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Aftershock Statistics of the 1999 Chi–Chi, Taiwan Earthquake and the Concept of Omori Times

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Abstract—In this paper we consider the statistics of the aftershock sequence of the $m = 7.65$ 20 September 1999 Chi–Chi, Taiwan earthquake. We first consider the frequency-magnitude statistics. We find good agreement with Gutenberg–Richter scaling but find that the aftershock level is anomalously high. This level is quantified using the difference in magnitude between the main shock and the largest inferred aftershock Δm^*. Typically, Δm^* is in the range 0.8–1.5, but for the Chi–Chi earthquake the value is $\Delta m^* = 0.03$. We suggest that this may be due to an aseismic slow-earthquake component of rupture. We next consider the decay rate of aftershock activity following the earthquake. The rates are well approximated by the modified Omori's law. We show that the distribution of interoccurrence times between aftershocks follow a nonhomogeneous Poisson process. We introduce the concept of Omori times to study the merging of the aftershock activity with the background seismicity. The Omori time is defined to be the mean interoccurrence time over a fixed number of aftershocks.

Key words: Earthquakes, aftershocks, Omori times, interoccurrence times.

1. Introduction

The behavior of aftershock sequences has been discussed widely (i.e. Kisslinger 1996). There are three applicable scaling laws: (1) The Gutenberg–Richter (GR) law for frequency-magnitude scaling of aftershocks (Gutenberg and Richter 1954). The number N of earthquakes with magnitudes greater than or equal to m is well approximated by the relation:

$$\log_{10} N(\geq m) = a - b(m). \tag{1}$$

where b is the b-value and a is a measure of seismic intensity. (2) Båth's law for the difference between the magnitude of the main shock and the largest aftershock. This law states that the difference in magnitude, Δm, between the main shock and its largest aftershock is approximately constant independent of the magnitude of the main shock

$$\Delta m = m_{\mathrm{ms}} - m_{\mathrm{max\,as}} \tag{2}$$

where m_{ms} is the magnitude of the main shock and $m_{\mathrm{max\ as}}$ is the magnitude of the largest aftershock, typically $\Delta m \approx 1.2$ (Båth 1965). Many studies have been carried out regarding the statistical variability of Δm (Vere-Jones 1969; Kisslinger and Jones 1991; Tsapanos 1990; Felzer *et al.* 2002, 2003; Console *et al.* 2003; Helmstetter and Sornette 2003; Shcherbakov and Turcotte 2004). Perhaps Console *et al.* (2003) developed a mathematical model showing a substantial dependence of Δm on the magnitude thresholds chosen for the main shocks and the aftershocks. This partly explains the large Δm values reported in the past. (3) Omori's law for the temporal decay of aftershocks (Omori 1894), and the modified Omori's law (the Omori–Utsu law) which was proposed by Utsu (1961). We will utilize the modified Omori's law in the form proposed by Shcherbakov *et al.* (2004)

$$r_{\mathrm{a}}(t, m_{\mathrm{c}}) = \frac{1}{\tau_{\mathrm{a}}(m_{\mathrm{c}})} \frac{1}{[1 + t/c(\mathrm{m_c})]^p} \tag{3}$$

where $r_{\mathrm{a}}(t,m_{\mathrm{c}}) \equiv \mathrm{d}N/\mathrm{d}t$ is the rate of occurrence of aftershocks with magnitudes greater than or equal to a lower cutoff m_{c}, t is the time elapsed since the time of the main shock. In the limit $t \to 0$ we have $r_{\mathrm{a}} = \tau_{\mathrm{a}}^{-1}$, the characteristic time $\tau_{\mathrm{a}}(m_{\mathrm{c}})$ is the reciprocal of the initial (constant) rate of aftershock activity at early times. The characteristic time $c(m_{\mathrm{c}})$ is the time of transition from their rate to the power-law decay of aftershock activity.

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There are two limiting cases for the behavior of Omori's law. In the first it is assumed that c_0 is a constant and that $\tau_a(m_c)$ depends on the cutoff magnitude m_c. In the second it is assumed that τ_0 is a constant and that $c(m_c)$ depends on the cutoff magnitude m_c. Nanjo *et al.* (2007) has discussed these limits in some detail with applications to four Japanese earthquakes. In this paper we will assume c_0 to be constant and $\tau_a(m_c)$ is determined from the data. In this limit the modified form of Omori's law given in Eq. (3) becomes

$$r_a(t, m_c) = \frac{1}{\tau_a(m_c)} \frac{1}{[1 + t/c_0]^p} \quad (4)$$

For all values of time t the values of the aftershock rate $r_a(t, m_c)$ for different m_c are related by

$$\frac{r_a(t, m_{c1})}{r_a(t, m_{c2})} = \frac{\tau_a(m_{c2})}{\tau_a(m_{c1})} \quad (5)$$

However, the rates of aftershock occurrence for different values of m_c satisfy the GR law. From Eq. (1) we obtain

$$\frac{r_a(t, m_{c1})}{r_a(t, m_{c2})} = 10^{-b(m_{c1} - m_{c2})} \quad (6)$$

Combining Eqs. (5) and (6) we find

$$\frac{\tau_a(m_{c2})}{\tau_a(m_{c1})} = 10^{-b(m_{c1} - m_{c2})} \quad (7)$$

We will obtain a b-value from GR scaling and will then fit aftershock statistics for several values of m_c to obtain preferred values of c_0, p, and the $\tau_a(m_c)$. We illustrate it in the Sect. 2.

In this study, we analyze the scaling laws for the aftershock sequence from the $m = 7.65$ 20 September 1999 Chi–Chi, Taiwan earthquake. The aftershocks are in good agreement with the Gutenberg–Richter law for frequency–magnitude scaling and the aftershock decay rates satisfy the modified Omori's law. An interesting result in this paper is that we find that the Chi–Chi earthquake triggered an anomalously large number of aftershocks. We also consider the statistics of interoccurrence times for Chi–Chi aftershocks. The observed statistics of interoccurrence times for the Chi–Chi earthquake sequence has a power-law dependence on the times between successive aftershocks over several orders of magnitude. The distribution of interoccurrence time is well approximated by a nonhomogeneous Poisson (NHP) process driven by the modified Omori's law over a finite time interval T (Shcherbakov *et al.* 2005, 2006). At the end of this paper, we introduce the concept of Omori times to analyze the interoccurrence times for the Chi–Chi aftershock sequence. We calculate the mean interoccurrence interval over a fixed number of aftershocks $N = 25$, 50, 100, 200, and compare the Chi–Chi aftershocks with a combination of Omori decay and a steady-state background.

2. *Scaling of Chi–Chi Aftershock Sequences*

The Chi–Chi earthquake struck central Taiwan on 20 September 1999 at 17:47UTC. It ruptured along the Chelungpu fault, and the moment magnitude, m_w, was 7.65. The hypocenter of the Chi–Chi earthquake was located at 23.853°N, 120.816°E, at a depth of 8 km. In this paper we study the aftershock sequence of this earthquake. We combine three catalogs from 1994 to 2008 for our analyses. These three catalogs include: (1) the Central Weather Bureau seismic network (CWBSN) catalog from the Central Weather Bureau (CWB) of Taiwan, (2) the Taiwan Strong Motion Instrumentation Program (TSMIP) (Chang *et al.* 2007) which provides good coverage for early aftershocks, and (3) the Centroid-Moment-Tensor (CMT) catalog for large aftershocks. We use the TSMIP catalog for the first hour of Chi–Chi aftershocks and the CMT catalog for aftershocks $m > 5$. The completeness magnitude for the area analyzed is $m \geq 2.0$. We combine these catalogs and then define the Chi–Chi aftershock region.

In Fig. 1 we define the spatial window for the Chi–Chi aftershocks. We compare the spatial distribution of seismic activity in Taiwan for 1,000 days after the Chi–Chi earthquake with the activity for 1,000 days before the Chi–Chi earthquake. We choose the area with the largest change in seismic activity as the Chi–Chi aftershock region. Our purpose is to exclude the region of high seismicity to the east. The epicenter of the mainshock is shown as a black star. The dashed lines show the region of seismic activity we associate with the Chi–Chi aftershocks. During the 1,000 day time interval after

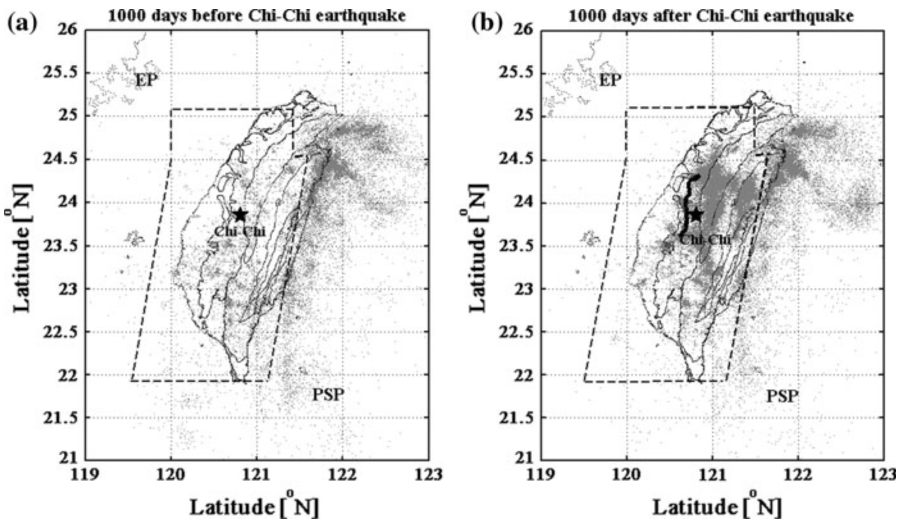

Figure 1
The spatial distribution of seismicity activity for 1,000 days before the 20 September 1999 Chi–Chi earthquake in (**a**), and 1,000 days after the Chi–Chi earthquake in (**b**). The magnitude of these earthquakes are great than 2.0. The epicenter of the Chi–Chi earthquake is shown as a *black star*. The *black line* shows the surface rupture of the Chi–Chi earthquake. The *dash line* shows the region of the aftershocks for the statistic of Chi–Chi aftershocks. *EP* Eurasian Plate, and *PSP* Philippine Sea Plate

the Chi–Chi earthquake, 42,952 aftershocks were recorded with magnitudes $m \geq 2.0$, and nine of the aftershocks had magnitudes $m \geq 6.0$. A comparison of Fig. 1a with b indicates that less than 5% of the earthquakes in our region were not aftershocks and less than 5% of the aftershocks occurred outside the chosen region. Since the majority of aftershocks have been included we therefore expect the minor difference in the spatial extent does not affect the following analysis.

First, we consider the frequency–magnitude scaling for the Chi–Chi aftershock sequence. The frequency–magnitude distribution of the seismicity in the Chi–Chi aftershock area (Fig. 1b) for 1,000 days after the earthquake is given as a function of m in Fig. 2. The role over for small amplitudes $m < 2$ is attributed to lack of sensitivity of the networks for small aftershocks. The behavior for large amplitudes $m > 5$ is attributed to relatively few aftershocks. We obtain the least square fit of the GR scaling relation Eq. (1) in the magnitude range $2 < m < 5$ and find that $b = 0.84$, and $a = 6.4$ (the straight dashed line in Fig. 2).

We next consider the application of Båth's law, Eq. (2), to the Chi–Chi earthquake. The magnitude of the mainshock was $m_w = 7.65$ and the magnitude of the largest aftershock was $m_w = 6.70$ so that $\Delta m = 0.95$. Shcherbakov and Turcotte (2004) proposed a modified version of Båth's law which is based on an extrapolation of Gutenberg–Richter statistics for aftershocks. The inferred magnitude of the largest aftershock m^* is

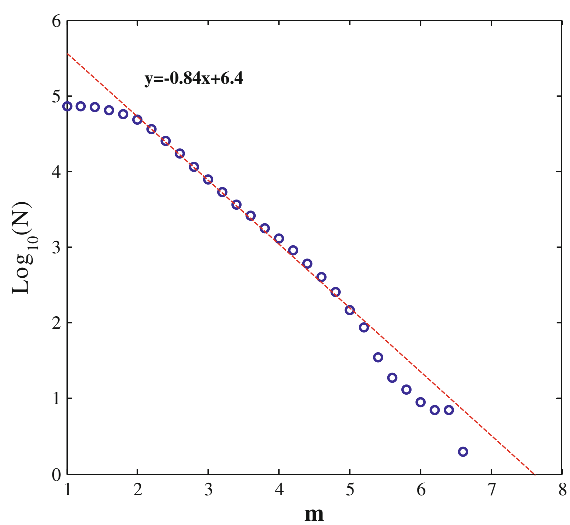

Figure 2
The cumulative frequency–magnitude distribution of Chi–Chi aftershocks for 1,000 days after the main shock. The *dash line* is the best fitting for data with the $b = 0.84$ by Gutenberg-Richter relation

deduced by taking $\mathrm{Log}_{10}N(\geq m^*) = 1$ for a given aftershock sequence. From Eq. (1) we find

$$a = bm^* \tag{8}$$

The difference in magnitude between the mainshock and inferred largest aftershock $\Delta m^*$is given by

$$\Delta m^* = m_{\mathrm{ms}} - m^* \tag{9}$$

Substitution of Eqs. (8) and (9) into Eq. (1) gives

$$\mathrm{Log}_{10}N(\geq m) = b(m^* - m) = b(m_{\mathrm{ms}} - \Delta m^* - m) \tag{10}$$

In Fig. 2, from the fit of the Gutenberg–Richter relation Eq. (1), we find from Eq. (8) that $m^* = a/b = 7.62$ and $\Delta m^* = 0.03$. For the Chi–Chi earthquake the magnitude of the largest actual aftershock, $m_{\mathrm{w}} = 6.70$, is much smaller than the largest inferred aftershock, $m^* = 7.62$. For ten large earthquakes in California, SHCHERBAKOV and TURCOTTE (2004) found on average $\Delta m^* = 1.11$. If this value had been valid for the Chi–Chi earthquake, the main shock magnitude would have been $m_{\mathrm{ms}} = 8.73$. Clearly, the Chi–Chi earthquake had a large number of small aftershocks.

NANJO *et al*. (2007) carried out a detailed study of aftershock statistics for four moderate sized Japanese earthquakes. The relevant data were obtained from the seismic catalog maintained by the Japan Meteorological Agency. For the $m = 7.3$ 1995 Kobe earthquake $m^* = 6.27$ and $\Delta m^* = 1.03$, for the $m = 7.3$ 2000 Tottori earthquake $m^* = 6.14$ and $\Delta m^* = 1.16$, for the $m = 6.8$ 2004 Niigato earthquake $m^* = 7.15$ and $\Delta m^* = -0.35$, and for the $m = 7.0$ 2005 Fukuoka earthquake $m^* = 6.27$ and $\Delta m^* = 0.73$. Thus, the Niigato earthquake had a large excess of aftershocks similar to the Chi–Chi earthquake.

We next consider the decay rate of aftershock activity following the Chi–Chi earthquake. Figure 3 shows the rates of occurrence of aftershocks with magnitudes greater than m_{c} in numbers per day for a time period of 1,000 days after the Chi–Chi earthquake. Different symbols corresponds to different lower magnitude cutoffs, m_{c}, which are taken to be $m_{\mathrm{c}} = 2.0$, 3.0, and 4.0. To quantify the observed aftershock occurrence scaling, we use the generalized Omori's law given in Eq. (3). As previously discussed we will assume that c_0 is constant and $\tau_{\mathrm{a}}(m_{\mathrm{c}})$ is a function of m_{c} so that we will use the form of Omori's law given in Eq. (4) to fit the data in Fig. 3. Taking $b = 0.84$ from Fig. 2, we find from Eq. (7) that

$$\frac{\tau_{\mathrm{a}}(m_{\mathrm{c}} = 4)}{\tau_{\mathrm{a}}(m_{\mathrm{c}} = 3)} = \frac{\tau_{\mathrm{a}}(m_{\mathrm{c}} = 3)}{\tau_{\mathrm{a}}(m_{\mathrm{c}} = 2)} = 10^b = 6.92 \tag{11}$$

The dashed lines in Fig. 3 have been obtained from the least square best fit of Eq. (4) with conditions given by Eq. (11). We find that $p = 1.05$ and $c_0 = 6\times10^{-3}$ days. $\tau_{\mathrm{a}}(m_{\mathrm{c}} = 2) = 6.71 \times 10^{-7}$ days, $\tau_{\mathrm{a}}(m_{\mathrm{c}} = 3) = 4.70 \times 10^{-6}$ days, and $\tau_{\mathrm{a}}(m_{\mathrm{c}} = 4) = 3.30 \times 10^{-5}$ days. For large times there is generally good agreement. The deviations at small times for the $m_{\mathrm{c}} = 2$ and $m_{\mathrm{c}} = 3$ data are can be attributed to a failure to record early weak aftershocks.

SHCHERBAKOV *et al*. (2006) studied the interoccurrence time statistics for Parkfield aftershock sequences. The distribution of interoccurrence times is well approximated by a nonhomogeneous Poisson (NHP) process driven by the modified Omori's law over a finite time interval T (SHCHERBAKOV *et al*. 2005). In this study we also analyze the temporal

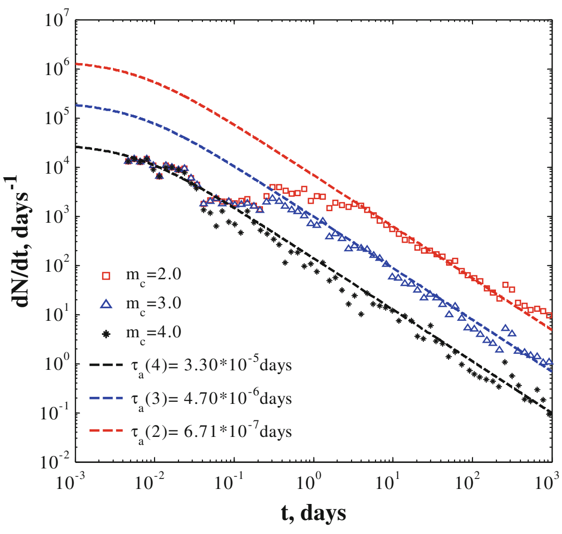

Figure 3
The rates of occurrence aftershock with magnitude grater than m_{c} in number per day for a time period of 1,000 days after Chi–Chi earthquake. Difference *symbol* corresponds to a different lower magnitude cutoffs m_{c}, which were taken to be $m_{\mathrm{c}} = 2.0$, 3.0, and 4.0. The *dash line* is the best fitting of the generalized Omori's law with $p = 1.05$ and $c_0 = 6 \times 10^{-3}$. The value of characteristic times $\tau_{\mathrm{a}}(\mathrm{m_c})$ for $m_{\mathrm{c}} = 2.0$, $m_{\mathrm{c}} = 3.0$, and $m_{\mathrm{c}} = 4.0$ are $\tau_{\mathrm{a}} = 6.71 \times 10^{-7}$ days, 4.70×10^{-6} days, and 3.30×10^{-5} days

correlation properties of the Chi–Chi aftershock sequence. We treat all aftershocks with magnitudes equal to or greater than m_c as a point process (SHCHERBAKOV *et al.* 2006). The interoccurrence times between successive aftershocks are defined as $\Delta t_i = t_i - t_{i-1},\ i = 1,\ 2\ldots$. In Fig. 4 we give the probability distribution function of the interoccurrence times between aftershocks, $P(\Delta t,\ m_c)$, each symbol corresponds to a different magnitude cutoff, $m_c = 2.0$, 3.0 and 4.0. We consider the time interval following the main shock of $T = 1{,}000$ days. We apply the data binning technique proposed by CHRISTENSEN and MOLONEY (2005) which is using the log span for the $P(\Delta t, m_c)$ to reduce the noise effect of long interoccurrence times. The observed statistics of interoccurrence times for the Chi–Chi aftershock sequence has a power-law dependence on the times between successive aftershocks for different magnitude cutoffs.

The distribution of interoccurrence times can be approximated by a distribution derived from the assumption that aftershocks follow the NHP process (SHCHERBAKOV *et al.* 2005). The probability distribution function of interoccurrence times at time t, until the next event in accordance with the NHP hypothesis has the following form:

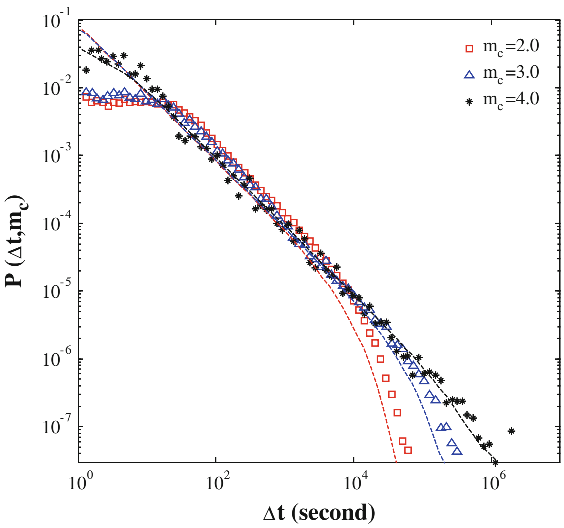

Figure 4
The probability distribution function of the interoccurrence times between aftershocks, $P(\Delta t,\ m_c)$. Each *symbol* corresponds to a different magnitude cutoff m_c, $m_c = 2.0$, 3.0 and 4.0. A time interval following the mainshock $T = 1{,}000$ days in considered. The resulting theoretical distribution from the nonhomogeneous Poisson (NHP) process is shown by *dashed curves*

$$F(t, \Delta t) = 1 - e^{-\int_t^{t+\Delta t} r(u)\mathrm{d}u} \quad (12)$$

where $r(u)$ is the rate of occurrence of aftershocks at time t. The probability density function of interoccurrence times over a finite time interval T is given by

$$P_T(\Delta t) = \frac{1}{N}\left[\int_0^{T-\Delta t} r(s)r(s+\Delta t)e^{-\int_0^{s+\Delta t} r(u)\mathrm{d}u}\mathrm{d}s + r(\Delta t)e^{-\int_0^{\Delta t} r(u)\mathrm{d}u}\right] \quad (13)$$

where N is the total number of events during a time period T. In order to evaluate the rate $r(t)$ we take the values from Eq. (4) that have been given as the dashed lines in Fig. 3. Substituting the values for $m_c = 2, 3$, and 4 in Eq. (13) and integrating gives the dashed lines plotted in Fig. 4. In Figs. 3 and 4 we compare our theoretical derivations of aftershock rates and distributions of interoccurrence times from Chi–Chi aftershocks, we see excellent agreement with $m_c = 4.0$. This is evidence that the catalogue is nearly complete for $m \geq 4.0$ with few missing early aftershocks. But for the smaller aftershocks with $m < 4.0$, it is clear that significant numbers early in the aftershock sequence are lost.

We next introduce the concept of Omori times for the Chi–Chi region (Fig. 1) from 1994 to 2008. The Omori time τ_N is defined as the mean interoccurrence interval over a fixed number N of earthquakes

$$\tau_N(t_n) = \frac{1}{N}\sum_{m=n-N}^{n-1}(t_{m+1} - t_m) \quad (14)$$

We assign the values of τ to the end t_n of the subsequence of N events. The Omori time is the reciprocal of the average of the rate of aftershock activity r for N aftershocks. In Fig. 5 we give the Omori times for the 1999 Chi–Chi Taiwan earthquake considered above. The earthquake magnitudes are greater than $m_c = 2.0$. The Omori times τ_N are given for $N = 25$, 50, 100, and 200. For the 6 years before the Chi–Chi earthquake, the data are reasonable well represented by the mean Omori time $\tau_b = 0.1753$ days (the grey dashed lines in Fig. 5), corresponding to a background rate $r_b = 5.7045$ day^{-1}. During the aftershock sequence, the modified form of Omori's law is given by Eq. (4). We consider the

Omori time behavior during the 9 years after the Chi–Chi earthquake, and assume that the rate of occurrence r is the sum of the rate of background seismicity, r_b, and the rate of aftershock seismicity r_a (Kisslinger 1996). With r_a given by Eq. (4) we obtain

$$r = r_b + r_a = r_b + \frac{1}{\tau_a(1 + t/c_0)^p} \qquad (15)$$

The Omori times are given by

$$\tau = \frac{1}{r} = \left[\frac{\tau_b + \tau_a(1 + t/c_0)^p}{\tau_b \tau_a(1 + t/c_0)^p}\right]^{-1} \qquad (16)$$

The Omori times for the Chi–Chi region (Fig. 5) are in good agreement with Eq. (16) taking $\tau_b = 0.1753$ days, $p = 1.05$, $c_0 = 6 \times 10^{-3}$ days, and $\tau_a(m_c = 2.0) = 6.71 \times 10^{-7}$ days (τ is the red dashed lines in Fig. 5). These parameters are from the Omori's law correlation given in Fig. 3.

3. Discussion and Conclusions

Seismicity is a complex system, and within this complexity there are several scaling laws. The GR scaling is equivalent to fractal scaling between the number of earthquakes and their rupture area, and this scaling may be the consequence of a fractal distribution of fault sizes. Presumably aftershocks satisfy

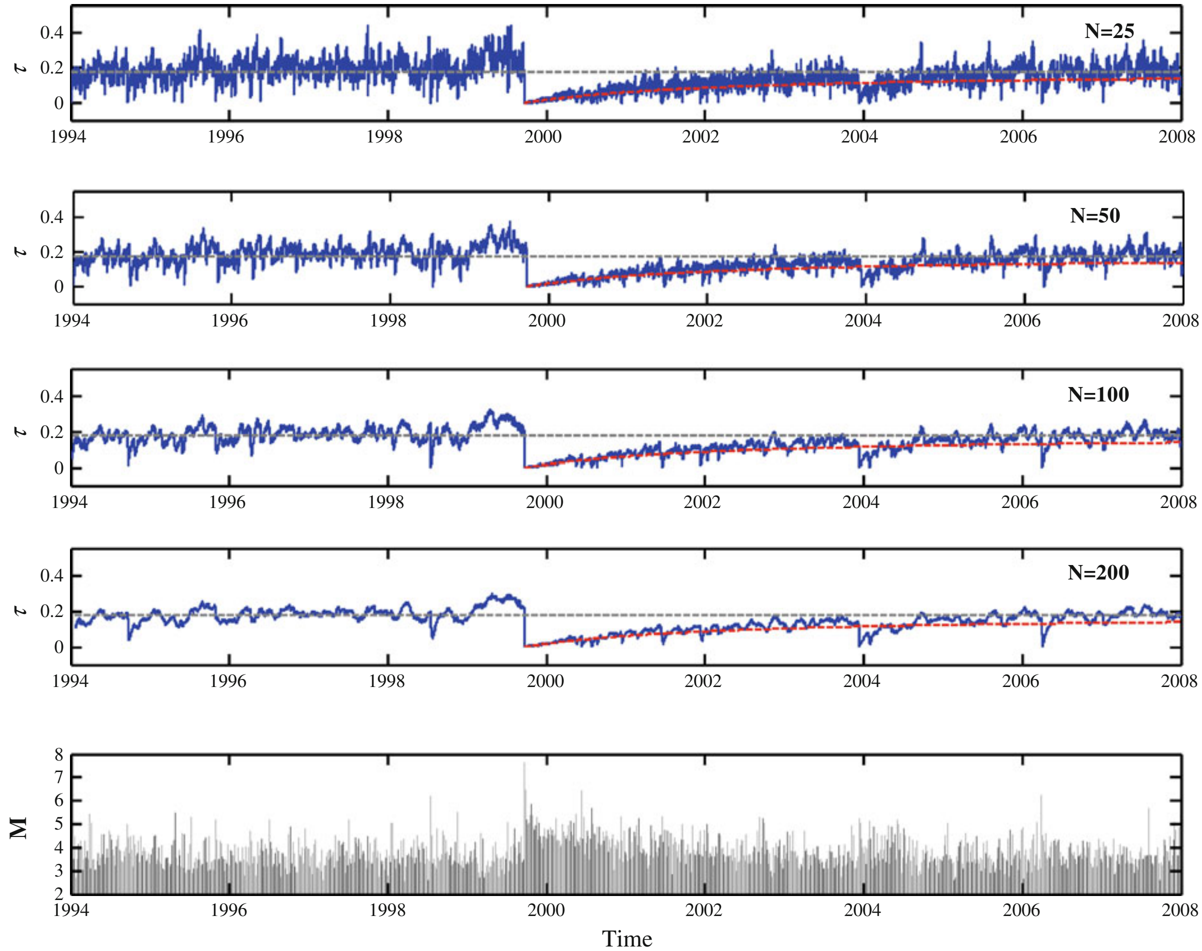

Figure 5
The Omori times for the Chi–Chi region (Fig. 1) from 1994 to 2008. The earthquake magnitudes are greater than 2.0. The Omori times τ_N are given for $N = 25$, 50, 100, and 200. The *gray dashed lines* are the mean Omori times before the Chi–Chi earthquake. The *red dashed lines* are the theoretical Omori times for Chi–Chi aftershocks from Eq. (12) with $\tau_0 = 0.1753$ days, $p = 1.05$, $c = 6 \times 10^{-3}$ days, and $\tau(m_c = 2.0) = 6.71 \times 10^{-7}$ days. The magnitude of these earthquakes are also given

GR scaling for the same reason that all earthquake do. However, there is no accepted theory for the explanation of the scale-invariant nature of this distribution. Generally, two models have been proposed: (1) each fault has a GR distribution of earthquake magnitudes and (2) there is a power-law frequency-area distribution of faults and each fault has recurring characteristic earthquakes (TURCOTTE *et al*. 2007).

SHCHERBAKOV *et al*. (2006) analyzed the scaling laws for the aftershock sequence from the 2004 Parkfield earthquake, and the aftershocks satisfy the GR relation with $b = 0.88$ and $a = 4.4$. They also considered Båth's law for Parkfield earthquake. The magnitude of the Parkfield earthquake was $m_{\mathrm{ms}} = 6.0$ and the magnitude of the largest aftershock was $m_{\mathrm{maxas}} = 5.0$ so that $\Delta m = 1.0$ which is close to the value of $\Delta m = 0.95$ for the Chi–Chi earthquake. The magnitude of the largest inferred Parkfield aftershock was also $m^* = 5.0$ so that $\Delta m^* = 1.0$, but for the Chi–Chi earthquake $\Delta m^* = 0.03$. As can be seen from Fig. 2, the Chi–Chi earthquake had large numbers of small aftershocks consistent with GR scaling but relatively few large aftershocks. As pointed out earlier, this behavior is similar to the aftershock sequence of the $m = 6.8$ 2004 Niigata earthquake. Most earthquakes have values of Δm^* in the range 0.8–1.5 but a few, such as the Chi–Chi earthquake, have small values of Δm^*. These earthquakes have many more small aftershocks than normal. Aftershocks are generally attributed to the transfer of stress during the main shock rupture. The excess of small aftershocks can be attributed to a larger component of stress transfer. Our possible explanation is a slow (silent) component of rupture associated with the main shock.

Omori's law also appears to be universally applicable to aftershock sequences. Some regions experience an increase in stress during a main shock, and aftershocks relieve the excess stress in these regions. Many studies try to explain the systematic time delay before the occurrence of aftershocks. DAS and SCHOLZ (1981), MAIN (2000), and OJALA *et al.* (2003) attributed this decay to stress corrosion combined with a critical stress intensity factor. SHAW (1993) has used a phenomenological approach to the dynamic of subcritical crack growth. For aftershock decay, RUNDLE (1989), RUNDLE and KLEIN (1993), and RUNDLE *et al.* (1999) have proposed the spinodal line for critical point nucleation to relate aftershock sequences to the power–law scaling.

The temporal evolution of the rate of occurrence of aftershocks is quantified using Omori's law Eq. (3). This paper also introduces another quantity, Omori times, to quantify the temporal evolution of interoccurrence times. In Fig. 5 we give the Omori times for the period from 1994 to 2008 for the Chi–Chi earthquake. It includes the Chi–Chi aftershocks with a combination of Omori decay and a steady-state background. The result shows that during the period 1999 after the Chi–Chi earthquake to 2008, the rate of seismicity decayed systematically with the exception of a burst of seismicity in 1999. The distribution of Omori times during the period 2000–2008 is in good agreement with the theoretical relation given in Eq. (16) (the red dashed lines in Fig. 5). During the period 1994 to 1999, the rate of seismicity was relatively stable. In this paper we also argue that the aftershocks of Chi–Chi earthquake still continue today.

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