Spatio-temporal characteristics of aftershocks and seismogenic structure of the 2011 $M_W9.0$ Tohoku earthquake, Japan*

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Abstract The Tohoku megathrust earthquake, which occurred on March 11, 2011 and had an epicenter that was 70 km east of Tohoku, Japan, resulted in an estimated ten's of billions of dollars in damage and a death toll of more than 15 thousand lives, yet few studies have documented key spatio-temporal seismogenic characteristics. Specifically, the temporal decay of aftershock activity, the number of strong aftershocks (with magnitudes greater than or equal to 7.0), the magnitude of the greatest aftershock, and area of possible aftershocks. Forecasted results from this study are based on Gutenberg-Richter's relation, Bath's law, Omori's law, and Well's relation of rupture scale utilizing the magnitude and statistical parameters of earthquakes in USA and China (Landers, Northridge, Hector Mine, San Simeon and Wenchuan earthquakes). The number of strong aftershocks, the parameters of Gutenberg-Richter's relation, and the modified form of Omori's law are confirmed based on the aftershock sequence data from the $M_W9.0$ Tohoku earthquake. Moreover, for a large earthquake, the seismogenic structure could be a fault, a fault system, or an intersection of several faults. The seismogenic structure of the earthquake suggests that the event occurred on a thrust fault near the Japan trench within the overriding plate that subsequently triggered three or more active faults producing large aftershocks.

Key words: 2011 $M_W9.0$ Tohoku earthquake; aftershock; seismogenic structure

CLC number: P315.3 **Document code:** A

1 Introduction

On March 11th, 2011, an earthquake of magnitude $M_W9.0$ occurred at off the pacific coast of Tohoku, Honshu island, Japan, at 05:46:24.1 (UTC), which is located at 38.297°N, 142.373°E, and at a depth of 9 km. Approximately 30 000 people were killed or are missing as a result of the earthquake and consequent tsunami, and significantly more people were displaced by the subsequent nuclear power plant accident.

Of critical importance to the scientific community

and modern civilization is whether there is any difference between a typical strong earthquake and a very large event (with magnitudes greater than or equal to 8.0) like the $M_W9.0$ Tohoku earthquake? For strong earthquakes, in general, a series of aftershocks would be expected, and the spatio-temporal distribution of these aftershocks should meet certain statistical laws. However, for such an atypical large earthquake (with magnitudes of 8.0 or above), it is not known whether the aftershock pattern complies with these laws. Nor is known what might cause the main difference.

This paper focuses on spatio-temporal characteristics of aftershocks distribution of the $M_W9.0$ Tohoku earthquake, such as the temporal decay of aftershock activity, the number of strong aftershock (with magnitudes greater than or equal to 7.0), the magnitude of

* Received 18 February 2012; accepted in revised form 2 June 2012; published 10 June 2012.

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the greatest aftershock, and possible area of aftershock. Results are forecasted based on Gutenberg-Richter's relation (Gutenberg and Richter, 1954), Bath's law (Bath, 1965), Omori's law (Omori, 1894), the relation of rupture scale to magnitude (Donald and Kevin, 1994), and statistical parameters of earthquakes occurrence in California area (Landers, Northridge, Hector Mine, San Simeon) and Chengdu area (Wenchuan) (Robert et al., 2005; Kisslinger and Jones, 1991; Zhao, 2010). Based on the data of 3 659 aftershocks with magnitude greater than or equal 4.0 of the $M_W 9.0$ Tohoku earthquake (NE-IC), the number of strong aftershocks, the parameters of Gutenberg-Richter's relation, Bath's law, the modified form of Omori's law, and the relation of rupture scale to magnitude are confirmed. Comparisons of results of a-prior forecast and post statistics showed that there are differences in the first three relations, but the differences are negligible. Conversely, the differences with regards to the relation of rupture scale to magnitude are significant. For a very large earthquake (with magnitudes of 8.0 or above), in fact, the seismogenic structure suggests the event may have occurred on a fault system rather than a single fault similar to the Wenchuan earthquake, and may potentially have involved several intersecting faults as did the Hongdong earthquake. The seismogenic structure of the earthquake will be discussed followed by a discussion of aftershock locations.

This comprehensive study of the seismogenic structure of the earthquake indicates that the event occurred on a thrust fault near the Japan trench within the overriding plate, which subsequently triggered three or more active faults that were responsible for the large aftershocks.

2 A-prior forecast of the aftershock

Aftershocks meet four statistical relations. The first is Gutenberg-Richter frequency-magnitude scaling, which states that aftershocks satisfy Gutenberg-Richter (GR) frequency-magnitude scaling, which all earthquakes do. It is essential to note that the validity of the GR scaling is related to fractal scaling between the number of earthquakes and their rupture areas. Thus, aftershock distributions are scale invariant in terms of the frequency and rupture-area. The GR relation (Gutenberg and Richter, 1954)

$$\log_{10} N(\geq m) = a - bm, \quad (1)$$

where, $N(\geq m)$ is the cumulative number of earthquakes in a specified region and time window with magnitudes greater than m . The constant b varies from region to region, but is generally within the range of $0.8 < b < 1.2$. The constant is a measure of the regional level of seismicity and gives the logarithm of the number of earthquakes with magnitudes greater than zero.

Another important scaling law concerning aftershocks is Bath's law. This law states that it is a good approximation to assume that the difference in magnitude between the main shock and its largest aftershock is a constant independent of the magnitude of the main shock (Bath, 1965). That is

$$\Delta m = M_{ms} - M_{as}^{\max}, \quad (2)$$

where, M_{ms} is the magnitude of the main shock, $M_{as}^{\max}$ is the magnitude of the largest aftershock, and Δm is taken to approximately a constant, and typically be $\Delta m = 1.2$.

A third scaling relation, the modified form of Omori's law, describes the temporal decay of aftershock activity and is given in the form (Utsu et al., 1995; Shcherbakov et al., 2004)

$$f(t) = \frac{K}{(c+t)^p}, \quad (3)$$

where, $f(t)$ is the rate of occurrence of aftershocks with magnitudes greater than m , t is the time that has elapsed since the main shock and K , p , and c are parameters. This law is a manifestation of temporal correlations in aftershock sequences, which can be viewed as complex relaxation processes occurring after main shocks. In his original formulation, Omori (1894) introduced equation (3) with $p = 1$, usually quite a good approximation.

A fourth scaling relation, Well's relation of rupture scale with magnitude (Donald and Kevin, 1994), which describes positions where aftershocks will occur. Regressions of subsurface rupture length and down dip rupture width with moment magnitude (all type) are

$$\log_{10} l_r = -2.44 + 0.59M, \quad \sigma = 0.16, \quad (4)$$

$$\log_{10} w_r = -1.01 + 0.32M, \quad \sigma = 0.15. \quad (5)$$

Based on the four statistical relations, and the regression parameters on Landers, Northridge, Hector Mine and San Simeon earthquakes in California (Table 1) (Robert et al., 2005; Kisslinger and Jones, 1991), a-prior forecast of the aftershocks of the $M_W 9.0$ Tohoku earthquake list as follows.

Presumably aftershocks satisfy the GR scaling for the same reason that all typical earthquakes do. However, no generally accepted theory is available to explain the scale-invariant nature of this distribution. Regardless, aftershock activity is directly related to the generating fault, and assuming b for the Tohoku earthquake generating fault equals to the mean of the five aforementioned earthquakes ($b=0.94$, Table 1). Adopting $\Delta m = 1.2$ given by the empirical Bath's law, since the magnitude of the largest aftershock is $M_W 7.8$, we choose N ($M \geq 7.8$) = 1, and $a=7.332$ in formula (1) as well as $N(\geq 4)=3733$. Selecting $c = 0.55$ in the original formulation Omori introduced (3) with $p = 1$, $\int_0^T [K/(0.05 + t)]dt = 3733$, then $K = 419.64$, when $T = 365$ days. The forecast results are

$$\log_{10} N(\geq m) = 7.332 - 0.94m, \quad (6)$$

$$M_{ms} - M_{as}^{max} = 1.2, \quad (7)$$

$$f(t) = \frac{419.64}{0.05 + t}. \quad (8)$$

Table 1 Partial parameters of regression in California

Earthquake	M_{ms}	Δm	b
Landers	7.3	1.0	0.98
Northridge	6.7	0.8	0.91
Hector Mine	7.1	1.3	1.01
San Simeon	6.5	1.7	1.00
Wenchuan	8.0	1.7	0.798

Note: M_{ms} is the magnitude of main shock, Δm is the difference in magnitude between the main shock and its largest aftershock, b is the Gradient of frequency-magnitude statistics of earthquakes.

Using the results of structure of Japan trench by Suyehiro and Nishizawa (1994) and Miura et al. (2005), we adopt that dip angle of the earthquake fault which assumes responsibility for the $M_W 9.0$ main shock is 20° , then the most of aftershocks will be located at an area of length of ~ 750 km, width of ~ 70 km. Figure 1 illustrates the result of a-prior forecast of the aftershock ($M \geq 4.0$), and the main points are

- 1) Magnitude of the largest aftershock is $M_W 7.8$, it occurs one time only;
- 2) Aftershocks with magnitudes greater than or equal to 7.0 may occur 5–6 times;
- 3) The frequency of aftershocks is high; it may occur 1937 times with magnitudes greater than or equal 4.0 within five days following the main shock;
- 4) Aftershocks will occur in a narrow zone with length and width of ~ 750 km and 70 km, respectively.

3 Post statistics of aftershocks

Figure 2 shows the location distribution of 3 659 aftershocks with magnitudes greater than or equal to 4.0 that occurred by January 28, 2012, following the $M_W 9.0$ Tohoku earthquake (NEIC, <http://earthquake.usgs.gov/regional/neic>).

Figure 1 A-prior forecast of the aftershock. (a) GR relation; (b) Omori law.

For the sake of convenience, a local Cartesian coordinate system (x - y - z) is defined in Figures 2 and 6, and local time initial point ($T=0$) is set as 05:46:24.1 (UTC), March 11, 2011. For Figures 3e and 3f the units are days.

A least-squares fit of (1) to the $M \geq 4.0$ aftershocks data gives the GR relation on the fault

$$\log_{10} N(\geq m) = 7.573 - 0.957m, \quad \sigma = 0.135. \quad (9)$$

By January 28, 2012, the number of aftershock with magnitude greater than or equal 7.0 was 4 (Table 2). This was less than the result of a-prior forecast of the aftershock, and less than the result of formula (9), from Figure 4.

The largest aftershock magnitude was 7.9. The difference in magnitude between the main shock and its largest aftershock is $\Delta m=1.1$, a little less than 1.2 given by Bath's law.

For global optimization method fit of formula (3) the data from 1 to 323 days following the main shock (the record of 0–1 day seems incomplete), the modified Omori's law is

$$f(t) = \frac{625}{(0.001 + t)^{1.095}}, \quad \sigma = 4.389. \quad (10)$$

As seen from the data shown in Figure 5, the number of aftershocks by a-prior forecasting is getting larger than that of actually with increaing time, and the trend of two diagrams is the same. However, the actual

situation is different, with the frequency of aftershocks between 90–120 days increases abruptly (Figures 3f and 5). This is likely related to seismogeologic condition (barriers), stress state and dislocation distribution.

Figure 2 Aftershock distribution with respect to the location of the main shock. x - y is a local Cartesian coordinate system, and z direction is shown in Figure 6.

Table 2 Catalogue of the $M \geq 7.0$ aftershocks of the Tohoku earthquake

No.	Origin time (BT)		t/d	Lat./°N	Long./°E	Depth/km	M
	Date	Time					
	a-mo-d	h:min:s					
1	2011-03-11	06:15:40.9	0.020	36.271	141.107	48	7.9
2	2011-03-11	06:25:50.3	0.027	38.058	144.590	19	7.7
3	2011-04-07	14:32:43.2	27.365	38.275	141.573	42	7.1
4	2011-07-10	00:57:10.8	120.799	38.034	143.264	23	7.0

In general, parameter changes of the Gutenberg-Richter’s relation, Bath’s law, the modified form of Omori’s law in a-prior forecast, and post statistics are not significant. Although, from Figure 2, it can be seen that aftershocks occurred in a relative narrow area, with a length of 650 km, shorter than the result of a-prior forecast, and a width of 300 km, which is much greater than 75 km. Therefore, a change of the spatial distribution of aftershocks or the mainshock rupture scale in a-prior forecast and post statistics is significant, which

likely results from the seismogenic structure of the larger earthquake.

For a large earthquake, where the seismogenic structure is complex and is not localized on a single fault such as the Wenchuan earthquake (Xu, 2009), or occurs on several intersecting faults such as the Hongdong earthquake (Jiang, 2004), seismogenic structure of the earthquake will be discussed by feature of its aftershocks.

4 Seismogenic structure

The Japan trench is interpreted to be a single fault zone, which separates the overriding plate from the subducting Pacific plate. Near the trench, the zone

dips at 7° and steepens to 25° beneath the east coast of Tohoku (Suyehiro and Nishizawa, 1994; Miura et al., 2005). Takashi (2012) detected active faults around the Japan trench using 3D images viewed through red cyan glasses, and found that the active faults in this area are

Figure 3 Spatio-temporal distribution of aftershocks of the $M_w9.0$ Tohoku earthquake. Note that the time initial point ($t=0$) is set as 05:46:24.1 (UTC). (a) Magnitude distribution across the generating fault. (b) Aftershock number for per unit x length along the generating fault. (c) Magnitude distribution along the generating fault. (d) Aftershock number for per unit y length along the generating fault. (e) Magnitude versus through time. (f) Variation of logarithmic aftershock number with time.

grouped into the following three fault zones. From west to east, they include (1) lineaments on the shelf slope, (2) extensive thrust faults on the trench slope, and (3) normal faults on outer rise (Figure 7).

The most extensive thrust fault on the trench slope extends from Sanriku-Oki to Ibaraki-Oki for about 400 km, which is associated with fault scarps of approximately 1 500 m in height and tectonic bulges to the west

in regions to the north and south. At Sanriku-Oki, close to the trench axis, a 200 km-long active thrust fault is identified by a steep straight escarpment extending from north to south between the extensive fault mentioned above and the Japan trench. On the eastern part of the shelf slope to the west of the extensive thrust fault, several elongated bulges are fringed along their eastern margins by flexure scarps. They are presumably formed by subsurface reverse faulting on west-dipping fault planes.

N-S trending lineaments are densely distributed in

Figure 4 Comparison diagrams of GR relation.

Centroid moment tensor analysis indicates that the main shock occurred on a gently-dipping reverse fault with a WNW-ESE compressional axis and occurred on the plate boundary between the continental plate and the Pacific plate (Hirose et al., 2011). Youichi (2011) suggests that the aftershocks exhibited a variety of focal mechanisms. Aftershocks with thrust focal mechanisms in the overriding plate could no longer occur in coseismic slip area due to the large amount of stress release during the main shock rupture, whereas the aftershocks in surrounding regions were caused by a stress concentration in these regions due to large slip associated with the main shock. Normal-fault-type aftershocks were widely distributed in the overriding plate and the outer rise of the Pacific plate. These aftershocks may have been due to a tensional stress change caused by the coseismic slip. Thrust-fault-type aftershocks in the subducting Pacific plate were also interpreted as being due to compressional stress change as a result of the coseismic slip.

As previously mentioned, aftershocks cover an area

the eastern part of the shelf slope. They mainly concentrate on tectonic bulges, especially on their flexure scarps, where the seafloor has been extended due to hanging wall folding above thrust faults.

Normal faults on the outer rise strike in N-S direction. Faults are sinuous, sub-parallel and evenly spaced, being separated by approximately 5 km, and form a basin and range type horst and graben topography. These fault scarps have a down-to-the-east sense of displacement with relief over 300 m high near the trench axis.

Figure 5 Comparison diagrams of Omori law.

of 650 km×300 km (Figures 2 and Figures 3), with most of them occurred on the contact zone around the main shock and some occurred seaward the Japan trench within the Pacific plate.

Here we discuss the seismogenic structure or generating faults of the $M_W 9.0$ earthquake by utilizing the aftershock distribution on active faults around the Japan trench (Takashi et al., 2012) and focal mechanisms of the main shock and some aftershocks (Youichi et al., 2011). The aftershock area was divided into 12 small strips (Figure 2, A-L) the aftershock location in each small strip on ($x-z$) section was statistically analyzed. Potential generating faults were then plotted and shown on Figure 6 based on combined result of geological structure, focal mechanism, area of stress release during the main shock rupture and area of intensive small aftershocks. Possible generating fault lines and crushed zones were drawn (Figure 7).

In combination with the Japan trench structure (Ludwig, 1966; Takashi et al., 2012); and some aftershock focal mechanism (Hirose et al., 2011; Youichi,

2011), application of these potential generating fault lines indicate that the generating fault of the earthquake is a thrust fault near the Japan trench in overrid-

ing plate, which consequently triggered three or more active faults producing large aftershocks (Figure 7).

Figure 6 Inferred seismogenic structure of main shock based on the distribution of aftershocks along the direction of x and z .

5 Discussion and conclusions

One year following such a devastating earthquake, we analyzed spatio-temporal characteristics of after-

shocks the $M_W 9.0$ Tohoku earthquake in a-prior forecast and post statistics. In general, the GR relation, Bath's law, and Omori's law are well applicable, how-

ever, Well's relation of rupture scale with the magnitude is not consistent with that at $M_W 9.0$, suggesting that the seismogenic structure may not be characterized by

a single fault plane, but rather several faults formed within a fault zone.

Figure 7 Seismogenic structure map of the 2011 $M_W 9.0$ Tohoku earthquake.

1) The result of a-prior forecast of the aftershock is reasonable based on finite parameters of Gutenberg-Richter's relation, Bath's law, Omori's law, Well's relation of rupture scale with the magnitude and assumptions b and Δm .

2) The number of strong aftershocks, the parameters of Gutenberg-Richter's relation and the modified form of Omori's law are confirmed based on the data of aftershock sequence of the $M_W 9.0$ Tohoku earthquake.

There exist some differences on the results of a-prior forecast and post statistics, especially in the width of source rupture and the largest magnitude of aftershock, but the tendencies are the same.

3) The aftershock area is divided into 12 small strips, location distribution ($x-z$) of the aftershocks in each small strip were statistical analyzed, and the possible generating fault lines and crushed zone were drawn, and combined with the geological structure around Japan trench and some aftershock focal mechanisms. This research indicates that the generating fault

of the earthquake is a thrust fault near the Japan Trench in overriding plate, and subsequently triggered three or more active faults producing large aftershocks.

Acknowledgements This work was financially supported by the National Natural Science Foundation of China (No. 51278474), Special Research Project of Earthquake Engineering (No. 201108003) and International Science and Technology Cooperation Program of China (No. 2011DFA21460).

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