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Spatial variation of seismogenic depths of crustal earthquakes in the Taiwan region: Implications for seismic hazard assessment

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ABSTRACT

This paper presents the first whole Taiwan-scale spatial variation of the seismogenic zone using a high-quality crustal seismicity catalog. The seismicity onset and cutoff depths (i.e., seismogenic depths) are determined by the earthquake depth–moment distribution and used to define the upper and lower boundaries of the seismogenic zone, respectively. Together with the published fault geometries and fault area–moment magnitude relations, the depth difference in the onset and cutoff depths (i.e., seismogenic thickness) is used as the fault width to determine the moment magnitudes of potential earthquakes for the major seismogenic faults. Results show that the largest (*Mw*7.9–8.0) potential earthquake may occur along the Changhua fault in western Taiwan, where the seismic risk is relatively high and seismic hazard mitigation should be a matter of urgent concern. In addition, the first-motion focal mechanism catalog is used to examine the relation between the seismogenic depths and earthquake source parameters. For crustal earthquakes (≤50 km), the shallowest onset and cutoff depths are observed for normal and strike-slip events, respectively. This observation is different from the prediction of the conventional continental-rheology model, which states that thrust events have the shallowest cutoff depth. Thus, a more sophisticated rheology model is necessary to explain our observed dependence of the seismogenic depths on faulting types. Meanwhile, for intermediate to large crustal (*Mw* ≥ 4; depth ≤ 50 km) earthquakes, thrust events tend to occur at the bottom region of the seismogenic zone, but normal and strike-slip events distribute at a large depth range.

1. Introduction

Taiwan is located in an oblique convergent zone at a plate boundary, where the Philippine Sea Plate subducts northward beneath the Ryukyu Arc, while the Eurasia Plate subducts eastward beneath the Luzon Arc. A relative plate convergence at a rate of approximately 8 cm/yr along an azimuth of N50°W (e.g., DeMets et al., 2010; Yu et al., 1997) generates numerous earthquakes and complex geological features in Taiwan (Fig. 1). Here, we only briefly introduce the regional geology of Taiwan; a more detailed description has been presented in Ho (1986). As shown in Fig. 1, the geological structures of Taiwan generally trend NNE–SSW, and the prominent geological provinces from west to east are as follows (Ho, 1986): (1) the Coastal Plain, the present-day foreland basin; (2) the Western Foothills, comprising accreted and deformed sediments in the foreland basin; (3) the Hsuehshan Range, comprising a thick sequence of Eocene and Oligocene sedimentary rocks; (4) the Backbone Range, composed of Miocene to Eocene slates; (5) the Eastern Central Range, the pre-Tertiary basement of the continental margin; (6) the Longitudinal Valley, the suture between the Eurasia and Philippine Sea plates; and (7) the Coastal Range, the compressed Luzon Arc and its forearc. Two small volcanic islands of Lutao and Lanyu in the southeastern offshore are remnant Neogence island arc. In addition, two prominent tectonic structures, the Peikang High (PH) and the Lukang Magnetization High (LMH), are located in western Taiwan. The former presents the shallow pre-Createaceous Chinese continental basement (Lin and Watts, 2002), and the latter could be viewed as a zone of relatively rigid crust (Hsu et al., 2008). These tectonic structures have been suggested to dominate earthquake occurrence and stress distribution in western Taiwan (Hsu et al., 2008; Hu et al., 1997; Lin, 2001; Wu et al., 2010).

During the last century, Taiwan has experienced serious damage from several destructive earthquakes inland and offshore (e.g., Ma and Liang, 2008; Shin and Teng, 2001; Wang, 1998) (Fig. 1), indicating that the unique tectonic setting of Taiwan is capable of accumulating a large amount of elastic strain that produces large earthquakes. Thus, it

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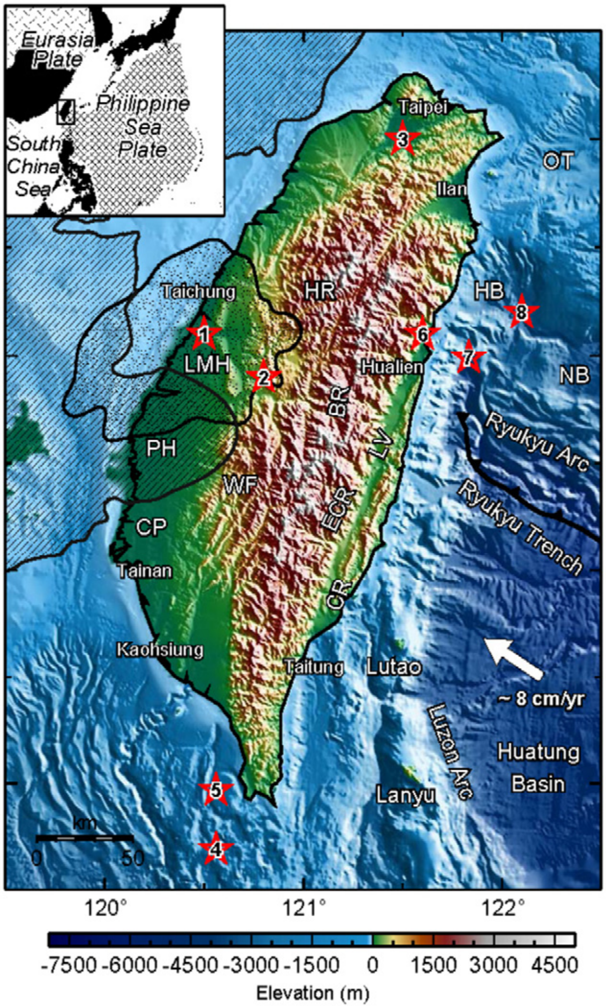

Fig. 1. Tectonic setting (inset) and major geologic units of the Taiwan region. CP: Coastal Plain; WF: West Foothill; HR: Hsueshan Range; BR: Backbone Range; ECR: East Coastal Range; LV: Longitudinal Valley; CR: Costal Range; HB: Hoping Basin; NB: Nanao Basin; RT: Ryukyu Trench; RTST: Ryukyu Taiwan Stress Transition; LMH: Lukang Magnetization High; PH: Peigan High. Open stars are disastrous earthquakes mentioned in the context. 1: the 1848 *M*7.1 Changhua earthquake; 2: the 1999 *Mw*7.6 Chi-Chi earthquake; 3: the 1694 *M*7 Taipei earthquake; 4: the 2006 *M*7 Pingtung earthquake (first event); 5: the 2006 *M*7 Pingtung earthquake (second event); 6: the May 1986 *Ms*6.3 Hualien earthquake; 7: the November 1986 *Ms*7.8 Hualien earthquake; 8: the 2002 *Mw*7.0 Hualien earthquake.

is critical to specifically assess the seismic hazard for the whole Taiwan region. For a successful seismic hazard assessment, the fundamental step is to determine potential moment magnitudes (*Mw*) of future large earthquakes on distinctive seismogenic structures.

The moment magnitude of an earthquake is proportional to the rupture area, which is the product of the rupture length and width (depth extent), of a brittle fault (Hanks and Kanamori, 1979; Kanamori and Anderson, 1975). Hence, it is critical to accurately determine the lengths and widths of seismogenic faults for the determination of moment magnitudes. However, the fault width is more difficult to define than the fault length, and only a few segments of active faults in Taiwan have been delineated by the reflection method (e.g., Wang et al., 2001; Wang et al., 2003; Wang et al., 2004; Wang et al., 2002). Due to a lack of a complete and reliable database of fault width for the active faults in Taiwan, previous studies have estimated the maximum magnitudes of future earthquake events (e.g., Cheng, 2002; Cheng et al., 2010; Shyu et al., 2005a) and the probability of seismic hazard (e.g., Cheng, 2002; Cheng et al., 2010; Lee, 2004) by assuming a constant rupture width (mostly 15 km) and a rupture length constrained from geologically mapped active faults. To achieve a more accurate seismic hazard model, a more realistic estimation of the rupture width with lateral variations is required, which will in turn improve the estimation of moment magnitudes of potential earthquakes on any particular fault or seismic source.

In addition, a profusion of observations and simulations have suggested that buried-rupture earthquakes generate stronger near-fault ground motion than surface-rupturing earthquakes (e.g., Dalguer et al., 2008; Kagawa et al., 2004; Somerville, 2003). These studies have led to the adoption of a depth-dependence rupture model in next-generation ground-motion predictions (Power et al., 2008). It is widely accepted that the inclusion of the depth-to-top rupture extent in a strong motion simulation is crucial for seismic hazard mitigation. Unfortunately, the spatial distribution of the top edge of rupture faulting in the Taiwan region has not been delineated.

The seismogenic zone is generally defined as the earth's layer where earthquakes occur at depths, and the thickness of the seismogenic zone (seismogenic thickness, ST) is defined as the depth interval between the upper and lower boundaries of the seismogenic zone. These boundaries are reasonably assumed as proxies for the top and bottom edges of fault ruptures, respectively. The lower boundary of the seismogenic zone, above which a large percentage of earthquakes occur, is termed the seismicity “cutoff depth” (SCD) (Sibson, 1982). Similarly, the upper boundary of the seismogenic zone, where earthquakes begin to occur, is termed the seismicity “onset depth” (SOD). For the sake of conciseness, hereafter both SCD and SOD are referred to as the seismogenic depths. Furthermore, the seismogenic depths and the ST are termed as the seismogenic parameters.

A large number of studies have analyzed the earthquake depth-frequency distributions to determine the SCD in California and Japan (e.g., Bonner et al., 2003; Doser and Kanamori, 1986; Ito, 1990; Magistrale, 2002; Omuralieva et al., 2012; Sibson, 1982; Tanaka and Ishikawa, 2002; Williams, 1996). In Taiwan, Wang et al. (1994) and Ma and Song (2004) used the earthquake depth-frequency distribution to determine the SCD. Nevertheless, their study areas are limited and the resolution in their results may not be well constrained because of a relatively large uncertainty in the hypocenters from the seismicity catalogs they used. Wang et al. (1994) also suggested that earthquake faulting type is the second dominator in controlling seismicity depth in the Taiwan region. However, such a conclusion was drawn on the basis of investigation of limited regions with fewer data and less quantitative analysis for focal mechanism solutions. In addition, although a number of studies have reported that moderate to large earthquakes tend to occur near the bottom of the seismogenic zone (e.g., Das and Scholz, 1983; Ito, 1990; Sibson, 1982; Sibson, 1984; Yang et al., 2012), this relation is still unclear for Taiwan.

In this study, we first use an updated relocation seismicity catalog to determine the spatial distributions of the seismogenic parameters for the whole Taiwan region. Then, the high-resolution ST is used to determine the most likely magnitude of future events for major seismogenic faults in Taiwan and evaluate associated seismic potentials with recently published results. Finally, we explore relations between the seismogenic depths and source parameters of intermediate to large crustal earthquakes. Our results not only provide critical parameters for the seismic hazard evaluation but also shed new light on seismogenic behaviors of crustal earthquakes.

2. Data and analysis

2.1. Relocated seismicity catalog

An accurate and complete earthquake dataset will guarantee determination of reliable spatial distribution of the seismogenic zone from background seismicity. In our analysis, we use a well-relocated seismicity catalog containing data between 1990 and 2015, which is obtained by applying a 3D ray-tracing method (Um and Thurber, 1987) with