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Three-dimensional patterns of seismic deformation in the Taiwan region with special implication from the 1999 Chi-Chi earthquake sequence

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Abstract

We compile a comprehensive list of hypocentral locations and source parameters for earthquakes occurred in the Taiwan region. The collected database is used to construct 3D patterns of seismic deformation that are associated with various tectonic processes such as subduction and collision between the Philippine Sea plate and Eurasia. Specifically, we divide the entire Taiwan region into a 3D grid of 10km interval and the amount of seismic moment released at each point is the sum of all individual events in the vicinity. In case when the physical dimension of an earthquake is larger than 10km, the corresponding seismic moment is distributed across multiple grid points. This quantitative approach gives a better depiction on many first-order features in the region. The most intriguing one is that a significant deficit in the total amount of released seismic moment can be clearly identified around the Chi-Chi source region before the big earthquake occurred in 1999. The deficit trough is then filled by the seismic moment of the Chi-Chi earthquake sequence. This deficit-then-fill pattern in a region's seismic moment distribution can be used as an indicator to pinpoint the locations of large earthquakes in the foreseeable future. Following this argument, we suggest that disastrous earthquakes with magnitudes comparable to that of the Chi-Chi earthquake are due for the two regions adjacent to the Chi-Chi source area (i.e., the Miaoli-Hsinchu domain to the north and the Chiayi domain to the south).

Keywords: Seismic moment; Chi-Chi earthquake; Focal mechanism

1. Introduction

The 1999 Chi-Chi earthquake sequence is the largest seismic event on the island of Taiwan since modern seismological observation began there in the early 1970s (Tsai et al., 1977). It is also the most devastating natural disaster in the region, causing an estimated loss of US$ 4billion in property and more than 2400 human fatalities. The mainshock, measured moment magnitude (M_w) ~ 7.6, ruptured about one fourth of the island's N–S dimension along the active out-of-sequence Chelongpu fault on the western side of central Taiwan (Fig. 1; Kao and Chen, 2000).

The Chi-Chi earthquake sequence is generally interpreted as the manifestation of compressive deformation in response to the collisional process between the Philippine Sea plate (PSP) and the Eurasia plate (EP) (Suppe, 1984; Angelier et al., 1986). In fact, paleoseismological surveys at the Chelungpu fault reveal that at least 4 large events occurred before the Chi-Chi earthquake during the past 1900years (Ota et al., 2001; Chen et al., 2004b). The recently proposed neotectonic architecture of Taiwan, based upon structural and geomorphic expression of active faults and folds both in the field and on shaded relief maps, prescribes the Taiwan region into several domains that are all capable of generating future seismic events with magnitudes similar to the Chi-Chi earthquake's (Shyu et al., 2005), and indicates that the Chelungpu fault is only one of the principal components within the western neotectonic belt of Taiwan (Shyu et al., 2005). Therefore, there is

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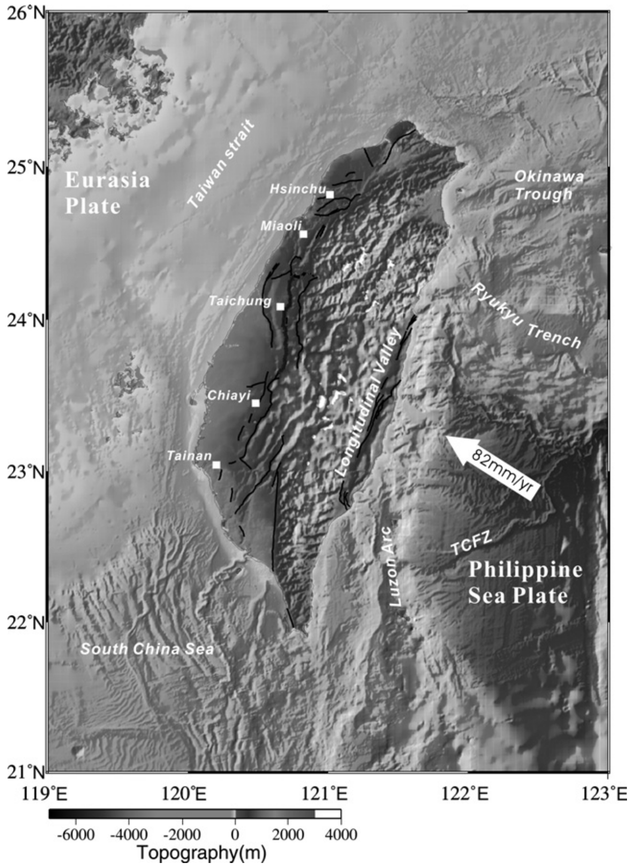

Fig. 1. Topographic map showing the regional tectonic setting of Taiwan. Major active faults, represented by thin solid lines, can be found throughout the highly populated west Taiwan where major cities are marked as open squares. The thick gray line marks the out-of-sequence Chelungpu thrust, which is responsible for the occurrence of 1999 Chi-Chi earthquake. TCFZ: Taitung Canyon Fault Zone as defined by Kao et al. (2000).

little doubt that the highly populated western Taiwan will be struck by large earthquakes in the future.

Taking a statistical approach, Zhuang et al. (2005) report that the Chi-Chi epicentral area was seismically quiescent during the period of 1960–1990. Although this observation is significant to hint that elastic strain had been accumulating in the Chi-Chi source region prior to its occurrence in 1999, it does not give any quantitative description on how much into the deficit was the seismically released deformation before the entire system began to readjust. Since other active neotectonic domains in western Taiwan are not addressed in that statistic analysis, perhaps due to the lack of sufficient data samples, it is hard to quantitatively evaluate the potential of large local earthquakes in the future. In this study, we characterize the seismic deformation in the Taiwan region from a different approach, taking into account of various factors such as different magnitudes, focal mechanisms, epicentral locations, and focal depths. Instead of showing each seismic event as a point in the volume, we distribute the seismic source onto a plane whose dimension and orientation are determined by the earthquake's fault plane. Source parameters of 1986 earthquakes are compiled and analyzed in this study. The results, complimented by historical seismicity and routinely reported earthquake catalogues, are mapped into a grid system to give the 3D patterns of seismic source distribution for the entire region. Our results give the most compelling evidence that the 1999 Chi-Chi earthquake sequence occurred in the region with the largest deficit in seismic moment release. Finally, built on top of our conclusion, we point out other regions in western Taiwan where significant deficits in seismic moment release are also observed. The possibility of large earthquakes striking these regions in the future should not be overlooked.

2. Data compilation

We adopt the locations and magnitudes of regional seismicity from the earthquake catalogues routinely prepared by the Central Weather Bureau (CWB), Taiwan. The dataset covers all significant events since 1900 and is considered complete for events with $M_L \geq 1.5$ since 1991 (Chang, 2004). For those that had caused destruction of property and/or human casualties, the hypocentral and source parameters that have been carefully calibrated by modern analysis are used in this study (e.g., Sheu et al., 1982; Tsai et al., 1983; Lin, 1987; Cheng and Yeh, 1989; Huang and Yeh, 1992). Earthquake source studies in the Taiwan region can be roughly divided into several stages. In the years before early 1970's when the Taiwan Telemetered Seismographic Network (TTSN) had not been established yet, most focal mechanism solutions were derived from *P* wave first motions recorded at stations of the World-Wide Standardized Seismographic Network (WWSSN) (e.g., Katsumata and Sykes, 1969; Wu, 1970). The routine operation of TTSN (and the later much expanded Taiwan Seismic Network operated by CWB) enabled mass production of first-motion mechanism solutions for smaller local earthquakes (e.g., Lee, 1983; Chen and Wang, 1988; and the CWB Seismological Database). In the 1980s and 1990s, long-period body waveform inversion became the popular method to obtain accurate earthquake source parameters (e.g., Pezzopane and Wesnousky, 1989; Wu et al., 1989; Kao and Wu, 1996; Kao et al., 1998b; Ma and Chen, 1999; Kao et al., 2000). Meanwhile, centroid-moment-tensor (CMT) solutions using teleseismic waveforms with period > ~ 120s were routinely reported by the Harvard group for large and moderate-sized ($M_w \geq 5.5$) events worldwide (Dziewonski et al., 1981). The establishment of the Broadband Array in Taiwan for Seismology (BATS) in the early 1990s marked the most recent leap in the earthquake source study of Taiwan, extending the M_w threshold of CMT inversion down to ~ 3.0 (Kao et al., 1998a; Kao and Jian, 1999; Kao and Jian, 2001; Kao et al., 2001, 2002a,b; Liang et al., 2003, 2004).

By searching through the literature and various databases, we collect source parameters for a total of 1986 earthquakes that occurred in the Taiwan region (21°N–26°N, 119°E–123°E; Fig. 2). About 40% of them are BATS CMT solutions (813), whereas Harvard CMT solutions make up another 8%. About 50 solutions are determined by body waveform inversion. The rest are *P* wave first-motion solutions (some with constraints from amplitude ratios between *P* and *S* phases). A complete list of source parameters used in this study (all 1986 earthquakes) can be found in the electronic appendix.