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Detailed surface co-seismic displacement of the 1999 Chi-Chi earthquake in western Taiwan and implication of fault geometry in the shallow subsurface

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A B S T R A C T

The northern segment of the Chelungpu Fault shows an unusually large co-seismic displacement from the event of the Mw 7.6 Chi-Chi earthquake in western Taiwan. Part of the northern segment near the Fengyuan City provides an excellent opportunity for characterizing active thrust-related structures due to a dense geodetic-benchmark network. We reproduced co-seismic deformation patterns of a small segment of this Chelungpu Fault using 924 geodetic benchmarks. According to the estimated displacement vectors, we identified secondary deformations, such as local rigid-block rotation and significant shortening within the hanging wall. The data set also allows us to determine accurately a 3D model of the thrust fault geometry in the shallow subsurface by assuming simple relations between the fault slip, and the horizontal and vertical displacements at the surface. The predicted thrust geometry is in good agreement with borehole data derived from two drilling sites close to the study area. The successful prediction supports our assumptions of rigid displacement and control of displacement in the hanging wall by the fault geometry being useful first approximations.

1. Introduction

Large earthquakes generated by thrust activation commonly induce complex deformation near the surface, especially in the hanging wall as happened in the 1980, with the Mw 7.3, El Asnam earthquake (Philip and Meghraoui, 1983). Likewise, the 1999, Mw 7.6, Chi-Chi earthquake in west Central Taiwan was one of the largest onshore earthquakes in the past century (Fig. 1). This earthquake re-activated the 100-km-long Chelungpu Fault, with a N-S striking surface rupture that closely followed the mountain front of the Taiwan mountain belt (Central Geological Survey, 1999; Kao et al., 2000; Angelier et al., 2001; Lee et al., 2002; Chen et al., 2003; Chan et al., 2005; Lee and Chan, 2007).

From the geodynamic point of view, the Chi-Chi earthquake was a typical expression of the ongoing collision of the Taiwan orogen in terms of seismotectonic location and mechanism (Ho, 1986; Kao and Chen, 2000; Kao and Angelier, 2001). From the point of view of structural geology, the deformation in the hanging wall was complex, involving multiple faults (Wang et al., 2002a,b) and pop-up structures (Lee et al., 2002). In particular, partitioning accommodated the oblique thrusting between the main Chelungpu thrust and a hanging wall deformation zone with significant left-lateral strike-slip (Angelier et al., 2003a,b).

The Philippine Sea plate converges on the Chinese continental margin in a NW–SE direction across the Taiwan mountain belt at a rate of 8.2 cm per year (Yu et al., 1997). This convergence behavior contrasts to the longer term, WNW-ESE-directed contractional deformation of Taiwan (Yu et al., 2001; Chang et al., 2003). The contraction is consistent with the maximum compression direction indicated by stress inversion of focal mechanisms of the Chi-Chi main shock and aftershock sequence (Angelier, 2002). Both surface-deformation and crustal-stress characteristics agree with the direction of plate convergence (e.g., Seno et al., 1993) based on numerical modelling of the relationships between relative displacement, strain and stress (Hu et al., 1996, 2001). The strain partitioning along the Chelungpu Fault can be regarded as a local expression of the accommodation of NW–SE convergence that is oblique to the NNE-SSW structural grain of the collision belt, which represents a counter-clockwise deviation of shortening direction as compared with relative plate motion.

In this paper, we conduct a detailed analysis of active deformation and related faults by using a dense network of geodetic benchmarks and two boreholes. We determine the co-seismic displacement, and construct a 3D model of deformation at depth to determine the fault geometry and behavior in the shallow subsurface.

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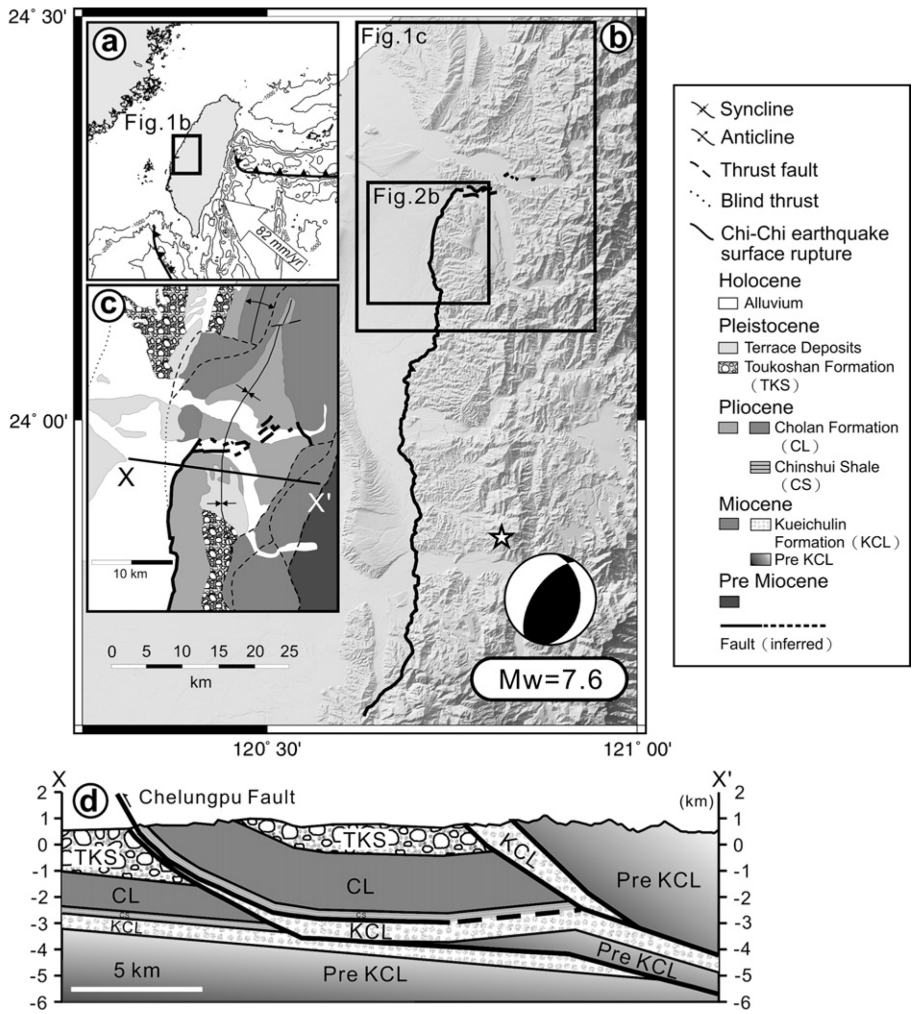

Fig. 1. Geological setting and location of the study area. (a) Geodynamic framework, with an open arrow indicating the 82 mm/yr motion of the Philippine Sea plate relative to the Eurasian plate towards azimuth 306° (Yu et al., 1997). (b) Shaded relief map of west central Taiwan surrounding the study area, which is located as solid line quadrangles. The star symbol – epicenter of the Chi-Chi earthquake with the lower-hemisphere, equal-area stereonet for the focal mechanism solution (Kao et al., 2000). (c) Simplified geological map and location of the cross-section (*X*–*X*′). (d) Geological cross-section *X*–*X*′ modified from Mouthereau et al., 2001.

2. The data: a dense network of city-planning benchmarks

In Fengyuan City, the second largest town of Taichung County, accurate 1/1000-scale urban-planning maps were created before the 1999 Chi-Chi earthquake. We use these maps and the geodetic measurements of benchmarks made before and after the earthquake as the basis for our analysis (Fig. 2).

In the study area, the vertical offset across the Chelungpu Fault scarp ranged from 2.5 to 4 m, whereas the horizontal displacement was approximately 7 m (Central Geological Survey, 1999). Such large displacements produced complex deformation in the hanging wall, creating many fissures, faults, and small folds (Kelson et al., 2001). However, detailed characterization of deformation was limited by the lack of quantitative data. Although previous studies characterized co-seismic displacement (Kelson et al., 2001; Lin et al., 2001; Lee et al., 2002, 2003; Angelier et al., 2003a,b; Dong et al., 2003), these studies did not reveal much concerning the deformation pattern in the hanging wall. Measurements of several GPS stations in this region (Central Geological Survey, 1999; Yu et al., 2001) provided vertical and horizontal displacement data; yet, their limited spatial distribution density prevented spatially detailed deformation analysis. In contrast, the densely spaced distribution of the city-planning benchmarks in Fengyuan provides us with a novel basis to perform accurate local determination of the deformation within the hanging wall. The resolution of this approach makes it advantageous compared to other approaches such as the correlation of aerial photographs or satellite images (Dominguez et al., 2003) because of greater accuracy for vertical relative displacements.

3. Determination of horizontal and vertical co-seismic displacements: the method

The city map provides accurate locations of human constructions, in particular houses, roads, and benchmarks. Because of extensive surface damage and large landform modification, the eastern part of Fengyuan City was remapped after the Chi-Chi earthquake. The map before the Chi-Chi earthquake was surveyed in 1992, adopting the coordinate system of the Taiwan Datum 67 (TWD 67), which was commonly used in Taiwan in the 1970s–1990s. The map made after the Chi-Chi earthquake was finished in 2002, using the coordinate system of the Taiwan Datum 97 (TWD 97), a new system adopted in Taiwan recently. Not only does the new map contain all the old city-planning benchmarks, it also includes the surface rupture of the earthquake and a Digital Terrain Model of a few meters resolution.

To compare these two maps, we first transformed the coordinates of benchmarks of the new map from TWD 97 to TWD 67.