic stations on October 5, 15 days after the main shock. The stations are distributed between permanent seismic stations operated by the CWB (Fig. 1). We designed the configuration of the temporary stations so that both the permanent and the temporary networks complement each other.

Each temporary seismic station consists of a 3-component, 1-Hz seismometer, a 16-bit digital recorder operating at a sampling rate of 100 Hz and a GPS receiver for timing (Shinohara *et al.*, 1997). The GPS data were recorded every four hours. The battery-powered recorders ran continuously for 40 days, and we re-deployed the seismographs in mid-November to continue observations until the mid-December. Some seismic stations were installed in public schools or temples in small towns and the others were along roads. One of the stations, TJ09, was located near the Chelungpu Fault (Photos 1,2,3). Locations and periods of operation of each temporary seismic station are listed in Table 1.

Three persons from the Earthquake Research Institute (ERI) visited Taiwan for two weeks to deploy the seismographs, and one seismologist from Taiwan National

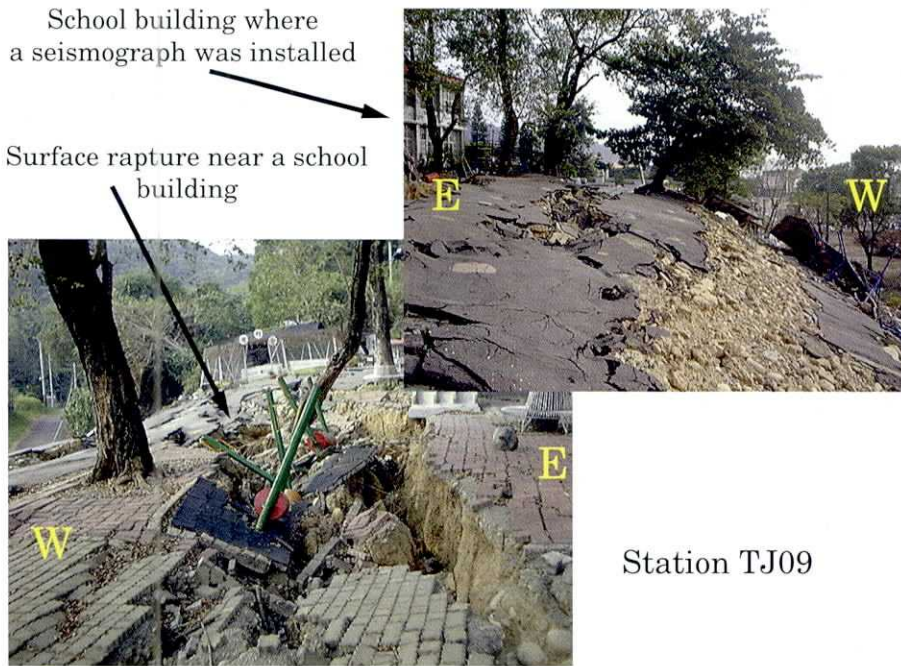


Photo 1.

Station TJ09



Photo 2.

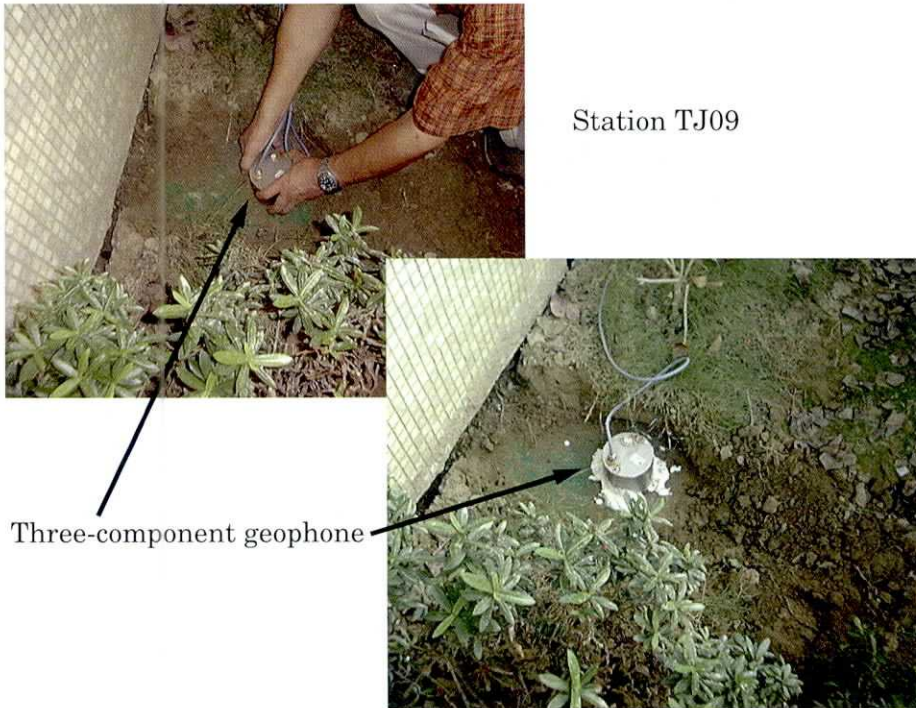


Photo 3.

Central University participated in the deployment. For the second deployment, one seismologist and two technicians visited Taiwan from ERI. The instruments were retrieved by two technicians from ERI and one assistant acting as an interpreter from the Institute of Earth Science, Academia Sinica. The personnel are tabulated in the Appendix.

### 3. Data Processing

Because we recorded ground motion continuously, we processed the data for editing after the observations. We obtained about 80 GB of digital records in total. We first decompressed the original field data, which are compressed at recording, and converted them into the win format (Urabe, 1994) routinely used in the Earthquake Research Institute for telemetered seismic observations. During decompression we used the GPS data to calibrate the internal clock of the recorder. The corrected data have a timing error of 1 ms or less, which is sufficient for phase picking.

During conversion into the win format we multiplexed the data from all stations to have a common time base. We detected seismic events on the multiplexed data to make event files. The event files were scanned by an automated phase picker to get *P*- and *S*-wave arrival times. We examined all event files again by eye to confirm whether the automatically picked phase data were correct or not, especially for



Table 1. Station locations and station corrections of the temporary observation sites.

Code	Latitude(N)			Longitude(E)			Elevation m	Date of operation	Correction		Station name	
	(1)	(2)	(3)	(1)	(2)	(3)			P(s)	S(s)		
TJ01	24	10	53	121	29	12	520	10/14 - 12/20	-0.21	-1.22	天祥	Tianshiang
TJ02	24	0	57	121	23	12	1220	10/13 - 12/19	-0.22	-1.02	盤石	Panshi
TJ03	23	58	2	121	28	54	190	10/13 - 12/19	0.01	-0.55	銅門	Tongmen
TJ04	23	42	46	121	23	53	180	10/12 - 12/19	-0.05	-1.14	萬榮	Wanrung
TJ05	23	34	18	121	21	11	200	10/12 - 12/19	0.16	-1.00	富源	Fuiuan
TJ06	23	19	16	121	14	40	250	10/12 - 12/19	-0.06	-0.58	鹿鳴	Luming
TJ07	24	13	13	121	1	57	920	10/11 - 12/20	-0.09	-0.96	谷關	Gugan
TJ08	24	10	22	120	53	15	540	10/11 - 12/20	0.34	-0.05	和平	Heping
TJ09	24	10	50	120	43	36	170	10/12 - 12/20	1.64	2.31	軍功	Jungung
TJ10	24	1	23	121	10	38	1080	10/07 - 12/22	-0.13	-1.12	廬山	Lushan
TJ11	23	57	42	120	59	48	620	10/07 - 12/22	-0.02	-0.90	埔里	Puli
TJ12	24	2	0	120	49	12	340	10/10 - 12/22	0.65	0.63	清涼	Chinglieng
TJ13	24	0	31	120	36	23	140	10/10 - 12/22	1.65	2.60	芬園	Fenyuan
TJ14	23	53	20	120	47	45	240	10/10 - 12/21	0.89	1.19	中寮	Jungliau
TJ15	23	53	16	120	36	20	160	10/10 - 12/22	1.49	2.14	朝興	Chaoshing
TJ16	23	47	5	120	56	26	610	10/08 - 12/21	-0.11	-0.89	雙龍	Suanlung
TJ17	23	41	29	120	50	10	580	10/08 - 12/21	0.49	0.37	信義	Shinyi
TJ18	23	44	3	120	40	51	210	10/12 - 12/21	1.25	1.76	秀林	Shiulin
TJ19	23	33	47	120	55	15	1140	10/09 - 12/21	-0.10	-0.72	東埔	Dongbu
TJ20	23	29	3	120	41	30	1480	10/09 - 12/21	****	****	石卓	Shizhuo

(1) degree, (2) minute, (3) second, \*\*\*\*: not used for the present work.

S-phase pickings. Because the aftershock activity was very high, with aftershocks occurring almost every 10 s (Fig. 3), we first processed the data from the first four days to see the spatial distribution of the aftershocks. We present preliminary results for the first four days of data in this report.

#### 4. Analysis

We located 736 aftershocks during the period from October 11 to 14, 1999. The total number of aftershocks in this period is greater than those we located, because at this stage we have not processed the entire record. We first tried to locate the aftershocks using the one-dimensional velocity model (Fig. 4) used by the CWB (Chen, Y.L., 1995). The resulting distribution shown in Fig. 5 is nearly the same as that reported by the CWB (Fig. 1).

We found a systematic residual in travel times for each station by carrying out an iterative analysis of station delays and hypocenters. First, we located aftershocks and calculated the mean residual arrival times for *P*- and *S*-waves at every station. We then used these values for station correction, relocated the hypocenters,

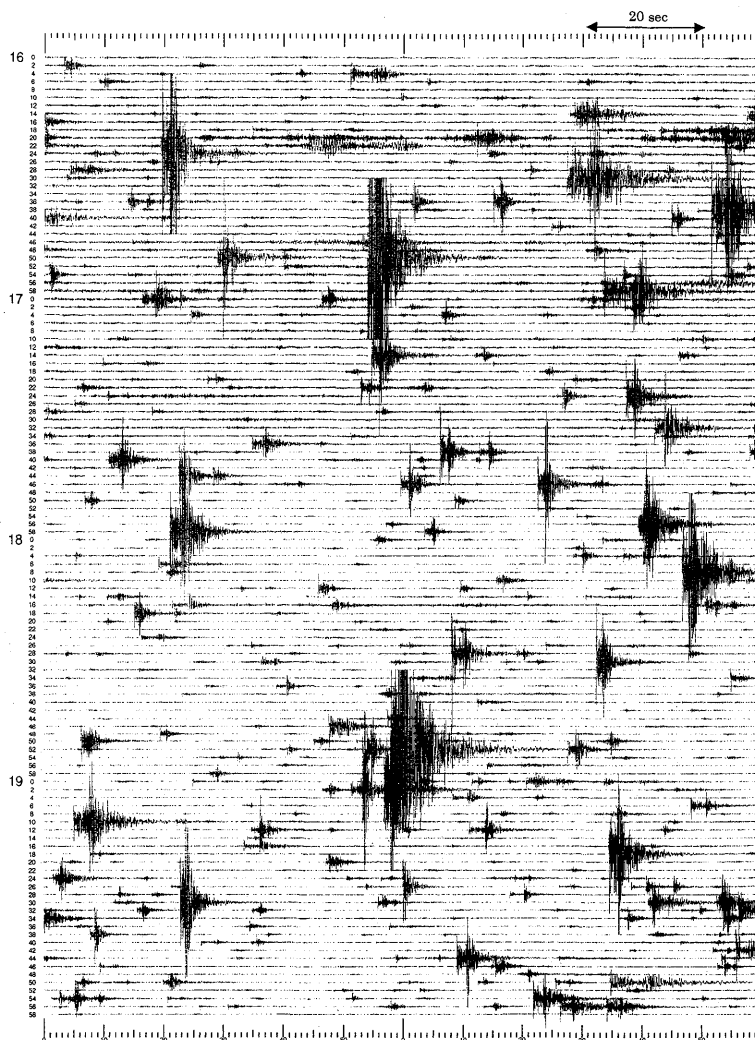


Fig. 3. Example of the waveform data from the aftershocks. Continuous seismic data for 4 hrs recorded at station TJ10 are shown (Oct. 12. 16: 00-20: 00. UT).

and computed new station corrections. We repeated the procedure several times until we got almost identical hypocentral distributions after iteration. We have relatively large final station corrections for both *P*- and *S* arrivals, suggesting lateral heterogeneity in the crust. The estimated station corrections are listed in Table 1. More detailed studies of the crustal heterogeneity will appear elsewhere.

## 5. Results

We show hypocenters of the aftershocks with station corrections in Fig. 6. The microseismic activity is distributed in an area of 100 km in both the north-south and

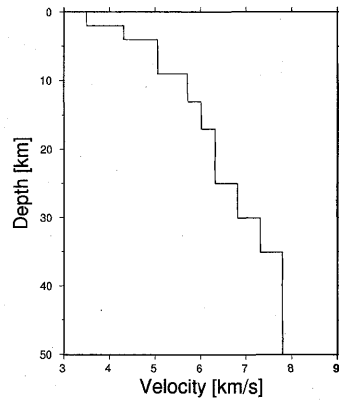


Fig. 4. Velocity model used by the CWB (Chen, Y.L., 1995).

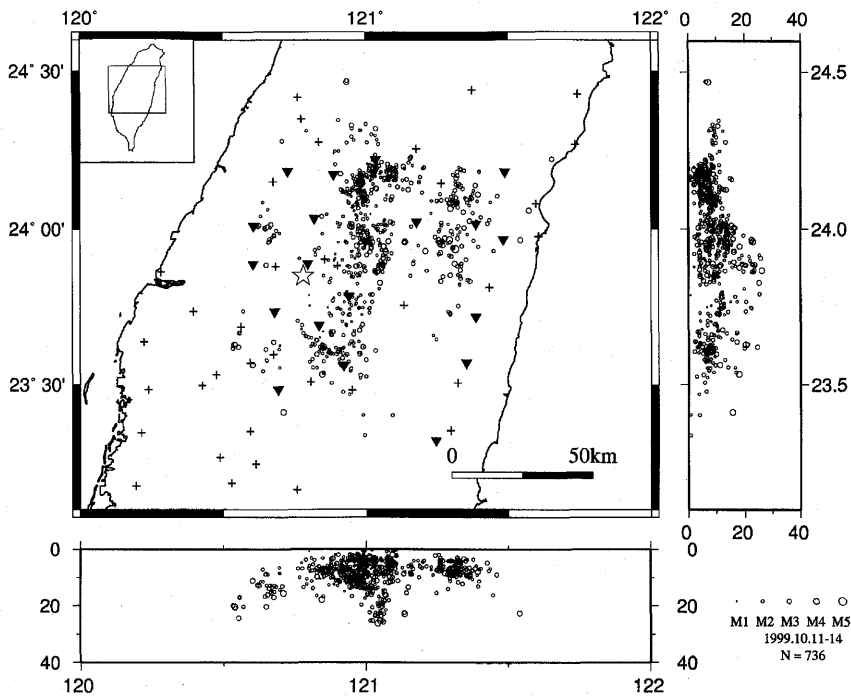


Fig. 5. Aftershock distribution determined by temporary seismic observations without station corrections. The distribution during Oct. 11 to 14 is shown.



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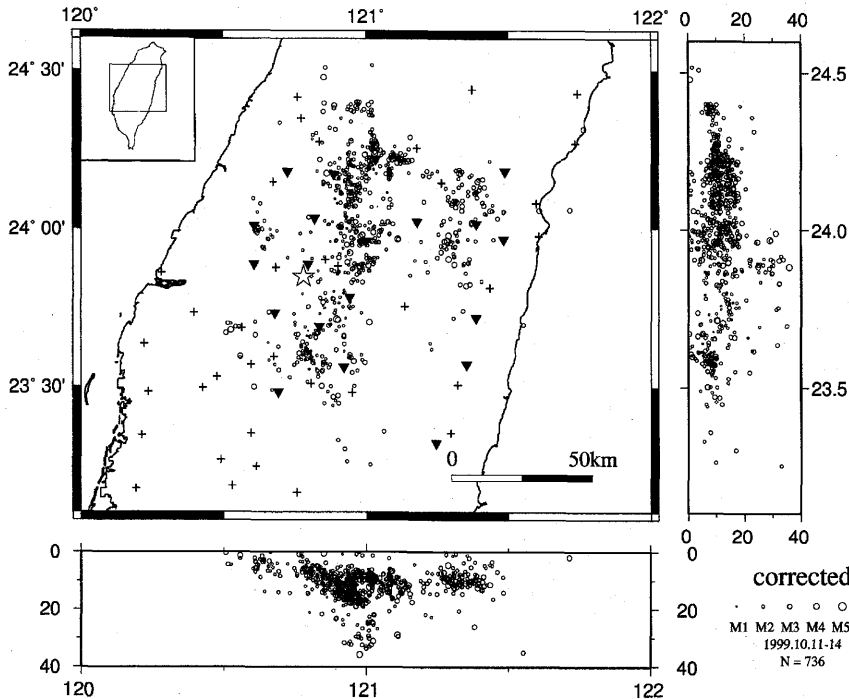


Fig. 6. Aftershock distribution determined by the temporary seismic observations after station corrections. The distribution during October 11 to 14 is shown.

east-west directions. The western boundary of the seismicity coincides in general with the surface trace of the Chelungpu fault, but there is minor activity west of the fault. Within the area are several clusters. Some of them occurred immediately after the main shock and the other started to be active since October 22, 1999. The former includes the cluster near Fenyuan (Station TJ13) and the latter comprises aftershocks of the  $M_L=6.4$  earthquake near Chiayi.

The east-west cross section shows three particular trends in the distribution of hypocenters. The first is an east-dipping distribution with a dip angle of about 30 degrees. The trend projects to the surface at the Chelungpu Fault. The strike and the dip of this aftershock trend are consistent with the focal mechanism of the main shock (Kikuchi and Yamanaka, 1999). The second trend is a very low angle or almost flat cluster at a depth of about 10 km. From the east-west profile in Fig. 6, the flat and the east-dipping distributions seem to intersect each other. However, in a horizontal section, the flat activity is located in the northern area and the east dipping trend lies in the middle to southern area of the aftershocks. The third cluster lies at depths from 20 to 30 km, apparently deeper than the other clusters and 20 km east of the main shock.

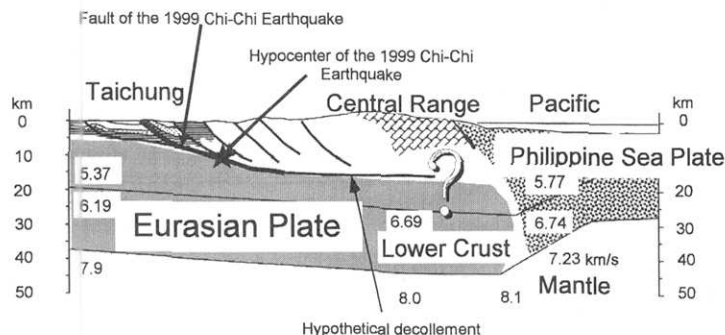


Fig. 7. Schematic model for the crustal structure of Taiwan and the 1999 Chi-Chi, Taiwan, Earthquake. Numbers are  $P$ -wave velocities in km/s from Shih *et al.* (1998).

## 6. Discussion

In western Taiwan a west-vergent thrust system is well developed with a NS strike parallel to that of the Island of Taiwan itself. This fold-and-thrust belt mainly deforms late Tertiary sedimentary rocks. The collision tectonics started in the Pliocene, and the area has suffered an intense shortening deformation (Page and Suppe, 1981). The geologic structure is characterized by a well-developed fold-and-thrust belt very similar to that found along the trench slope of subducted plate (Fig. 7). Sedimentary material has been thickened by thrusting due to the eastward subduction of the Eurasian Plate. The westward migration of the thrust front is well recorded in the sedimentary successions in western Taiwan.

The preliminary analysis of the aftershock activity suggests that the 1999 Chi-Chi, Taiwan Earthquake occurred along the base of the accreted material and cuts to the surface on a thrust fault (Suppe, 1981, Sato and Hirata, 1999). We observed active seismicity at a depth of 10 km, which may correspond to the decollement between the Eurasian Plate and the accretionary wedge (Fig. 7).

According to a teleseismic study, the Chi-Chi Earthquake has a seismic moment  $M_0$  of  $2.4 \times 10^{20}$  Nm ( $M_w = 7.5$ ) and an average stress drop of 3.3 MPa with an assumed fault area of  $80 \times 40$  km<sup>2</sup> (Kikuchi and Yamanaka, 1999). The estimated stress drop,  $\Delta\sigma$ , is smaller than that of a typical inland earthquake such as the 1995 Hyogoken-nanbu, Kobe, Earthquake ( $\Delta\sigma = 10$  MPa), but is similar to that of the plate boundary earthquakes that occur in trench areas. Because the average stress drop,  $\Delta\sigma = 2.5 M_0/S^{1.5}$ , where  $S$  is the area of the fault, depends on both  $M_0$  and  $S$ , if  $S$  is larger than that used for their estimate, then  $\Delta\sigma$  can be smaller. The small  $\Delta\sigma$  suggests that the Chi-Chi earthquake has similar characteristics to that of a plate boundary earthquake near the oceanic trench. Moreover, Seno (2000) claims that the Chi-Chi earthquake is a subduction zone earthquake.

There have been several large earthquakes in Taiwan in this century, including the 1906 Chiayi Earthquake ( $M_s = 6.8$ ) and the 1935 Taichung Earthquake ( $M_s = 7.1$ ),

between which the Chi-Chi earthquake occurred. To fully understand the tectonics that generated the Chi-Chi earthquake, we will need to synthesize both seismic and geodetic observations, especially data from recent GPS observations (e.g., Yu *et al.*, 1997).

## 7. Conclusions

We conducted aftershock observations for the 1999 Chi-Chi, Taiwan Earthquake for two months. We deployed 20 seismic stations in and around the focal area of the main shock. We continuously recorded ground velocity and later extracted the aftershock records. We analyzed 736 aftershock records, from which a distribution of the aftershock hypocenters was derived. Taking lateral heterogeneity of the crustal structure into account, we obtained clear depth distributions of the hypocenters. The east-dipping distribution is consistent with the fault plane solution of the main shock. A flat or very low angle distribution of seismicity coincides with the hypothesized decollement between the accretionary wedge and the upper boundary of the Eurasian Plate. The data we obtained may provide key information to help understand the tectonic processes that generate large earthquakes at convergent plate boundaries.

## Acknowledgments

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## References

- CHEN, Y.L., Three dimensional velocity structure and kinematic analysis in Taiwan area, Master's thesis, National Central University, 172 pp., 1995 (in Chinese).
- KIKUCHI, M. and Y. YAMANAKA, EIC Seismological Note, No. 66, Earthq. Res. Inst., 1999 (in Japanese).
- LI, Y.H., Denudation of Taiwan island since the Pliocene Epoch, *Geology*, 4, 105-107, 1975.
- PAGE, B.M. and J.F. SUPPE, The Pliocene Lichi Melange at Taiwan: its plate tectonic and

- olistostromal origin, *Amer. J. Sci.*, **281**, 193-227, 1981.
- SATO, H. and N. HIRATA, Exploration of a deep structure of the Intra-arc large Earthquake, *Kagaku*, **70**, 58-65, 2000 (in Japanese).
- SENO, T., Tectonics in Taiwan, Zisin (*J. Seism. Soc. Jpn.*), **2**, **46**, 461-477, 1994.
- SENO, T., The Sept. 20, 1999 Chichi Earthquake in Taiwan as implication for tsunami earthquakes, submitted to T.A.O., 2000.
- SENO, T., S. STEIN and A.E., GRIPP, A model for the motion of the Philippine Sea plate consistent with NUVEL-1 and geological data, *J. Geophys. Res.*, **98**, 17941-17948, 1993.
- SHIH, R.C., C.H. LIN, H.L. LAI, Y.H. YEH, B.S. HUANG and H.Y. YEN, Preliminary crustal structures across central Taiwan from modeling of the onshore-offshore wide-angle seismic data, TAO, **9**, 317-328, 1998.
- SHINOHARA, M., N. HIRATA and S. MATSUDA, Long-term low-power DAT seismic digital data recorder with GPS clock, Zisin (*J. Seism. Soc. Jpn.*), **50**, 119-124, 1997 (in Japanese with English abstract).
- SUPPE, J., Mechanics of mountain building and metamorphism in Taiwan, *Mem. Geol. Soc. China*, **4**, 67-89, 1981.
- URABE, T., A common format for multi-channel earthquake waveform data, *Prog. Abs. Seismo. Soc. Jpn.*, **1**, 384, 1994 (in Japanese).
- WU, Y.M., T.C. SHIN, C.C. CHEN, Y.B. TSAI, W.H.K. LEE and T.L. TENG, Taiwan Rapid Earthquake Information Release System, *Seismo. Res. Lett.*, **68**, 931-943, 1997.
- YU, S.B., H.Y. CHEN and L.C. KUO, Velocity field of GPS stations in the Taiwan area, *Tectonophysics*, **274**, 41-59, 1997.

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## Appendix

The present study is part of the Japan-Taiwan Cooperative Research Program, which was organized after the 1999 Chi-Chi, Taiwan Earthquake. The research includes a mission from Japan to Taiwan in 1999 and 2000. The following were members of the mission group from Japan.

(i) Principal Investigator

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Masaru Kobayashi (Earthquake Research Institute, the University of Tokyo, Seismology)

Yasuhiro Hirata (Earthquake Research Institute, the University of Tokyo, Geodesy)

(iv) Seismotectonics

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## 1999 年台湾集集地震の余震観測

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1999 年 9 月 21 日 (現地時間) に台湾で起きた集集地震の臨時余震観測を行なった。震源断層面を取り囲むように、100 km 四方の領域に 20 点の観測点を配置した。観測は、DAT に連続記録を収録する方式で、乾電池で約 1 ヶ月間稼働することができる。本震発生 2 週間後の 10 月 7 日から 12 月 22 日まで観測を行ない、数多くの余震を観測した。このうち初期の 4 日間のデータを再生し、736 個の余震の震源決定を行なった。地殻の速度構造の不均質を考慮した観測点補正値を導入し、詳細な震源分布を得た。東下がりの余震分布は本震の震源断層面を表し、ほぼ水平な分布は付加帯とユーラシアプレートとの境界面であるデコルマ、そしてより深部の分布はプレート内で発生した地震を表している。