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

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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.

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TECTONOPHYSICS

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 Chiavi 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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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 preexisting 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). Skempton coefficient), and *CFS* are computed through the widely used expression:

$$CFS = \tau + \mu' \sigma_n, \tag{2}$$

where $\mu' = \mu(1 - B)$ is the apparent friction coefficient. Previous study (Chan and Stein, 2009) found no discernible differences in the results of Coulomb stress given the inevitable uncertainties in friction and Skempton's coefficient in the Taiwan region. We estimated *CFS* for different μ' and confirmed indistinguishable results from each other. In this study, we only represent the calculation results for an intermediate value of $\mu' = 0.4$. This value is also in good agreement with the range of friction coefficient between 0.2 and 0.5 inferred from the study of earthquake focal mechanisms in Taiwan (Hsu et al., 2010).

The shear stress τ and the normal stress σ_n can be also expressed in terms of the principal stresses:

$$\tau = \frac{1}{2} \left(\sigma_1^{\ t} - \sigma_3^{\ t} \right) \sin 2\beta, \tag{3}$$

$$\sigma_n = \frac{1}{2} \left(\sigma_1^t + \sigma_3^t \right) - \frac{1}{2} \left(\sigma_1^t - \sigma_3^t \right) \cos 2\beta, \tag{4}$$

respectively, where σ_1^t and σ_3^t are the maximum and minimum stress magnitudes of the total stress, respectively. The total stress is the sum of pre-existing regional stress and the stress change due to the mainshock. β is the orientation of the failure plane to the σ_1 axis. Eq. (2) then becomes

$$CFS = \frac{1}{2} \left(\sigma_1^t - \sigma_3^t \right) \left(\sin 2\beta - \mu' \cos 2\beta \right) - \frac{1}{2} \mu' \left(\sigma_1^t + \sigma_3^t \right), \tag{5}$$

Differentiating Eq. (5) as a function at β , the maximum Coulomb stress occurs when

$$tan2\beta = -\frac{1}{\mu'}.$$
(6)

The optimally oriented plane (OOP) after an earthquake rupture corresponds to the plane with the maximum Coulomb stress (King et al., 1994). We compute the orientation of the principal stress from the total stress. The OOP is oriented at $\beta(=0.5 \cdot \arctan(-1/\mu'))$ from the maximum principal stress axis, σ_1^c . Note that the OOP are determined from the stress change due to the mainshock as well as regional deviatoric stress, rather than the absolute magnitudes of stress components. The *CFS* caused by a coseismic dislocation in a homogeneous half-space is computed using the COULOMB 3.2 code (Toda and Stein, 2002).

In the next paragraph, we investigate different stress states before the Chi-Chi rupture and evaluate OOPs according to the coseismic slip model from the joint inversion of GPS and strong motion data by Ji et al. (2003). To examine their feasibility, we compare the OOP results with focal mechanisms of the consequent earthquakes in central Taiwan.

3. The stress orientation in central Taiwan

We first assume that the horizontal stress before the Chi-Chi earthquake is isotropic. Based on this assumption, the horizontal stress will be either greater or smaller than the vertical one. According to these two possibilities, we evaluated OOPs at the depth of 10 km using the coseismic slip model from Ji et al. (2003) (Fig. 2). With the assumption of isotropic horizontal stress, the coseismic stress perturbation is able to cause spatial heterogeneity of the maximum horizontal stress axis regardless of the vertical stress magnitudes (Fig. 2). These OOP results do not agree with the orientations of maximum horizontal stress observed after the Chi-Chi earthquake (Fig. 1b), which are roughly aligned with the direction of plate convergence (Seno, 1977; Seno et al.,

1993; Yu et al., 1997). In the case of isotropic horizontal stress with the magnitude smaller than the vertical stress (Fig. 2b), focal mechanisms are favorable to normal-faulting ubiquitously. Such distribution of focal mechanisms can only tally with few aftershocks and disagree with the region stress field (Fig. 1b). Therefore, we conclude that the maximum stress is close to horizontal and should be NW–SE directed.

According to the discussion above, we knew the maximum stress before Chi-Chi earthquake is aligned with the horizontal direction. Here, we test whether the magnitude of vertical stress is in between the magnitudes of maximum and minimum horizontal stresses or lower than the minimum horizontal stress. When the σ_2 axis is vertical (Fig. 3a), the crustal stress regime is dominated by strike-slip faulting, consistent with focal mechanisms of some consequent earthquakes, such as the northern part of the Chelungpu Fault and the Fengshan region (Fig. 1b). When the σ_3 axis is vertical (Fig. 3b), the thrust-faulting mechanism predominates in the crust, that is also in agreement with some observations, such as the earthquakes near the décollement (Fig. 1b). When the magnitudes of the intermediate stress and minimum stress are the same (Fig. 3c), the mechanisms of OOPs represent coexistence of strike-slip and thrust mechanisms, agreeing with most of the focal mechanism observations (Fig. 1b). For example, the OOPs to the east of the epicenter indicate thrust mechanisms corresponding to earthquakes near the décollement (Chi and Dreger, 2004). In the Fengshan region, the OOPs represent strikeslip faulting corresponding to the rupture along an existing active fault (Lee and Chan, 2007). In the Chiayi region, the OOPs represent coexistence of thrust and strike-slip mechanisms in accordance with the mechanisms of the 1999 Chiayi sequence (Chang and Wang, 2006; Chen et al., 2008). Furthermore, previous studies also suggest the increases of Coulomb stress in these regions and confirm their mainshock-aftershock relation (Chan and Ma, 2004b; Chan and Stein, 2009; Ma et al., 2005). However, the predicted OOPs do not outright conform to the focal mechanisms of the consequent seismicity. In the Nantou region, the OOPs show thrust mechanisms (Fig. 3c). On the contrary, aftershocks show either strike-slip or normal faulting (Fig. 1b). The occurrence of these events can be associated with rupture along the pre-existent faults, which are produced by the rifting of the South China Sea (Kao and Chen, 2000) in the Miocene. The faults are promoted to failure due to the $\triangle CFS$ increase by the Chi-Chi earthquake (Chan and Stein, 2009).

Through the results above, we found that both the minimum horizontal stress and the vertical stress are similar in magnitude. However, their relative magnitudes were not resolved since some of the possible ambiguity in the least and intermediate principal stress orientations may be due to a change in stress state with depth. Besides, the variations of fault types are only sensitive to the change of deviatoric stress. Henceforth, we assumed identical stress magnitudes for the minimum horizontal stress and vertical stress in the following analyses.

4. The magnitude of deviatoric stress in central Taiwan

We determined that the maximum principal stress is NW–SE directed and the amplitude of the least and intermediate principal stress is similar in the previous section. Here, we further test possible magnitudes of the deviatoric stress through comparison between the OOPs, the in-situ observations in the TCDP drill site, and aftershock focal mechanisms.

4.1. Stress state near the TCDP drill site

Assuming that the strike of σ_1 is 100° corresponding to the analysis of focal mechanism in the northern segment of the Chelungpu Fault before Chi-Chi (Wu et al., 2010), we compute the Chi-Chi coseismic stress change taking account different magnitudes of background deviatoric stress. We then calculate the OOPs at different depths in



Fig. 2. Modeled OOPs according to different assumptions of the stress orientations. In these two cases, isotropic horizontal stress is assumed before the Chi-Chi mainshock. The magnitude of the horizontal stress is (a) larger than; and (b) smaller than the vertical stress (σ_V). Cross and circle represent orientations of the maximum (σ_1) and the minimum (σ_3) stress axes, respectively. Dashed circle in each focal mechanism represents the plunge of 45°. The target depth for the OOP calculation is 10 km. Inset shows the distribution of the Chi-Chi coseismic slip by Ji et al. (2003). Color scale indicates the coseismic slip.

the TCDP drill site (Fig. 4) and compare them with observations (Table 1).

With a deviatoric stress of 5 MPa or smaller, the OOPs are favorable to thrust faulting (plunge of $\sigma_3 > 45^\circ$) at the depth of 0.9–1.3 km (first two columns in Fig. 4). They do not fulfill any of in-situ observations inferred from various methodologies (Table 1).

With a deviatoric stress of 60 MPa or larger, the OOPs are favorable to thrust faulting at the depth of 1.1 km, where the Chi-Chi rupture passed through (last column in Fig. 4). They do not fulfill any of the insitu observations inferred from different methodologies (Table 1).

When a deviatoric stress is in the range of 10 to 50 MPa, plunges of σ_1 and σ_3 axes are less than 45° at the depth of 0.9 and 1.1 km (Fig. 4) suggesting that OOPs are favorable to strike–slip faulting. Such results agree with the in-situ observations (Table 1). At the depth of 1.3 km, the OOP indicates normal faulting (plunge of σ_1 is more than 45°), which conforms to the observations by Yabe et al. (2008) (Table 1). The results in Fig. 4 show that the deviatoric stress magnitude does not really affect the stress regimes except for extremely low (<10 MPa) and high values (>50 MPa).

4.2. Stress state in central Taiwan

We compared the OOPs at different depths with observations in the TCDP drill site and proposed a possible range of deviatoric stress in the previous section. Here, we aim to find the range of deviatoric stresses explaining aftershock focal mechanisms as well (Fig. 5). We assume that the strikes of σ_1 are 100° and 122° in the northern and southern segments of the Chelungpu Fault, respectively, which correspond to the analysis of focal mechanisms before the Chi-Chi earthquake (Wu et al., 2010).

With a deviatoric stress of 0.1 MPa (Fig. 5a), many of the OOPs in central Taiwan are favorable to normal faulting. This is not consistent with observations (Fig. 1b). Besides, only 15 of 49 (30%) observed focal mechanisms shown in Fig. 1b have similar σ_1 orientations as those predicted in the OOPs (difference within 20°). Significant rotations of the maximum horizontal stress axes of more than 20° are predicted in almost the entire area (blue focal mechanisms in Fig. 5a), disagreeing with observations after the Chi-Chi earthquake (Fig. 1b). This feature implies that a larger deviatoric stress is required in central Taiwan.

With an assumed deviatoric stress of 30 MPa (Fig. 5b), the rotation of σ_1 axis due to the mainshock is negligible except in the areas that experienced large coseismic slip (blue focal mechanisms in Fig. 5b). The OOP pattern corresponds to the stress orientations inferred from the stress tensor inversion (Wu et al., 2010). Since the same magnitudes are assumed for the σ_2 and σ_3 axes, the mechanisms of OOPs represent coexistence of strike–slip and thrust faulting, in agreement with the majority of aftershock focal mechanisms (Fig. 1b). Overall, 26 of 49 (53%) focal mechanisms have similar σ_1 orientations as predicted by the OOPs.

With a deviatoric stress of 60 MPa (Fig. 5c), the OOPs are generally similar to those with a deviatoric stress of 30 MPa (Fig. 5b) and in agreement with many aftershock focal mechanisms. However, the rotation of σ_1 axis due to the coseismic perturbation is negligible even in the northern segment of the Chelungpu Fault. Such results imply that a smaller deviatoric stress is expected in order to explain



Fig. 3. Modeled OOPs according to different assumptions of the stress orientations. The azimuth of σ_1 is assumed to be NW–SE directed before the Chi-Chi mainshock. The magnitude of the minimum horizontal stress is (a) smaller than, (b) larger than, and (c) equal to the vertical stress (σ_V). Cross and circle represent orientations of σ_1 and σ_3 , respectively. Dashed circle represents the plunge of 45°. The target depth for OOP calculation is 10 km. In panel (c), OOPs in the rectangular regions marked by dashed lines are used to compare with aftershock focal mechanisms in Fig. 1. Inset shows the distribution of coseismic slip by Ji et al. (2003). Color scale indicates the coseismic slip.



OOPs for different deviotoric stress

Fig. 4. Modeled OOPs imparted by the Chi-Chi earthquake at different depths in the TCDP drill site (denoted as triangle in Fig. 1). The orientation of the σ_1 axis is fixed to 100° and the magnitudes of the σ_2 and σ_3 axes are identical. Dashed circle in each focal mechanism represents the plunge of 45°. Different magnitudes of deviatoric stresses are tested.



Fig. 5. Modeled OOPs according to different deviatoric stresses. The orientations of σ_1 are fixed to 100° and 122° in the northern and southern segments of the Chelungpu Fault, respectively. The magnitudes of the σ_1 axis are 0.1, 30, and 60 MPa larger than those of the σ_2 and σ_3 axes in (a), (b), and (c), respectively. Dashed circle in each focal mechanism represents the plunge of 45°. Blue focal mechanisms represent rotation of the σ_1 axis larger than 20° after the Chi-Chi mainshock. Inset shows the distribution of coseismic slip by Ji et al. (2003). Color scale indicates the coseismic slip.

rotations of stress axes after the Chi-Chi earthquake (Wu et al., 2010). To compare with observations, 24 of 49 (49%) focal mechanisms correspond to the predicted OOPs. With a deviatoric stress of 60 MPa, the OOPs have a slightly weak predicting ability in comparison to a deviatoric stress of 30 MPa (53%). Through comparison between OOPs with observed aftershock focal mechanisms, we find that a background deviatoric stress of 30 MPa results the smallest misfit. This magnitude is within the range of 10–50 MPa (Section 4.1), which predicts ideal OOPs consistent with the in-situ measurements (Fig. 4).

5. Discussion and conclusions

We have tested a variety of regional stress fields in central Taiwan, examined their feasibility through comparison with in-situ stress measurements as well as earthquake focal mechanisms, and modeled stress variations before and after the Chi-Chi earthquake. According to the TCDP in-situ observations (Table 1), either σ_1 or σ_2 is aligned with the vertical direction near the Chelungpu Fault. Such stress states do not fulfill the focal mechanisms of neighboring earthquakes after the Chi-Chi earthquake (Fig. 1b). Previous studies (Wu et al., 2007; Yabe et al., 2008) ascribed such heterogeneity to the Chinshui Shale, a significant deformable zone. In this study, we have calculated the OOPs at different depths in the TCDP drill site with a given deviatoric stress of 10 to 50 MPa. The results suggest strike-slip and/ or normal faulting at the depth of 0.9-1.3 km and strike-slip faulting at the depth of 10 km (Fig. 4), which satisfy both the in-situ observations (Haimson et al., 2010; Hung et al., 2009; Yabe et al., 2008) (Table 1) and the earthquake focal mechanisms (Wu et al., 2010) (Fig. 1). We speculate that the abnormal normal faulting at shallow depths could also be attributed to a rough coseismic rupture or the geometry complexity of the Chelungpu Fault at shallow depths. However, influences of fault geometry on stress heterogeneity are beyond the scope of this study.

Since the seismicity is absent in the northern part of the Chelungpu Fault after the mainshock (Chang et al., 2007), this feature

may suggest that the stress has been released completely, or nearly completely, during the coseismic period. In this study, we infer that the magnitude of deviatoric stress is within a range of 10-50 MPa, which is on the same level of the stress drop during coseismic rupture (Ma et al., 2001). Ma et al. (2001) investigated the rupture process of the Chi-Chi earthquake, using near-source strong-motion records, broadband teleseismic displacement waveforms, and GPS data, and suggested a stress drop of 22.5 MPa in the northern part of the Chelungpu Fault. However, our results do not outright conform to all of the previous studies. Hsu et al. (2009a) investigated the GPS observations and focal mechanisms near the décollement and suggested a smaller deviatoric stress within a range of 1–3 MPa. The discrepancy of the deviatoric stress magnitude might be attributed to spatial stress heterogeneity. In addition, our result seems to be larger than those obtained from strike-slip fault systems. For instance, Hardebeck and Hauksson (2001) computed the deviatoric stress magnitude of about 10 MPa using the rotations of stress axes associated with the 1992 Landers earthquake; the study of the Denali earthquake showed that the shear stress on the fault is on the order of 1-4 MPa prior to the earthquake and was reduced to about 0 MPa after the earthquake (Wesson and Boyd, 2007). A high deviatoric stress obtained in this study may be resulted from comparing TCDP measurements with the coseismic slip model with very rough slip pattern near the surface rupture such that a high stress is required.

We have found that the rotation of σ_1 axis after the Chi-Chi earthquake is significant in the areas that experienced large coseismic deformation (Fig. 5b). The significant coseismic stress perturbation may explain unsuccessful aftershock forecasting in the northern part of the Chelungpu Fault as demonstrated by Catalli and Chan (2012), since they assumed identical stress field before and after the mainshock and calculated the ΔCFS solved on the spatial variable receiver faults acquired by pre-Chi-Chi focal mechanisms. In this study, we test the forecasting ability for consequent earthquakes after the Chi-Chi mainshock by considering the variation of stress orientations and using the OOPs as receiver faults (Fig. 5b). We



Fig. 6. Map-view of the Coulomb stress change by the Chi-Chi mainshock (star) solved on the OOPs using a deviatoric stress of 30 MPa for the background stress state (as shown in Fig. 5b). Relocated seismicity with $M \ge 2.0$ and hypocentral depth of ≤ 30.0 km in a three-month period after the mainshock (Chan and Stein, 2009) is superimposed on the map. About 94% of them are in the stress-increased region.

calculate the Chi-Chi Coulomb stress change (Fig. 6) and compare with the relocated seismicity with magnitude larger than 2 and focal depth less than 30 km over a three-month period after the mainshock (Chan and Stein, 2009). About 94% of the consequent events are in the stress-increased region, including in the northern part of the Chelungpu Fault. In comparison with the $\triangle CFS$ solved on the spatial variable receiver faults, which forecasts 63% aftershocks in the stress-increased region, ΔCFS solved on the OOPs has a significant better forecasting ability. Even though the OOPs are considered as receiver faults, 6% of the aftershocks are failure to be predicted, that could be attributed to the uncertainties of aftershock locations (Catalli and Chan, 2012), the dynamic stress triggering (Fischer et al., 2008), or/and the evolution of the stress during the postseismic period imparted by afterslip and viscoelastic rebound model (Chan and Stein, 2009). Our results suggest that focal mechanisms of future earthquakes can be evaluated in cooperation with the background stress state and stress perturbation in order to obtain a better forecasting ability.

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