Tectonophysics 541-543 (2012) 81–88

Contents lists available at SciVerse ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Possible stress states adjacent to the rupture zone of the 1999 Chi-Chi, Taiwan, earthquake

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ARTICLE INFO

Article history:
Received 4 January 2012
Received in revised form 8 March 2012
Accepted 23 March 2012
Available online 3 April 2012

Keywords:
Stress state
Optimally oriented planes
Focal mechanism
TCDP
Chi-Chi earthquake
Taiwan

ABSTRACT

We explore regional stress states in the vicinity of the rupture area of the 1999 Chi-Chi, Taiwan, earthquake by reconciling data from the Taiwan Chelungpu-Fault Drilling Project (TCDP) in-situ measurements and earthquake focal mechanisms. Given the background deviatoric stress in the range of 10–50 MPa and the horizontal NW–SE directed maximum principal stress axis, the predicted fault types show strike–slip and normal faulting near the coseismic surface rupture and thrust and strike–slip faulting in central Taiwan. Such predictions are able to fit TCDP in-situ observations in a local scale and aftershock earthquake focal mechanisms in a regional scale. Additionally, the proposed stress state explains remarkable rotations of the maximum stress axes observed near the northern segment of the Chelungpu Fault. This result provides key information for forecasting of consequent earthquakes and evaluation of focal mechanisms after the occurrence of a large earthquake.

1. Introduction

Many devastating earthquakes occurred in central Taiwan in the past century (Fig. 1), such as the 1935 Hsinchu–Taichung M_{GR}7.1 earthquake (Huang and Yeh, 1992), the 1998 Rueyli M_w5.7 earthquake (Chan and Ma, 2004a; Chen et al., 1999; Wu et al., 2003), the 1999 Chi-Chi M_w7.6 earthquake, which is the largest earthquake ever recorded inland Taiwan (e.g., Chang et al., 2007; Ji et al., 2001, 2003; Shin and Teng, 2001; Yu et al., 2001), and the 1999 Chiayi M_w6.2 earthquake (Chan and Ma, 2004a; Chang and Wang, 2006; Chen et al., 2008). Due to a dense urban population in central Taiwan, it is necessary to investigate crustal stress regimes in order to build up a seismic hazard mitigation system. By comprehending crustal stress orientation and magnitude, one can evaluate possible focal mechanisms of future earthquakes and their respective magnitude or recurrence time (Linsley et al., 2005). According to background stress state and stress perturbation imparted by earthquakes, one can calculate stress evolution and further forecast spatial distribution of consequent earthquakes (King et al., 1994).

Previous studies have inferred crustal strain or stress states in Taiwan from different data sets. Seno (1977), Seno et al. (1993), and Yu et al. (1997) investigated the plate motion between the Eurasia Plate and the Philippine Sea Plate according to the earthquake focal mechanisms and GPS observations, respectively. Both results indicate the orientation of plate convergence is NW–SE directed in the Taiwan region. More detailed analysis of spatial variations of stress or strain states before the Chi-Chi earthquake were conducted from fault–slip data sets (Angelier et al., 1986), borehole breakout and elongation data (Suppe et al., 1985), GPS observations (Bos et al., 2003; Chang et al., 2003; Hsu et al., 2009b), and earthquake focal mechanisms (Yeh et al., 1991). They found that the orientations of the maximum horizontal compressive stress are generally NW–SE directed, consistent with the orientation of plate motion (Seno, 1977; Seno et al., 1993; Yu et al., 1997).

In this study, we are interested in variations of stress states associated with the 1999 Chi-Chi earthquake in different spatial scales. The earthquake nucleated at 8 km depth and produced surface rupture of ca. 100 km along the Chelungpu Fault (Chen et al., 2001). The coseismic slip of more than 10 m occurred predominantly at shallow depths (Ji et al., 2003). Wu et al. (2010) used earthquake focal mechanisms determining by P-wave first motion polarities to study fault types (Fig. 1) and variations of principal stress axes before and after the Chi-Chi earthquake. They found that most earthquakes are characterized by strike–slip or thrust faulting mechanisms. Using the stress tensor inversion methodology proposed by Michael (1984, 1987), Wu et al. (2010) evaluated spatial and temporal variations of stress orientations. They found significant rotations (>20°) of the maximum horizontal compressive axis immediately after the Chi-Chi earthquake in the northern segment of the Chelungpu Fault, wherein coseismic slip of more than 10 m occurred (Ji et al., 2003). On the contrary, a negligible rotation of the stress axis in the southern segment of the Chelungpu Fault was observed, consistent with slight

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0040-1951/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2012.03.031

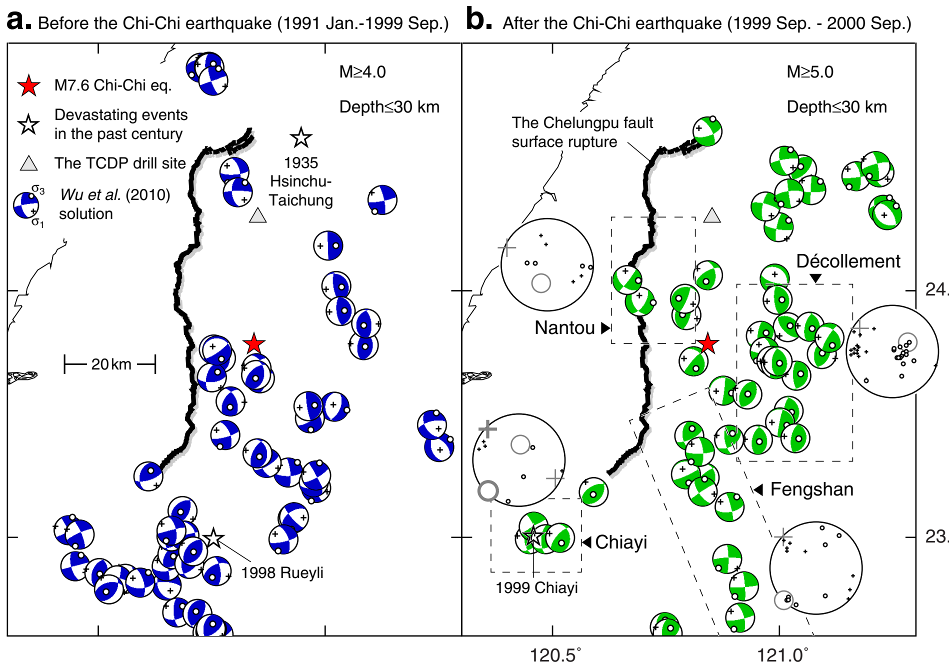

Fig. 1. Earthquake focal mechanisms in the time periods (a) before (1991 January–1999 September) and (b) after (1999 September–2000 September) the Chi-Chi earthquake. The focal mechanisms are determined by P-wave first motion polarities (Wu et al., 2010). Cross and circle represent orientations of the maximum (σ_1) and minimum (σ_3) stress axes, respectively. Focal mechanisms in the rectangular regions marked by dash lines are used to compare with the calculated OOPs in Fig. 3c. Inset figures showing the stereographic projections of observed focal mechanisms (small cross and circle) and calculated OOPs (large cross and circle) in the sub-regions (blue focal mechanisms in Fig. 3c). Note that two sets of modeled stress states are presented in the Chiayi region in different thicknesses.

coseismic deformation to the south. The study of Wu et al. (2010) provides a good constraint on regional stress orientations; however, the magnitude of crustal stress is not well investigated.

Hsu et al. (2009a) discussed the deviatoric stress in the crust from GPS observations. They observed a 10°–20° rotation of fault slip vectors after the Chi-Chi mainshock and suggested a low deviatoric stress of about 1–3 MPa on the décollement beneath the Central Range. The stress state can also be acquired from in-situ measurements at depths, which provide detailed information in a local scale. The Taiwan Chelungpu-Fault Drilling Project (TCDP) was initiated to gain a comprehensive understanding of faulting and rupture processes during the Chi-Chi earthquake (Ma et al., 2006 and references therein). Deep drilling to a depth of 2 km was carried out 5 years after the earthquake at a site located on the hanging-wall of the northern part of the Chelungpu Fault. The in-situ stress states at different depths in terms of magnitude and orientation have been inferred from different methodologies, such as the stress memory of rocks (Yabe et al., 2008), leak-off test (Haimson et al., 2010; Hung et al., 2009), the true triaxial strength criteria (Haimson et al., 2010), and the borehole-breakout (Haimson et al., 2010; Hung et al., 2009). The average azimuth of maximum stress axis agrees with observations inferred from local (Blenkinsop, 2006; Wu et al., 2007), regional (Hsu et al., 2009a; Wu et al., 2010), and tectonic scales (Seno, 1977; Seno et al., 1993; Yu et al., 1997). However, some of the in-situ observations concluded that either σ_1 or σ_2 is aligned with the vertical direction (Table 1). Such stress states are not consistent with focal mechanisms of neighboring earthquakes after the Chi-Chi earthquake (Fig. 1b). Previous studies (Wu et al., 2007; Yabe et al., 2008) attributed such stress heterogeneity to the existence of a significant deformable zone, the Chinshui Shale. However, it is not clear if it can also result from fault geometry complexity or pre-existing spatial stress heterogeneity in a local scale by various factors such as existing fault networks, lithology, geologic history, and so on.

In general, early works showed some diversity in crustal stress states between in-situ stress measurements and earthquake focal mechanisms. Limited by insufficient information of fault geometry and detailed spatial distribution of the stress states before Chi-Chi earthquake, we assume the stress heterogeneity solely resulted from the large stress perturbation during the mainshock. We construct models of pre-Chi-Chi regional stress states in terms of magnitude and orientation and examine their feasibility through modeling and comparing with observations. Finally, we provide a better constraint for the magnitude of deviatoric stress satisfied by observations in different spatial and temporal scales.

2. Coulomb failure stress and estimation of optimally oriented planes

According to the Coulomb criterion, Coulomb failure stress (*CFS*) on a specific plane can be presented as

$$CFS = \tau + \mu(\sigma_n + P), \tag{1}$$

where τ is the shear stress computed along the slip direction on the assumed fault plane (positive along slip direction), σ_n is the normal stress (positive for unclamping), P is the pore pressure, and μ is the friction coefficient. According to the constant apparent friction model (Cocco and Rice, 2002; Harris, 1998, and references therein), P is proportional to the normal stress changes ($P = -B\sigma_n$, where B is the

Table 1
Favorable faulting mechanisms at different depths in the TCDP drill site (denoted as triangle in Fig. 1) observed by different studies.

Depth (km)	Yabe et al. (2008)	Hung et al. (2009)	Haimson et al. (2010)
0.9	SS	SS	SS
1.1	SS or NF	SS	SS
1.3	SS or NF	SS	SS

SS: strike–slip faulting (σ_2 aligned with the vertical direction).
NF: normal faulting (σ_1 aligned with the vertical direction).