Ⓔ

2012 Seismicity Quiescence in Taiwan a Result of Site-Effect Artifacts

by Tz-Shin Lai, Himanshu Mittal, and Yih-Min Wu

ABSTRACT

A significant seismic quiescence in Taiwan was reported by Wu and Chiao (2006) before the occurrence of the 1999 M_w 7.6 Chi-Chi earthquake. A similar kind of activity was also observed in the 2012 earthquake catalog reported by Central Weather Bureau (CWB). Seven months in the 2012 catalog seem to have lower monthly seismicity rates than the one standard deviation below the mean (673 ± 82) for earthquakes with $M_L \geq 2.0$. Here, we checked the seismic network in Taiwan and found that some new seismic stations, including the Broadband Array in Taiwan for Seismology (BATS), were incorporated within the Taiwan Central Weather Bureau Seismic Network (CWBSN) since 2012. Most of these BATS stations are located on hard-rock sites, which may affect magnitude estimation because of their site characteristics. To account for the impact of site effect, earthquake catalog data during the period of 1994 to 2014 was collected and station correction was calculated for each station. A strong correlation is found between station corrections determined in this study and geological settings of the region. Stations located on soil sites have high amplifications with negative station corrections. On the other hand, stations located on hard-rock sites have low amplifications with positive station corrections. After applying station correction, the mean seismicity rate is found to be 716 events per month with a standard deviation of 76 events for earthquakes with $M_L \geq 2.0$. We conclude that the reason behind the apparent low seismicity in 2012 is due to the installation of new seismic stations on rock sites, which lead to underestimation of M_L.

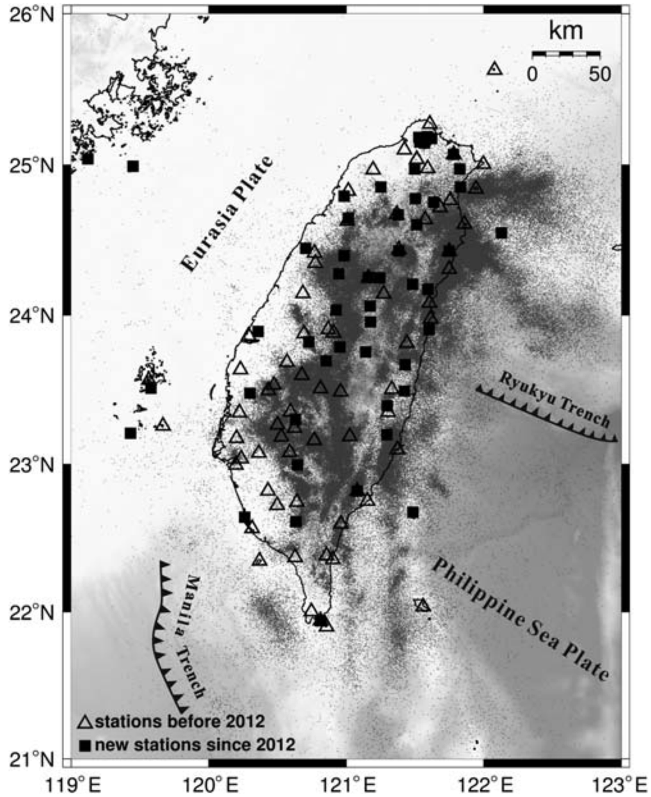
Online Material: Table of station corrections.

INTRODUCTION

Being located on the western Circum-Pacific seismic belt, Taiwan is perhaps one of the most seismically active regions in world due to collision of Eurasian plate (EP) and Philippine Sea plate (PSP) (He and Tsukuda, 2003; Legendre *et al.*, 2015). Toward east, PSP subducts northward beneath the EP, and toward south the EP subducts eastward under PSP. The suture zone between PSP and EP divides Taiwan into two tectonic regions. Because of this geological setting, most of this part of Taiwan has southeast–northwest compression with a convergence rate of about 8 cm/yr (Yu *et al.*, 1999; Legendre, Chen, and Zhao, 2014; Legendre, Deschamps, *et al.*, 2014). The collisions between PSP and EP leads to numerous earthquakes of magnitude 4 and above every year inland and off the east coast of the Taiwan island (Fig. 1).

A number of techniques are used to evaluate seismic activity of a particular region and seismic quiescence is one of them. Seismic quiescence is defined as the decrease in earthquake activity in a seismically active region during a certain period, as compared to ongoing activity in that region. It is one of the primary changes in seismic activity, prior to some major earthquakes, and is widely observed (Mogi, 1979; Wyss and Habermann, 1988; Wiemer and Wyss, 1994; Huang *et al.*, 2001; Huang and Nagao, 2002; Chen, 2003; Huang, 2004, 2006, 2008; Wu and Chiao, 2006; Mignan and Di Giovambattista, 2008; Wu *et al.*, 2008; Huang and Ding, 2012; Mignan, 2012). Wu and Chiao (2006) confirmed this seismic quiescence before the occurrence of the great 1999 Chi-Chi earthquake (M_w 7.6) in Taiwan. In their findings, they reported that seismicity fell outside the range of one standard deviation (not so significant) during the anomalous period, which occurred about 9 months prior to the mainshock. During anomalous period, the seismicity was observed to be 314 events per month, as compared to the standard 435 events per month. Wu *et al.* (2008) studied the variations in seismicity pattern in the Taiwan region before the 2003 Cheng Kung, Taiwan, earthquake (M_w 6.8) and found low seismicity and a decrease in b-value, which may be precursory phenomenon related to seismic quiescence. The statistical method, so-called "region–time–length algorithm", may be one of the useful methods in evaluating the seismicity change before the occurrence of larger earthquakes (Huang *et al.*, 2001; Huang and Nagao, 2002; Huang, 2004). The standard normal deviate Z-test is another method repeatedly used to evaluate the seismic quiescence (Wiemer and Wyss, 1994; Wu and Chiao, 2006). Thus, seismic quiescence may be one of the important seismic precursors in different parts of the world. However, sometimes quiescence is a weak pattern in general and other factors, such as the introduction of new instruments in existing seismological

doi: 10.1785/0220150260



▲ **Figure 1.** Epicentral distribution of earthquakes used in this study from 1994 to 2014 (the gray dots). The triangles show the locations of the Taiwan Central Weather Bureau Seismic Network (CWBSN) stations used before 2012. The squares show the locations of new stations incorporated into CWBSN after since beginning of 2012.

network and a change in data processing methods, play a major role in observing quiescence (e.g., van Stiphout *et al.*, 2011). We analyzed the earthquake catalog from 1994 to 2014 and observed low seismicity during an anomalous period of 7 months in 2012. In the present work, we sought to know whether this low seismicity was related to seismic quiescence before a large earthquake or if some other factors worked behind this anomalous activity.

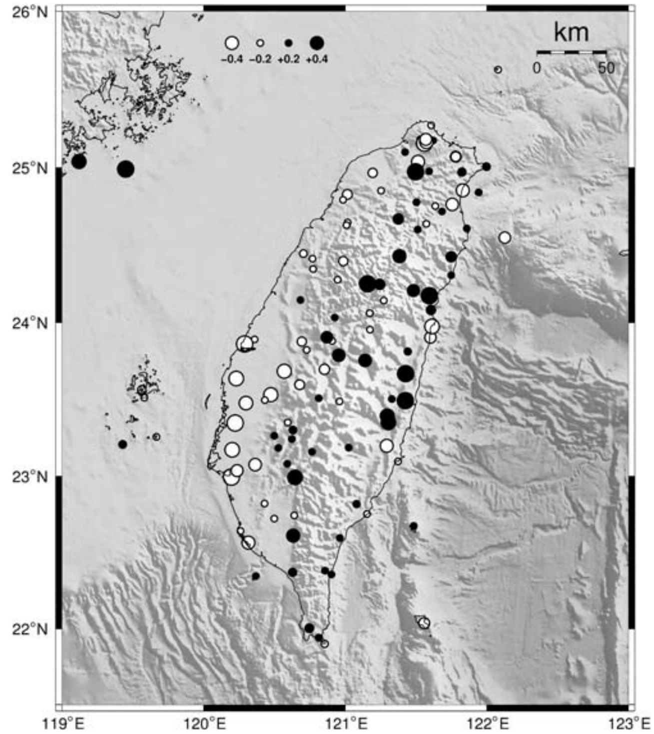
DATA

Taiwan CWBSN is the official agency responsible for earthquake monitoring in Taiwan. CWBSN started modern monitoring of seismic activity in Taiwan in the beginning of the 1990s (Wu *et al.*, 2008). CWBSN consisted of a central recording system with 71 telemetered stations that are equipped with three-component Teledyne/Geotech S13 short-period seismometers before 2012. Since 2012, the consideration of BATS in CWBSN enhanced its performance in detection of small events. Simultaneously, seismic signal digitization was upgraded from 12 to 24 bit. Until the end of 2014, the CWBSN had a total of 142 stations (Fig. 1). The CWBSN instruments were operated in a triggered-recording mode until the end of 1993. The operation mode of instruments is changed to continuous recording in late 1993 only. Data from these instruments are received at a central recording system in Taipei, where they are analyzed to manually pick arrival times of P and S waves for the determinations of earthquake location and magnitude M_L (Shin, 1993).

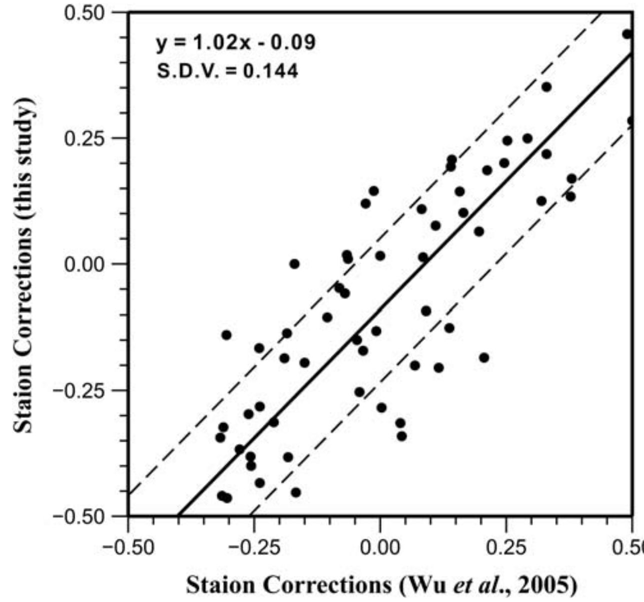
CWBSN used to report more than 20,000 events every year from 2009 to 2011. However, after the inclusion of BATS and network upgrading in the beginning of 2012, more than 30,000 events are reported every year in the Taiwan region. We investigated the earthquake catalog for these events, for which regional magnitude completeness (M_c) is about 2.0 (Chang, 2004; Wu and Chiao, 2006; Mignan *et al.*, 2011). After observation, we found the number of events with $M_L \geq 2.0$ in 2012 to be less than the number of events detected between 2009 and 2011. Based on previous experiences in Taiwan, this low seismicity may be attributed to a seismic quiescence before large earthquake (Wu and Chiao, 2006). However, adding new broadband stations with different geological settings may also affect the magnitude estimation as documented by Wu *et al.* (2005). We focused on an anomalous data period in 2012, keeping in mind two aspects: seismic quiescence and site effects due to the use of the BATS network. To reduce the impact on site effects, we applied station corrections in magnitude determination. Finally, we investigated the difference between M_L from the CWNSN and the revised M_L with station corrections to examine low seismicity in 2012.

METHOD

Aftershock activity will influence the seismicity and the related statistics. To enhance the reliability of this study, we chose to eliminate the aftershock sequences from our data set. For the analysis of the catalog, a magnitude threshold should be considered. The CWBSN has greatly enhanced earthquake monitoring capability in Taiwan with the M_c value down to about M_L 2.0 since the end of 1993 (Chang, 2004; Wu and Chiao, 2006). We applied the method of time and spatial double-link cluster analysis to eliminate the aftershocks sequence in the earthquake catalog (Wu and Chiao, 2006; Wu and Chen, 2007; Wu *et al.*, 2008). This method is similar to the single-link cluster-analysis method proposed by Davis and Frohlich (1991). Using a magnitude threshold of mainshocks, declustering algorithm specifies two linking parameters in time and space scales. An earthquake will be treated as aftershock when its occurrence is related to location and its time falls within the specified area of some larger earthquake. The same procedure is applied iteratively to look for secondary aftershocks, that is, the aftershock of an earlier aftershock. Using the temporal and spatial linking parameters of 3 days and 5 km, respectively, we removed the aftershocks generated from mainshocks with $M_L \geq 4.0$. In this study, there are 927 clusters in total from 1 January 1994 to 31 December 2014 with 24% aftershocks within 500,460 earthquake events. Finally, an aftershock-eliminated catalog is used to investigate seismicity during this period.



▲ **Figure 2.** Map of station corrections and topography. Mostly negative corrections (the white circles) are on sedimentary sites, whereas positive corrections (the black circles) are on rock sites.



▲ **Figure 3.** The comparison of station corrections in this study with the corrections of Wu *et al.* (2005) for the similar stations (dots). The average offset between the two is 0.09, and the standard deviation (two dashed lines) is 0.144.

To estimate the station corrections and revise the magnitude, data from the CWBSN earthquake catalog has been analyzed. For each earthquake, magnitude difference (ΔM_{L}) is calculated between the earthquake magnitude (M_{L}) and the station magnitude ($M_{\mathrm{L}}^{\mathrm{S}}$) for each station using equation (1). The mean value of the total magnitude differences (ΔM_{L}) at a particular station is defined as the station correction of that station:

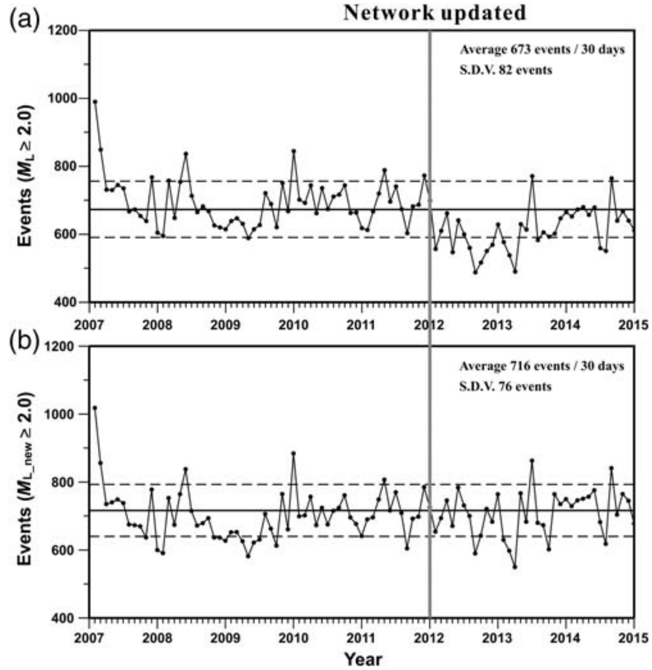
$$\Delta M_{\mathrm{L}} = M_{\mathrm{L}} - M_{\mathrm{L}}^{\mathrm{S}}, \tag{1}$$

in which station corrections are used to revise M_{L} determination. For each earthquake, we added the station correction to $M_{\mathrm{L}}^{\mathrm{S}}$ value for each station to get a revised station magnitude ($M_{\mathrm{L_{new}}}^{\mathrm{S}}$). The mean value of the total $M_{\mathrm{L_{new}}}^{\mathrm{S}}$ for each earthquake is the revised earthquake magnitude ($M_{\mathrm{L_{new}}}$). Finally, the values of the station corrections and $M_{\mathrm{L_{new}}}$ from this method can be refined using an iterative process. We decided to use the results of fifth iteration through checking the reductions of station corrections for each iteration.

RESULTS AND DISCUSSION

Ⓔ Parameters of the stations used in this study by calculating the station corrections from 1994 to 2014 in Taiwan are given in Table S1 (available in the electronic supplement to this article). The station correction factors are found to be large, ranging from −0.531 to 0.796. After plotting station corrections on the map, we found a strong correlation between the station correction and surface geology (Fig. 2). The western coastal plain, Taipei basin, and Lanyang plains are locations on soft-soil sites of high amplification with negative station corrections. In contrast, the central mountain range and the more mountainous areas of eastern Taiwan are located on hard-rock sites of low amplification with positive station corrections. Wu *et al.* (2005), in their analysis, picked 56 shallow earthquakes from 1995 to 2004 in Taiwan and determined station correction. All the events had M_{w} between 4.7 and 6.2 as reported in the Global Moment Tensor Catalog (Dziewonski *et al.*, 1981; Ekström *et al.*, 2012) and focal depths shallower than 35 km. Figure 3 depicts the comparison of our station corrections in this study with the corrections of Wu *et al.* (2005) for similar stations. There is a clear agreement between the results found by Wu *et al.* (2005) and the results of our study at all stations.

To avoid seismicity affected by larger earthquakes, such as the 2003 Cheng Kung earthquake (M_{w} 6.8) and the 2006 Pingtung earthquake sequence (M_{w} 7.0 and 6.9), we choose to show seismicity results from 1 January 2007 to 31 December 2014 and focus on the anomaly in 2012. After analyzing the original CWBSN catalog data with aftershock-elimination procedure, the monthly occurrence rates during this period are calculated by counting events with M_{L} 2.0 for every month (normalized to 30 days) (Fig. 4a). The average occurrence rate is found to be 673 events per month with a standard deviation of 82 events. Seven months of data starting from January 2012 show a significant low seismicity, with monthly event-occurrence rates falling outside one standard deviation range. After applying the station corrections in the determination of $M_{\mathrm{L_{new}}}$,

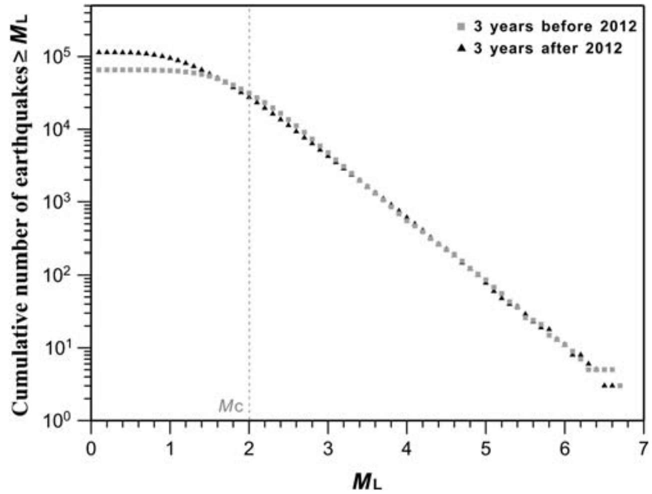


▲ **Figure 4.** (a) Monthly numbers of events count for M_L 2.0 from 2007 to 2014. The average occurrence rate is 673 events per month (center line) with a standard deviation of 82 events (two dashed lines). (b) Monthly numbers of events count for $M_{L_{new}}$ 2.0 from 2007 to 2014. The average occurrence rate is 716 events per month (center line) with a standard deviation of 76 events (two dashed lines).

the monthly occurrence rates from 2007 to 2014 are calculated by counting events with $M_{L_{new}}$ 2.0 for every month (Fig. 4b). The average occurrence rate is 716 events per month with a standard deviation of 76 events. These results in Figure 4b are significantly different from Figure 4a in 2012, with no low anomalous period. The earthquake events per month obviously increase in 2012.

Further, we plot the Gutenberg–Richter relationship (Gutenberg and Richter, 1949) for events 3 years before and after 2012 (Fig. 5). From Figure 5, it is evident that the number of earthquakes with magnitude ($M_L < 1.5$) obviously increases after 2012 due to the network upgrade, enhancing the detection of smaller events. However, when $M_L > 1.8$, the cumulative number of earthquakes after 2012 is less than before 2012. This indicates that network upgrade actually leads to the underestimation of earthquake magnitude.

The station corrections are important especially for smaller earthquakes, which are recorded only at stations close to the epicenter. All the recording stations may be on either hard-rock or soft-soil sites, which could lead to underestimates or overestimates in the magnitude determination. Thus, the distribution and the number of stations would affect the magnitude estimates. However, the station corrections are not applied by the CWB in their magnitude determination so far.



▲ **Figure 5.** Gutenberg–Richter relationship for events 3 years before and after 2012.

SUMMARY

Using a declustered version of the Taiwan earthquake catalog, we found the appearance of relatively low seismicity in 2012 by an analysis of the seismic activity. Nevertheless, after the application of the station corrections revised M_L, the seismicity revealed no low or high anomalies in 2012. Therefore, we consider that it was neither real low seismicity nor seismic quiescence in 2012. The anomalous period of low seismicity in 2012 is due to upgrade of the CWBSN and the deployment of new stations. Furthermore, most of these stations on hard-rock sites with low amplification lead to underestimates of the earthquake magnitude. This is an important issue for earthquake statistics, the seismicity, and analysis in seismic hazard. In this study, we discovered that the new generation seismic network of CWB in the beginning of 2012 enhances its performance in the detection of small earthquakes but causes the problem of earthquake magnitude underestimation and the artifacts of seismicity quiescence.

DATA AND RESOURCES

Earthquake data used in this study was obtained from Taiwan instrumentation network managed by Central Weather Bureau (CWB) of Taiwan available at http://gdms.cwb.gov.tw/index.php (last accessed October 2015). The Generic Mapping Tool (GMT) software from Wessel and Smith (1998) was used in plotting part of the figures and is gratefully acknowledged.

ACKNOWLEDGMENTS

The authors are profusely thankful to Ministry of Science and Technology (MOST) of Republic of China for funding the project, under which this study was carried out. The comments from two anonymous reviewers and editor helped in improving this article. Weian Chao and Cédric Legendre are greatly acknowledged for careful checking of article.

REFERENCES

Chen, C. C. (2003). Accelerating seismicity of moderate-sized earthquakes before the 1999 Chi-Chi, Taiwan, earthquake: Testing time-prediction of self-organizing spinodal model of earthquakes, *Geophys. J. Int.* **155,** F1–F5.

Chang, C. H. (2004). Application of a dense seismic network data on the study of seismogenic structures of central and eastern Taiwan, *Ph.D. Thesis*, Institute of Geophysics, National Central University, 156 pp.

Davis, S. D., and C. Frohlich (1991). Single-link cluster analysis of earthquake aftershocks: Decay laws and regional variations, *J. Geophys. Res.* **96,** 6336–6350.

Dziewonski, A. M., T.-A. Chou, and J. H. Woodhouse (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, *J. Geophys. Res.* **86,** 2825–2852.

Ekström, G., M. Nettles, and A. M. Dziewonski (2012). The global CMT project 2004-2010: Centroid Moment Tensors for 13, 017 earthquakes, *Phys. Earth Planet. In.* **200/201,** 1–9.

Gutenberg, B., and C. F. Richter (1949). *Seismicity of the Earth and Associated Phenomena*, Princeton University Press, Princeton, New Jersey, 17–19.

He, H., and E. Tsukuda (2003). Recent progresses of active fault research in China, *J. Geogr.* **112,** no. 4, 489–520.

Huang, Q. (2004). Seismicity pattern change prior to large earthquakes—An approach of the RTL algorithm, *Terr. Atmos. Ocean Sci.* **15,** 469–491.

Huang, Q. (2006). Seismicity associated with the 2000 earthquake swarm in the Izu island region, *J. Asian Earth Sci.* **26,** 509–517.

Huang, Q. (2008). Seismicity changes prior to the M_s 8.0 Wenchuan earthquake in Sichuan, China, *Geophys. Res. Lett.* **35,** no. 23, doi: 10.1029/2008GL036270.

Huang, Q., and X. Ding (2012). Spatiotemporal variations of seismic quiescence prior to the 2011 M 9.0 Tohoku earthquake revealed by an improved Region–Time–Length algorithm, *Bull. Seismol. Soc. Am.* **102,** no. 4, 1878–1883.

Huang, Q., and T. Nagao (2002). Seismic quiescence before the 2000 M = 7.3 Tottori earthquake, *Geophys. Res. Lett.* **29,** 1578.

Huang, Q., G. A. Sobolev, and T. Nagao (2001). Characteristics of the seismic quiescence and activation patterns before the M = 7.2 Kobe earthquake, January 17, 1995, *Tectonophysics* **337,** 99–116.

Legendre, C.P., Q.-F. Chen, and L. Zhao (2014). Lithospheric structure beneath the East China Sea revealed by Rayleigh-wave phase velocities, *J. Asian Earth Sci.* **96,** 213–225.

Legendre, C. P., F. Deschamps, L. Zhao, S. Lebedev, and Q.-F. Chen (2014). Anisotropic Rayleigh wave phase velocity maps of eastern China, *J. Geophys. Res.* **119,** no. 6, 4802–4820.

Legendre, C. P., L. Zhao, and Q. F. Chen (2015). Upper-mantle shear-wave structure under East and Southeast Asia from Automated Multimode Inversion of waveforms, *Geophys. J. Int.* **203,** no. 1, 707–719.

Mignan, A. (2012). Seismicity precursors to large earthquakes unified in a stress accumulation framework, *Geophys. Res. Lett.* **39,** no. 21, doi: 10.1029/2012GL053946.

Mignan, A., and R. Di Giovambattista (2008). Relationship between accelerating seismicity and quiescence, two precursors to large earthquakes, *Geophys. Res. Lett.* **35,** no. 15, doi: 10.1029/2008GL035024.

Mignan, A., M. J. Werner, S. Wiemer, C.-C. Chen, and Y.-M. Wu (2011). Bayesian estimation of the spatially varying completeness magnitude of earthquake catalogs, *Bull. Seismol. Soc. Am.* **101,** no. 3, 1371–1385.

Mogi, K. (1979). Two kinds of seismic gaps, *Pure Appl. Geophys.* **117,** 1172–1186.

Shin, T. C. (1993). The calculation of local magnitude from the simulated Wood–Anderson seismograms of the short-period seismograms, *Terr. Atmos. Ocean Sci.* **4,** 155–170.

van Stiphout, T., D. Schorlemmer, and S. Wiemer (2011). The effect of uncertainties on estimates of background seismicity rate, *Bull. Seismol. Soc. Am.* **101,** no. 2, 482–494.

Wessel, P., and W. H. F. Smith (1998). New improved version of Generic Mapping Tools released, *Eos Trans. AGU* **79,** no. 47, 579.

Wiemer, S., and M. Wyss (1994). Seismic quiescence before the Landers (M = 7.5) and Big Bear (M = 6.5) 1992 earthquakes, *Bull. Seismol. Soc. Am.* **84,** 900–916.

Wu, Y. M., and C. C. Chen (2007). Seismic reversal pattern for the 1999 Chi-Chi, Taiwan, M_w 7.6 earthquake, *Tectonophysics* **429,** 125–132.

Wu, Y. M., and L. Y. Chiao (2006). Seismic quiescence before the 1999 Chi-Chi, Taiwan M_w 7.6 earthquake, *Bull. Seismol. Soc. Am.* **96,** 321–327.

Wu, Y. M., R. M. Allen, and C. F. Wu (2005). Revised M_L determination for crustal earthquakes in Taiwan, *Bull. Seismol. Soc. Am.* **95,** 2517–2524.

Wu, Y. M., C. C. Chen, L. Zhao, and C. H. Chang (2008). Seismicity characteristics before the 2003 Cheng Kung, Taiwan M_w 6.8 earthquake, *Tectonophysics* **457,** 177–182.

Wyss, M., and R. E. Habermann (1988). Precursory seismic quiescence, *Pure Appl. Geophys.* **126,** 319–332.

Yu, S. B., L. C. Kuo, R. S. Punongbayan, and E. G. Ramos (1999). GPS observation of crustal deformation in the Taiwan-Luzon region, *Geophys. Res. Lett.* **26,** 923–926.

Tz-Shin Lai[1]
Himanshu Mittal
Yih-Min Wu[2]
Department of Geosciences
National Taiwan University
Taipei 106, Taiwan
himanshumitt10@gmail.com

Published Online 4 May 2016
Corrected Online 11 May 2016

[1] Also at Seismological Observation Center, Central Weather Bureau, Taipei 10048, Taiwan.

[2] Also at National Center for Research on Earthquake Engineering, NARLabs, Taipei 10668, Taiwan.