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Seismogenic structure in a tectonic suture zone: With new constraints from 2006 Mw6.1 Taitung earthquake

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[1] A Mw 6.1 earthquake occurred on April 1st, 2006 near Taitung, eastern Taiwan. It produced significant coseismic ground displacements and a large number of aftershocks in the ensuing month. This event provides an opportunity to diagnose the seismogenic structure in the southern Longitudinal Valley (LV) of eastern Taiwan, long viewed as one of the collision sutures between the Philippine Sea and the Eurasian plates. With precisely relocated main- and aftershock hypocenters, focal mechanisms for $M \geq 3.8$ events, and coseismic ground displacements from strong motion records, we determine a main shock dislocation model. Our results indicate that the main shock occurred on a high angle fault (azimuth 198°, dip 77°). The model comprises a fault with two segments; the main shock and a large number of aftershocks are associated with the northern segment that exhibited predominantly left-lateral strike-slip motion, in agreement with P-wave first motions and waveform (USGS) solutions. The southern segment exhibits a slightly larger thrust component, in agreement with CMT solutions. Tectonically, this event highlights a NNE-trending fault on the west side of the LV, which is predominantly strike-slip. The aftershocks clustered to the east of the main shock, which exhibit mainly thrust mechanisms, indicate that shortening is still acting on the sedimentary materials deposited between the Coastal and Central ranges prior to collision. As a result, the southern LV is undergoing slip partitioning along different faults, which has never been specified before. **Citation:** Wu, Y.-M., Y.-G. Chen, C.-H. Chang, L.-H. Chung, T.-L. Teng, F. T. Wu, and C.-F. Wu (2006), Seismogenic structure in a tectonic suture zone: With new constraints from 2006 Mw6.1 Taitung earthquake, *Geophys. Res. Lett.*, *33*, L22305, doi:10.1029/2006GL027572.

1. Introduction

[2] Taiwan is located along the plate boundary between the Philippine Sea plate and Eurasian plate, where two arc-trench systems have been interacting since the Miocene. Arc-continent collision initiated about 5–6 million years ago [*Ho*, 1986; *Teng*, 1990] due to the flipped subduction polarities from southern system into northern system [*Suppe*, 1984; *Tsai et al.*, 1977; *Wu*, 1978; *Kuochen et al.*, 2004] (see inset in Figure 1). As a result, the Taiwan region is highly active in terms of tectonics and seismicity [*Wu et al.*, 1997; *Wang*, 1998; *Shyu et al.*, 2005a]. Large earthquakes have long been regarded as one of the major hazards; however, they are also important scientifically in understanding of earthquake mechanisms, since a few of the seismic events are large enough to provide reliable information on the rupturing behavior [*Ma et al.*, 2001; *Wu et al.*, 2006]. An earthquake (Mw 6.1) happened on April 1st, 2006 near Taitung, eastern Taiwan (Figure 1). The epicenter is located near the southernmost LV, which has long been defined as one of the collisional sutures between the Philippine Sea and Eurasian plates [*Teng*, 1990; *Shyu et al.*, 2005b; *Willett and Brandon*, 2002] since it is seismically active [*Hsu*, 1971]. Based on the GPS results [*Yu et al.*, 1997], the LV absorbs shortening about 3-4 cm out of a total of 8.2 cm/yr between the offshore islands to the southeast and the Taiwan Strait. In 1951, two large earthquakes associated with the LV (M_L 7.3, 7.1) [*Hsu*, 1962; *Taiwan Weather Bureau*, 1952; *Cheng*, 1995; *Abe*, 1981] were determined to occur on the east-dipping Coastal Range fault [*Hsu*, 1962; *Chung*, 2003] (see COF in Figure 1). In 2003, another earthquake (Mw 6.8) [*Wu et al.*, 2006] occurred 40 km to the NNE of Taitung and ruptured the southern segment of the COF. Other than COF, surface geology and geomorphology [*Biq*, 1965; *Angelier et al.*, 1997; *Lee et al.*, 2003; *Shyu et al.*, 2006] (see CNF in Figure 1) suggest the existence of a west-dipping thrust bounding the western margin of the LV. By model test on GPS data, a west-dipping CNF is also suggested by *Johnson et al.* [2005]. The previous seismological study found the LV is dominated by a nearly vertical seismic cluster and a west-dipping fault in its northern ending [*Kim et al.*, 2006]. To the southern LV only one of the aftershocks in the 2003 earthquake sequence was confirmed as a west-dipping rupture [*Kuochen et al.*, 2006]. Although the LV has long been regarded as one of the collision suture and stress partitioning is expected due to the oblique relation to the plate motion [*Wu et al.*, 2004], the detailed structure framework and slip partitioning along faults have not been well documented. We would take the opportunity of newly happened event to shed light on the points mentioned above.

2. Data and Methods

[3] The initial epicentral location of the 2006 Taitung event was placed at 22.83°N and 121.06°E (Figure 1, Central Weather Bureau (CWB), available at http://www.cwb.gov.tw/V5e/index.htm, 2006). Its focal depth was esti-

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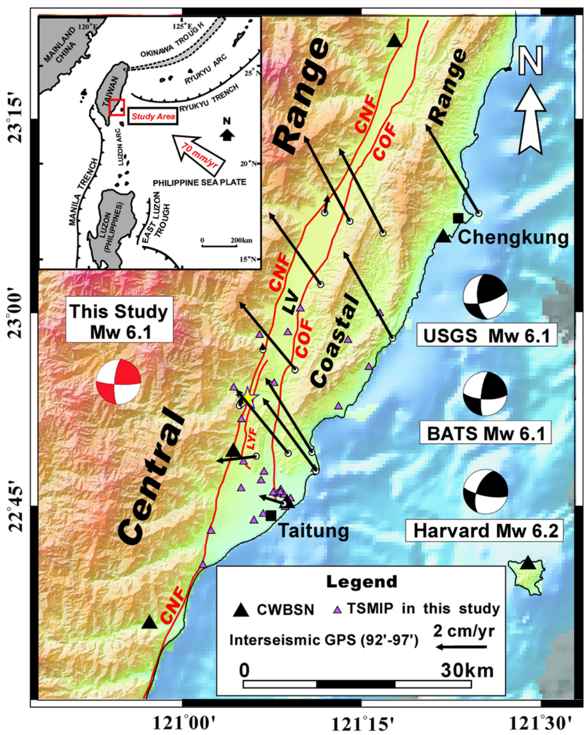

Figure 1. Map showing the epicenter and focal mechanisms of 2006 Taitung earthquake, geomorphic features, major structures, locations of seismic stations, and interseismic surface displacements. Inset shows that the current tectonic environment surrounding Taiwan is composed of two arc-trench systems.

mated as 10 km. The Harvard CMT solution (strike 201°, dip 58° and rake 18°) and the Broadband Array in Taiwan Seismology (BATS; strike 187°, dip 76° and rake 20°) both indicate predominantly strike-slip motion with a small amount of reverse motion.

[4] In this paper we use phase data from the catalogs of the CWB Seismic Network (CWBSN) and strong motion records from the Taiwan Strong Motion Instrumentation Program (TSMIP). The CWBSN consists of 71 telemetered stations equipped with 3-component S13 seismometers. In total, 1265 events within April of 2006 were selected for earthquake relocation and 14 for focal mechanism determination. The event selection criteria were: (1) located in the region of 22.50 ~ 23.25°N and 120.75 ~ 121.50°E, (2) recorded by at least six stations with clear P or S arrivals, and (3) focal depths shallower than 30 km. A total of 625 strong motion records from twenty-eight TSMIP stations were retrieved (Figure 1). Although most of the stations are not equipped with an absolute timing system, the S-P time differences can be used effectively for improving earthquake location. The S-P time differences and P-wave polarities from those records are added to the CWBSN data for both relocating the hypocenters and determining their focal mechanisms. We also use fifteen strong motion records of the main shock to derive the coseismic ground displacement, and with these data we model the fault rupture by the spatial distribution of relocated seismicity. The average of the RMS of the travel time residuals, the error in horizontal, and the error in depth are 0.15 sec, 0.22 km, and 0.35 km, respectively. Thus, we suggest that the relocation accuracy will be less than 1.0 km or even better if the seismicity number is large enough.

3. Spatial Distribution of Seismicity

[5] The LV is a challenging location for seismic studies; with the Coastal Range on the Philippine Sea plate side and the Central Range on the Eurasian side, the velocity structure in the study area is unavoidably complex, and the data are asymmetrically distributed because the LV is situated next to the ocean, and there are not many CWBSN stations in the study area. To minimize the effect of the crustal velocity heterogeneities, we increase our dataset by combining CWBSN P and S phase data and input TSMIP S-P times in a 3-D earthquake location algorithm [*Thurber and Eberhart-Phillips*, 1999]. We use the three-dimensional P- and S-wave velocity model derived earlier from the local dense arrays of CWBSN and TSMIP [*Wu and Chang*, 2005]. The relocated epicenters of the study sequence are shown in Figure 2, but the first 3 hours are shown in Figure 3. The relocated main shock is at 22.892°N, 121.078°E with a depth of 10.8 km. Three clusters are identified. The main cluster is located under the LV and its immediate west. The second cluster is located in the south and seems to be southern extension of the western main cluster. The third one is located offshore to the east of the main cluster. The side view (Figure 2b) further reveals two hypocenter sub-clusters for the main cluster, in which the main shock is included within the western sub-cluster, striking 198° and dipping 77°W.

[6] Our focal mechanism, a strike-slip dominant main shock (185°, 72°, and 10°), only slightly differs from the solutions of BATS, USGS and Harvard. Focal mechanisms of other 13 aftershocks of $M_L \geq 3.8$ were also determined (Figure 2). The mechanisms located within the western main cluster show strike-slip motions, while the mechanisms from eastern main cluster and off-shore cluster are dominated by thrust ruptures. Since the western main cluster contains the main shock and its orientation matches the focal mechanism, we then propose the seismogenic fault strikes 198° and dips 77°W. The extension of this seismogenic fault not only can run through the southern sparse cluster, but also is parallel to all the major tectonic elements, LV, CNF, and COF. The aftershocks, located in the offshore cluster and the eastern main cluster, are both dominated by thrust mechanisms, indicating faults other than the major strike-slip one in the west are also actively associated.

4. Coseismic Deformation and Dislocation Fault Model

[7] The 650 TSMIP stations use 16-bit digital recording systems and force-balanced accelerometers, with a sampling rate of 200 sps or better. At a full range of ±2g, they provide us with on-scale DC-50 Hz near-source strong-motion waveforms. The coseismic displacement at the station site can be obtained by double integration with simple baseline corrections [*Chung and Shin*, 1999; *Shin et al.*, 2001; *Wu et al.*, 2006]. With fifteen stations surrounding the source region, a good sampling of the coseismic ground displacement field is derived (Figure 3).

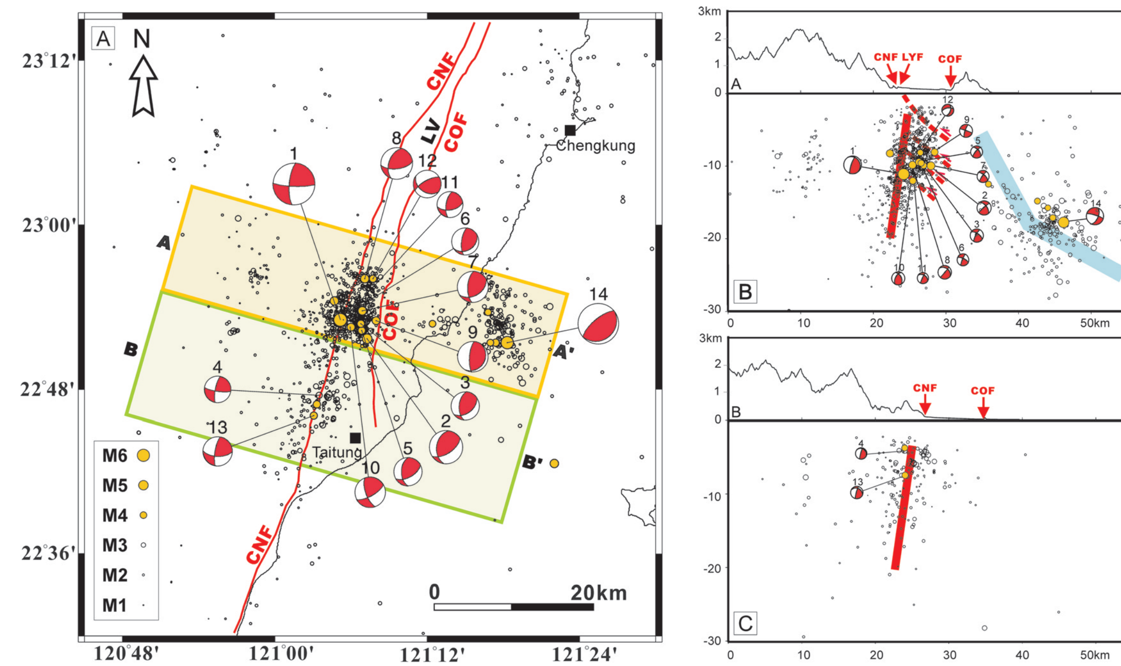

Figure 2. (a) The epicenters of the 2006 Taitung earthquake sequence are shown in circles and their size is proportional to the magnitude. Also shown are focal mechanisms of the aftershocks greater than 3.8, which are numbered by the order of time. Three clusters are clearly identified. Besides the one located offshore, the other two are on-land. The northern on-land one is the main cluster, which can be further subdivided into western and eastern two sub-clusters and the main shock is located in the western one. The southern cluster is sparse and seems to be the extension of the western main cluster. Based on the occurrence time, the western main cluster leads the sequence. The eastern main cluster was triggered right after the main shock. The offshore one came days later in the sequence. (b) Profile showing the vertical geometry of northern two clusters. The thick red line represents the modeled seismogenic fault of the 2006 event. The eastern main cluster is dominated by evident thrust motion and the red dashed lines are proposed faults. The offshore cluster (i.e., the blue kink-line) is spatially related to the COF (*Wu et al.*, 2006; *Kuochen et al.*, 2006). (c) The southern on-land cluster shares the orientation and focal mechanism of the western main cluster. The red line represents the southern extension of the modeled seismogenic fault of 2006 event.

[8] The horizontal components (blue arrows in Figure 3a) on the Central Range side, close to the main cluster, show southwestward or southward motions ranging from 1 up to 2 cm. On the eastern side of the main cluster the motions show toward and away from the main cluster in the south and north respectively (Figure 3a), with amplitudes from 1.5 up to 5 cm. Our result shows not much vertical displacements in the epicentral area, but significant subsidence in the Taitung region with magnitudes from 0.5 to 1.5 cm (Figure 3b).

[9] The finite fault model is determined from inversion of the displacement field [*Wu et al.*, 2006] using the method for an elastic dislocation in a homogeneous half-space [*Okada*, 1992]. Three displacement components (E–W, N–S, and vertical) are used for each out of 15 TSMIP stations. Guided by the hypocentral distribution in few hours after the main shock, we adopt a width of 18 km for the fault plane with the top edge of 2 km below the surface. We first found that using one long fault plane, the ground-deformation pattern shown in Figure 3 cannot be fit satisfactorily, especially the subsidence in the Taitung area. However, after dividing the fault plane into two segments of 6 km and 11 km in length, the overall fit was significantly improved. The two-segment model only gives a small rake change in the southern segment. The finite fault geometry is in fact the best-fit solution of the minimum misfit on the coseismic deformation after a grid search. The northern segment matches with the area of the main cluster, while the southern one with the southern sparse cluster.

[10] The derived slip on the northern segment is 15.3 cm with a rake of −3.7°, nearly pure strike-slip. On the other hand, the slip on the southern segment is 19.6 cm (i.e., 18.4 cm sinistral strike-slip and 6.8 cm thrust) with a rake of 20.2°, consistent with BATS and Harvard CMT solutions. Based on the area and slip on ruptured surface, we find M_w 5.7 and M_w 6.0 for the northern and southern segment, respectively. The combined moment magnitude, $M_w = 6.1$, agrees with the BATS and Harvard CMT solutions. The computed horizontal and vertical ground displacements are shown in Figures 3a and 3b; they are generally consistent with the observed ground displacements.

5. Discussion and Conclusion

[11] After a long quiescence, the study earthquake finally sheds light on the seismogenic structure in the southern LV, especially the boundary with the Central Range. For some time, the mechanism of the Central Range uplift at just west of the LV has remained enigmatic. It was suggested that the steep topography of the western Central range indicates the presence of a west-dipping Central Range fault [*Biq*, 1965; *Shyu et al.*, 2006] (CNF in Figures 1–3); therefore it was

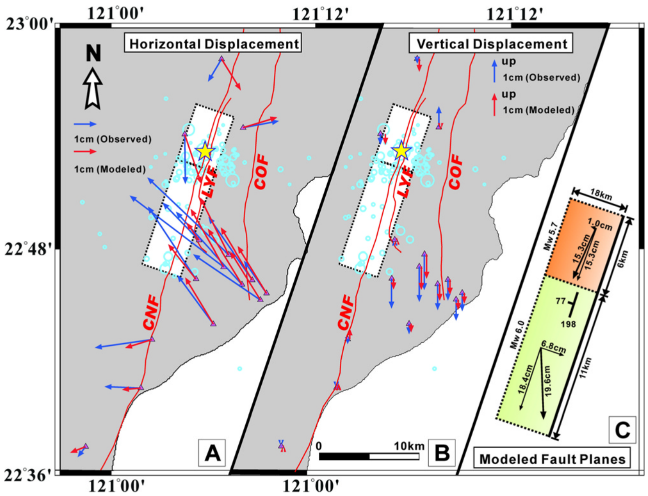

Figure 3. Co-seismic ground displacements derived from records of strong motion stations and modeled by the supposed fault plane (white rectangles) are shown as vectors in blue and red respectively for (a) horizontal and (b) vertical components. Blue circles are the seismicities occurred in a few hours after main shock, delineating an area for the modeled fault plane. (c) Modeled fault slips and moment magnitudes for different segments.

proposed that the CNF largely exhibits dip-slip motion. Our result shown above suggests the seismogenic fault of 2006 Taitung earthquake is dipping steeply to the west and rooted 18 km deep beneath the eastern flank of the Central Range, but it is a strike-slip dominant fault. Not only because of the sense but also the spatial offset, this seismogenic fault could not directly support the previously suggested surface CNF [*Shyu et al.*, 2006] (see Figure 1). However, its orientation and spatial distribution support the idea of the Central Range fault system [*Shyu et al.*, 2006], which is composed of a series of thrust faults stacking upward from lower crust to the surface. The surface trace of the CNF could be the uppermost thrust fault in this system. In other words, this event does reveal that, in addition to thrust dominated CNF and COF, a steep strike-slip and west-dipping fault is located on the western side of LV. This fault may be part of the CNF system, but accommodates the strike slip. The finding of this study not only refines the idea that the COF is the only major active fault in this tectonic suture [*Malavieille et al.*, 2002], but also reveals the west-dipping CNF system is quite complicated. We therefore propose that the active fault systems acting along the LV consist of the Coastal Range fault system in the east and the Central Range fault system in the west. Each system may be composed of both strike-slip and thrust faults due to the stress caused slip partitioning.

[12] The occurrence of 2006 Taitung earthquake can be seismologically deciphered as a result of stress transfer after the occurrence of the 2003 Chengkung earthquake. According to the Coulomb stress transfer modeling done by *Cheng* [2005], the Taitung epicenter is located in a region where the stress was increased up to 1 bar. In addition to the seismogenic fault of the main shock; however, this earthquake sequence contains two other seismic clusters, one is located in the south and the other is offshore to the east. Examining the order of occurrence of the larger aftershocks (i.e., consecutively numbered in Figure 2), the on-land cluster under the LV occurred right after the main shock and the offshore cluster occurred about 15 days later with a large aftershock of M6. We believe this is once more a case that can be deciphered by stress transfer in response to the Taitung earthquake.

[13] It is interesting to note that despite our many attempts in relocation (3-D tomographic and hypoDD) the eastern main cluster does not collapse into nearly planar structures. Rather the hypocenters are smeared out in a zone of about 5 km wide. Since all the larger earthquakes are thrust events with dips of 40–50°, they may occur on a series of different fault planes in this zone. Looking at the surface fault distribution (Figure 1), one east-dipping thrust fault, the Luyeh fault (LYF), branches out from the Coastal Range fault system, which is only distributed in the very southern LV. It probably reveals that two major rigid geologic entities, the Coastal Range and Central Range, have not yet closely contacted in the southern LV. Part of the shortening in response to the plate motion is absorbed by the sediments in between. The eastern main cluster may be interpreted as accommodating this distributed shortening between the LV. We further propose a tectonic model to summarize the seismological and geological data to date. Considering the geological entities in this region, the Coastal Range and Central Range are both lithologically competent. The interfaces between these two rigid bodies and the relatively compliant sedimentary rocks within LV are the major fault systems, the Coastal Range fault system and the Central Range fault system in the east and west respectively. The Coastal Range fault system is dominated by a listric shape thrust fault, which has been well known as the COF and historically produced large earthquakes in 1951, 2003, and the offshore aftershocks presented above. The Central Range fault system is composed of west-dipping thrust faults [*Shyu et al.*, 2005b, 2006] and at least a high angle strike-slip fault, which is the seismogenic fault in 2006, but whether this fault is continuous along the whole length of the LV is still in question. Between these two major fault systems, there are a number of thrust faults within the relatively unconsolidated sediments within the LV. According to the focal mechanisms revealed in 2006, thrust faults are abundant, indicating that the shortening in response to the tectonic collision is partially absorbed within this suture.

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