ANNALS OF GEOPHYSICS, 61, 4, SE445, 2018; doi: 10.4401/ag-7699

"SEISMICITY BOUNDARY DEPTH OF MAINLAND CHINA"

Muhammad Zafar Iqbal[1,3], Tae Woong Chung[1,*], Hui Zhou[2], Sung Oh Cho[1], Myung Jin Nam[1]

(1) Sejong University, Seoul, Korea
(2) The second monitoring and application cater, China Earthquake Administration, Xi'an, China
(3) Microseismic Studies Program (MSSP), Islamabad, Pakistan

Article history
Receveid **March 23, 2018**; accepted **July 11, 2018.**
Subject classification:
California; *b*-value; Large earthquakes; East China; Boundary of 9 km.

ABSTRACT

The boundary between upper and lower seismogenic layers, below which large earthquakes tend to occur, is very important to estimate future seismic hazards. To estimate the depth of the seismogenic boundary, this study analyzes more than 38,000 earthquakes ($M \geq 2.5$) that occurred in mainland China from 2008 to 2016. Assuming Gutenberg-Richter distributions, a significant change of b-value was obtained at about the depth range of 9 km, as observed in California. East China, as a region of reliable depth, also shows the same boundary of 9 km with frequent occurrence of large earthquakes ($M > 5$).

1. INTRODUCTION

The seismogenic layer as an origin of most shallow continental earthquakes have received some particular attention due to recent hazardous earthquakes [e.g., Nazareth and Hauksson, 2004; Pace et al., 2006]. The seismogenic layers generally shows seismicity between an upper boundary at depths of 3-4 km and a lower boundary at a variety of depths (the depth above which 90% of earthquakes occur). In addition, small-magnitude earthquakes were mainly observed at the upper seismogenic layer, whereas large-magnitude ones were at the lower seismogenic layer [e.g. Jackson and White, 1989]. This difference was shown by a distinct b-value difference at a depth of 9 km at the seismicity of north and south California [Figure 1, Mori and Abercrombie, 1997]. Quantitative studies for depth-dependence are, however, very few for other regions.

In China's mainland, Teng et al. [2014] observed the boundary of seismicity separated approximately at 11 km. Similar boundary depths were also observed in relocation studies in China and its surrounding areas [Molnar and Chen, 1983; Déverchère et al., 2001]. However, this boundary was still not supported by a quantitative analysis based on a b-value study.

Recently, South Korea experienced several moderate ($M > 5$) earthquakes, the damage of which were closely correlated with the focal depth. Thus the boundary of the seismogenic layer, where large earthquakes tend to occur, is important to estimate future seismic hazards. South Korea, however, is largely aseismic compared with its surrounding areas, such as Japan and mainland China, and it is hard to obtain sufficient data with various magnitudes for a study of the b-value [e.g. Wiemer and Wyss, 2002]. A reliable analysis requires at least 500 pieces data for depth bins [e.g. Mori and Abercrombie, 1997].

In this study, more than 38,000 earthquakes were analyzed that occurred in China's mainland from 2008 to 2016 (Figure 1). Data was based on the earthquake catalog produced by the China Earthquake Networks Center (CENC) provided by the Western Data Centre branch

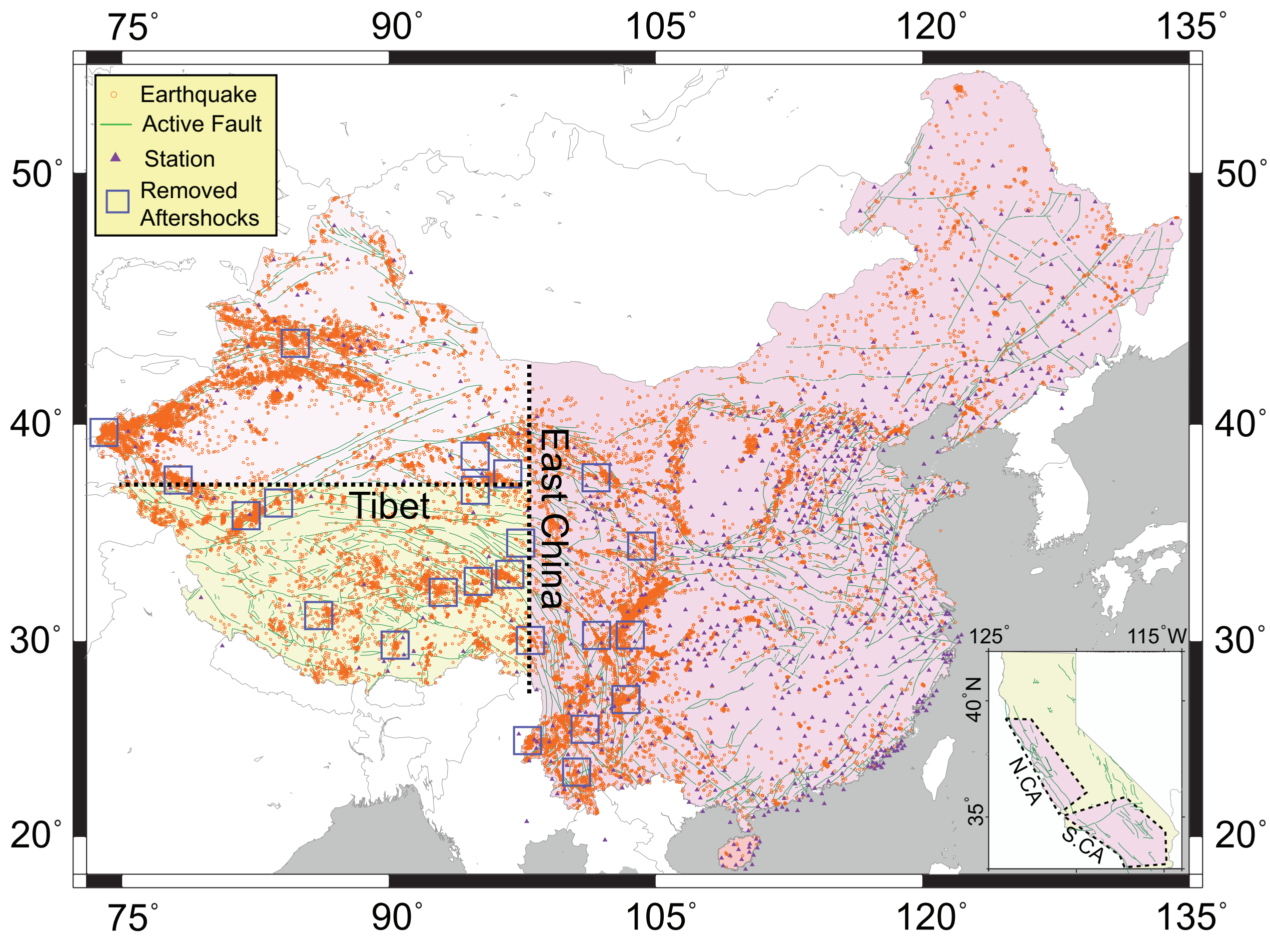

FIGURE 1. Map of studied region classified by density of network (violet triangles) as Mainland China, China except Tibet, and East China. Earthquakes (orange circles) distribution with active faults (green lines, Deng et al., 2002) were removed for offshore regions and Taiwan. The squares refer to regions of removed aftershocks for large earthquakes (M ≥6). The previously studied region by Mori and Abercrombie (1997) is north and south California, shown as right-lower insets.

of China. The CENC catalog has been referenced by several studies [e.g. Zheng et al., 2010; Peng et al., 2011; Mignan et al., 2013; Bai, 2017]. Despite the limitation that the error in focal depth from the catalogue cannot be determined, the significant depth dependence was observed as the seismicity boundary [Teng et al., 2014]. To constrain the structure of seismogenic layers as continental crust, this study excluded data from offshore regions and Taiwan. The analyses were performed the same way as California [Mori and Abercrombie, 1997] to compare the two regions.

2. PROCEDURE

The frequency-magnitude analyses were considered for five depth ranges as 0-3, 3-6, 6-9, 9-12, and 12-15 km. Whereas the California data were studied for the minimum magnitude both for *M* 2.0 and *M* 2.5, our data was restricted as *M* 2.5 (Table 1).

The number of earthquakes (N) having a magnitude ≥ *M* are expressed as the Gutenberg-Richter (GR) equation (1942) as

$$Log\ N = a - b\ M$$

where the constant a represents the seismicity level and the constant b is the relative size distribution of events. For the plots of the GR equation (Figure 2), b values with uncertainties were obtained based on the maximum likelihood method of Aki [1965]. The plots and calculation were performed by the software SEISAN [Hacskov and Ottemoller, 1999].

The study of California separated out aftershock sequences for the earthquakes of *M* ≥ 6.0. Our study also applied this separation for aftershocks for the same magnitude earthquakes. The aftershocks were regarded as 2 year events that occurred as clusters in the near re-

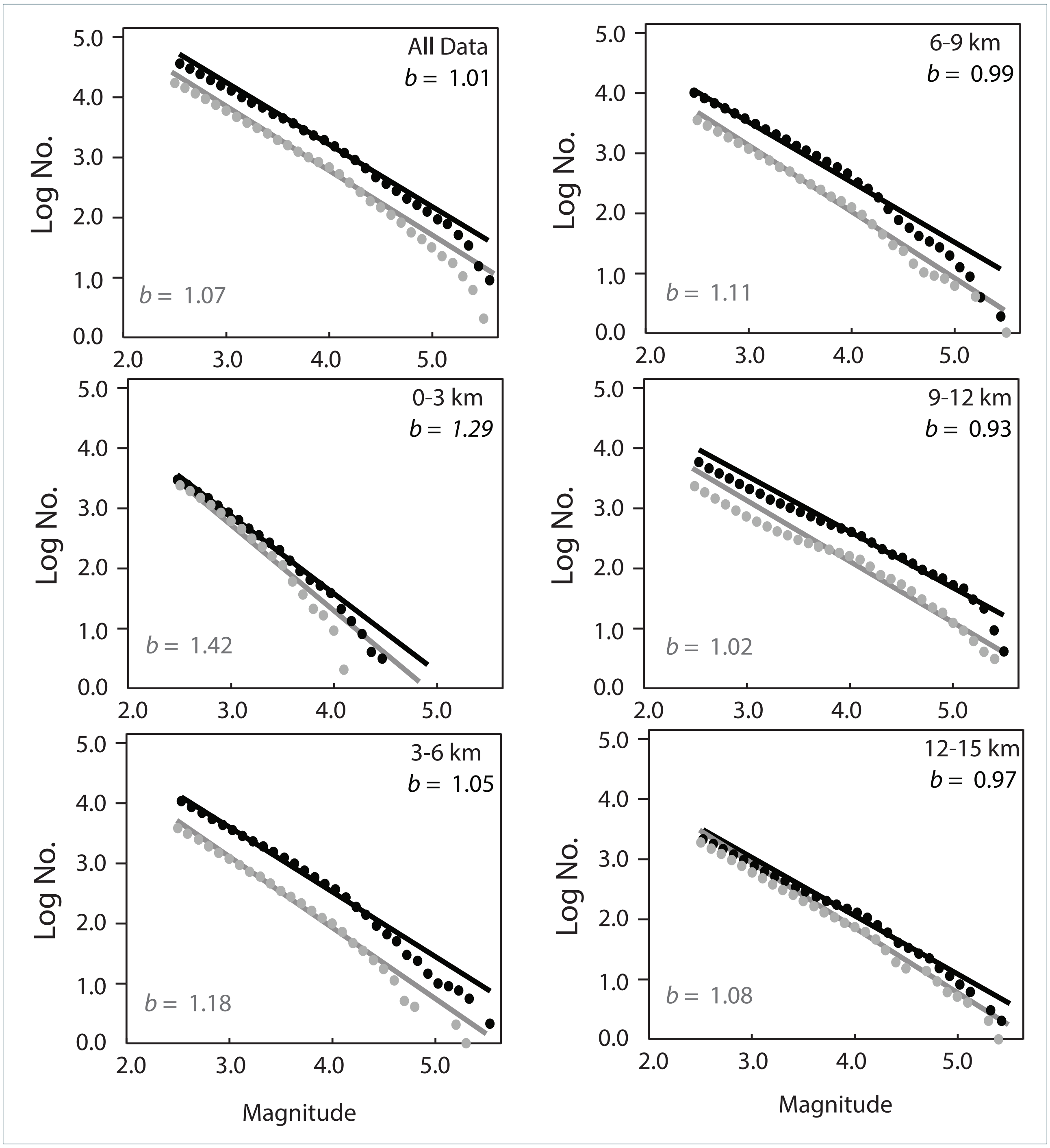

FIGURE 2. Frequency-magnitude distributions by depth are compared for Mainland China (blacks) and East China (gray). Lines show the maximum likelihood estimates of the *b* value. For each depth, the *b* value of Mainland China and East China is shown in upper-right and lower-left, respectively.

gion of the main event (Figure 1).

Mainland China shows that the eastern region has a dense network, which is relatively sparse in other regions (Figure 1). In particular, the region of Tibet showed large depth differences between the CENC catalogue and accurate relocation because of a sparse network and a complex structure [Lin et al., 2017]. Our analysis, therefore, classified regions as Mainland China, China except Tibet, and East China (Figure 1).

3. DISCUSSION AND CONCLUSION

The GR fits for frequency-magnitude were separated into five depth ranges (0-3, 3-6, 6-9, 9-12, and 12-15 km) as done in California. The example of these fits are shown for the comparison between Mainland and East China (Figure 2), because the similar values were obtained for East China and China except Tibet (Table 1 and Figure 3). The GR fit (Figure 2), however, becomes

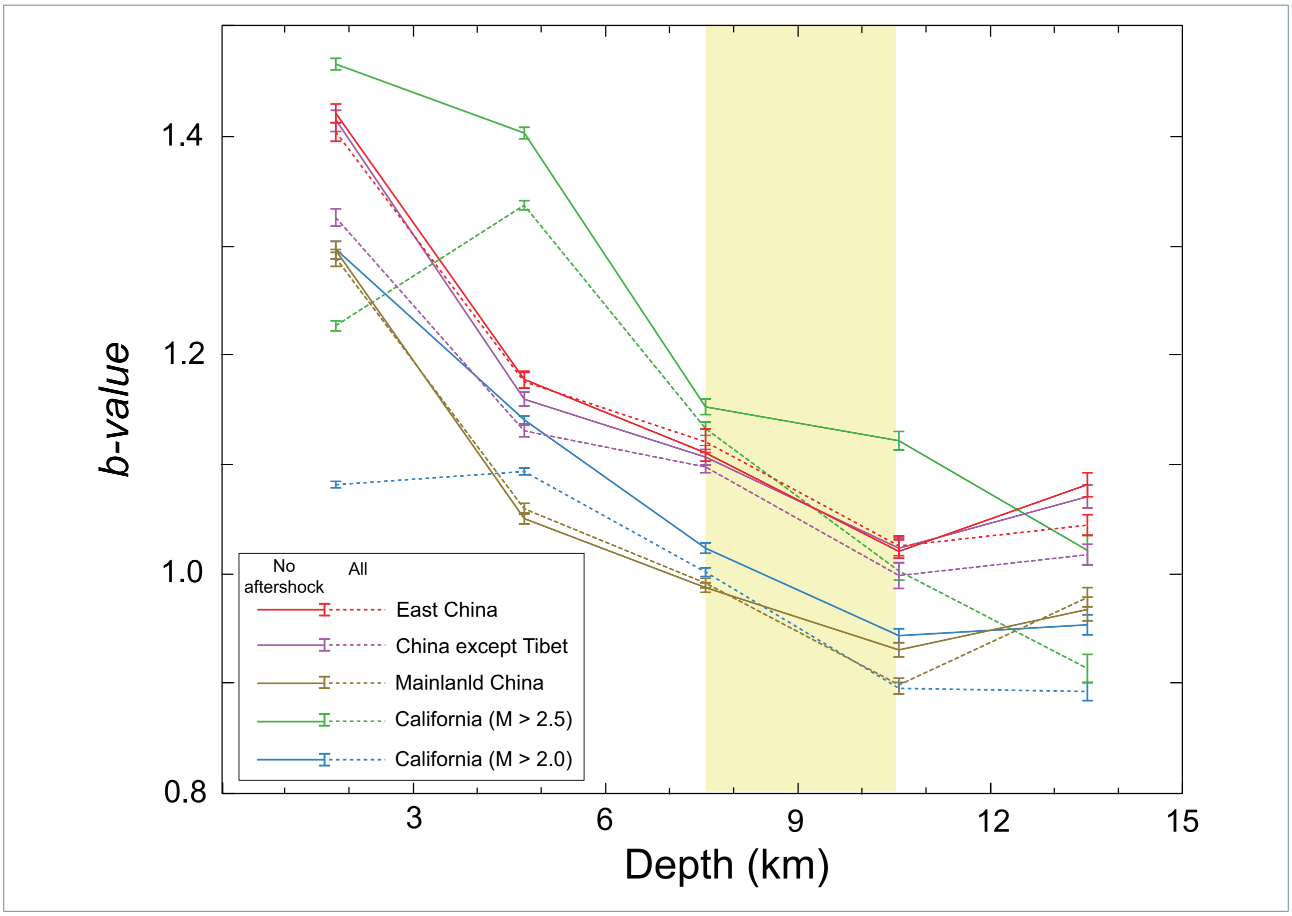

FIGURE 3. The *b* values versus depth for the various data sets are shown in Table 1. Error bars are the 95% confidence limits using the maximum likelihood estimate (Aki, 1965). Significant change of *b* values between the range of 6-9 and 9-12 km is expressed as the yellow zone.

Region		No. of Data	*b* Values					
			All Data	0-3 km	3-6 km	6-9 km	9-12 km	12-15 km
California (≥ 2.0)*	All	44027	1.026 ± 0.004	1.081 ± 0.007	1.093 ± 0.008	1.001 ± 0.009	0.895 ± 0.011	0.892 ± 0.017
	No aftershocks	28497	1.105 ± 0.005	1.296 ± 0.009	1.140 ± 0.010	1.023 ± 0.011	0.943 ± 0.014	0.953 ± 0.020
California (≥ 2.5)*	All	15599	1.162 ± 0.007	1.226 ± 0.013	1.336 ± 0.013	1.132 ± 0.016	1.002 ± 0.018	0.913 ± 0.027
	No aftershocks	9392	1.256 ± 0.009	1.465 ± 0.018	1.402 ± 0.017	1.152 ± 0.019	1.121 ± 0.022	1.021 ± 0.032
Mainland China	All	34029	1.006 ± 0.006	1.288 ± 0.023	1.059 ± 0.012	0.991 ± 0.010	0.898 ± 0.013	0.978 ± 0.020
	No aftershocks	31102	1.011 ± 0.006	1.295 ± 0.024	1.050 ± 0.012	0.987 ± 0.010	0.930 ± 0.014	0.967 ± 0.023
China except Tibet	All	29421	1.048 ± 0.007	1.325 ± 0.024	1.130 ± 0.014	1.097 ± 0.013	0.998 ± 0.017	1.017 ± 0.022
	No aftershocks	20790	1.071 ± 0.008	1.414 ± 0.028	1.159 ± 0.017	1.106 ± 0.018	1.023 ± 0.022	1.070 ± 0.026
East China	All	22526	1.066 ± 0.008	1.403 ± 0.027	1.175 ± 0.017	1.120 ± 0.017	1.025 ± 0.021	1.044 ± 0.023
	No aftershocks	17323	1.069 ± 0.009	1.420 ± 0.028	1.177 ± 0.020	1.110 ± 0.020	1.020 ± 0.025	1.081 ± 0.027

TABLE 1. The comparison of *b* values between California (Mori and Abercrombie, 1997) and China for various data sets. ( )* of California denote to M. For China, $M \geq 2.5$.

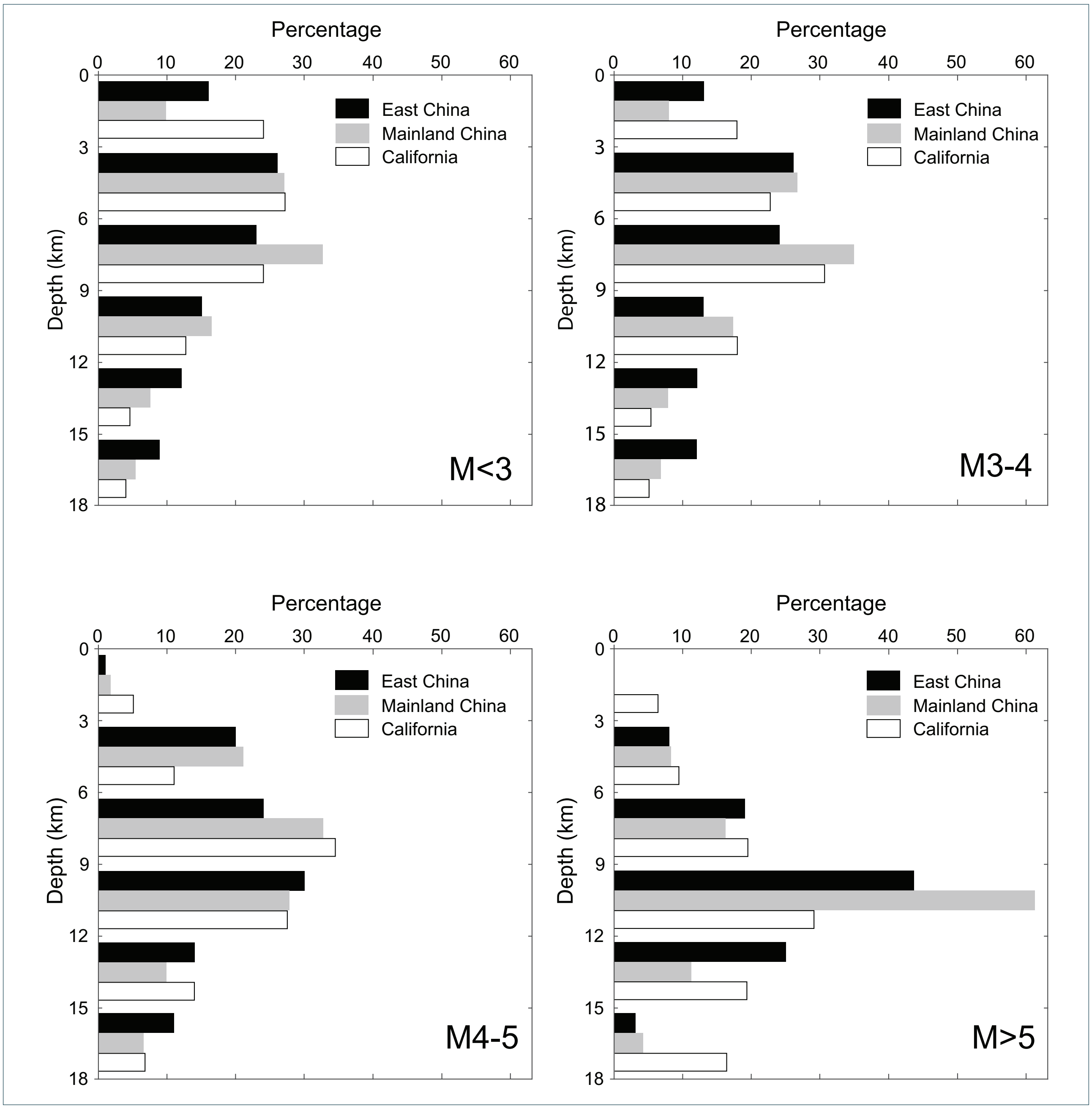

FIGURE 4. Depth distribution for several magnitude ranges were compared for East China, Mainland China and California, after Mori and Abercrombie, [1997]. Aftershocks from large (M ≥ 6) events have not been included.

worse for the large magnitudes (M 4.0-5.0). This deviation at the large magnitude was also observed in California when the use of 2.5 instead of 2.0, which can be explained as a serious effect by the minimum magnitude for the b-value [e.g. Wiemer and Wyss, 2002]. The depth-dependent trends, however, were not affected in this study because our results also show a significant change of the b-value between the range of 6-9 and 9-12 km as shown in California (Table 1, Figure 2). This change was more significant for East China and China except Tibet than Mainland China (Figure 3). Since the b-value decline at shallow range reflects increasing pressure [Scholz, 1968], the significant decrease at the deep range, around 9 km, suggests a dramatic change in lithological conditions.

Although the separation of aftershocks appears to not be as significant in the Chinese data as the case of California (Figure 3), this study showed data separated aftershocks in Figures 2 and 4. In Figure 4, the frequent seismicity for M > 5.0 are also observed in the Chinese data as in California at the depth range of 9-12 km. This frequency, however, appears to be anomalously high for Mainland China. The anomalous value in Mainland China can be attribute to inaccurate depths at Tibet because less frequent seismicity was observed for East China.

East China as a region of reliable depths, however, still shows significant frequent seismicity for M>5.0, and also shows significant change of b-value between the range of 6-9 and 9-12 km as shown in California, although much larger and tectonically complex than California. The boundary of about 9 km depth, observed in both studies, suggest the boundary between upper and lower layers of the seismogenic layer. The frequent small earthquakes in the upper layer were attributed to the "stopping" of earthquakes in the heterogeneous upper seismogenic layer due to cracks [Mori and Abercrombie, 1997]. Because these cracks gradually close with increasing depth, the stress field of the lower seismogenic layer becomes relatively homogeneous; a rupture beginning in the lower seismogenic layer would therefore be less preventable. Such a scenario would generate relatively fewer small seismic events but would nucleate large ones because large earthquakes tend to nucleate from the base of the seismogenic layer [Scholz, 1988].

The seismicity boundary depth of seismogenic layers, as a plausible upper limit of large earthquakes, is important not only for scientific information but also for the seismic hazard assessment. More regional studies are required to constrain the seismicity boundary depth of the seismogenic layer.

Acknowledgements. This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSSIT) (No. 2018R1A2A3074595), and was also benefited from the Energy Efficiency & Resources of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) sponsored by the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20164010201120).

REFERENCES

Aki, K., 1965, Maximum likelihood estimate of b in the formula log N = a – b M and its confidence limits, Bulletin of the Earthquake Research Institute, The University of Tokyo, 43, 237-239.

Bai, L., Li, G. Khan, N. G., Zhao, J., and Ding, L., 2017, Focal depths and mechanisms of shallow earthquakes in the Himalayan–Tibetan region, Gondwana Research, 41, 390-399,

Déverchère, J., Petit, C., Gileva, N., Radziminovitch, N., Melnikova, V., and San'Kov V., 2001, Depth distribution of earthquakes in the Baikal rift system and its implications for the rheology of the lithosphere, Geophysical Journal International, 146, 714-730.

Deng, Q. D., P. Z. Zhang, Y. K. Ran, X. P. Yang, W. Min, and Q. Z. Chu, 2002, Basics characteristics of active tectonics of China (in Chinese), Sci. China, Ser. D Earth Sci., 32, 1020–1030.

Gutenberg, B., Richter, C. F., 1942, Earthquake magnitude intensity, energy, and acceleration. Bulletin of the Seismological Society of America, 32, 163–191.

Havskov, J., and Ottemoller, L., 1999, SeisAn earthquake analysis software, Seismological Research Letters, 70, 532-534.

Jackson, J.A. and White, N.J., 1989, Normal faulting in the upper continental crust: observations from regions of active extension, Journal of Structural Geology, 11, 15-36.

Ling, B., Li, G., Khan, N. G., Zhao, J., and Ding, L., 2017, Focal depths and mechanisms of shallow earthquakes in the Himalayan–Tibetan region, Gondwana Res., 41, 390-399.

Mignan, A., Jiang, C., Zechar, J.D., Wiemer, S., Wu, Z., and Huang, Z., 2013, Completeness of the Mainland China Earthquake Catalog and Implications for the Setup of the China Earthquake Forecast Testing Center, Bulletin of the Seismological Society of America, 103, 845-859.

Molnar, P. and Chen, W. –P., 1983, Focal depths and fault plane solutions of earthquakes under the Tibetan Plateau, J.ournal of Geophysical Research, 88, 1180–1196.

Mori, J., and Abercrombie, R. E., 1997, Depth dependence of earthqake frequency-magnitude distributions in California: Implication for rupture initiation, Journal of Geophysical Research, 102, 15,081-15090.

Nazareth, J.J. and Hauksson, E., 2004, The seismogenic thickness of the southern California crust, Bulletin of the Seismological Society of America, 94, 940-960.

Pace, B., Peruzza, L., Lavecchia, G. and Boncio, P., 2006, Layered Seismogenic Source Model and Probabilistic Seismic-Hazard, Bulletin of the Seismological Society of America, 96, 107-132.

Peng, H., Wu, Z., Wu, Y., Yu, S., Zhang, D., and Huang, W., 2011, Developing a Prototype Earthquake Early Warning System in the Beijing Capital Region, Seismol. Res. Lett. 82, 394-403.

Scholz, C. H., 1968, The frequency-magnitude relation of microfracturing in rock and its relation to earthquakes, Bulletin of the Seismological Society

of America, 58, 399-415.
Scholz, C. H., 1988, The brittle-plastic transition and the depth of seismic faulting, Geologische Rundschau, 77, 319-328.
Teng, J., Deng, Y., Badal, J. and Zhang, Y., 2014, Moho depth, seismicity and seismogenic structure in China mainland, Tectonophysics, 627, 108-121.
Wiemer, S. and Wyss, M., 2002, Mapping spatial variability of the frequency-magnitude distribution of earthquakes, Advanced Geophysics, 45, 259–302.
Zheng, X.-F., Yao, Z.-X., Liang, J.-H., and Zheng, J., 2010, The Role Played and Opportunities Provided by IGP DMC of China National Seismic Network in Wenchuan Earthquake Disaster Relief and Researches, , Bulletin of the Seismological Society of America, 100, 2866-2872.

*CORRESPONDING AUTHOR: Tae Woong CHUNG,
Sejong University, Seoul, Korea
email: chungtw@sejong.ac.kr