Int. J. Disaster Risk Sci. 2012, 3 (3): 155–162
doi:10.1007/s13753-012-0016-0

ARTICLE

Predicting Earthquakes: The Mw9.0 Tohoku Earthquake and Historical Earthquakes in Northeastern Japan

Jifu Liu[1,*] and Yongsheng Zhou[2]

[1]State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China
[2]State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China

Abstract A magnitude 7.3 foreshock occurred two days before the magnitude 9.0 Tohoku Earthquake. The energy release of earthquakes within two days after the M7.3 earthquake is obviously different from the aftershocks of the Mw9.0 earthquake. But guided by historical earthquake experience, seismologists regarded the M7.3 earthquake as the main shock rather than a foreshock of another greater earthquake. Based on the analysis of historical earthquakes in coastal areas of northeastern Japan, the recurrence time of earthquakes is in quasi-periods of decadal or centennial scale. These quasi-periods are related to fault rupture along subduction zones located in marine environments adjacent to the coast. The probabilistic prediction for future earthquakes made by Japanese seismologists using historical earthquake data is based on a decadal scale quasi-period. It is difficult, however, to make relatively reliable predictions about the recurrence interval of rare great earthquakes based on historical earthquakes due to the very long intervals between large magnitude quakes and the limited historical and scientific records about their characteristics.

Keywords earthquake prediction, foreshock, historical earthquake, Japan, Tohoku Earthquake

1 Introduction

Short-range strong earthquake prediction according to a great quantity of intensive small earthquakes is one of the common methods employed in earthquake prediction, and the prediction of the Haicheng Earthquake in China is the most successful example (Chen 2009; Xu et al. 1982). But it is difficult to tell whether an earthquake that has occurred is a foreshock of another quake or is itself the main event. On the other hand, due to a lack of foreshocks (Marzocchi and Zechar 2011), no forecast was issued for the Tangshan and Wenchuan Earthquakes, both of which resulted in considerable casualties.

On 11 March 2011, a Mw9.0 earthquake happened in the northeast of Japan. Before this Mw9.0 earthquake, a M7.3 earthquake occurred on March 9 in the same place. The M7.3 earthquake did not attract much attention due to its occurrence under the sea over 130 km away from the shore. In this location, the M7.3 quake caused neither severe destruction nor a devastating tsunami, although the quake belonged in the strong earthquake category in terms of magnitude. By examining this earthquake and the subsequent earthquake sequence, researchers later concluded that these earthquakes were actually a foreshock sequence of a greater earthquake rather than a typical aftershock sequence of the M7.3 earthquake (He, Zhou, and Ma 2011; Ozawa et al. 2011). Why was the M7.3 earthquake not recognized earlier as a foreshock? Seismologists attributed this to the lack of a history of great earthquakes in northeastern Japan. Thus the prediction of such an earthquake went beyond the cognitive range of their seismic activities. Similarly, since no such strong earthquake occurred in the Longmenshan area before the Wenchuan Earthquake in China in 2008 (Wen et al. 2009), seismologists took it for granted that there would be no strong earthquake in the future in the area, and thus paid little attention to its possible occurrence.

According to historical earthquake catalogues, earthquakes have occurred periodically. In China, there have been five active seismic periods since 1895, marked by the occurrence of large earthquakes (Zhang, Fu, and Gui 2001). Period of seismic activity is often used to predict the future trend of earthquakes. Internationally, Geller and colleagues (1997) and Sykes, Shaw, and Scholz (1999) hold somewhat opposite views. According to the self-organized critical (SOC) phenomenon, Geller and colleagues believe that earthquakes cannot be predicted. But Sykes, Shaw, and Scholz think that at a certain scale large earthquakes can be predicted. Predicting the future trend of earthquakes according to the quasi-period of historical earthquakes clearly involves great uncertainties. In practice, prediction according to the causative rules of historical earthquakes is one of the common methods for predicting middle- and long-term earthquakes (Wang 2009). But it is unavoidable for such a method to fail in predicting great earthquakes with an especially long causative cycle. This article discusses the limitations of predicating earthquakes based on historical earthquakes by analyzing the foreshock characteristics and historical record of earthquakes in eastern Japan.

* Corresponding author. E-mail: liujifu@bnu.edu.cn

2 Foreshock Activities and Aftershock Characteristics of the Tohoku Earthquake

On 9 March 2011, a M7.3 earthquake occurred in northeastern Japan off the Sanriku coast; it was accompanied by active aftershocks including a M6.8 event the next day. These events were located just north of the Pacific Ocean center of the Tohoku Earthquake, which took place two days later on 11 March 2011 (Figure 1a). Since the M7.3 earthquake was a significant earthquake event in its own rights, based on their experience seismologists took it as the principal earthquake. Because it caused no damage, the M7.3 earthquake received little attention from the research community, government, and general public. But the cruel fact was that this earthquake and the subsequent earthquake sequence associated with it were actually a foreshock sequence of a larger magnitude earthquake rather than a typical aftershock sequence to the M7.3 earthquake (Figure 1b). Figure 1c shows that the energy had already been in a gradual attenuation situation more than half a day after the M7.3 earthquake, and the maximum magnitude of quakes did not surpass M6.0. However, three earthquakes stronger than M6.0 happened during the more than three hour period from 18:06 to 21:22 on March 9, which made the earthquake energy release rate increase rapidly. From that point on another five earthquakes stronger than M5.0 took place, although with a somewhat reduced energy release rate. The tail end of the curve in Figure 1c is the occurrence time of the Mw9.0 earthquake. Figure 1c shows that although the energy release rate before the great earthquake was lower compared with immediately after the M7.3 quake, it was absolutely not completely calm (He, Zhou, and Ma 2011).

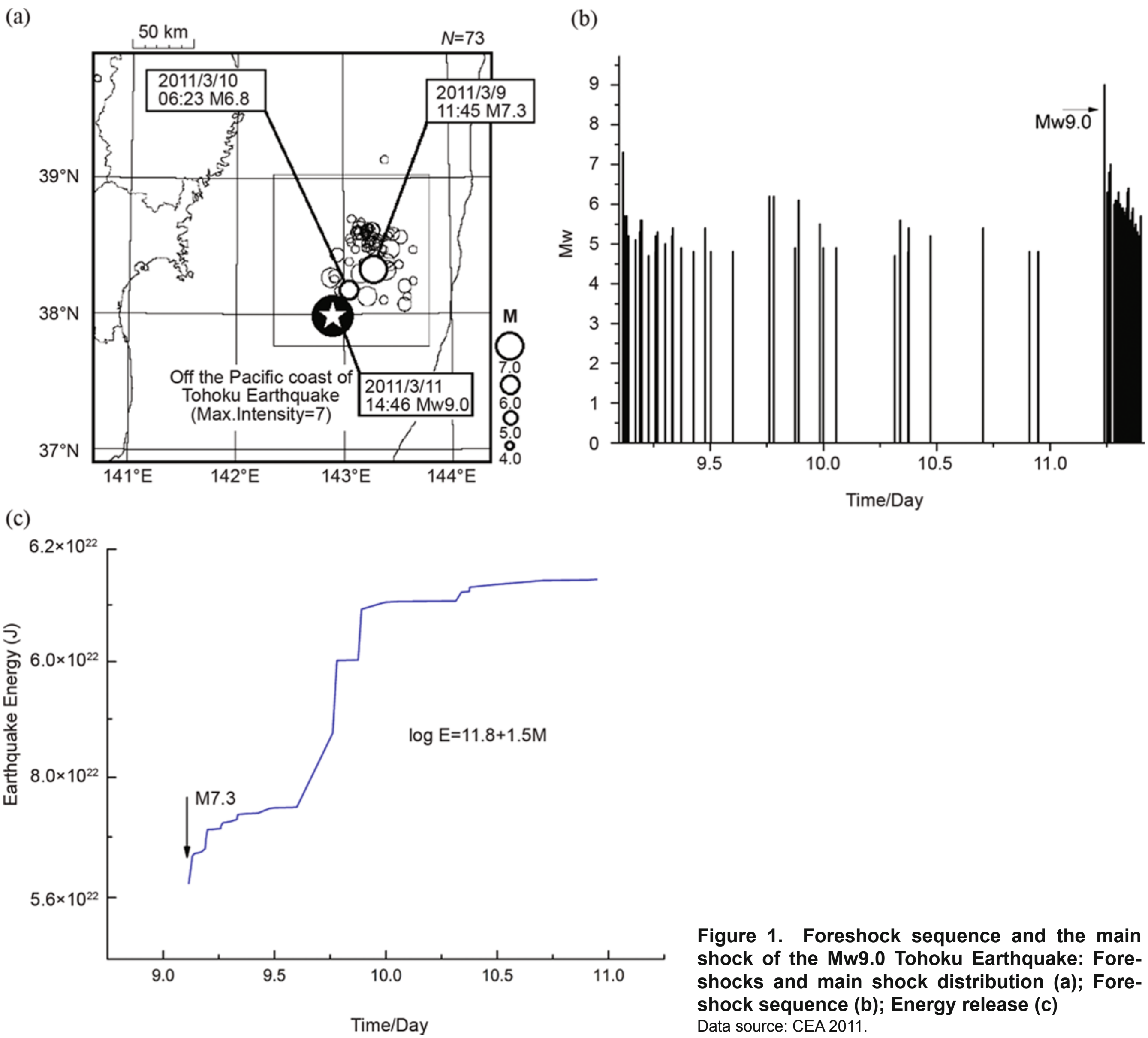

Figure 1. Foreshock sequence and the main shock of the Mw9.0 Tohoku Earthquake: Foreshocks and main shock distribution (a); Foreshock sequence (b); Energy release (c)
Data source: CEA 2011.

Compared with the foreshocks, there were intensive strong aftershocks for several days after the Mw9.0 great earthquake (Figure 2), which were embodied in crowed lines in the M-T diagram (Figure 1b), while the frequency of strong aftershocks decreased gradually (Figure 3a). The variation tendency of the energy release rate is basically degraded without obvious fluctuation in the foreshock sequence (Figure 3b).

These earthquake sequences show that the M7.3 earthquake was not the principal earthquake, but part of a foreshock sequence. Through analyzing sequences of historical earthquakes and probabilities of future earthquakes predicted by Japanese seismologists prior to the great earthquake based on historical earthquakes, this article explains why seismologists mistook the M7.3 earthquake as a principal earthquake. The article also discusses the limitations of predicating earthquake according to the data provided by foreshocks and the historical earthquake record.

3 Characteristics of Historical Earthquake Sequences in Coastal Areas of Northeastern Japan

The Tohoku Earthquake happened in the sea off the coast of Sanriku in northeastern Japan, which belongs to the Pacific seismic and volcanic activity zone (He, Zhou, and Ma 2011). Northeast Japan is located at the subduction zone of the Pacific Plate as it approaches the Japanese archipelago, with the subduction zone forming the Japan Trench (Figure 4).

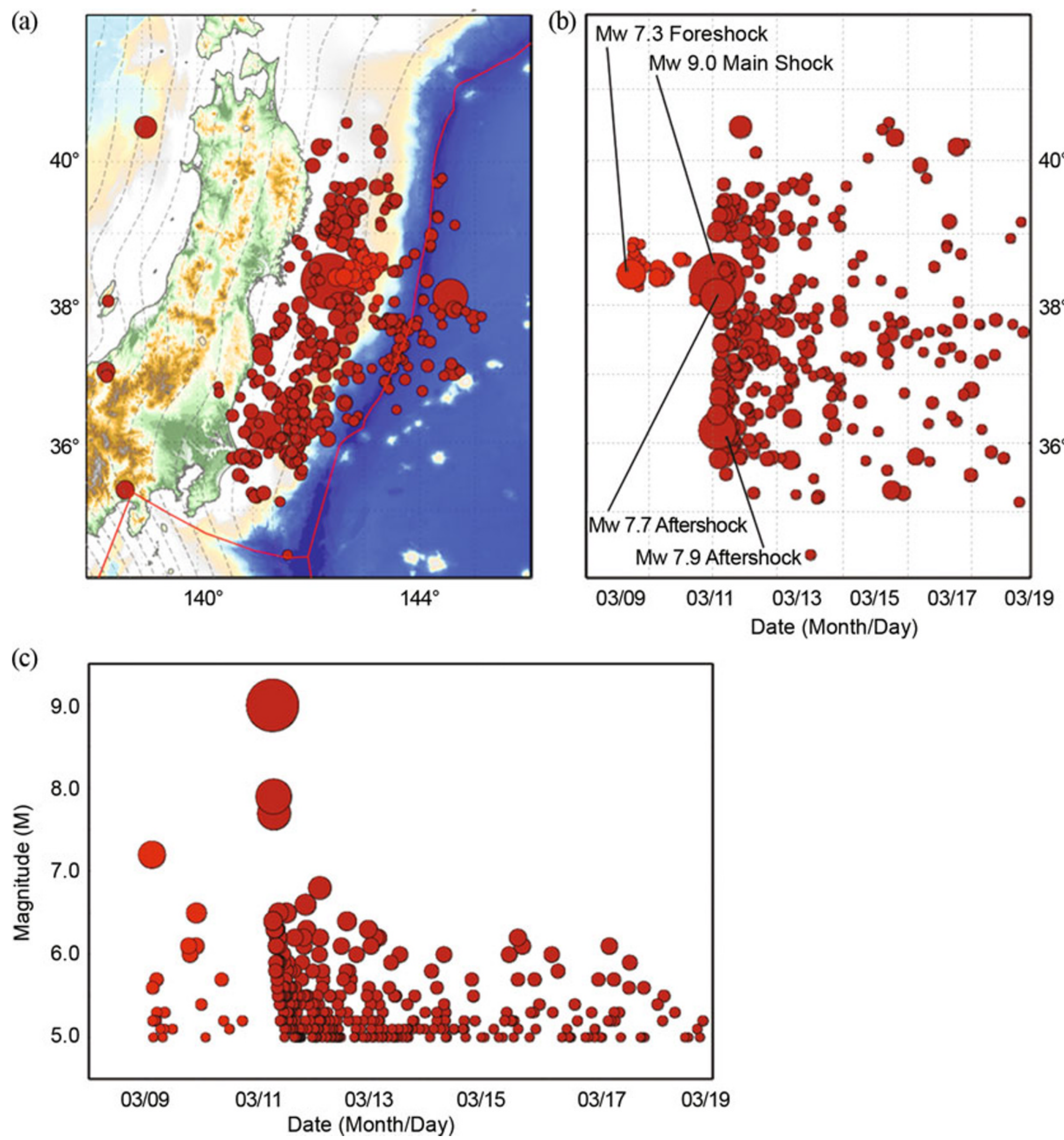

Figure 2. Foreshocks, main shock, and aftershocks distribution: Spatial distribution of foreshocks, main shock, and aftershocks (a); Temporal distribution of foreshocks, main shock, and aftershocks (b); M-T Diagram of the M7.3 foreshock and other foreshocks stronger than M4.4 prior to the Mw9.0 main earthquake (c)

Data source: Helmholtz-Centre Potsdam - German Research Centre for Geosciences (GFZ) 2011.

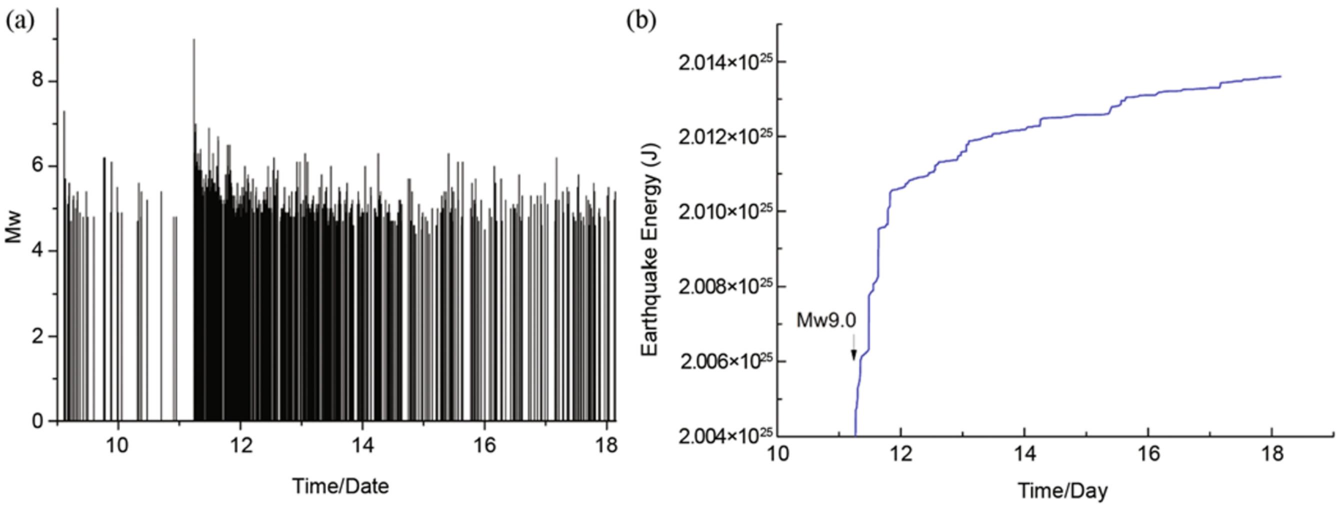

Figure 3. Aftershock sequence and energy release of the Mw9.0 Tohoku Earthquake: M-T Diagram of aftershocks stronger than M4.4 (a); Changes of accumulated earthquake energy after the Mw9.0 Tohoku Earthquake (b)
Data source: Helmholtz-Centre Potsdam - German Research Centre for Geosciences (GFZ) 2011.

Southeast Japan is located at the subduction zone of the Phillipine Plate as it sinks under the Japanese archipelago, which stretches southward from Izu Peninsula to Shikoku Island. The Nankai Trough of Japan is formed at the boundary of the subduction zone (Figure 4a). The boundary between these two subduction zones is called the Sagami Trough and the Lzu-Ogasawara Trench.

According to the characteristics of historical seismicity, the eastern coastal area of the Japanese islands can be divided into four earthquake zones from the north to south, that is, the Sanriku area and its near seas earthquake zone, Miyagi area and its adjacent marine earthquake zone, Kanto area and its offshore earthquake zone, and the Nankai trough earthquake zone. Based on the spatial and temporal patterns of historical

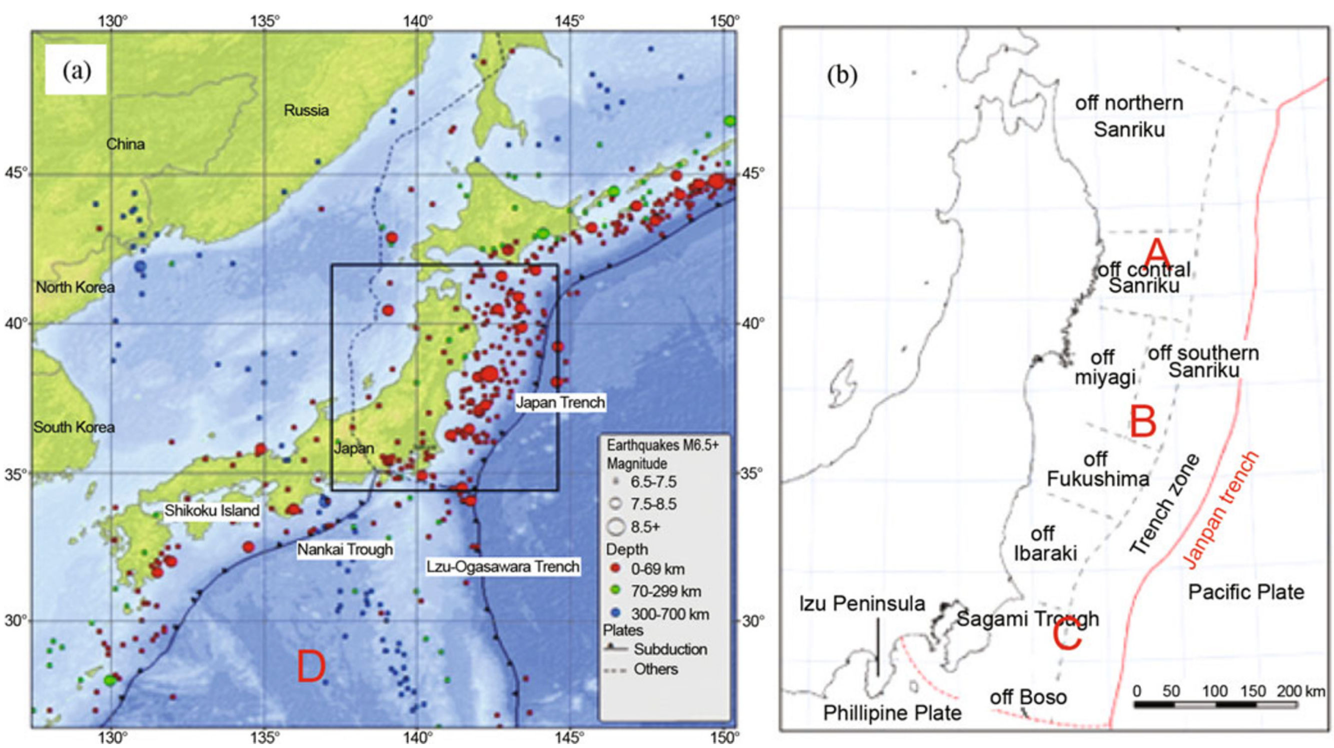

Figure 4. Tectonic settings of the Mw9.0 Tohoku Earthquake in northeastern Japan. A, B, C, and D are the historical earthquake areas depicted schematically in Figures 5–8. (b) is the detailed map of the rectangular area in (a)
Source: Adapted from He, Zhou, and Ma 2011.

earthquakes in these areas, Japanese seismologists make predictions about the probability of occurrence of future earthquakes (Okada 2011).

3.1 Historical Earthquakes in the Sanriku Area and Its Near Seas

The oldest strong earthquake in history in Sanriku happened in 869, and the next strong earthquake occurred in 1611. Thereafter, three M8.0 or greater earthquakes with accompanying tsunami happened in 1677, 1896, and 1933 respectively (Figure 5a). So the tectonics in the offshore areas of both Sanriku and Fukushima provide the necessary conditions for the occurrence of M8.0 or greater earthquakes. According to the predictions based on historical earthquakes, the probability of occurrence of M8.0 earthquakes in northern and central Sanriku and its nearby seas is about 0.5–10 percent in the 97 years after 1933. In contrast, the probability of the occurrence of M7.7 earthquakes centered offshore from southern Sanriku is 80–90 percent in the future 105 years (Okada 2011) (Figure 5a). According to the energy release diagram of historical earthquakes (Figure 5b), this prediction corresponds with the basic patterns of energy release. The time sequence and energy release of the last four earthquakes suggest that the interval between the first two earthquakes (one cluster) and the last two earthquakes (another cluster) since 1611 is short, about a few decades, while the interval between the two clusters is about 200–300 years. This implies that there may exist two periods for the seismicity in this area: one is short, about 50–100 years, and the other is long, about 200–300 years. Both periods are important for understanding the occurrence of earthquakes in the area.

3.2 Historical Earthquakes of Miyagi and Offshore Areas

A M8.2 earthquake occurred in 1793 in Miyagi and nearby seas, and a series of M7.4 and above earthquakes followed this quake until 1978. The average interval between these quakes was about 37 years (Figure 6a). When the earthquake of M7.2 happened in 2005, Japanese seismologists thought that the energy did not reach the historical earthquake level. When the M7.3 earthquake broke out on 9 March 2011, almost all seismologists believed that it was related to the earthquake in 2005 (Figure 6b). Therefore the experts thought the energy had been basically released. Based on historical earthquakes, Japanese seismologists estimated that the probability of a M7.5 earthquake reoccurring in Miyagi and offshore was 99 percent. But if Miyagi marine areas are linked to South Sanriku, M8.0 earthquakes with the same probability of 99 percent are possible (Okada 2011).

The evaluation and prediction were reasonable from the perspective of historical earthquakes. The truth, however, was that the Mw9.0 great earthquake broke out just two days after the M7.3 earthquake. The Mw9.0 earthquake was not only the manifestation of the linkage of Miyagi and near seas with South Sanriku, but it also revealed the linkage of the entire northeast ocean trench of Japan because these areas formed a crack of 400 km along the ocean trench (Ozawa et al. 2011). The energy released in this strong earthquake exceeded the total energy released from historical earthquakes since 1835 (Figure 6c). This was totally beyond both historical experience and seismologists' cognitive scope, since there was no Mw9.0 earthquake on record in this area (Ozawa et al. 2011). Evidently, there is a large uncertainty in predicting future strong earthquakes based solely on historical earthquakes. It is relatively reliable to predict moderately-strong earthquakes with a quasi-period of a decadal scale. But for huge earthquakes, the quasi-period reaches from centennial to millennial scale, and seismologists have limited knowledge of this type of great earthquakes. For example, according to paleoseismic analysis, the seismic period of the Wenchuan Earthquake in 2008 is between 2000 and 3000 years (Zhang et al. 2008; Wen et al. 2008; Ran et al. 2010).

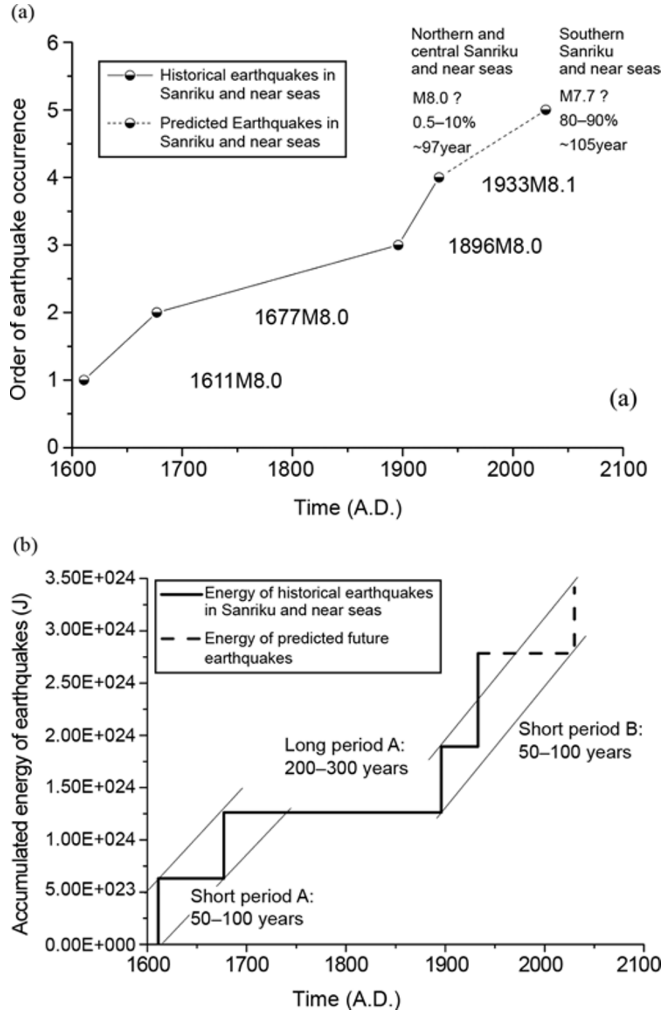

Figure 5. Historical earthquakes and future earthquake probability of the Sanriku area and its adjacent marine areas
Data source: CEA 2011.

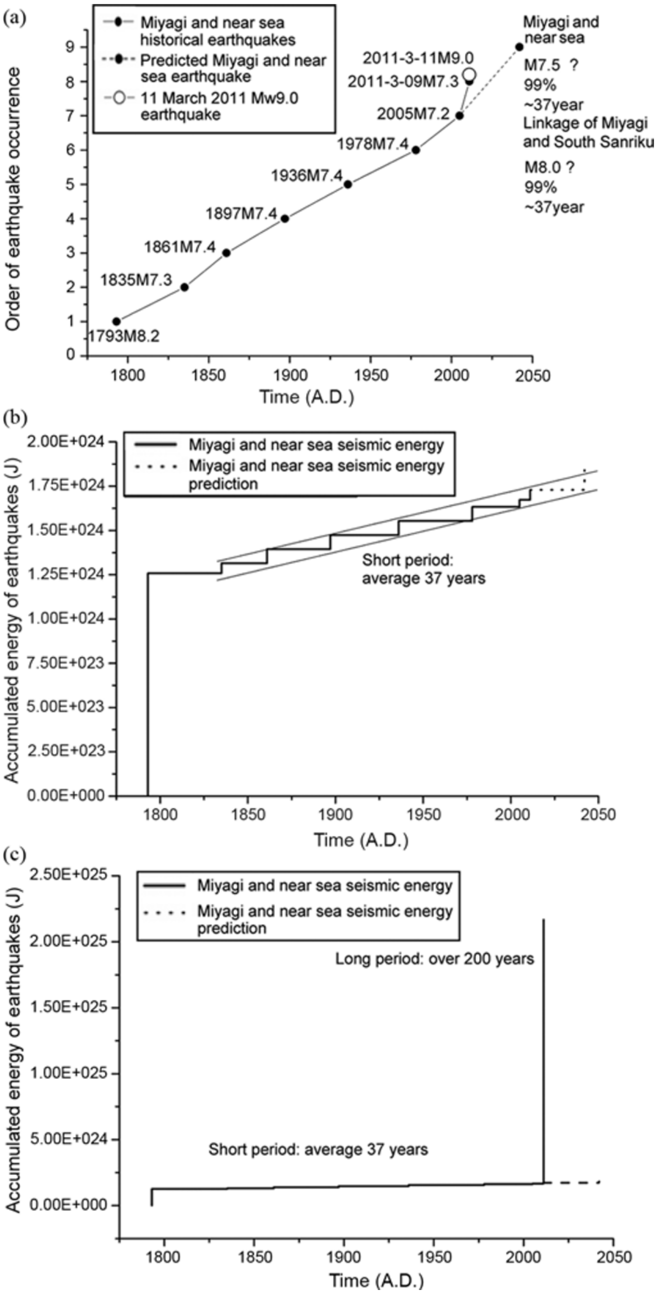

Figure 6. Historical earthquakes and the future probability of earthquakes in the Miyagi area and adjacent ocean areas
Data source: CEA 2011.

3.3 Historical Earthquakes of the Kanto Area and Offshore Regions

The Kanto area is controlled by both the Pacific Plate and the Philippine Plate subduction, and the Pacific Plate subducts beneath the Philippine Plate, forming the Sagami Trough at the intersection of the Izu-Ogasawara Trench (the boundary of the Philippine Plate and the Pacific Plate) and the Japan Trench (Figure 4) (He, Zhou, and Ma 2011; Ozawa et al. 2011). Five M8.0 earthquakes have occurred in the Kanto area and offshore districts since 1677. Based on the earthquake time series and energy release data, the first two and the last three quakes have a short time interval of about 20–40 years. The time interval between the two clusters is 200–250 years. Therefore, two activity periods exist in the earthquakes of this area, which includes a short period of 20–40 years and a long period of 200–250 years (Figure 7).

3.4 Historical Earthquakes of the Tokai Area and the Nankai Trough

In history, the Tokai earthquake had prominent one-place repeatability (Imoto, Wiemer, and Matsuzawa 2006). But since the Suruga Trough is the extension of the Nankai Trough, it usually slides with faults along the Nankai Trough during earthquakes, resulting in energy release that is large in magnitude and spatial scale. Therefore, the magnitude of these earthquakes was relatively high, averaging around M8.0. The earliest three recorded earthquakes were in the year of 684, 887, and 1096 and 1099 (a double earthquake type) respectively, with an interval of about 200 years between major quakes. There was no great earthquake in the

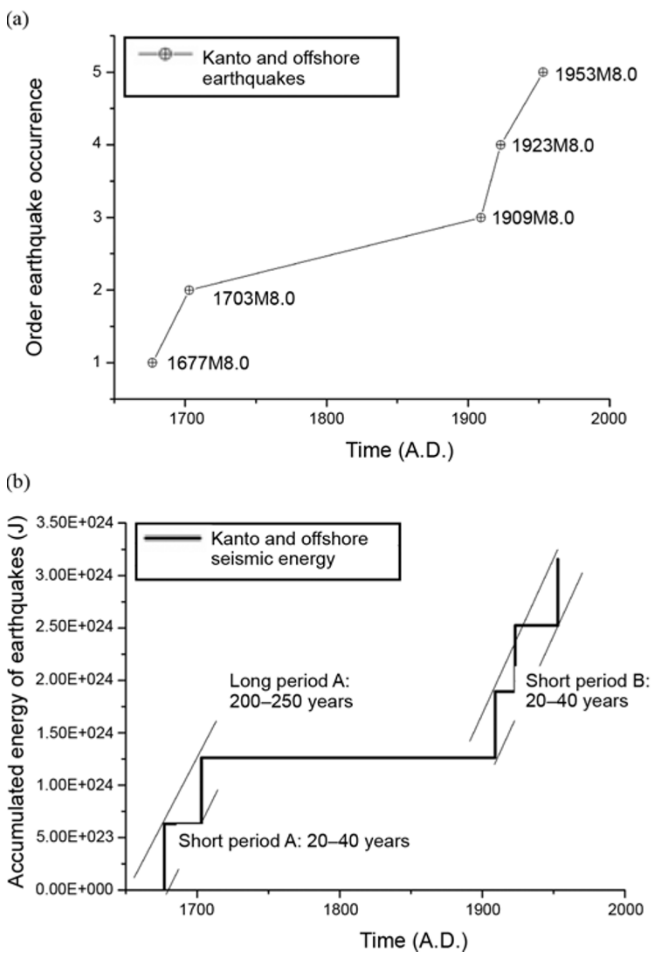

Figure 7. Historical earthquake time series of the Kanto area and offshore regions
Data source: CEA 2011.

following 400 years until the M8.4 strong earthquake in 1498. Since this earthquake, five more great earthquakes of about M8.0 broke out (He, Zhou, and Ma 2011). The two most recent of these quakes occurred in 1944 and 1946 with a magnitude of M7.9 and M8.0 respectively. Coming so close together, these latest two strong quakes belong to the double earthquake type, and they can be treated as a single event in terms of energy release. Therefore, the average period of the 5 earthquakes since 1498 is 110 years (Figure 8). From 1946 onward, 65 years have passed. By counting simply using the 110-year average period, the next Tokai earthquake will occur in four to five decades. But this deduction lacks any theoretical basis (He, Zhou, and Ma 2011).

Theoretically, there are several periods in this seismic sequence, which is irregular in time, with a short period of around 110 years, a medium period of around 200 years, and a long period of around 400 years. These periods correspond with the slip of fault segments. But when checking the fault slip and rupture segments in each earthquake, close examination will reveal completely different periods. The latest study, for example, indicates that the 1854 Tokai earthquake most probably corresponds to the 1498 earthquake and the double earthquake in 1096 and 1099 in term of fault slip segment (He, Zhou, and Ma 2011). So the average recurrence period is about 400 years. The double earthquake in 1944 and 1946 corresponds to the earthquakes in 1707, 1361, and 887, with an average time interval of 350 years. Therefore, calculating from these two periods, a major M8.0 earthquake will strike the Tokai area 200 years from now.

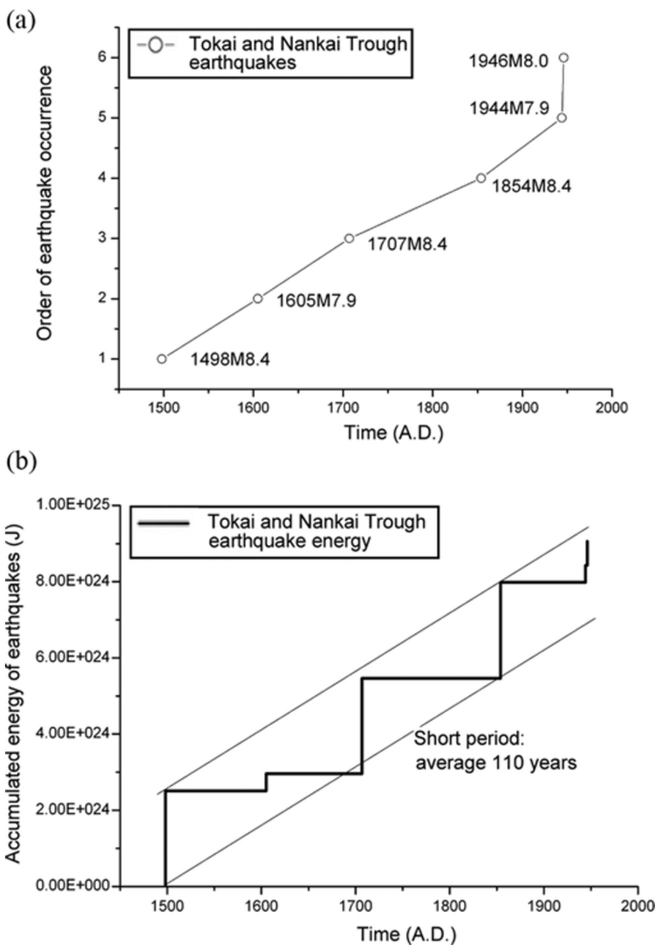

Figure 8. Historical earthquake time series of the Tokai and Nankai Trough areas
Data source: CEA 2011.

Therefore, predictions made according to the seismic quasi-period determined by earthquake time series may prove erroneous for medium- and long-term earthquakes. Only by studying the rupture segment clusters of seismic faults of similar earthquakes can we determine a relatively reliable earthquake period, thus acquiring valuable seismic activity prediction for improved disaster preparedness.

4 Discussions

This section discusses some of the limitations encountered in the prediction of major earthquakes by focusing on the following two aspects.

4.1 The Limitation of Predicting Major Earthquake from Foreshocks

Despite the M7.3 foreshock and a series of medium foreshocks that happened before the strong Mw9.0 earthquake in northeastern Japan, correct conclusions were not drawn about their significance due to the difficulty in recognizing those quakes as foreshocks rather than main shock and aftershocks at the time when they occurred. Whether there is a foreshock before a major earthquake depends on the degree of fault instability in the earthquake zone. Ma and Wang (2008) distinguished three types of earthquake instability: (1) a rupture earthquake induced by rock failure; (2) a stick-slip earthquake caused by the unstable sliding along a fault; and (3) a mixed earthquake that results from the combination of a stick-slip fault and rock failure. Experiments with rocks under high temperature and high pressure conditions show that the mechanisms of the three types of earthquakes are different, and thus the abnormal precursors such as foreshocks before strong earthquakes may also differ. In rupture type earthquakes, strain energy is usually consumed in rock rupture, so the magnitude of the resulting quake is not high despite a significant number of abnormal precursors that can be observed before its actual occurrence. The rupture quake can be described as "much cry, but little done," which tends to make people overestimate the earthquake's magnitude and results in a false forecast. The stick-slip earthquake is characterized by the strain energy focused on the unstable slip movement along the fault. In stick-slip quakes the magnitude of the event is often high. Although there are abnormal precursors, they are not very noticeable and often also appear shortly before the main quake occurs. Current technology is unable to measure the precursors, thus leads to a missed report. The mixed earthquake embraces rock rupture along the fault, and also involves unstable lateral slip along the fault. The magnitude of mixed earthquakes is high, there are precursor events such as foreshocks, and this type of earthquake offers significant predictive possibilities.

4.2 The Limitation of Predicting Strong Earthquake According to Historical Earthquakes

The earthquakes of northeastern Japan have a quasi-periodicity of both decadal and centennial scales. These earthquakes are not only regulated by seismic activity at plate boundaries, but also influenced by inner plate seismic dynamics. The difference in quasi-period is a consequence of fault segmental dislocation. Fault friction stick-slip experiments conducted under experimental conditions discovered that stick-slip events have multiplied periodicity (Ma and He 2001), which means that period doubling bifurcation of stress drop is one of the non-linear dynamic phenomena in the transition from stable sliding to stick-slip. Historical earthquakes in Xianshuihe-Anninghe-Zemuhe fault zone in southwestern China have occurred in prominent clusters in time and space, while the seismic rupture of historical earthquakes has clear segmentation. Medium to strong magnitude earthquakes cause segmental slip of the fault, forming seismic rupture. Strong earthquakes cause the overall slip of the entire fault (Wen et al. 2008). This kind of fault rupture segmentation is always controlled by plate or interaction along inner plate boundaries. For example, the north Bayan Har block and east boundary fault slip in western China have a prominent relation to great earthquake series (Wen et al. 2011).

5 Conclusion

Although there exist many limitations in earthquake prediction, we believe that with advances in research and experiments many earthquakes can be predicted. For rare great earthquakes, however, as the seismic period is long and records are few or even absent, it is difficult to make reliable prediction based solely on historical earthquakes. The work presented in this article aimed at establishing a new method for earthquake prediction. But future research is needed to provide a theoretical basis in support of this method.

Acknowledgments

This research was supported by the State Key Laboratory of Earth Surface Processes and Resource Ecology of Beijing Normal University, State Key Laboratory of Earthquake Dynamics (Grant No. LED2009A01), the Key Project of the National Natural Science Foundation of China (91024024), and the 12th Five-Year Science and Technology Support Program of the Ministry of Science and Technology, China (2012BAK10B03).

References

CEA (China Earthquake Administration). 2011. Earthquake Catalogues of China and Adjacent Areas (Internal Document) (in Chinese).

Chen, Y. T. 2009. Earthquake Prediction: Retrospect and Prospect. *Science of China* 39 (12): 1633–58 (in Chinese).

Geller, R. S., D. D. Jackson, Y. Y. Kagan, and F. Mulargia. 1997. Earthquakes Cannot Be Predicted. *Science* 275 (5306): 1616–17.

Helmholtz-Centre Potsdam - German Research Centre for Geosciences (GFZ). 2011. GFZ Seismological Data (Exchange Data).

He, C. R., Y. S. Zhou, and J. Ma. 2011. Tohoku Off-Pacific-Coast Megaquake: Another Lesson from Nature to Mankind. *Chinese Journal of Nature* 33 (2): 63–69 (in Chinese).

Imoto, M., S. Wiemer, and T. Matsuzawa. 2006. Asperity, Repeating Earthquakes and Probabilistic Prediction: New Aspects of Seismic Activity in Kanto Tokai, Japan. *Tectonophysics* 417 (1–2): 1–3.

Ma, S., and C. He. 2001. Period Doubling as a Result of Slip Complexities in Sliding Surfaces with Strength Heterogeneity. *Tectonophysics* 337 (1): 135–45.

Ma, J., and K. Y. Wang. 2008. *Earthquake Type and Earthquake Precursor*. http://www.hyey.com/Health/sxzt/dizhen/gydz/200805/129118.html (in Chinese).

Marzocchi, W., and J. D. Zechar. 2011. Earthquake Forecasting and Earthquake Prediction: Different Approaches for Obtaining the Best Model. *Seismological Research Letters* 82 (3): 442–48.

Okada, Y. 2011. *Preliminary Report of the 2011 off the Pacific Coast of Tohoku Earthquake*. http://www.bosai.go.jp/e/pdf/Preliminary_report110328.pdf.

Ozawa, S., T. Nishimura, H. Suito, T. Kobayashi, M. Tobita, and T. Imakiire. 2011. Coseismic and Postseismic Slip of the 2011 Magnitude-9 Tohoku-Oki Earthquake. *Nature* 475 (7356): 373–76.

Ran, Y. k., L. C. Chen, J. Chen, H. Wang, G. H. Chen, J. H. Yin, X. Shi, C. X. Li, and X. W. Xu. 2010. Paleoseismic Evidence and Repeat Time of Large Earthquakes at Three Sites along the Longmenshan Fault Zone. *Tectonophysics* 491 (1–4): 141–53.

Sykes, L. R., B. E. Shaw, and C. H. Scholz. 1999. Rethinking Earthquake Prediction. *Pure and Applied Geophysics* 155 (2): 207–32.

Wang, P. D. 2009. Discussion on the Policy for Improving Earthquake Forecast. *Recent Developments in World Seismology* 2: 1–8 (in Chinese).

Wen, X. Z., F. Du, P. Z. Zhang, and F. Long. 2011. Correlation of Major Earthquake Sequences on the Northern and Eastern Boundaries of the Bayan Har Block, and Its Relation to the 2008 Wenchuan Earthquake. *Chinese Journal of Geophysics* 54 (3): 706–16 (in Chinese).

Wen, X. Z., S. L. Ma, X. W. Xu, and Y. N. He. 2008. Historical Pattern and Behavior of Earthquake Ruptures Along the Eastern Boundary of the Sichuan-Yunnan Faulted-Block, Southwestern China. *Physics of the Earth and Planetary Interiors* 168 (1–2): 16–36.

Wen, X. Z., P. Z. Zhang, F. Du, and F. Long. 2009. The Background of Historical and Modern Seismic Activities of the Occurrence of the 2008 M8.0 Wenchuan, Sichuan, Earthquake. *Chinese Journal of Geophysics* 52 (2): 444–54 (in Chinese).

Xu, S. X., B. Q. Wang, L. M. Jones, X. F. Ma, and P. W. Shen. 1982. The Foreshock Sequence of Haicheng Earthquake and Earthquake Swarm—The Use of Foreshock Sequences in Earthquake Prediction. *Tectonophysics* 85 (1–2): 91–105.

Zhang, G. M., Z. X. Fu, and X. T. Gui. 2001. *Introduction to Earthquake Prediction*. Beijing: Science Press (in Chinese).

Zhang, P. Z., X. W. Xu, X. Z. Wen, and Y. K. Ran. 2008. Slip Rates and Recurrence Intervals of the Longmen Shan Active Fault Zone, and Tectonic Implications for the Mechanism of the May 12 Wenchuan Earthquake, 2008, Sichuan, China. *Chinese Journal of Geophysics* 51 (4): 1066–73 (in Chinese).