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Structural geology of a classic thrust belt earthquake: the 1999 Chi-Chi earthquake Taiwan ($M_w = 7.6$)

Li-Fan Yue[a,*], John Suppe[a], Jih-Hao Hung[b]

[a]*Department of Geosciences, Princeton University, Princeton, NJ 08544, USA*
[b]*Institute of Geophysics, National Central University, Chung-Li, Taiwan, ROC*

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Abstract

We document the structural context of the 1999 Chi-Chi earthquake ($M_w = 7.6$) in western Taiwan, which is one of the best-instrumented thrust-belt earthquakes. The main surface break and large slip (3–10 m) is on two segments of the shallow otherwise aseismic bedding-parallel Chelungpu–Sanyi thrust system, which shows nearly classic ramp-flat geometry with shallow detachments (1–6 km) in the Pliocene Chinshui Shale and Mio-Pliocene Kueichulin/Tungkeng Formations. However, rupture is complex, involving at least six faults, including a previously unknown deeper thrust (8–10 km) on which the rupture began. We compare the coseismic displacements with a new 3D map of the Chelungpu–Sanyi system. The displacements are spatially and temporally heterogeneous and well correlated with discrete geometric segments of the 3D shape of the fault system. Geodetic displacement vectors are statistically parallel to the nearest adjacent fault segment and are parallel to large-scale oblique fault corrugations. The displacement magnitudes are heterogeneous at several scales, which requires in the long term other non-Chi-Chi events or significant aseismic deformation. The Chelungpu thrust has a total displacement of ~14 km but the area of largest Chi-Chi slip (~10 m) is on a newly propagated North Chelungpu Chinshui detachment (~0.3 km total slip) which shows abnormally smooth rupture dynamics.

Keywords: Active tectonics; Thrust faulting; Coseismic displacement; Fault geometry; Chi-Chi earthquake; Taiwan

1. Introduction

It has been said that large earthquakes are the quanta of upper crustal structural geology, making them focal points in studies of active tectonics (King et al., 1988; Stein et al., 1988; Yeats et al., 1996). Many structures grow largely by the summation of a few thousand large earthquakes, with 1–10 m growth per earthquake (Stein and King, 1984). Unfortunately, the subsurface structural geology of large earthquakes is normally only rather weakly constrained, making it difficult to form robust relationships between the displacements in large earthquakes—as constrained by geodesy, seismology and geomorphology—and the subsurface fault and fold geometry. The fault geometries of well-studied large earthquakes such as Izmit, Kobe, Loma Prieta, Landers, and Hector Mine are constrained largely by surface breaks, geodesy and earthquake seismology. Slip models of such earthquakes are typically based on simplified rectangular planar fault models, oriented parallel to main-shock focal mechanisms and to the general trends of surface breaks (e.g. Izmit: Bürgmann et al., 2002; Kobe: Ide and Takeo, 1997; Loma Prieta: Hartzell et al., 1991; Landers: Freymueller et al., 1994; Hector Mine: Kaverina et al., 2002; Chi-Chi: e.g. Ma et al., 2001). In contrast, the 1999 Chi-Chi thrust-belt earthquake in Taiwan is unusual, because we can independently determine the 3D geometry of the most important faults in considerable detail using techniques and data outlined below. Furthermore the Chi-Chi earthquake is one of the best instrumented large thrust-belt earthquakes (Ma et al., 1999) and thus presents an unusual opportunity to observe coseismic structural growth, comparing coseismic displacements with an independently determined 3D fault model. Finally, significant constraints exist for placing the Chi-Chi earthquake in its larger structural and tectonic setting within the western Taiwan thrust belt.

* Corresponding author. Tel.: +1 609 258 1515; fax: +1 609 258 1274.
E-mail address: lyue@princeton.edu (L.-F. Yue).

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2. Basis for Chelungpu–Sanyi fault model

The largest offsets (3–9 m) of the 85-km-long surface break of the Chi-Chi earthquake lie along the northern 50 km segment of the Chelungpu thrust that runs parallel in map view to bedding in the hanging wall in the Pliocene Chinshui Shale (Fig. 1; Lee et al., 2000, 2003). We argue that the Chelungpu thrust must also run parallel to bedding in the subsurface in classic thrust-belt fashion, based on the following evidence: [1] In map view the Chelungpu thrust

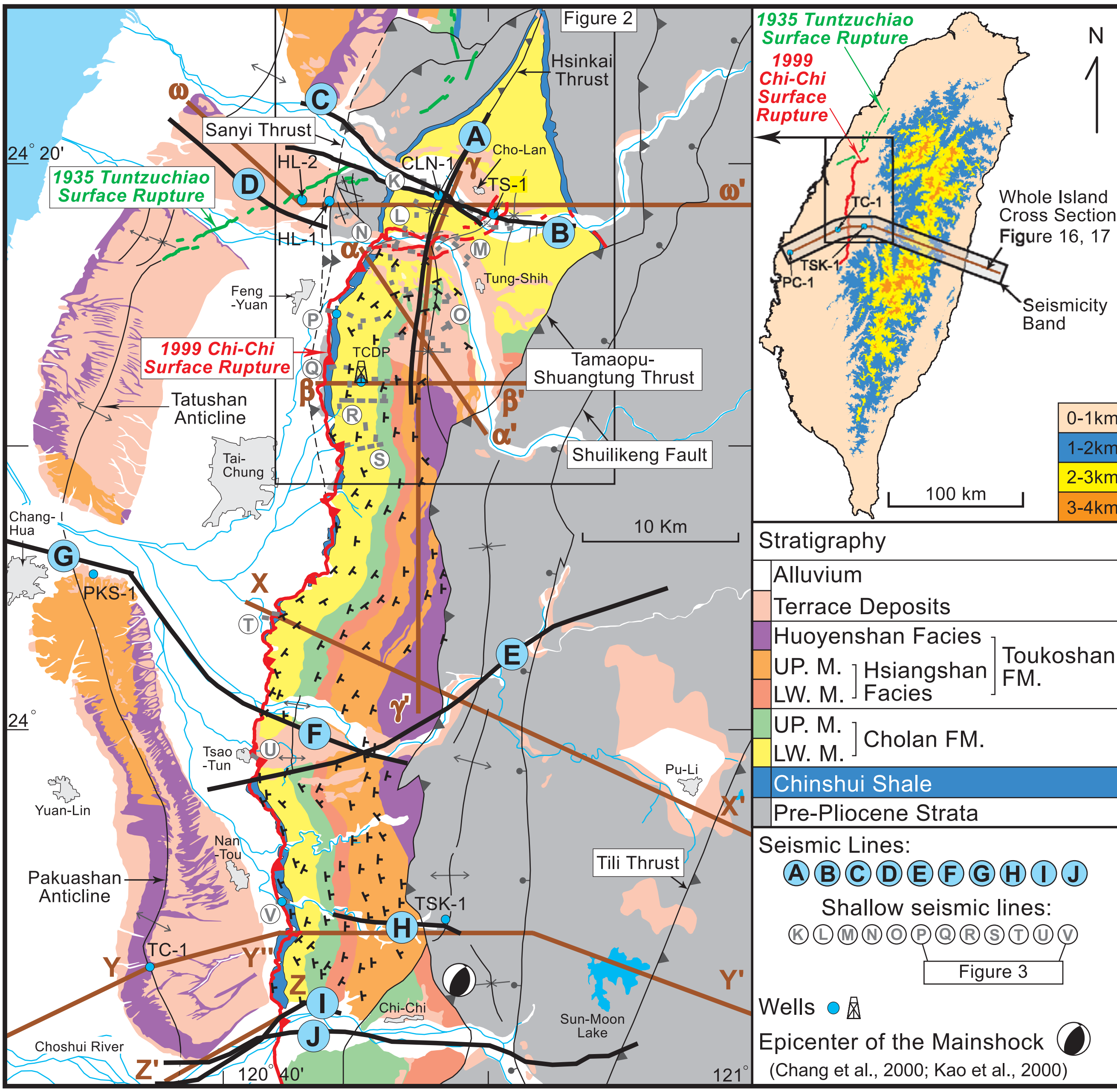

Fig. 1. Geologic map of Chelungpu thrust sheet with the 1999 surface rupture of the Chi-Chi earthquake ($M_w = 7.6$) shown in red (Central Geological Survey, 1999a,b). The trace of the fault runs regionally parallel to hanging wall bedding in the Pliocene Chinshui Shale and to the overlying strata. This parallelism reflects a hanging wall detachment with classic ramp-flat geometry, as shown in cross-sections that are constrained by seismic lines and boreholes. The parallelism between hanging wall bedding and the fault allows us to use surface dip data as a high-resolution constraint on our 3D fault model (Figs. 8 and 9). Geologic maps in Figs. 1 and 2 are compiled from Chinese Petroleum Corporation (1968, 1974, 1982, unpublished), Central Geological Survey (Chang, 1994; Lo et al., 1999; Ho and Chen, 2000; Huang et al., 2000; Lee, 2000) and Chang (1971). Surface breaks of 1935 Tuntzuchiao earthquake ($M_L = 7.1$) in green are from Bonilla (1975). Seismic lines: *A*: Wang (2003); *B*: Hung and Wiltschko (1993); *C* and *D*: Wang et al. (2003); *E*, *F* and *J*: Wang et al. (2002a); *G*: Chen (1978); *H*: Wang et al. (2000); *I*: Hung and Suppe (2002); *K–V*: Wang (2002) and C.Y. Wang et al. (2002a,b,c, 2004). Wells: TS-1, CLN-1, HL-1 and HL-2: Hung and Wiltschko (1993); TSK-1: Suppe (1980); TC-1: Dahlen et al. (1984); PC-1: Lee (1962); TCDP: Taiwan Chelungpu-Fault Drilling Project (in progress).