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A Modified Form of Båth's Law

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Abstract Båth's law states that the differences in magnitudes between mainshocks and their largest aftershocks are approximately constant, independent of the magnitudes of mainshocks. In our modified form of Båth's law we introduce the notion of the inferred "largest" aftershock from an extrapolation of the Gutenberg-Richter frequency-magnitude statistics of the aftershock sequence of a given mainshock. To illustrate the application of this modified law we consider 10 large earthquakes that occurred in California between 1987 and 2003 with magnitudes equal to or greater than $m_{ms} \geq 5.5$. The mean difference in magnitudes between these mainshocks and their largest detected aftershocks is 1.16 with a standard deviation $\sigma_{\Delta m} = 0.46$ (Båth's law). Our estimated mean difference in magnitudes between the mainshocks and the inferred "largest" aftershocks is 1.11 with $\sigma_{\Delta m^*} = 0.29$. The scaling associated with the modified Båth's law implies that the stress transfer responsible for the occurrence of aftershocks is a self-similar process. We also estimate the partitioning of energy during a mainshock-aftershock sequence and find that about 96% of the energy dissipated in a sequence is associated with the mainshock and the rest is due to aftershocks. We suggest that the observed partitioning of energy could play a crucial role in explaining the physical origin of Båth's law.

Introduction

Statistical properties of aftershock sequences can be described empirically by several scaling laws (Kisslinger, 1996). Gutenberg–Richter (G-R) scaling has been found to be applicable to aftershock frequency-magnitude statistics, and the temporal decay of aftershock sequences in many instances satisfies the modified Omori's law. An extension of the modified Omori's law is the epidemic type aftershock sequence (ETAS) model where the rate of aftershock occurrence is an effect of combined rates of all secondary aftershock subsequences produced by each aftershock (Kagan and Knopoff, 1981; Ogata, 1988). A third scaling law concerning aftershocks is Båth's law. This law states that it is a good approximation to assume that the differences in magnitude between mainshocks and their largest aftershocks are constant, independent of the magnitude of the mainshocks (Båth, 1965). That is

$$\Delta m = m_{ms} - m_{as}^{max} \qquad (1)$$

with m_{ms} the magnitude of the mainshock, m_{as}^{max} the magnitude of the largest detected aftershock, and Δm approximately a constant typically taken to be $\Delta m \approx 1.2$.

A number of extensive studies of the statistical variability of Δm have been carried out (Vere-Jones, 1969; Tsapanos, 1990; Kisslinger and Jones, 1991; Console *et al.*, 2003; Helmstetter and Sornette, 2003). Despite some progress in understanding the nature of Båth's law its validity still remains an open question. Vere-Jones (1969) analyzed a simplified model in which he assumed that events in an aftershock sequence are drawn from the negative exponential distribution and are distributed independently of each other. He showed that the distribution of the difference between the largest and the second largest event is the same negative exponential distribution. Using this result he obtained the value of $\Delta m = 1/b \ln 10$. For the typical values of the parameter $b \approx 1.0$, this gives $\Delta m \approx 0.43$, which is smaller than the observed value. Recently, Helmstetter and Sornette (2003) pointed out that the selection process of aftershock sequence as a subset of the whole seismic catalog plays a significant role in calculating Δm. They argue that this difference is controlled not only by the magnitude scaling but also by the aftershock productivity.

In this article we propose a modified form of Båth's law. We infer the "largest" aftershock from an extrapolation of the G-R frequency-magnitude scaling of all measured aftershocks for a given mainshock-aftershock sequence. The modified form of Båth's law states that it is a good approximation to assume that the differences in magnitude between the mainshocks and inferred "largest" aftershocks are constant. In general, this extrapolated value will differ from the mean value of the largest aftershock obtained by averaging over an ensemble of mainshock-aftershock sequences having the same mainshock magnitude. We test the applicability of both forms of Båth's law for 10 large earthquakes in California. We also analyze the partitioning of energy during a mainshock-aftershock sequence and its relation to the modified Båth's law.

Modified Form of Båth's Law

Under a wide range of conditions earthquakes satisfy G-R frequency-magnitude scaling given by (Gutenberg and Richter, 1954):

$$\log_{10} N(\geq m) = a - bm, \quad (2)$$

where $N(\geq m)$ is the cumulative number of earthquakes with magnitudes greater than m occurring in a specified area and time window, and a and b are constants. This relation is valid for earthquakes both regionally and globally with magnitudes above some lower cutoff m_c, which defines the completeness of the catalog. In general, the constant b or "b-value" is in the range $0.8 < b < 1.2$ (Frolich and Davis, 1993). The constant a is a measure of the regional level of seismicity and gives the logarithm of the number of earthquakes with magnitudes greater than zero.

It has been recognized that the aftershocks associated with a mainshock also satisfy G-R scaling (2) to a good approximation (Kisslinger, 1996). In this case $N(>m)$ is the cumulative number of aftershocks of a given mainshock with magnitudes greater than m. It has also been demonstrated that the b-value for aftershocks is generally near unity, similar to regional and worldwide values for mainshocks.

In this work we propose to extrapolate G-R scaling (2) for aftershocks to obtain an upper cutoff magnitude in a given aftershock sequence. The magnitude of this inferred "largest" aftershock m^* is deduced by formally taking $N(\geq m^*) = 1$ for a given aftershock sequence. Substituting this value into equation (2), we obtain

$$a = bm^*. \quad (3)$$

It should again be noted that this extrapolated value of m^* will differ from the mean value of the largest aftershock in sequences distributed according to (2).

If Båth's law is applicable to the inferred values of m^* we can write

$$\Delta m^* = m_{ms} - m^*, \quad (4)$$

where m_{ms} is the magnitude of the mainshock and Δm^* is approximately a constant. Substitution of equations (3) and (4) into equation (2) gives

$$\log_{10}[N(\geq m)] = b(m_{ms} - \Delta m^* - \mathrm{m}) \quad (5)$$

with b, m_{ms}, and Δm^* specified, the frequency-magnitude distribution of aftershocks can be determined using equation (5). This defines a truncated distribution where the expected number of events with magnitudes greater than $m^* = m_{ms} - \Delta m^*$ is equal to one.

We believe our approach provides a better test of the validity of Båth's law than the standard use of only the largest instrumentally detected aftershock. In extrapolating the G-R scaling (2) we utilize a large number of aftershocks in the range of magnitudes where they follow G-R scaling. The slope of this scaling or b-value plays a crucial role in estimating the "largest" inferred magnitude m^*.

Application to California

To test the applicability of our modified form of Båth's law we consider 10 earthquakes in California that occurred between 1987 and 2003. The California region was selected because the magnitudes were determined in a uniform manner (catalogs are provided by the Southern California Earthquake Center, Southern California Seismic Network catalog, www.data.scec.org/, and the Northern California Earthquake Data Center, Northern California Seismic Network, catalog, quake.geo.berkeley.edu/ncedc/) and, for the period considered, the network was sufficiently dense that relatively complete catalogs of aftershocks with magnitudes greater than about $m_c = 2.0$ were available. The 10 earthquakes considered had magnitudes $m = 5.5$ or greater and were sufficiently separated in space and time so that no aftershock sequences overlapped with other mainshocks.

One of the primary problems in the study of aftershocks is to specify what is and what is not an aftershock (Molchan and Dmitrieva, 1992). To identify aftershocks we defined space and time windows for each sequence. In each case we consider a square area centered on the mainshock epicenter with the linear size of the box taken to be of the order of the linear extent of the aftershock zone L, which scales with the magnitude of the mainshock m_{ms} as $L = 0.02 \times 10^{0.5 m_{ms}}$ km (Kagan, 2002). Time intervals of 92, 183, 365, and 730 days are taken except for the Landers and Hector Mine earthquakes where we also use 1095 days. For the San Simeon earthquake we use only the 100 days of available data. The frequency-magnitude statistics for each case are shown in Figures 1 and 2. These values bracket the spatial distributions of aftershocks and the times required for the seismic activity in the regions to return to background levels. The results are not so sensitive to the range of areas and time periods considered.

For the Landers earthquake the mainshock magnitude was $m_{ms} = 7.3$ and the largest detected aftershock had a magnitude $m_{as}^{max} = 6.3$. From equation (1) the difference in magnitude between the mainshock and largest aftershock is $\Delta m = 1.0$. We have correlated the aftershock frequency-magnitude data given in Figure 1a with G-R scaling (2) and find $b = 0.98 \pm 0.01$ and $a = 6.08 \pm 0.05$. The square area $1.2° \times 1.2°$ was used. From equation (4) the inferred magnitude of the largest aftershock is $m^* = 6.20 \pm 0.05$. From equation (5) the difference in magnitude between the

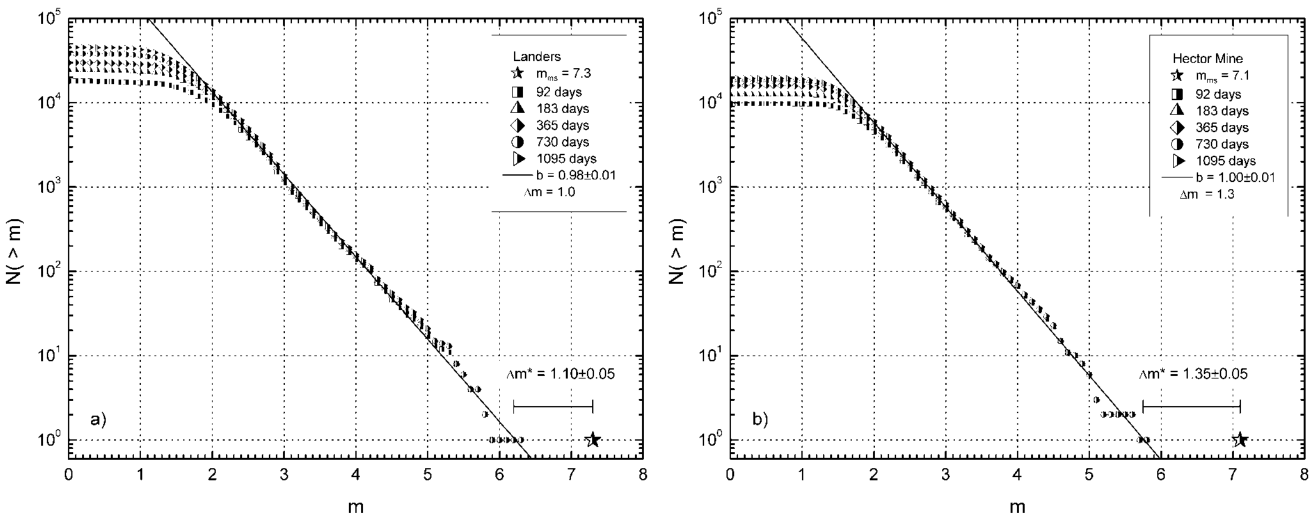

Figure 1. Cumulative numbers of aftershocks of the Landers (a) and Hector Mine (b) earthquakes with magnitudes greater than *m*, $N(>m)$, are given as functions of aftershock magnitude *m*. Square areas centered on the epicenter of the mainshocks for time periods of 92, 183, 365, 730, and 1095 days following the mainshock were used. The straight lines are the best-fits of equation (5) to the data (for $m_c \geq 2.0$). The method of estimating the inferred "largest" aftershock m^* is also illustrated.

mainshock and the inferred largest aftershock is $\Delta m^* = 1.10 \pm 0.05$. For the Hector Mine earthquake from Figure 1b the same analysis gives the values $\Delta m = 1.3$, $b = 1.00 \pm 0.01$, $a = 5.76 \pm 0.04$, $m^* = 5.75 \pm 0.05$, and $\Delta m^* = 1.35 \pm 0.05$ (the square area $1.0° \times 1.0°$ was used).

Results for the other eight earthquakes in California that we have considered are shown in Figure 2. The cumulative numbers of aftershocks with magnitudes greater than *m*, $N(>m)$, are given as functions of *m*. In each case the best fit to the G-R relation (5) is used to obtain a *b*-value and a value of Δm^*. For these earthquakes the mean of the differences between mainshock and largest detected aftershock magnitudes is $\overline{\Delta m} = 1.16$ with a standard deviation $\sigma_{\Delta m} = 0.46$. For the same earthquakes the mean of the inferred values of Δm^* obtained from the best fit of equation (5) is $\overline{\Delta m^*} = 1.11$ with a standard deviation $\sigma_{\Delta m^*} = 0.29$. The two approaches give similar results for the prediction of the largest aftershock and these are close to the value 1.2 originally suggested by Båth. However, the standard deviation of the values is considerably less for our modified approach, 0.29 versus 0.46. For the 10 earthquakes the mean *b*-value is $b = 0.97$ with a standard deviation $\sigma_b = 0.16$. The obtained results are summarized in Table 1.

The dependencies of both Δm and Δm^* on the mainshock magnitude m_{ms} are given in Figure 3a for these earthquakes. No significant dependence on mainshock magnitude is seen over the range of magnitudes we have considered. The dependence of Δm^* on Δm is given in Figure 3b for the same earthquakes. There is a positive correlation between values of Δm^* and values of Δm.

Partitioning of Energy

The magnitude distribution of aftershocks clearly exhibits a near-universal scaling relative to the mainshock magnitude. To explore this relation further we will determine the ratio of the total seismic energy radiated in the aftershock sequence to the seismic energy radiated in the mainshock. The energy *E* radiated in an earthquake is related empirically to its moment magnitude *m* by (Utsu, 2002)

$$\log_{10}\,[E(m)] = \frac{3}{2}\,m + \log_{10} E_0, \tag{6}$$

with $E_0 = 6.3 \times 10^4$ J. This relation can be used directly to relate the radiated energy from the mainshock E_{ms} to the moment magnitude of the mainshock m_{ms},

$$E_{ms} = E_0\, 10^{3/2\ m_{ms}} \tag{7}$$

The total radiated energy in the aftershock sequence E_{as} is obtained by integrating over the distributions of aftershocks. This can be written

$$E_{as} = \int_{-\infty}^{m^*} E(m) \left(-\frac{dN}{dm}\right) dm. \tag{8}$$

Taking the derivative of equation (5) with respect to the aftershock magnitude *m* we have

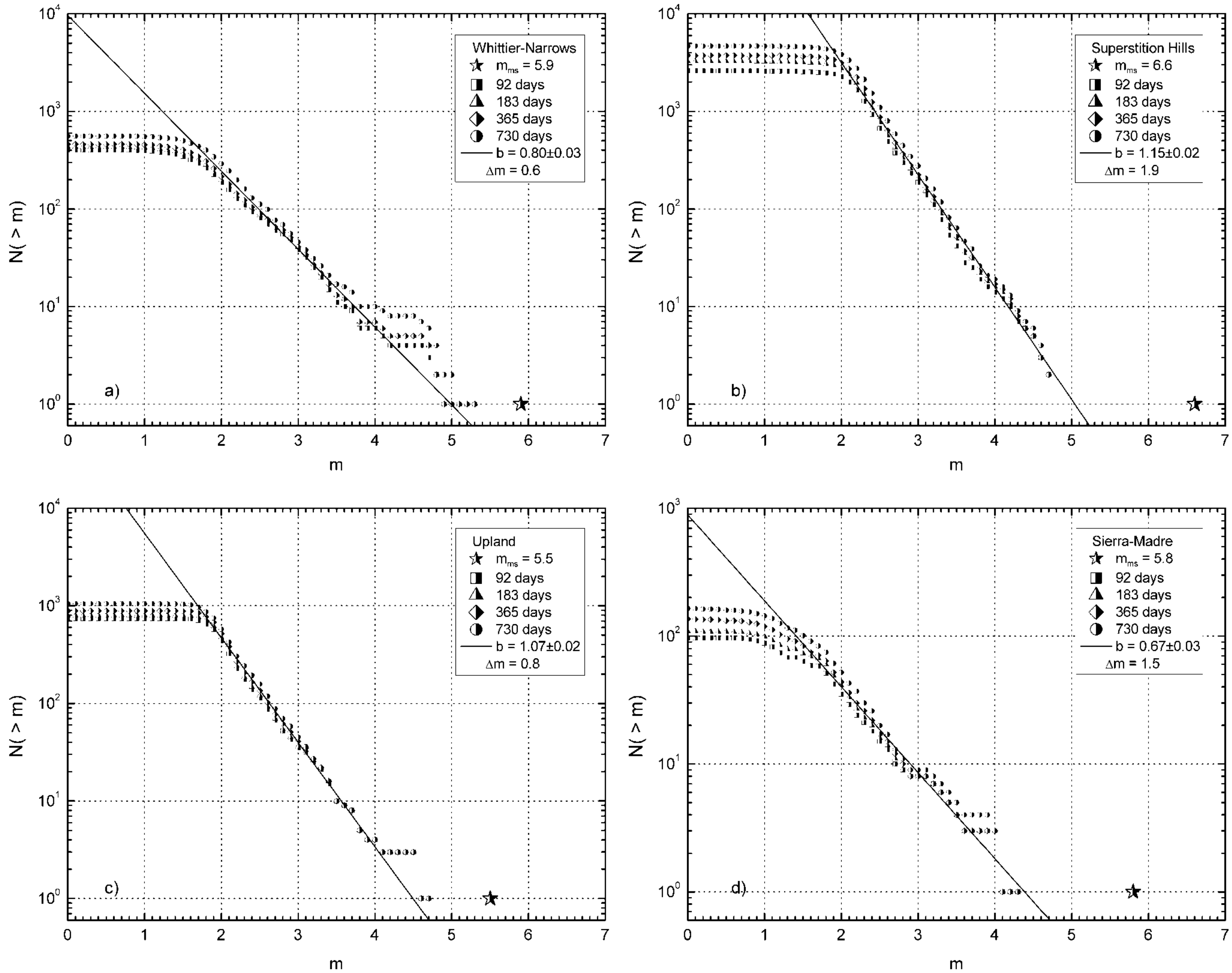

Figure 2. Cumulative numbers of aftershocks with magnitudes greater than *m*, $N(>m)$, are given as functions of aftershock magnitude *m* for the other eight earthquakes considered: (a) Whittier Narrows, (b) Superstition Hills, (c) Upland, (d) Sierra Madre, (e) Northridge, (f) Ridgecrest, (g) Baja, and (h) San Simeon. The straight lines are the best-fits of equation (5) to the data (for $m_c \geq 2.0$); the derived values of Δm and b are also given. (*continued*)

$$dN = -b(\ln 10)\ 10^{b(m_{\mathrm{ms}} - \Delta m^* - m)}\ dm. \tag{9}$$

Substitution of equations (6) and (9) into equation (8) gives

$$E_{\mathrm{as}} = b(\ln 10)\ E_0\ 10^{b(m_{\mathrm{ms}} - \Delta m^*)} \int_{-\infty}^{m^*} 10^{(3/2 - b)m} dm. \tag{10}$$

Carrying out the integration using equation (4) we find

$$E_{\mathrm{as}} = \frac{2b}{(3 - 2b)}\ E_0\ 10^{3/2(m_{\mathrm{ms}} - \Delta m^*)}. \tag{11}$$

The ratio of the total radiated energy in aftershocks E_{as} to the radiated energy in the mainshock E_{ms} is obtained by dividing equation (11) by equation (7) with the result

$$\frac{E_{\mathrm{as}}}{E_{\mathrm{ms}}} = \frac{2b}{3 - 2\ b}\ 10^{-3/2\ \Delta m^*}. \tag{12}$$

If we further assume that all earthquakes have the same seismic efficiency (ratio of radiated energy to the total drop in stored elastic energy), then this ratio is also the ratio of the drop in stored elastic energy due to the aftershocks to the drop in stored elastic energy due to the mainshock.

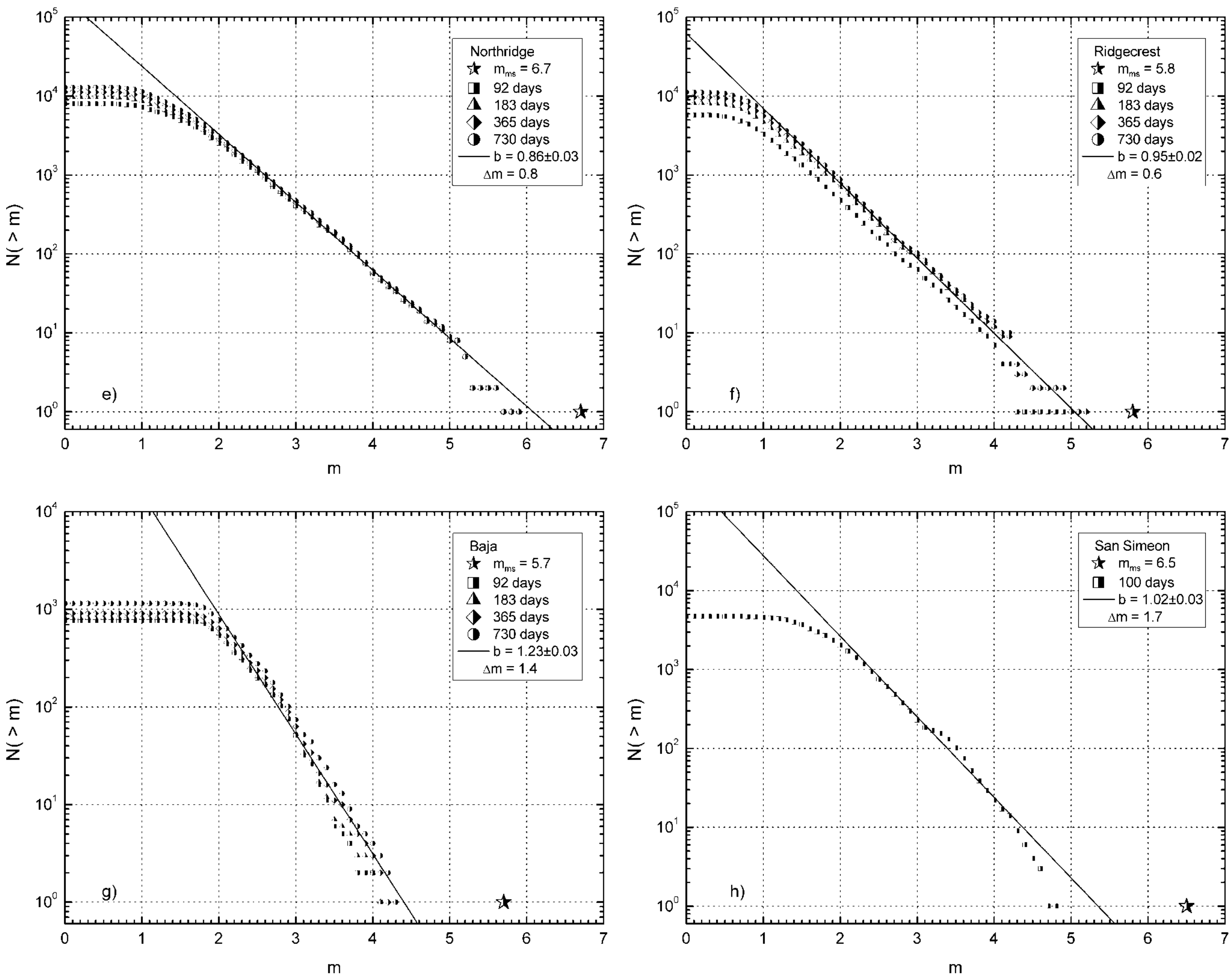

Figure 2. *Continued.*

Table 1
Summary of the Data and Results

Earthquake	Date (mm/dd/yy)	Area	m_{ms}	m_{as}^{max}	Δm	b	m^*	Δm^* (A)	Δm^* (B)
Whittier–Narrows	10/10/87	0.5° × 0.5°	5.9	5.3	0.6	0.80 ± 0.03	5.00 ± 0.05	0.90 ± 0.05	0.50 ± 0.06
Superstition Hill	11/24/87	1.0° × 1.0°	6.6	4.7	1.9	1.15 ± 0.02	5.10 ± 0.05	1.50 ± 0.05	1.62 ± 0.02
Upland	02/28/90	0.4° × 0.4°	5.5	4.7	0.8	1.07 ± 0.02	4.50 ± 0.05	1.00 ± 0.05	0.78 ± 0.07
Sierra Madre	06/28/91	0.4° × 0.4°	5.8	4.3	1.5	0.67 ± 0.03	4.40 ± 0.05	1.40 ± 0.05	1.25 ± 0.05
Landers	06/28/92	1.2° × 1.2°	7.3	6.3	1.0	0.98 ± 0.01	6.20 ± 0.05	1.10 ± 0.05	0.96 ± 0.02
Northridge	01/17/94	0.7° × 0.7°	6.7	5.9	0.8	0.86 ± 0.03	6.10 ± 0.05	0.60 ± 0.05	0.65 ± 0.03
Ridgecrest	09/20/95	0.4° × 0.4°	5.8	5.2	0.6	0.95 ± 0.02	5.05 ± 0.05	0.75 ± 0.05	0.56 ± 0.07
Hector Mine	10/16/99	1.0° × 1.0°	7.1	5.8	1.3	1.00 ± 0.01	5.75 ± 0.05	1.35 ± 0.05	1.24 ± 0.01
Baja	02/22/02	0.6° × 0.6°	5.7	4.3	1.4	1.23 ± 0.03	4.40 ± 0.05	1.30 ± 0.05	1.39 ± 0.05
San Simeon	12/22/03	0.9° × 0.9°	6.5	4.8	1.7	1.02 ± 0.03	5.35 ± 0.05	1.15 ± 0.05	1.38 ± 0.03

The values of Δm^* are estimated using the notion of inferred "largest" aftershock from the extrapolation of G-R scaling (A) and the partitioning of energy (13) (B).

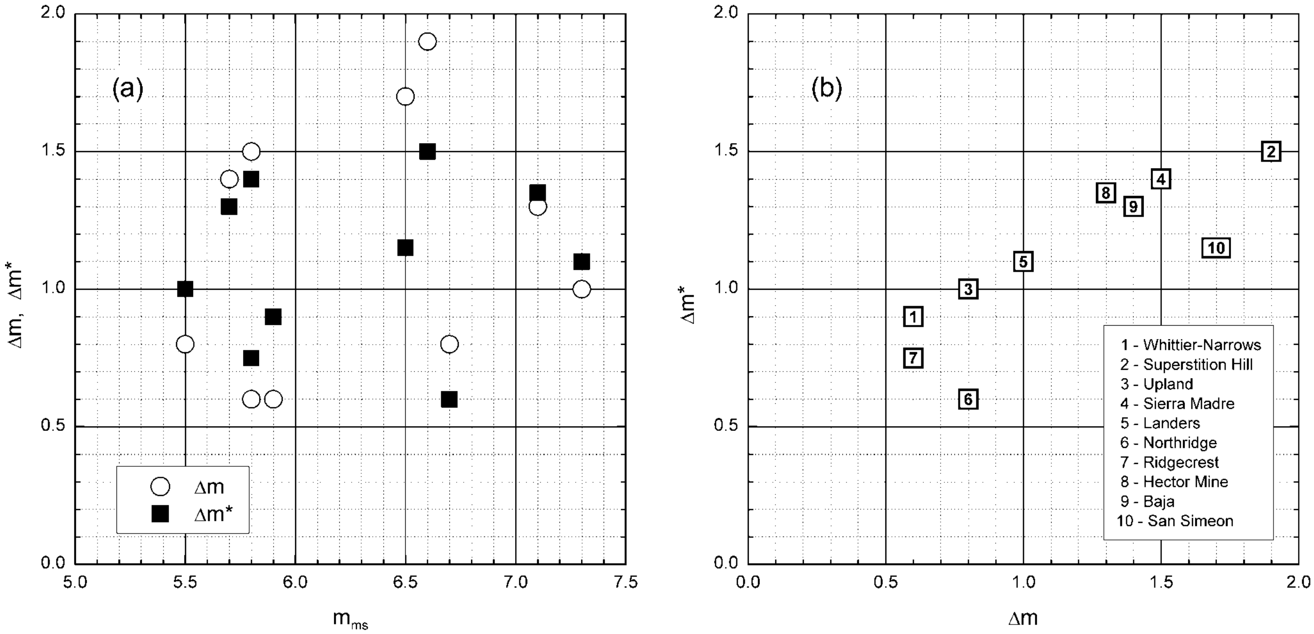

Figure 3. (a) Dependence of the magnitude differences Δm and Δm^* on the mainshock magnitude m_{ms} for the 10 earthquakes considered. (b) Dependence of the inferred magnitude difference between the mainshock and "largest" aftershock Δm^* on the actual magnitude differences Δm between the mainshock and largest observed aftershock.

From equation (12) the fraction of the total energy associated with aftershocks is given by

$$\frac{E_{as}}{E_{ms} + E_{as}} = \frac{1}{1 + \frac{3 - 2b}{2b} 10^{3/2\ \Delta m^*}}. \qquad (13)$$

Taking $b = 0.8$, 1.0, and 1.2, this result is plotted in Figure 4.

For the 10 earthquakes considered in the previous section we had $\bar{b} = 0.97 \pm 0.05$ and $\overline{\Delta m^*} = 1.11 \pm 0.09$. Substitution of these values into equation (12) gives $E_{as}/(E_{ms} + E_{as}) = 0.038$. The applicability of the modified form of Båth's law requires that the ratio of radiated energy in aftershocks to the radiated energy in the mainshock be constant. This is consistent with the generally accepted condition of self-similarity for earthquakes. For these earthquakes on average about 96% of the available elastic energy goes into the mainshock and about 4% into the aftershocks.

To test the validity of the derived ratio (13) we estimated $E_{as}/(E_{ms} + E_{as})$ for each mainshock-aftershock sequence under consideration. In each case the time interval of 365 days was taken for aftershock sequences except for the San Simeon earthquake where it was 100 days. The values of Δm^* were calculated with equation (13) and b-values were obtained from the G-R scaling. The results are plotted as open squares in Figure 4. For comparison, we also plotted the the same estimated ratios $E_{as}/(E_{ms} + E_{as})$ against the values of Δm^* obtained in the Application to California sec-

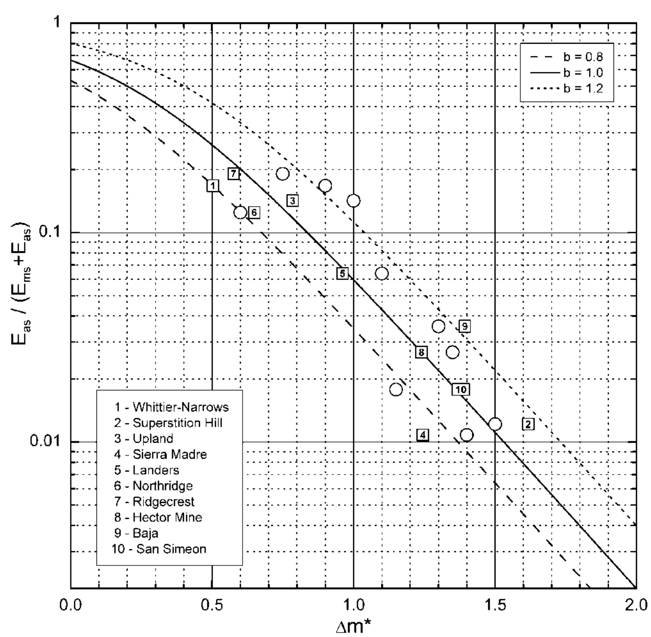

Figure 4. Dependence of the fraction of the total energy loss associated with aftershocks, $E_{as}/(E_{ms} + E_{as})$ on the difference in magnitude between the mainshock and the inferred "largest" aftershock Δm^* from (13). Symbols are the energy loss versus the estimated values of Δm^* using G-R scaling (open circles) and energy partitioning (open squares), respectively, for the 10 large California earthquakes.

tion from the extrapolation of G-R scaling. They are shown as open circles in Figure 4. Both approaches give approximately similar values of Δm^* within statistical errors.

Discussion

Aftershocks universally occur after crustal earthquakes. It is accepted that aftershocks are caused by stress transfer during an earthquake. When an earthquake occurs there are adjacent regions where the stress is increased. The relaxation of these stresses causes aftershocks (Rybicki, 1973; Das and Scholz, 1981; Mendoza and Hartzell, 1988; King *et al.*, 1994; Marcellini, 1995; Hardebeck *et al.*, 1998). Several scaling laws are also found to be universally valid for aftershocks. Aftershocks obey the G-R frequency-magnitude scaling given in equation (2), observed b-values for aftershocks are generally near one, similar to regional and worldwide values. Båth's law states that, to a good approximation, the difference in magnitude between a mainshock and its largest aftershock is a constant independent of the mainshock magnitude. In this article we combine Båth's law and G-R scaling to introduce an upper magnitude cutoff for the given aftershock sequence m^*, which is related to the a and b values in the G-R scaling by the relation (3).

For the 10 large earthquakes in California we obtain values for the difference between the mainshock magnitude m_{as} and the largest detected aftershock magnitude m_{as}^{max} and the "largest" inferred aftershock m^*. We propose a modified form of Båth's law in which the difference in magnitude between the mainshock and inferred "largest" aftershock, Δm^*, is a constant. For these earthquakes the modified Båth's law has considerably (factor of 2) less scatter than the original Båth's law.

A relatively simple explanation can be given for the validity of both Båth's law and our modified form. The fraction of the elastic energy that goes into increasing the stress in adjacent rock is independent of the size of the earthquake. This conclusion is valid even though the first-order aftershocks have second-order aftershocks, and second-order aftershocks have third-order aftershocks, etc. All aftershocks play a similar roll in relaxing the stress transferred by the mainshock. The partitioning of energy suggests that a large fraction of the accumulated energy is released in the mainshock and only a relatively small fraction in the aftershock sequence. From the derived result (13) that is illustrated in Figure 4 it is seen that decreasing Δm^* increases the energy content of the aftershock sequence. The estimated values of Δm^* for large past earthquakes in California suggest that on average the largest aftershock following the mainshock is one magnitude unit smaller than the mainshock. The estimation of the largest aftershock in a sequence is very important from a hazard assessment point of view, where it is crucial to know the rates and magnitudes of aftershocks following the mainshock.

The primary purpose of this work is to propose an alternative means of testing the validity of Båth's law. We infer the "largest" aftershock by extrapolating G-R scaling for all observed aftershocks of a given mainshock. Because this extrapolation is based on a large number of aftershocks, we believe our alternative formulation of Båth's law provides a preferred test of the law's validity. This is also supported by studies of the partitioning of energy during a mainshock-aftershock sequence.

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