

## Quantifying the seismicity on Taiwan

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### SUMMARY

We quantify the seismicity on the island of Taiwan using the frequency–magnitude statistics of earthquakes since 1900. A break in Gutenberg–Richter scaling for large earthquakes in global seismicity has been observed, this break is also observed in our Taiwan study. The seismic data from the Central Weather Bureau Seismic Network are in good agreement with the Gutenberg–Richter relation taking  $b \approx 1$  when  $M < 7$ . For large earthquakes,  $M \geq 7$ , the seismic data fit Gutenberg–Richter scaling with  $b \approx 1.5$ . If the Gutenberg–Richter scaling for  $M < 7$  earthquakes is extrapolated to larger earthquakes, we would expect a  $M > 8$  earthquake in the study region about every 25 yr. However, our analysis shows a lower frequency of occurrence of large earthquakes so that the expected frequency of  $M > 8$  earthquakes is about 200 yr. The level of seismicity for smaller earthquakes on Taiwan is about 12 times greater than in Southern California and the possibility of a  $M \approx 9$  earthquake north or south of Taiwan cannot be ruled out. In light of the Fukushima, Japan nuclear disaster, we also discuss the implications of our study for the three operating nuclear power plants on the coast of Taiwan.

**Key words:** Probabilistic forecasting; Seismicity and tectonics; Statistical seismology.

### 1 INTRODUCTION

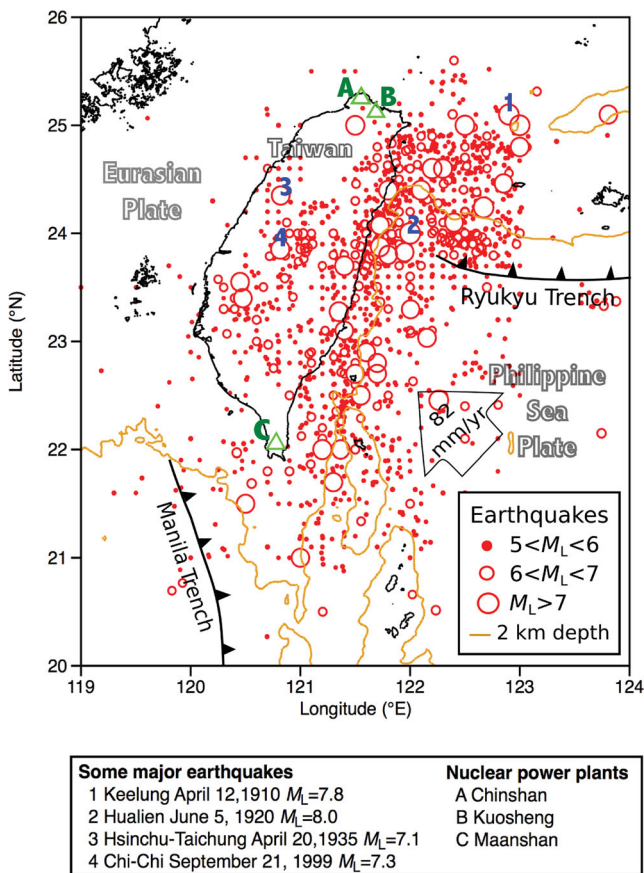
The island of Taiwan is a part of the complex boundary between the Eurasian Plate and the Philippine Sea Plate (Tsai *et al.* 1977; Wu 1978; Shyu *et al.* 2005). The tectonic setting of Taiwan is illustrated in Fig. 1. The island straddles the compressional plate boundary between the Eurasian Plate to the west and the north and the Philippine Sea Plate to the east and south. The convergence velocity from plate tectonic studies is  $82 \text{ mm yr}^{-1}$  (Seno *et al.* 1993; Yu *et al.* 1997). East and north of Taiwan the Philippine Sea Plate is being subducted beneath the Eurasian Plate at the Ryukyu trench. South of Taiwan the Eurasian Plate is being subducted beneath the Philippine Sea Plate at the Manila trench. Near Taiwan this subduction is oblique with a predominant strike-slip component. Further east the trench bends to the north. Seismicity associated with the subducted plates has been identified in both cases (Tsai 1986).

Plate convergence is being taken up by crustal thickening within Taiwan on a complex of thrust faults resulting in mountain building in several north–south ranges. This complex deformation has generated mountain ranges on the island as high as 3952 m. Details of this complex zone of compression have been given by Shyu *et al.* (2005). Direct evidence for this compressional deformation without subduction comes from the extensive GPS studies that have been carried out on Taiwan. Ching *et al.* (2011) report results from 531 stations for the period 1995–2005. Horizontal velocities are given relative to the stable Eurasian Plate. Results from the east coast

show that it is part of the Philippine Sea Plate while results from the west coast show that it is part of the Eurasian Plate. During the study period the  $82 \text{ mm yr}^{-1}$  of compression were accommodated across central Taiwan.

The continental crust of Taiwan is attached to the stable continental crust of the Eurasian Plate both to the north and west. The continental crust in Taiwan is being extensively deformed whereas the continental crust to the west and north is rigid with little deformation. This difference can be attributed to the absence of a strong lithosphere beneath Taiwan. In a variety of tectonic settings this absence is attributed to lithospheric delamination (Kay & Kay 1993). The dense lithosphere and lower crust break away and sink into the mantle leaving a weak buoyant upper continental crust subject to internal deformation. Delamination beneath Taiwan has been proposed by Ustaszewski *et al.* (2012).

As a result of the extensive deformation, many earthquakes have occurred in the seismic areas north and east of Taiwan since 1900 as shown in Fig. 1. Two major earthquakes that took place in these two areas are illustrated in Fig. 1. The Keelung earthquake on 1910 April 12 is estimated to have had a magnitude  $M_L = 7.8$ , it was a deep earthquake with an estimated depth of 200 km. This was almost certainly a subduction zone earthquake associated with the oblique subduction of the Philippine Sea Plate beneath the Eurasian Plate. The largest earthquake since 1900 was the offshore Hualien earthquake on 1920 June 5 with an estimated magnitude  $M_L = 8.0$  (Theunissen *et al.* 2010). This earthquake occurred in a zone of high seismicity and may have accommodated the right-lateral strike-slip



**Figure 1.** Illustration of our test region based on the island of Taiwan. The convergence of  $82 \text{ mm yr}^{-1}$  between the Philippine Sea Plate and the Eurasian Plate is shown. Subduction of the Eurasian Plate at the Manila Trench and subduction of the Philippine Sea Plate at the Ryukyu Trench are illustrated. Locations of earthquakes with  $M_L \geq 5$  since 1900 are shown. Locations of some major earthquakes and the three operating nuclear power plants are given. The 2-km-depth contour marks the transition from continental to oceanic crust.

motion between the Eurasian Plate and the Philippine Sea Plate. A detailed study of the seismicity north of Taiwan has been given by Ando *et al.* (2012).

Another consequence of the extensive deformation is deadly earthquakes on the island. The deadliest earthquake on Taiwan with 3276 deaths was the Hsinchu-Taichung earthquake on 1935 April 20 with  $M_L = 7.1$  (Sen & Wu 1996). The second deadliest event with 2470 deaths was the Chi-Chi earthquake on 1999 September 21 with  $M_L = 7.3$  ( $M_w = 7.6$ ; Shin & Teng 2001). The locations of these two earthquakes are given in Fig. 1. Most of the earthquakes, including these two earthquakes, were shallow thrust events in the relatively populous west-central part of the island. Of particular concern to the public is the risk to the three operating nuclear power plants on the coast of Taiwan. Therefore, we utilize Gutenberg–Richter frequency–magnitude scaling to quantify the level of seismicity on Taiwan.

## 2 GUTENBERG–RICHTER SCALING

One of the most widely used scaling relations in seismicity is the Gutenberg–Richter frequency–magnitude relation (Gutenberg & Richter 1959)

$$\dot{N}_c = \dot{a} \times 10^{-bM}, \quad (1)$$

where  $\dot{N}_c$  is the cumulative number of earthquakes per year with magnitudes greater than  $M$  occurring in a specified region and  $b$  and  $\dot{a}$  are constants. The  $b$ -value varies from region to region but generally is in the range  $0.8 < b < 1.2$  (Frohlich & Davis 1993). The constant  $\dot{a}$  is a measure of the regional intensity of seismicity.

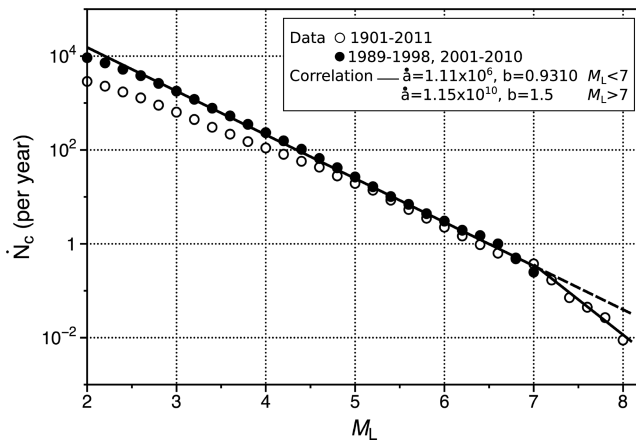
Eq. (1) can be used to determine the number of large earthquakes that would be expected to occur based on the observed number of smaller earthquakes. If  $b = 1$  and ten  $M > 5$  earthquakes are observed to occur each year, one magnitude  $M > 6$  earthquake would be expected, on average, each year, and a magnitude  $M > 7$  earthquake would be expected, on average, each 10-yr period. This extrapolation is routinely used to assess the regional seismic hazard in many countries (Kossobokov *et al.* 2000). Specifically it has been used by the United States Geological Survey in the preparation of seismic hazard maps in the United States (Frankel 1995).

A break in Gutenberg–Richter scaling for large earthquakes has been suggested by many authors, beginning with Rundle (1989). These studies have concentrated on global catalogues because they include large numbers of large earthquakes. Sornette *et al.* (1996) carried out a detailed study of alternative fits to the large earthquake data and concluded the preferred fit was to two applications of the Gutenberg–Richter scaling given in eq. (1), they suggested  $b \approx 1$  for  $M_w < 7.6$  and  $b \approx 1.5$  for  $M_w > 7.6$ . A detailed up-to-date study using worldwide data from the CMT catalogue has been given by Yoder *et al.* (2012), they conclude that  $b = 1.009$  for  $M_w < 7.6$  and  $b = 1.497$  for  $M_w > 7.6$ .

Rundle (1989) and Pacheco *et al.* (1992) have suggested that a transition from  $b \approx 1$  to 1.5 is due to smaller earthquakes being approximate equidimensional (depth  $\approx$  length) whereas large earthquakes would have much greater lengths than depths (e.g. long shallow strike-slip earthquakes). Taking the accepted scaling between earthquake rupture area and magnitude (Kanamori & Anderson 1975) we find the global transition at  $M_w = 7.6$  corresponds to a rupture area of  $2110 \text{ km}^2$  or a characteristic length if 46 km. Since large earthquakes in the global catalogue are dominated by deep subduction zone events this value is reasonable.

## 3 FREQUENCY–MAGNITUDE STATISTICS FOR TAIWAN

We now turn to the frequency–magnitude statistics for the Taiwan area. Tsai *et al.* (1973, 1981) and Wang (1988) have studied the earthquake statistics in Taiwan. In this study, we use the current catalogue covering the period 1900–2011, which is provided by the Central Weather Bureau (CWB). During the period 1900–1972 earthquakes were recorded locally on a few mechanical seismometers (Shin & Chang 2005) and on global networks. During the period 1973–1992 the seismic network-Taiwan Telemetered Seismographic Network (TTSN), was operated by the Institute of Earth Sciences (IES), Academia Sinica (Wang 1989; Wang & Shin 1998). After 1991, the TTSN was upgraded to a new seismic network-Central Weather Bureau Seismic Network (CWBSN; Shin 1992; Kuo *et al.* 1995; Shin & Chang 2005). Shin (1993) used a normalized attenuation function considering the focal depth of earthquakes in the Taiwan area to simulate the Wood–Anderson seismogram with the CWBSN seismograms, the result shows that the local magnitude inferred from this attenuation function can present the properties of earthquakes in Taiwan. In 1994, the CWB adopted the local magnitude with the attenuation function proposed by Shin (1993) to



**Figure 2.** Frequency–magnitude statistics of earthquakes in our test region. The cumulative numbers of earthquakes per year  $\dot{N}_c$  with magnitude greater than  $M_L$  are given as a function of  $M_L$ . We consider all catalogue earthquakes for the period 1901–2011 as well as earthquakes during 1989–1998 and 2001–2010. Best-fitting correlations with Gutenberg–Richter scaling, eq. (1), are also included.

quantify earthquakes. To obtain a uniform catalogue, Cheng *et al.* (2011) collected and analysed the earthquake data in Taiwan starting in 1900 and converted the various magnitudes to Shin’s local magnitude scale. Thus the earthquake catalogue established by CWB is a complete and consistent catalogue with  $M_L$  greater than approximately 5.

The locations of earthquakes in our test region since 1900 with  $M_L \geq 5$  are given in Fig. 1. The frequency–magnitude statistics of earthquakes in our test region are shown in Fig. 2. The open circles show the numbers of earthquakes per year  $\dot{N}_c$  with magnitudes greater than  $M_L$  for the period from 1901 to 2011. We also use the higher quality data to give frequency–magnitude statistics for the period 1989–2010 since the seismic network was upgraded to modern standards in 1991. We exclude the years 1999 and 2000 because a large number of aftershocks were generated by the Chi-Chi earthquake. For this 20-yr period the number of earthquakes per year  $\dot{N}_c$  with magnitudes greater than  $M_L$  are shown as solid circles in Fig. 2.

We see that in the magnitude range  $5 < M_L < 7$  the results for the two periods are in quite good agreement. The difference for magnitudes less than  $M_L = 5$  can be attributed to catalogue incompleteness during the first half of the 20th century. For this reason, we fit the recent data to Gutenberg–Richter scaling, eq. (1), taking  $b = 0.9310$  and  $\dot{a} = 1.11 \times 10^6 \text{ yr}^{-1}$  which is shown as the solid line for  $2 < M_L < 7$  and the dashed line for  $M_L > 7$  in Fig. 2. Quite good agreement is found over the magnitude range  $2 < M_L < 7$ . For the earthquake data from 1901 to 2011 we see a significant deviation from the scaling given above for earthquakes with  $M_L > 7$ . Based on the discussion of global seismicity given above we correlate the  $M_L > 7$  earthquakes from 1901 to 2011 with  $b = 1.5$  and find that  $\dot{a} = 1.15 \times 10^{10} \text{ yr}^{-1}$  as the solid line for  $M_L > 7$  in Fig. 2.

#### 4 DISCUSSION

We next compare the break in slope in Fig. 2 at  $M_L = 7$  to the break in slope at  $M_w = 7.6$  observed for global earthquakes. Hanks &

Kanamori (1979) have given a relation between the seismic moment  $M_0$  and the moment magnitudes  $M_w$

$$\log M_0 = \frac{3}{2} M_w + 16.1. \quad (2)$$

Chen *et al.* (2007) have given a relation between the seismic moment  $M_0$  and CWBSN local magnitude  $M_L$

$$\log M_0 = (1.27 \pm 0.06) M_L + (17.23 \pm 0.35). \quad (3)$$

Kanamori & Anderson (1975) relate the moment of an earthquake to the rupture area  $A$  by

$$M_0 = \alpha A^{3/2}, \quad (4)$$

where  $\alpha$  is a constant. Turcotte (1997) utilized the worldwide earthquakes from the Centroid Moment Tensor (CMT) Catalogue for the period from 1977 January to 1989 June and obtained  $\alpha = 3.27 \times 10^6 \text{ Pa}$  with  $M_0$  in Joules.

From eqs (2) and (4) the transition at  $M_w = 7.6$  found in global earthquakes corresponds to a rupture area  $A = 2110 \text{ km}^2$  or a characteristic length  $A^{1/2} = 46 \text{ km}$ . From eqs (3) and (4) the transition in the Taiwan data at  $M_L = 7$  corresponds to a rupture area  $A = 253 \text{ km}^2$  or a characteristic length  $A^{1/2} = 16 \text{ km}$ . Comparing with the value 46 km for the global data, the characteristic length in Taiwan is much shorter. It can be observed from Fig. 1 that most of  $M_L > 7$  earthquakes took place along the subduction zone, that is, north and east of Taiwan and numerous  $M_L < 7$  earthquakes took place on the island. Wu *et al.* (2008) have shown that the focal depths of the earthquakes with  $M_L > 3$  are less than 30 km in western Taiwan. We attribute the difference in the characteristic length to the predominance of shallow crustal earthquakes in the Taiwan data.

One aspect of our study requires further discussion. Our study of global seismicity utilized moment magnitude  $M_w$  from the CMT catalogue. These magnitudes were obtained from the global seismic network and are complete for  $M_w > 5.5$ . In our study, we utilize the local magnitude  $M_L$  from the CWBSN catalogue based on the records from the Taiwan seismic networks. In some cases the magnitudes are significantly different: for the Chi-Chi earthquake, they are  $M_L = 7.3$  and  $M_w = 7.6$ . Other earthquakes for which both magnitude values are available are in better agreement. In order to obtain an uniform magnitude for the CWB catalogue, Cheng *et al.* (2011) collected and analysed the catalogues from 1900 to 2009 in different periods and transferred all the magnitudes with  $M_L > 4.0$  into the local magnitude used by current CWBSN. They also compared the different moment magnitudes from different sources and then adopted the moment magnitude  $M_w$  from the CMT catalogue as describing the earthquake size parameter. It is worth noting that the sizes of 38 large earthquakes with  $M_L > 7.0$  during 1900–1978 were re-estimated utilizing the moment magnitude  $M_w$  or surface wave  $M_s$  at the same time by Cheng *et al.* (2011). The catalogue given by Cheng *et al.* (2011) has been updated to the current CWBSN catalogue. Based on the completeness of the catalogue and the excellent consistency of the Taiwan data with Gutenberg–Richter scaling, eq. (1), we are confident that our use of the CWBSN catalogue is justified.

It is of interest to compare the level of seismicity in Taiwan with the level of seismicity in southern California. To do this we consider the number of  $M > 5$  earthquakes that occur per year. From Fig. 2, we estimate that 25  $M > 5$  earthquakes occur per year in Taiwan. Kossobokov *et al.* (2000) have carried out a similar study for southern California and concluded that about four  $M > 5$  earthquakes occur per year. Also, the area of southern California is

about twice as large as the area of Taiwan. Thus we conclude that the level of seismicity in our Taiwan study is about 12 times greater than in southern California.

Major earthquakes and their associated tsunamis constitute a risk to nuclear power plants on Taiwan. There are three operating plants, their locations are given in Fig. 1. The Chinshan and Kuosheng plants are on the north coast (Hong & Guo 1995). As can be seen in Fig. 1 these plants are adjacent to the subduction zone seismicity to the northeast. Another question of importance is whether a very large  $M \approx 9$  earthquake similar to the 2011 Tohoku (Japan) earthquake could occur on the subduction zones either north or south of Taiwan (Kao 1998). In terms of an extrapolation for Japan similar to that given in Fig. 2 the Tohoku earthquake was not a surprise. However seismologists had argued that the largest possible earthquake in the Tohoku region would be  $M \approx 8.4$  based on several estimates (Stein & Okal 2011). Seismologists in Japan did not expect such a large earthquake with magnitude 9.0 because of lack of historical record. The large earthquakes with magnitude 8.0 in the subduction zone has been record misled many seismologists to only considered the  $M \approx 8.0$  earthquakes. According to the research made by Ando (1975), the  $M \approx 8.0$  earthquakes can be induced by just one fault plane of the fault region with length about 130 km and width 70 km in Nankai trough area. The more fault planes rupture the bigger the earthquake is. In the other words, the size of the earthquake depends on the total rupture area. Hsu *et al.* (2012) have carried out that the rupture of a portion of the Ryukyu subduction zone with a rupture are of 8400 km<sup>2</sup> (120 km × 70 km) may cause a  $M \approx 8.7$  earthquake in northeast Taiwan. The higher convergence rate which is about 80 mm yr<sup>-1</sup> near Taiwan (Hsu *et al.* 2012) comparing with the convergence rate, which is about 46 mm yr<sup>-1</sup>, along the Nankai trough (Seno *et al.* 1993) may attribute to the occurrence of a bigger earthquake.

## 5 CONCLUSIONS

We have studied the statistics of the seismicity on Taiwan and in adjacent regions. To the northeast and southwest of Taiwan the seismicity is associated with subduction zones. However, on Taiwan the convergence of 82 mm yr<sup>-1</sup> is accommodated in shallow compressional deformation. The lithosphere has been delaminated and the convergence results in crustal thickening on a complex of thrust faults resulting in mountain building. We have considered the frequency–magnitude statistics of earthquakes in Taiwan since 1900. We conclude that these data are in good agreement with Gutenberg–Richter statistics taking  $b \approx 1$  as long as  $M_L < 7$ . We suggest that for larger earthquakes we can fit the available data with Gutenberg–Richter statistics taking  $b \approx 1.5$ . The transition at  $M_L \approx 7$  corresponds to an earthquake rupture area  $A \approx 253$  km<sup>2</sup> and a characteristic length  $A^{1/2} \approx 16$  km. This compares with similar break in frequency–magnitude statistics for global earthquakes at  $M_w = 7.6$  which corresponds to an earthquake with a rupture area  $A \approx 2100$  km<sup>2</sup> and a characteristic length  $A^{1/2} \approx 46$  km. We attribute this reduction to the absence of large faults in shallow crustal deformation on Taiwan.

Without the change in scaling a  $M > 8$  earthquake would be expected about every 25 yr. With the change in scaling a  $M > 8$  earthquake would be expected about every 200 yr. Although we note that a break in scaling at magnitude  $M = 7$  reduces the risk of large earthquakes the general level of seismic activity in Taiwan is 12 times greater than in southern California, so the risk remains significant.

Considering more segments of the subduction zone may rupture with a plate velocity 82 mm yr<sup>-1</sup>, we do not feel that it is possible to rule out a  $M \approx 9$  earthquake north or south of Taiwan. However, based on the data given in Fig. 2 the expected recurrence time of a  $M \approx 9$  earthquake would be about 3000 yr. A large subduction zone earthquake in this region is certainly expected, however the oblique subduction is likely to reduce the tsunami generation by such an earthquake. The operating Maanshan nuclear power plant is on the southern tip of the island (Wen *et al.* 2008). The direct subduction of the Eurasian Plate poses a severe tsunami risk, however the level of seismicity in this region is much lower.

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