Conjugate thrust faulting associated with the 1999 Chi-Chi, Taiwan, earthquake sequence

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[1] The geometrical structure of the responsible faults of the 20 September 1999 Chi-Chi, Taiwan, earthquake (M_L = 7.3, M_w = 7.6) and its aftershocks can be clearly depicted by well-located hypocenters and focal mechanisms of large aftershocks. The mainshock and two large aftershocks with M_L = 6.8 were characterized by thrust faulting along a N-S striking fault plane dipping to the east. The underground structure of the Chelungpu fault, which is probably merging with the decollement beneath the Western Foothills, can be clearly associated with the seismicity pattern and the focal mechanisms of the three largest events. A group of deeper aftershocks including two moderate events (M_L = 6.3 and 6.0, respectively) were located to the southeast of the mainshock along a fault plane dipping steeply to the west down to a depth of about 30 km. Our results suggest that the spatial pattern of the aftershocks in the southern part of the source area can be interpreted by a conjugate-fault system. This conjugate-fault system is comprised of the gently east-dipping Chelungpu fault and a steeply west-dipping deeper fault zone. *INDEX TERMS:* 7230 Seismology: Seismicity and seismotectonics; 7215 Seismology: Earthquake parameters; 9320 Information Related to Geographic Region: Asia

1. Introduction

[2] The 20 September 1999 Chi-Chi, Taiwan, earthquake (M_L = 7.3, M_w = 7.6) was the largest inland earthquake in Taiwan in the 20th century. The earthquake was located at 23.853°N and 120.816°E with a focal depth of 8 km and a thrust faulting focal mechanism with a strike of 5°, a dip of 34° and a rake of 65° [*Chang et al.*, 2000]. The earthquake initiated from the hypocenter in southern Chelungpu fault and ruptured both upward and laterally northward [*Chen et al.*, 2001; *Kikuchi et al.*, 2000; *Ma et al.*, 2000]. The thrust faulting produced surface ruptures about 100 km long along the Chelungpu fault with the largest displacement of 5 and 9 meters in the vertical and horizontal directions, respectively [*CGS*, 1999].

[3] In the first six months after the Chi-Chi earthquake, more than 20,000 aftershocks occurred over an area of 200 km × 100 km [*Chang et al.*, 2000]. However, a narrow zone of low aftershock activity was apparent near the Chelungpu fault. To accommodate the thin-skinned thrust model and aftershock distribution, *Wang et al.* [2000] suggested a decollement surface corresponding to an aseismic dipping plane at depths of 10 to 20 km. From the analyses of four-day aftershock activity recorded by a temporary seismic array, *Hirata et al.* [2000] reported that a very low angle east dipping plane extending down to a depth of about 10 km can be considered as the lower boundary of the aftershock seismicity. They also interpreted this plane as the decollement between the upper boundary of the Eurasian Plate and the accretionary wedge. *Kao and Chen* [2000] determined the focal depths and fault plane solutions of 42 larger aftershocks from broadband waveforms. They proposed that the main seismogenic zone is an out-of-sequence thrust of near planar geometry, dipping to the east at about 25° down to a depth of 15 km. They also suggested a sub-parallel second seismogenic fault down to a depth of 30 km below the main thrust fault.

[4] Although extensive surface breaking and large displacements took place along the entire Chelungpu fault, most large aftershocks (M_L > 6) occurred in the southern part of the fault. The seismicity pattern of aftershocks and the focal mechanisms of the large aftershocks would provide key information essential for our understanding of the complex faulting behavior during the Chi-Chi earthquake sequence. In this study, the seismicity pattern and focal mechanisms of the mainshock and four large aftershocks (M_L > 6) are used to study the fault geometry and to explore the relationship between the temporal-spatial development of the mainshock-aftershock sequence and the fault interaction. Understanding the fault system associated with a big earthquake sequence is important for correlating the regional deformation and tectonic stress distribution in this collision tectonic process.

2. Seismicity of Aftershocks

[5] Fourteen hours after the mainshock, a temporary seismic network (Figure 1) was deployed around the source area to monitor the aftershock activity by the Institute of Earth Sciences, Academia Sinica. The temporary seismic network consisted of 22 stations equipped with force-balance accelerometers, covering an area of 30 km × 65 km from the east of the mainshock to the west of the Chelungpu fault. The trigger threshold was set to 0.04% of full scale (2g) and the sample rate was 200 samples per second. In addition, each station was equipped with a GPS timing system to achieve timing accuracy of 0.5 milliseconds. During six months of operation, a total of 1164 events including the largest and the second largest aftershocks were recorded. Earthquakes were located preliminarily using the computer program HYPOELLIPSE [*Lahr*, 1989]. A velocity model for southwestern Taiwan [*Chen*, 1995] was adapted for the earthquake location. The events within and near the network were relocated using a joint hypocentral determination (JHD) technique [*Pujol*, 1988] to determine relative earthquake locations and to quantify lateral velocity variations from station corrections.

[6] The epicentral distribution of relocated aftershocks is shown in Figure 1. The mainshock was located in an area of low aftershock activity. In the source area, there are three major north-south trending Quaternary faults dipping moderately to the east [*Lin et al.*, 2000]. From west to east, they include the Changhua fault (F1) in the Coastal Plains, the Chelungpu fault (F2) and Shuangtung fault (F3) in the Western Foothills. The aftershocks to the west of the Chelungpu fault are mostly concentrated along a NW-SE trending seismic zone. Most aftershocks were located about 25 km to the east of the Chelungpu fault. It is noted that the mainshock and the following four large aftershocks (M_L > 6) occurred in the southern part of the Chelungpu fault.

[7] A N-S cross-sectional view of the aftershocks reveals that the hypocenters are mainly distributed in the upper crust shallower

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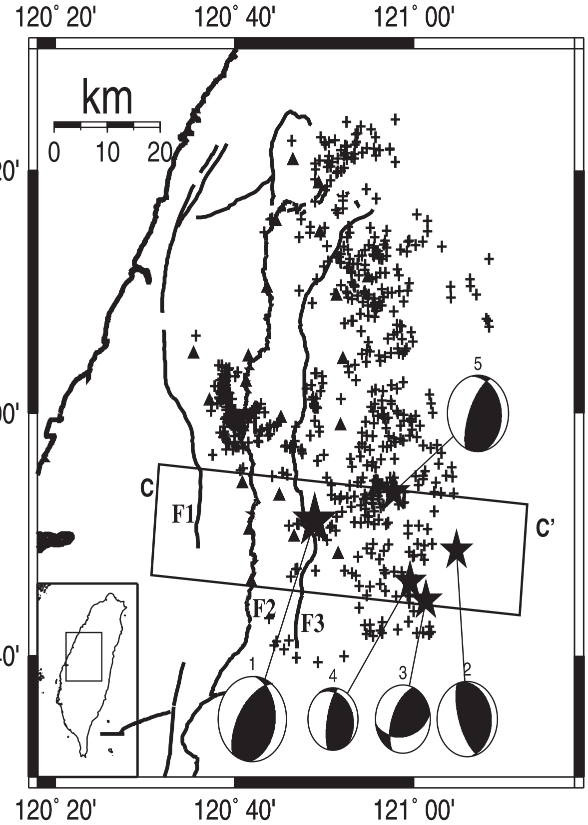

Figure 1. Epicentral map of the relocated aftershocks (crosses) recorded by a temporary seismic network, whose stations are shown in solid triangles. Big and small stars denote the locations of the mainshock and larger aftershocks, respectively. The thick solid lines mark the Changhua fault (F1), the Chelungpu fault (F2), and the Shuangtung fault (F3), respectively. Included also are the lower-hemisphere, first-motion focal mechanisms of the mainshock and four larger aftershocks.

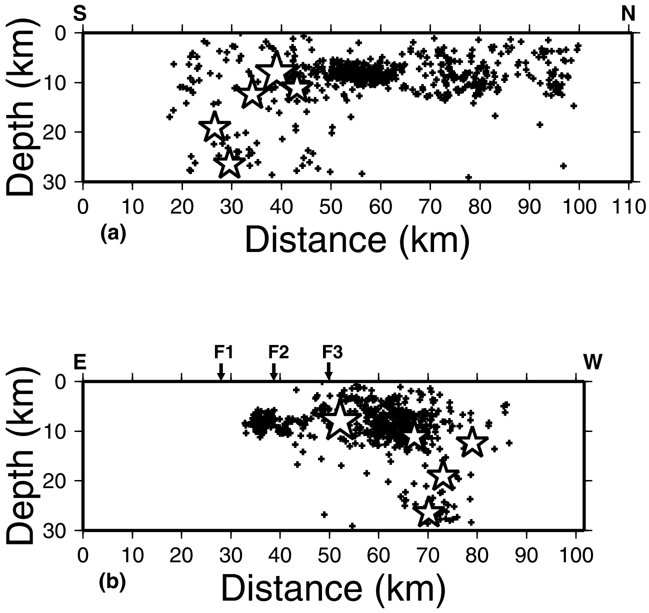

Figure 2. Depth cross sections of the aftershock hypocenters: (a) for the NS direction and (b) for the EW direction. Big Star denotes the mainshock and small stars show larger aftershocks. Note that both large and deeper events occurred in the southern part of seismic zone.

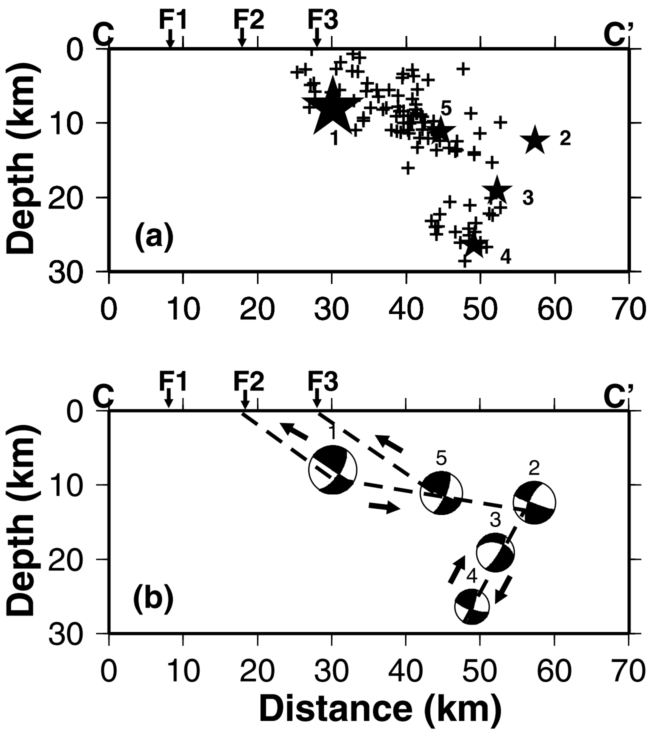

Figure 3. (a) A narrow depth cross section of the aftershocks along line CC' shown in Figure 1. (b) Cross-sectional view of focal mechanisms for the mainshock and four aftershocks. Big star denotes the mainshock and small stars show large aftershocks. The dashed lines display the fault geometry inferred from both the aftershock distribution and focal mechanisms of several larger-sized aftershocks.

than 12 km except the southern region (Figure 2a). Seismicity decreases remarkably below a depth of 12 km, especially in the northern part, indicating that this depth might be the base of the seismogenic zone. However, seismicity in the southern part, including the mainshock and four large events ($M_L > 6$), extends to a depth of about 30 km. A E-W cross-sectional view of aftershocks shows an increase in the thickness of seismogenic zone from west to east (Figure 2b). A cluster of events to the west of the Chelungpu fault are mainly distributed in the depth range between 5 km and 12 km. Deep seismicity can only be seen in the southeastern part of the source area.

[8] A narrow cross-sectional view (CC'), perpendicular to the surface rupture trace of the Chelungpu fault for the aftershocks within the box shown in Figure 1, reveals clearly an eastward-dipping trend of hypocenters extending to a depth of about 30 km (Figure 3a). This eastward dipping seismic zone with a dip angle of about 35° is consistent with the measured near-surface dip angle of the Chelungpu fault [*Chen et al.*, 2000]. However, the seismicity in the depth range from 12 to 20 km is low. This might indicate that the seismicity associated with the Chelungpu and Shuangtung faults seems to be terminated at depths 10 $\sim$ 12 km and is confined to an area above a gently east-dipping lower boundary of the seismic zone. The mainshock (event No. 1) and two large aftershocks ($M_L > 6$), i.e., events Nos. 2 and 5, are located near the lower boundary of the seismic zone. Immediately after event No. 2, deeper aftershocks including two large aftershocks, i.e., events Nos. 3 and 4, to the right hand side of CC'

Table 1. Source Parameters of the Mainshock and Four Larger Aftershocks

Date & Time	Lat. (Deg.)	Lon. (Deg.)	Depth (km)	Strike (Deg.)	Dip (Deg.)	Rake (Deg.)	M_L
1 09/20/17:47	23.853	120.816	8	5.0	34.0	65.0	7.3
2 09/22/00:14	23.812	121.080	12.4	161.3	69.0	86.8	6.8
3 09/22/00:49	23.743	121.023	19.1	203.6	60.1	52.3	6.3
4 09/22/12:17	23.769	120.994	26.4	191.0	72.6	105.7	6.0
5 09/25/23:52	23.892	120.963	11.1	351.1	24.9	60.4	6.8

section seem to be associated with a steeply west-dipping seismic zone.

3. Focal Mechanisms of the Mainshock and Five Large Aftershocks

[9] Fault-plane solutions of the mainshock and four large aftershocks were determined using the P-wave first motions, which were read from the short-period seismograms of the CWB seismic network and the strong-motion seismograms of the temporary seismic network. The fault-plane solutions and the related parameters for the five events (Figures 1 and 3b) are listed in Table 1. The mainshock and four large aftershocks ($M_L > 6$) are dominantly thrust faulting.

[10] Cross-sectional view of focal mechanisms for the five large events is shown in Figure 3b. The mainshock, which initiated at a depth of 8 km, is predominantly thrust faulting on an N-S striking fault plane dipping to the east [*Chang et al.*, 2000]. Thirty-one hours after the mainshock, No. 2 aftershock occurred at 12.4 km, revealing reverse faulting dipping moderately to the northeast. Immediately following the second largest aftershock, Nos. 3 and 4 aftershocks with reverse faulting occurred at a depth of 19 km and 26 km, respectively. Five days after the mainshock, No. 5 aftershock took place near the lower boundary of the shallow seismogenic zone between the mainshock and the No. 2 aftershock. The focal mechanism of the No. 5 aftershock shows thrust faulting with a dip angle of about 25° to the east.

4. Discussion

[11] The results from the surface geology [*CGS*, 1999], the GPS measurements [*Yu et al.*, 2001], and the source rupture processes modeling [*Kikuchi et al.*, 2000; *Ma et al.*, 2000] show that the northern Chelungpu fault region sustained larger surface and subsurface displacements than in the southern region. However, *Hsu et al.* [2001] reported a larger post-seismic deformation in the southern part than in the northern part. As mentioned above, depth distribution of the Chi-Chi aftershocks is very different between the northern and southern Chelungpu fault. In addition, large aftershocks occurred mainly in the southern part of the fault. All observations seem to indicate that there are significant differences in the physical and geological properties beneath the northern and southern Chelungpu fault regions.

[12] From the aftershock distribution and focal mechanisms of large aftershocks (Figures 3a and 3b), the geometrical structure of the related faults can be clearly delineated. The lower boundary of the aftershocks (shown by a dashed line and denoted by F2 in Figure 3) can be clearly associated with the downward extension of the Chelungpu thrust fault. It dips easterly at 34° to a depth of 8 km and extends eastwards along a gently dipping plane to a depth of 12.4 km. The mainshock and the two largest aftershocks are located almost near this lower boundary of the seismic zone and their dipping angles from the focal mechanism solutions are consistent with the lateral variation of dip angles of the lower boundary. Based on a deep seismic reflection profile [*CPC*, 2001], *Wang* [2001] delineated the underground structures of the Chelungpu fault and several other related faults previously proposed by geologists [*Lin et al.*, 2000]. The Chelungpu fault identified from the deep seismic reflection profile is very consistent with the lower boundary of the aftershock distribution. From surface geology [*Lin et al.*, 2000] and deep seismic profiling [*Wang*, 2001], we also draw the Shuangtung fault (F3) with dashed lines in the Figure 3b. The Shuangtung fault dips to the east at a low angle of about 25° and seems to merge with the Chelungpu fault at a depth of about 12 km. The largest aftershock (event No. 5) is located near the junction between the two faults. It is noteworthy that the lower boundary of the shallow aftershocks, or the Chelungpu fault, might be corresponding to the decollement of the thin-skinned thrust model proposed by *Suppe and Jamson* [1979].

[13] As shown in Figures 3a and 3b, numerous aftershocks below event No. 2 were located along a steeply west dipping seismic zone. The focal mechanisms of two moderate-sized events, i.e., events Nos. 3 and 4, show thrust faulting with two nodal planes: one dipping moderately to the east and the other steeply to the west. Trend of seismicity suggests the steeply west dipping nodal plane to be the preferred fault plane. If we selected the nodal plane dipping to the west with an angle of 73°, we can obtain a very consistent orientation of a west-dipping fault extending from 10 km to about 30 km as shown in Figure 3b. The west-dipping fault is clearly conjugate to the Chelungpu fault. Since event No. 2 is just located at the junction point of the two conjugate faults, it can be on either one. Under a regional stress field, a set of conjugate faults was found in the earthquake sequence [*Smith and Priestley*, 2000]. The fault movements inferred from the focal mechanisms (Figure 3b) are very reasonable to depict the tectonic process during the Chi-Chi earthquake sequence.

[14] *Kao and Chen* [2000] proposed that the main seismogenic zone of the Chi-Chi earthquake is an out-of-sequence thrust of near planar geometry, dipping to the east at about 25° down to a depth of 15 km. They also suggested a sub-parallel second seismogenic fault below the main thrust extending to a depth of 30 km to interpret the cluster of deeper seismic activity. Their proposition of the existence of sub-parallel thrust faults can not be explained properly by the existence of a westward-dipping concentration of aftershocks and their associated focal mechanisms. From an independent aftershock monitoring, *Hirata et al.* [2000] also observed the existence of a deeper seismic zone dipping to the west. Therefore, a conjugate fault system is preferred to interpret the tectonic process associated with the Chi-Chi earthquake sequence in the southern aftershock region.

5. Conclusions

[15] The aftershock activity and focal mechanisms of the Chi-Chi, Taiwan, earthquake sequence suggest that the Chelungpu fault dips to the east at approximately 34° down to a depth of 8 km and then extends eastwards along an almost horizontal plane to a depth of 12.4 km. The largest aftershock is closely associated with the Shuangtung fault that dips to the east at a low-angle of about 25° and seems to merge with the Chelungpu fault at a depth of about 12 km. The deeper aftershock distribution is associated with a fault, dipping steeply to the west down to a depth of about 30 km, which is conjugate to the eastward-dipping Chelungpu fault. The conjugate fault system can successfully interpret the tectonic process associated with the Chi-Chi earthquake sequence.

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