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Seismic cycle stress change in western Taiwan over the last 270 years

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[1] The island of Taiwan is affected by intense seismic activity, which includes large events as the disastrous 1999 Chi-Chi earthquake. To improve seismic hazard assessment in this area, we estimate the effect of both interseismic loading and major events since 1736 on the state of stress of major active faults. We focus our approach on western Taiwan, which is the most densely populated part of Taiwan. We pay a specific attention to faults geometry and to both interseismic and coseismic slip distributions. Our results suggest that both earthquakes and interseismic loading before 1999 increase the Coulomb stress in the north-western part of the Chelungpu fault, a region which experienced the highest coseismic slip during the Chi-Chi earthquake. More importantly our results reveal a Coulomb stress increase in the southern part of the Changhua thrust fault, below a densely populated area. **Citation:** Mouyen, M., R. Cattin, and F. Masson (2010), Seismic cycle stress change in western Taiwan over the last 270 years, *Geophys. Res. Lett.*, *37*, L03306, doi:10.1029/2009GL042292.

1. Introduction

[2] Taiwan is located at the plate boundary between the Eurasian and the Philippine Sea plates. Most part of the 82 mm a^{-1} convergence rate [*Yu et al.*, 1997] is accommodated by slip on a basal detachment initiating in western Taiwan and by shortening and thickening in the Western Foothills [*Suppe*, 1981]. The strength of these processes is illustrated by high seismic activity [*Kim et al.*, 2005] with several large earthquakes (Mw ≥ 6) over the last 270 years [*Bonilla*, 1975; *Tsai*, 1985; *Chen and Tsai*, 2008], including the 1999 Chi-Chi earthquake (Mw 7.6), which occurred along Chelungpu fault (Figure 1a). Here we investigate the effect of this tectonic activity on future earthquakes in western Taiwan assuming that the static Coulomb stress change is a reliable criterion to assess the location of future events. This assumption is supported by many previous studies, which include earthquake triggering [*Stein*, 1999; *King and Cocco*, 2001] and aftershocks location analysis [*King et al.*, 1994]. In Taiwan *Chan and Ma*'s [2004] result gives a good agreement between coseismic Coulomb stress increases and aftershocks distribution for several earthquakes. In this study, following *Stein et al.* [1997] and *Ali et al.* [2008] we assume that interseismic deformation has also a major effect on this triggering. Thus we rather focus on longterm stress change due to both coseismic slip of Mw ≥ 6 earthquakes and interseismic slip over the last three centuries.

2. Method

2.1. Coulomb Stress Change Reminder

[3] The Coulomb stress change (ΔCFF) is defined by

$$\Delta CFF = \Delta\tau - \mu(\Delta\sigma_n - \Delta p)$$

where $\Delta\tau$ is the shear stress change (positive in the slip direction of the fault), $\Delta\sigma_n$ is the static normal stress change (positive for compression), Δp is the pore fluid pressure (positive in extension) and μ is the friction coefficient. Introducing the apparent friction $\mu' = \mu(1 - B)$, with B the Skempton coefficient, we have

$$\Delta CFF = \Delta\tau - \mu'\Delta\sigma_n$$

Using analytical solution of *Okada*'s [1985, 1992] equations we calculate the 3-D stress change due to coseismic and interseismic slips on buried dislocations in a homogeneous elastic half space. We set Poisson ratio to 0.25 and shear modulus to $3\ 10^{10}$ Pa [*Jaeger and Cook*, 1979]. Considering faults geometries, the associated $\Delta\tau$ and $\Delta\sigma_n$ can be calculated. The Skempton coefficient links the change in pore pressure to the change in normal stress. Dealing with long period of time, we assume that pore fluid diffusion makes μ' rise to μ so that Skempton coefficient is set to 0. Following *King et al.* [1994], we set $\mu' = 0.4$. Finally, ΔCFF is computed for western Taiwan active faults. For a detailed description of ΔCFF computation, see *Cattin et al.* [2009]. Our approach is described with more details in the next section and summarized by a sketch in the auxiliary material.[3]

2.2. Coseismic Slip

[4] According to catalogs compiled by *Bonilla* [1975], *Tsai* [1985] or *Chen and Tsai* [2008], we estimate that 73 large earthquakes have occurred in Taiwan since 1736 (Figure 1a). For each earthquake the computation requires the knowledge of parameter set including slip, rake and fault rupture geometry (length, width, dip, depth and azimuth). The minimum information we have are the location, date and magnitude. Length, width and slip of the rupture plane, if unknown, are estimated using scale laws from *Wells and Coppersmith* [1994]. When dip, depth or azimuth of the plane are unconstrained, assumptions are made to determine the most likely faults involved in these events. Here we pay attention to the tectonic context described by *Shyu et al.* [2005] around the earthquake location. Focal mechanism, considered for rake,

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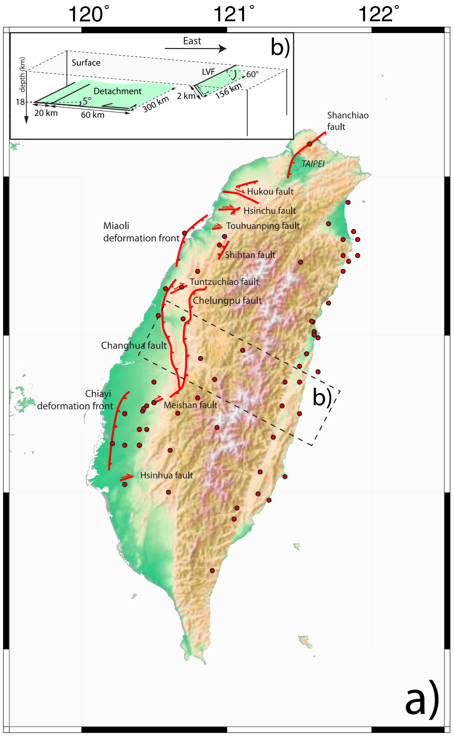

Figure 1. (a) Location of Mw ≥ 6 earthquakes (red dots) which occurred in Taiwan since 1736 [after *Bonilla*, 1975; *Tsai*, 1985; *Chen and Tsai*, 2008]. ΔCFF is computed on Western Taiwan active faults (red segments) which parameters are described in the work of *Shyu et al.* [2005]. (b) Cross section to precise detachment and LVF geometries.

is a key-parameter unknown for many earthquakes. We determine it from International Seismological Centre data and according to tectonic context. For unregistered events, focal mechanisms are estimated considering the tectonic context only. In the latter case, it is obviously roughly determined. However comparing estimated and published focal mechanisms for studied events shows a good accordance between both. Most of historical earthquakes require the use of these estimates. On the contrary, some earthquakes have been perfectly described, e.g., Chi-Chi earthquake [*Ji et al.*, 2003], the 2006 Chengkung earthquake [*Wu et al.*, 2006a] and others events [*Ma and Kikuchi*, 1994; *Wu et al.*, 2006b]. Between these two end-members we find detailed studies of some of the parameters we need [*Hwang and Kanamori*, 1989; *Chen et al.*, 1990], while the others have to be estimated. The used rupture parameters (excepted for Chi-Chi earthquake) are available in the auxiliary material.

2.3. Interseismic Slip

[5] The interseismic loading is calculated considering a slipping detachment beneath Taiwan [*Suppe*, 1981]. Based on our previous approach [*Mouyen et al.*, 2009] it is modeled, using two dislocations, as a single plane which western part has a lower slip velocity than the eastern part. This should reproduce the western slowing slip of the detachment [*Dominguez et al.*, 2003]. However, one must note that the velocity value on the western part exhibits some lateral variations. The detachment velocity is set to 45 mm a^{-1} on its eastern part [*Dominguez et al.*, 2003] and to 7 mm a^{-1} on its western part [*Cattin et al.*, 2004]. It extends from west of the Chelungpu fault to the Central Range with a slightly East-dipping shape (Figures 1a and 1b). The comparison of the convergence directions between Eurasian plate and Philippine Sea plate (305–310°N according to *Fisher et al.* [2002]) with the surface expression of the plate boundary (20°N for the Longitudinal Valley Fault-LVF) involves an obliquity of 20° between both. This results in a senestrial component on the detachment in addition to the main reverse one; its rake is consequently set to 70°. The last slip needed to reach the 82 mm a^{-1} of convergence rate between the Eurasian and the Philippine Sea plates is explained by a 30 mm a^{-1} creeping zone on the LVF [*Hsu et al.*, 2003] and modeled by a narrow dislocation plane (Figures 1a and 1b).

2.4. Receiver Faults

[6] Receiver faults are faults on which ΔCFF is computed. They are defined by a geometry, a location and a rake, i.e., normal, inverse, left-lateral or right-lateral slip and by one or several planes, which follow parameters described by *Shyu et al.* [2005]. Every receiver fault is divided in sub-faults for several depths. Following *McCloskey et al.* [2003] we assume that failure orientation is mainly controlled by geological structures (actual faults) rather than coseismic and regional field stress. Thus, in contrast with the commonly used approaches [e.g., *King et al.*, 1994], the planes optimally oriented for failure derived from regional field stress are not used in our calculation. The computation of ΔCFF is performed on western Taiwan active faults.

3. Coulomb Stress Change on Chelungpu Fault Before the Chi-Chi Event

[7] The strong 1999 Chi-Chi earthquake has been widely studied and the main features of its coseismic slip distribution are now well-constrained [Kao and Chen, 2000; *Ji et al.*, 2003; *Ma et al.*, 2005]. Here to test the robustness of our approach we compare the loading state of Chelungpu before the rupture with the slip distribution of the 1999 event.

[8] Computing the loading involved by historical earthquakes occurring before 1999 on the Chelungpu fault gives two patches of Coulomb stress increase (Figure 2a): one in the northern part of the fault reaching 0.7 MPa, and a second in the southern part, below 4 km depth, between 0.2 and 0.4 MPa. These results are consistent with the highest coseismic slips, as well as the location of the largest subevent in the minute past to the first mainshock, both observed in the northern part of the Chelungpu fault [*Yu et al.*, 2001; *Kao and Chen*, 2000]. However, these results do not highlight the nucleation area since no stress increase exists nearby the initial mainshock location.

[9] As proposed by *Kao and Angelier* [2001], the Chi-Chi earthquake is a manifestation of the mountain building in Taiwan, i.e., a longer running process. Thus we calculate the interseismic stress change along the Chelungpu fault (Figure 2b). Note that, as we use a slip rate, we obtained a stress change rate, in MPa a^{-1}. We identify four patches of Coulomb stress increase: along the lower edge of the fault (with at least 0.003MPa a^{-1}), in the northern sub-plane, close to the surface (~0.001 MPa a^{-1}) and deeper on the eastern edge (~0.003 MPa a^{-1}) and in the middle sub-plane of the fault, between 1 and 10 km depth, with an increase northward from 0.001 to 0.003 MPa a^{-1}.

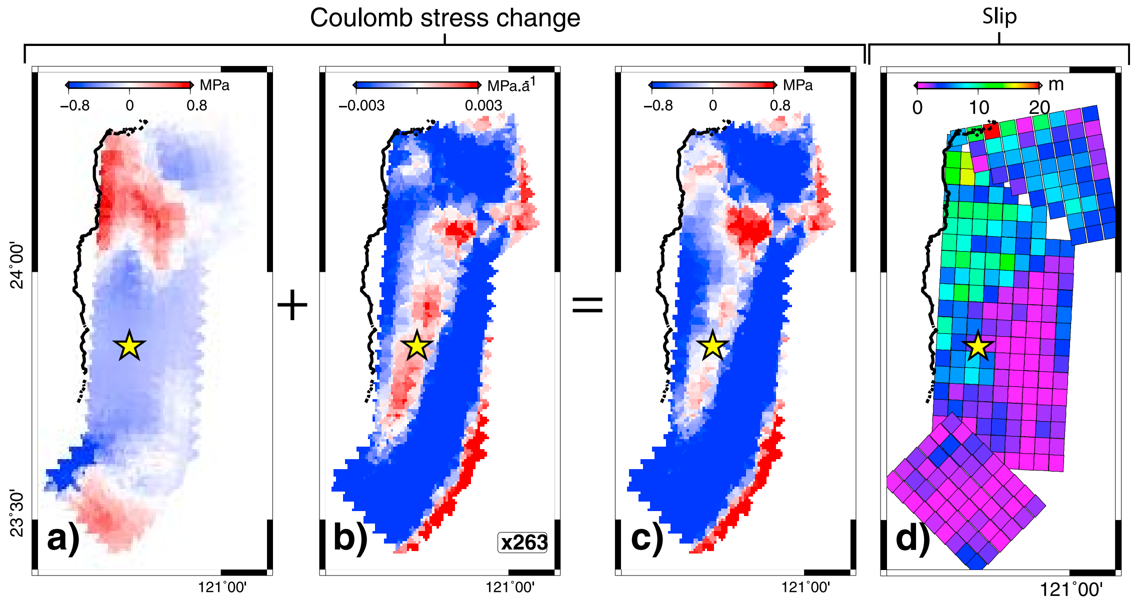

Figure 2. ΔCFF on Chelungpu fault before Chi-Chi earthquake involved (a) by coseismic slip, (b) by interseismic slip for one year and (c) by both coseismic and interseismic slips. To obtain Figure 2c we multiply the yearly effect of interseismic slip by 263, i.e., the number of years from 1736 to 1999. The star shows the Chi-Chi earthquake nucleation. (d) Slip distribution established by *Ji et al.* [2003].

[10] Following *Ali et al.* [2008] and based on elastic assumption, the yearly interseismic slip is extended over 263 years, from 1736 to 1999, and coseismic and interseismic effects are added to calculate the total ΔCFF (Figure 2c). The increasing slip to the north of the fault (Figure 2d) is in agreement with the increasing ΔCFF in the same direction and the nucleation area is loaded before the rupture. Our results thus demonstrate that both the interseismic loading and deformation related to previous events are required to explain the main features of the Chi-Chi event.

4. Current Coulomb Stress Change on Western Taiwan Active Faults

[11] To calculate the ΔCFF over the last 270 years in western Taiwan (Figures 3a–3c), we complete the catalog adding Mw ≥ 6 events occurring since Chi-Chi earthquake and up to 2006, including the three major Chi-Chi aftershocks [*Kao and Chen*, 2000].

[12] Figures 3a and 3b give the ΔCFF on western Taiwan active faults involved by coseismic slip before and after the Chi-Chi event, respectively. Comparing Figures 3a and 3b reveals significant stress increase limited to south Changhua fault. This active fault has therefore been loaded by the Chi-Chi earthquake.

[13] The ΔCFF involved by interseismic slip relaxes most of the frontal thrust faults excepted the deepest part of Changhua and loads lateral faults as Hukou, Meishan, Hsinhua, Tuntzuchiao and Touhuanping (Figure 3c). As mentioned by *Lin and Stein* [2004] the coulomb stress decrease on the western thrust faults could be explained by the wide stress shadow created by the detachment.

[14] Adding both the interseismic loading and coseismic stress change due to major earthquakes over the last 270 years we obtain a map of ΔCFF (Figure 3d), which can be used to assess the current seismic hazard on western Taiwan active faults. The stress shadow generated by the interseismic slip is significant and discharges most of the frontal thrusts faults. Nevertheless Hukou, Tuntzuchiao, Hsinhua, Shanchiao and Touhuanping faults are loaded and some of them have already generated disastrous earthquakes (e.g., Tuntzuchiao or Hsinhua). Moreover the stress accumulated on Changhua by the Chi-Chi earthquake is large enough to keep it loaded, in particular its southern part. This Coulomb stress increase and the low deformation observed along this fault [*Chang et al.*, 2003] result in high seismic hazard for the southern part of the Changhua fault. Concerning interseismic slip, we separated effects due to detachment and LVF. The LVF effects count for 2% of the whole effect. This gives to the detachment the main effects in the loading of western Taiwan active faults. Uncertainty may be introduced by only selecting large earthquakes for the ΔCFF computation as lower magnitude earthquakes are more numerous. However, the use of these events modifies ΔCFF value of ~10% without changing its distribution. Thus it does not affect significantly the general trend of the stress change.

5. Conclusion

[15] Our results suggest that coseismic movements as well as interseismic deformation take a significant part in loading active faults in western Taiwan. This demonstrates that interseismic deformation must be taken into account to improve seismic hazards assessment. We compute a present-day important loading on five western Taiwan active faults: Hukou, Tuntzuchiao, Hsinhua, Shanchiao and Touhuanping. We associate the higher seismic hazard to the Changhua fault due to its large loaded surface. Changhua fault has also be pointed out by *Shyu et al.* [2005], which attribute it possible large earthquakes. Nevertheless Shihtan, Shanchiao and

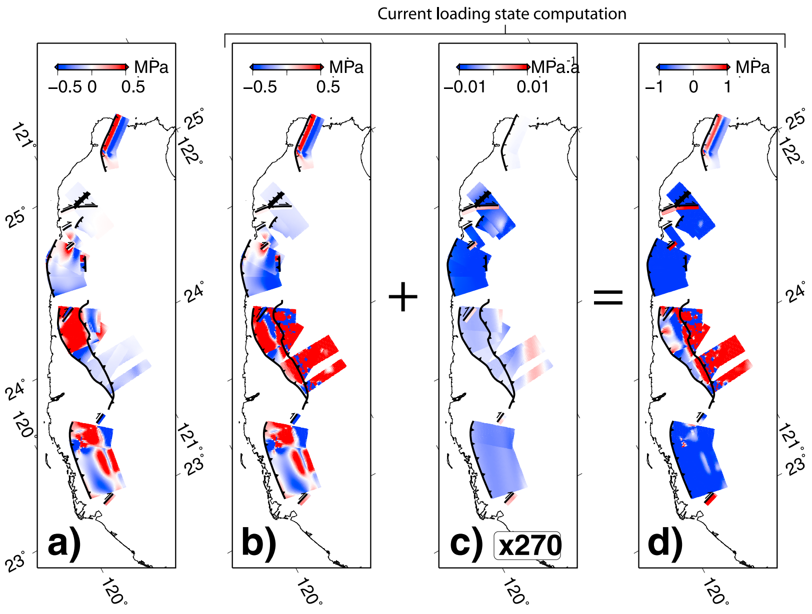

Figure 3. (a) ΔCFF on western Taiwan active faults involved by coseismic slip since 1736 and before the Chi-Chi event. (b) Same as Figure 3a but up to present day, including the Chi-Chi event. (c) ΔCFF on western Taiwan active faults involved by interseismic slip for one year. (d) Result of both coseismic and interseismic slips considering 270 years from 1736 up today. We do not show here the loading state of Chelungpu fault because the high slip variability of the fault model involves stress increase in its neighborhood, which is considered as a consequence of the rupture model discontinuity [*Ma et al.*, 2005].

Meishan faults are also a threat as they already have experienced large ruptures.

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