Analysis of aftershock and foreshock activity in stable continental regions: Implications for aftershock forecasting and the Hazard of strong earthquakes

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Analysis of Aftershock and Foreshock Activity in Stable Continental Regions: Implications for Aftershock Forecasting and the Hazard of Strong Earthquakes

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ABSTRACT

The Omori-law aftershock parameters for 13 earthquakes in stable continental regions (SCRs) globally are found to distribute in the same way as those for California aftershock sequences. Of 19 SCR mainshocks with $\mathbf{M} \geq 6.0$ since 1968, eight had their largest aftershock within five days of the mainshock and 11 within 30 days of the mainshock. The mean magnitude difference between the mainshock and the largest aftershock of these 19 SCR events is $1.4 \pm .7$ magnitude units, with a range from 0.3 to 3.6 magnitude units. From 1968 to 2003 the rate at which SCR earthquakes of $\mathbf{M} \geq 4.5$ worldwide were followed by a comparable or larger earthquake within the next 30 days is 5%. These statistics can be used to produce aftershock forecasts for strong SCR earthquakes and to estimate the chances that an SCR earthquake of $\mathbf{M} \geq 4.5$ will be followed by a larger seismic event within the next month.

INTRODUCTION

One area in which earthquake forecasting has been making progress is in the forecasting of the probabilities of aftershocks after a strong earthquake. For example, in California the U.S. Geological Survey (USGS) now puts out both spatial and temporal probability forecasts of aftershocks and possibly larger mainshocks on a regular basis (Gerstenberger *et al.* 2005; also see the Web site http://Pasadena.wr.usgs.gov/step). The temporal aftershock forecasts are based on an Omori-law aftershock model where the model parameters are estimated from California aftershock data (Reasenberg and Jones 1989, 1994). In operation, an initial aftershock forecast made immediately after a mainshock is based on the generic parameters for California sequences in the Reasenberg and Jones (1989) formulation. Each forecast, issued for a time period such as a week, consists of an estimate of the average number of aftershocks above some magnitude expected, the probabilities that strong aftershocks might be experienced, and the probability that an earthquake even stronger than the current mainshock will occur (*i.e.*, that the earthquake was a foreshock of a still larger event in the near future). These forecasts can be updated as the aftershock sequence evolves with time.

Because aftershock and foreshock probability forecasts are being routinely made after strong earthquakes in California, there is great interest in extending this capability to other regions, such as the stable cratonic intraplate region of the central and eastern United States (CEUS). In order to make accurate aftershock probability forecasts, one needs to know for each aftershock sequence the values of the parameters for the form of the Omori aftershock law being used for the aftershock forecast. There are very few large earthquakes in any single stable continental region (SCR) like the CEUS that have sufficient aftershocks that the Omori-law parameters can be found, and so it is necessary to look at the aftershocks of earthquakes from SCRs on a global basis to get more robust statistical estimates of the means and variances of these parameters. In fact, Ebel *et al.* (2000) already have published the Omori-law parameters for some SCR earthquakes, which they needed for a paleoseismicity analysis. Thus, there already are some data available concerning Omori-law aftershock parameters of SCR events. However, a more thorough study of aftershock and foreshock parameters for SCR earthquakes was needed in order to determine more statistically robust values of these parameters. Also, the statistics of SCR foreshocks had not yet been studied in detail by any investigators, and those statistics are needed if SCR foreshock probability forecasts are to be made. Thus, the purpose of this research is to document the aftershock and foreshock statistics of SCR earthquakes worldwide and to explore how the SCR Omori-law parameters and foreshock statistics can be used for aftershock and foreshock forecasts in SCRs like the CEUS.

SCR AFTERSHOCK AND FORESHOCK DATA SET

To find the aftershock parameters for SCRs worldwide, where strong events are rare but substantial populations can be at risk from earthquakes, the earthquake catalogs of strong SCR mainshocks compiled in the work by Fenton *et al.* (2006) and

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TABLE 1
Events Deleted from the USGS SCR M ≥ 6 Mainshock Catalog

Date	Latitude	Longitude	Origin Time	Continent	Depth (km)	Mw	Note
14/11/2001	7.8137	105.9438	9:30:43	Asia	33	6.5	No event in NEIC or ISC catalogs on this day
03/10/2001	–6.9671	137.0515	11:23:47	Australia	33	6.2	PDE location –3.50 139.72, plate boundary event
26/08/2001	76.3339	–20.322	18:27:52	North America	33	6.1	ISC location 79.85 2.74, plate boundary event
08/11/2000	77.04	–77.83	6:59:59	North America	17	6	PDE location –7.04 –77.83, plate boundary event
21/11/1972	76.58	–106.02	10:06:30	North America	29	6	Larger shock is on 27/12/1972

of strong SCR and intraplate earthquakes from the USGS Web site (Schulte and Mooney 2005; http://earthquake.usgs.gov/research/data/scr_catalog.php) were obtained. The Fenton *et al.* (2006) earthquake catalog only contains earthquakes to January 1990, while the USGS SCR catalog contains events to November 2003. In this study the USGS SCR catalog was used as the master catalog of SCR events, and the Fenton *et al.* (2006) catalog was used as a reference when questions arose about events prior to 1990 in the USGS SCR catalog.

Both the USGS SCR and Fenton *et al.* (2006) catalogs contain only **M** ≥ 4.5 earthquakes. The Fenton *et al.* (2006) catalog excludes dependent events like aftershocks. The USGS SCR catalog does not exclude foreshocks or aftershocks, but only 134 of the 1,043 events are listed as dependent events. There were insufficient data in these two earthquake catalogs to determine the Omori-law parameters for aftershock sequences or to determine the incidences of foreshocks of SCR earthquakes with magnitudes below 4.5. I decided to search the USGS National Earthquake Information Center (NEIC) global earthquake catalog and the International Seismological Centre (ISC) global earthquake catalog for lists of foreshocks within about one month and aftershocks within two years of all of the mainshocks of **M** ≥ 6.0 in the USGS SCR catalog since these catalogs commonly contain earthquakes with magnitudes below 4.5. In doing this search, I discovered that some of the events in the USGS SCR catalog were mistaken entries (Table 1). One of the events (14 November 2001) is not found in either the NEIC or ISC catalogs. Three of the other events have different epicenters compared to the NEIC or ISC catalogs, and all three are in fact plate boundary events with mistaken epicenters in the USGS SCR catalog. Finally, one of the events appears to be a slightly smaller foreshock (or slightly smaller additional mainshock) before a larger, nearby event. These five events were dropped from the SCR **M** ≥ 6 mainshock catalog, leaving a total of 19 SCR **M** ≥ 6 mainshocks that were analyzed in this study.

For almost all SCR mainshocks with **M** ≥ 6 (the 2001 Bhuj, India, earthquake being the only exception), the NEIC and ISC catalogs contain an insufficient number of aftershocks to constrain the Omori-law parameters. In order to increase the number of SCR events for which the Omori-law parameters could be found, I decided to utilize aftershock data from SCR mainshocks with magnitudes below 6. Aftershock sequences for six SCR mainshocks with **M** ≥ 5 since the late 1960s were obtained from regional seismic network databases in Australia, Europe, and North America. Data centers at Geoscience Australia, Lamont-Doherty Earth Observatory, and the Center for Earthquake Research and Information (CERI) at the University of Memphis were the sources of these aftershock sequences. In addition, the Omori-law parameters for six SCR aftershock sequences with **M** ≥ 5 had already been determined by Ebel *et al.* (2000), and those published values were incorporated into this study.

AFTERSHOCK AND FORESHOCK STATISTICS OF LARGE SCR EARTHQUAKES

I carried out two separate analyses as part of this research. In the first, I analyzed the data set of **M** ≥ 6 SCR mainshocks discussed in the previous section to assess the rate of foreshock occurrences prior to **M** ≥ 6 SCR mainshocks and to determine the times and magnitudes of the largest aftershocks of **M** ≥ 6 SCR mainshocks. In the second analysis, I compiled the Omori-law parameters for 13 SCR mainshocks with **M** ≥ 5. Table 2 summarizes the data that were used in the first analysis, and Table 3 summarizes the Omori-law parameters that were determined in the second analysis.

The values reported in Table 2 were compiled from the USGS SCR and Fenton *et al.* (2006) catalogs supplemented with data from the NEIC and ISC catalogs. In addition, some foreshock and aftershock data obtained from the Canadian Geological Survey and from Geoscience Australia were incorporated into Table 2. Also, the information on aftershocks of the 1983 earthquake in Guinea comes from Dorbath *et al.* (1984) and Langer *et al.* (1987). These studies of the Guinea earthquake do not report the dates and times of individual aftershocks but only summarize the results of short-term aftershock monitoring using portable instruments. Thus, in Table 2 for the 1983 event the magnitude of the largest aftershock from the field aftershock surveys is given as the largest aftershock, and the time of the largest aftershock is not specified. Because of the variety of data sources that were used for Table 2, the completeness threshold for the foreshocks and aftershocks likely varies significantly from region to region and from earlier to later time periods. Engdahl *et al.* (1998) showed that the global earthquake catalog is complete down to magnitude 5.2 from 1964 to 1999, and the completeness threshold is lower in well-instrumented parts of the world. Because the USGS SCR

TABLE 2
Foreshocks and Aftershocks of M ≥ 6 SCR Mainshocks from 1968 to 2003

Date	Lat.	Lon.	Origin Time	Depth (km)	Mw	mb	Ms	# FS	Max FS	Max AS	Time Max AS (days)	Location	Note
26/01/2001	23.44	70.31	3:16:40	16	7.6	6.9	7.9	0		5.9	1.9	Bhuj, India	M4.6 event 33 days before mainshock and 80 km from mainshock epicenter
23/12/2000	–7.83	135.89	7:13:36	13.7	6	5.7	5.3	0		4.7	15	Aru Islands	Only 2 aftershocks reported
10/08/1997	–16.15	124.34	9:20:34	20	6.2	5.8	5.9	0		4.2	22	Collier Bay, Australia	Only 4 aftershocks reported
29/09/1993	18.08	76.49	22:25:51	12	6.2	6.3	6.3	1	4.7	5.1	71	Khillari, India	M4.9 foreshock 31 days before mainshock
25/12/1989	60.05	–73.54	14:24:34	2.9	6	6.2	6.3	1	5.1	4.0	2.9	Angava Peninsula, Quebec	Only 3 aftershocks reported
22/01/1988	–19.90	133.86	12:04:59	6.3	6.6	6.1	6.5	0		5.8	0.3	Tennant Creek, Australia	Multiple mainshocks of M6.3, M6.4, and M6.6
21/05/1984	32.69	121.51	15:39:04	44.5	6.1	5.7	6	1	5.5	4.8	0.04	Jiangsu Province, China	Only 7 aftershocks reported
22/12/1983	11.86	–13.51	4:11:30	8	6.2	6.4	6.2	1	3.0	4.3	*	Guinea	> 1,000 aftershocks recorded
02/06/1979	–30.82	117.11	9:48:00	6.2	6.1	6	6.1	17	5.2	5.1	0.9	Cadoux, Australia	
23/04/1979	–16.62	120.16	5:45:11	31.2	6.1	5.9	5.7	1	4.7	4.8	4.6	Northwest of Australia	Only 5 aftershocks reported
18/01/1976	77.82	18.47	4:46:22	5.5	6	—	—	0		4.5	546	Svalbard	Only 2 aftershocks reported
27/09/1974	2.65	–71.36	4:09:00	20.6	6.3	5.5	—	0		4.9	3.1	Eastern Colombia	Only 2 aftershocks reported
23/09/1974	–0.30	12.76	19:28:14	2.7	6	—	—	0		5.2	536	Southwest Africa	Only 1 aftershock reported
10/05/1974	28.18	103.99	19:25:17	9.9	6.8	—	7.1	0		5.5	36	Sichuan Province, China	M4.5 foreshock 33 days before mainshock
27/12/1972	76.76	–107.09	22:59:27	3.3	6.3	5.7	6	4	4.9	5.4	36	Northwest Passage, Canada	Multiple mainshocks of MLg 5.6, MLg 5.7 and MLg 5.4
24/03/1970	–22.05	126.67	10:35:21	15	6	—	5.9	0		5.3	352	Lake Mackay, Australia	
29/09/1969	–33.19	19.34	20:03:30	15	6.4	5.9	6.3	0		6.1	197	South Africa	
14/1019/68	–31.52	116.98	2:58:51	5	6.6	6	6.9	15	4.2	5.7	1.0	Meckering, Australia	
15/05/1968	–15.92	26.10	7:51:18	25.5	6.8	5.7	—	0		3.2	33	Zambia	

FS – Number of foreshocks observed; a foreshock is defined in this table as a prior earthquake that is smaller than the mainshock and occurs within 50 km of the mainshock and within 30 days of the mainshock.
Max FS – Magnitude of the largest foreshock.
Max AS – Magnitude of the largest aftershock; an aftershock is defined in this table as a smaller earthquake that occurs within about 50 km of the mainshock and within two years of the mainshock.
Time Max AS – Time in days after the mainshock when the largest aftershock took place.
* Date and time of largest aftershock not given by Langer *et al.* (1987).

TABLE 3
Determinations of *a*, *b*, and *p* Parameters of Omori's Law for SCR Earthquakes

Event Name	Date	Time	Lat.	Lon.	Mag.	Mag. Type	Min. Mag.	*b* value	*p* value	*a* value
Miramichi, NB [1]	09/01/1982	12:53:52	46.98	−66.66	5.5	Mw	1.7	0.81	1.01	−0.77
Goodnow, NY [1]	07/10/1983	10:18:46	43.94	−74.25	5.1	Mc	1.5	0.85	0.74	−2.50
Swabian Jura, Germany [1]	03/09/1978	5:08:00	48.30	9.02	5.7	ML	1.0	0.53	0.98	−0.80
Lleyn, Wales [1]	19/07/1984	6:56:00	52.96	−4.38	5.4	ML	0.6	0.66	1.02	−1.16
Roermond, Netherlands [1]	13/04/1992	1:20:00	51.17	5.95	5.8	ML	2.0	1.05	1.29	−2.62
Au Sable Forks, NY [2]	20/04/2002	10:50:47	44.51	73.68	5.1	MbLg	1.5	0.60	0.78	−1.55
Mt. Carmel, IL [3]	18/04/2008	9:36:59	38.45	−87.89	5.2	Mw	1.5	0.56	0.78	−1.20
Bhuj, India [4]	26/01/2001	3:16:41	23.42	70.23	8.0	Mw	4.5	1.40	1.51	−3.77
Tennant Creek, Australia [1]	22/01/1988	12:04:59	−19.84	133.99	6.8	ML	1.8	0.91	0.96	−1.59
Meckering, Australia [5]	14/10/1968	2:58:51	−31.52	116.98	6.6	Mw	2.5	0.92	1.00	−2.67
Cadoux, Australia [5]	02/06/1979	9:47:59	−30.83	117.18	6.2	ML	2.0	0.80	1.22	−1.78
Lake Mackay, Australia [5]	24/03/1970	10:35:17	−22.05	126.61	6.7	ML	3.5	1.08	1.18	−2.17
Burakin, Australia [5]	28/09/2001	2:54:56	−30.54	117.06	5.2	ML	2.0	0.84	0.82	−1.65

[1] *a*, *b*, and *p* values from Ebel *et al.* (2000).
[2] Aftershock data provided by W.-Y. Kim, Lamont-Doherty Earth Observatory.
[3] Data provided by M. Withers, CERI, University of Memphis.
[4] Data from the USGS NEIC.
[5] Data from the Geosciences Australia Web site (http://www.ga.gov.au/). Information about the earthquakes on this Web site can be found from Leonard (2008).

and Fenton *et al.* (2006) catalogs contain events down to magnitude 4.5, it is assumed that the completeness threshold for all of those areas where SCR mainshocks are reported is 4.5 or less since 1968.

Regarding the foreshock data reported in Table 2, six of the 19 SCR mainshocks of $Mw \geq 6$ from 1968 to 2003 had a least one foreshock of **M** ≥ 4.5 within 30 days of the mainshock, and another of the mainshocks had a foreshock of magnitude 4.2. These statistics do not include the 1988 Tennant Creek, Australia, earthquake sequence, in which a shock of **M** 6.3 was followed by earthquakes of **M** 6.4 and **M** 6.6 within a few hours. According to Fenton *et al.* (2006) there are about four SCR events with **M** ≥ 4.5 each year worldwide. Thus, from 1968 to 2003, globally there were about 144 SCR events with **M** ≥ 4.5, and so seven out of 144 or about 5% of the **M** ≥ 4.5 SCR events were followed in their epicentral regions by comparable or larger earthquakes within the following 30 days. If the number of **M** ≥ 4.5 SCR events from 1968 to 2003 that were followed within 30 days by a larger event in the same epicentral area continues at this same rate into the future, then whenever an **M** ≥ 4.5 earthquake takes place in an SCR, there is about a 5% chance that a comparable or larger earthquake will take place in the same area during the following 30 days.

Some statistics concerning the largest aftershocks that follow **M** ≥ 6 SCR earthquakes can be gleaned from Table 2. Of the 19 mainshocks in Table 2, the mean magnitude difference between the mainshock and the largest aftershock is 1.4 ± .7 magnitude units, with a range from 0.3 to 3.6 magnitude units. The median magnitude difference between the mainshock and the largest aftershock is 1.3 magnitude units. For three of the mainshocks, the largest aftershock occurred within 24 hours of the mainshock, while in eight cases the largest aftershock occurred within five days of the mainshock. For 11 of the 18 mainshocks for which the time of the largest aftershock is known, the largest aftershock took place within 30 days of the mainshock. Thus, in 61% of the cases where aftershocks were reported after SCR mainshocks with **M** ≥ 6, the largest aftershock took place within 30 days of the mainshock. Table 2 also suggests that some aftershock sequences may be quite protracted, with several cases where the largest aftershock took place almost a year or more after the mainshock.

The second analysis carried out on the SCR earthquake data was to determine the Omori-law parameters that can be used to quantify the rate of aftershock occurrence with time following an SCR mainshock. As in California, the Reasenberg and Jones (1989) form of Omori's law was used in this study to parameterize the temporal behavior of SCR aftershocks. This version of Omori's law can be written as

$$\log_{10}(\lambda(t)) = a + b\,(M_m - M) - p(t + 0.05), \qquad (1)$$

where λ is the rate of aftershocks at time t in days after the mainshock of magnitude M_m, and M is the lower magnitude cutoff for the catalog that was used. The parameters a, b, and p need to be determined for each aftershock sequence. In total, 13 SCR events with magnitude of 5 or greater since 1968 were found in this study to have sufficiently documented aftershock sequences that the parameters a, b, and p could be independently determined. To derive the Omori-law aftershock parameters for each aftershock sequence, the distribution of magnitudes of the aftershocks for a mainshock were plotted on a cumulative Gutenberg-Richter plot, from which the linear part of the distribution was identified and the b value measured. The magnitude below which the distribution appeared to depart from linearity was used to find the minimum magnitude for which the earthquake data appeared to be complete. Counts per day of the number of aftershocks above this minimum magnitude were then used to find the p value of the aftershock decay in Omori's law. Once b and p were known, I computed the a value for Equation 1 from the distribution of the aftershocks with time. Generally, it was the aftershocks in the first 10–20 days after a mainshock that were used to determine the parameter p. This same procedure was used by Ebel *et al.* (2000), from which some of the a, b, and p values were taken for this study.

Table 3 lists the a, b, and p parameters found for the SCR aftershock sequences analyzed in this study. The events from North America and Europe are all less than Mw 6.0, but their aftershock sequences are well determined because of regional seismic network recordings or portable seismic station monitoring of the aftershocks. Regional seismic network recording also helped detect aftershocks of the mainshocks from Australia, most of which were above Mw 6.0.

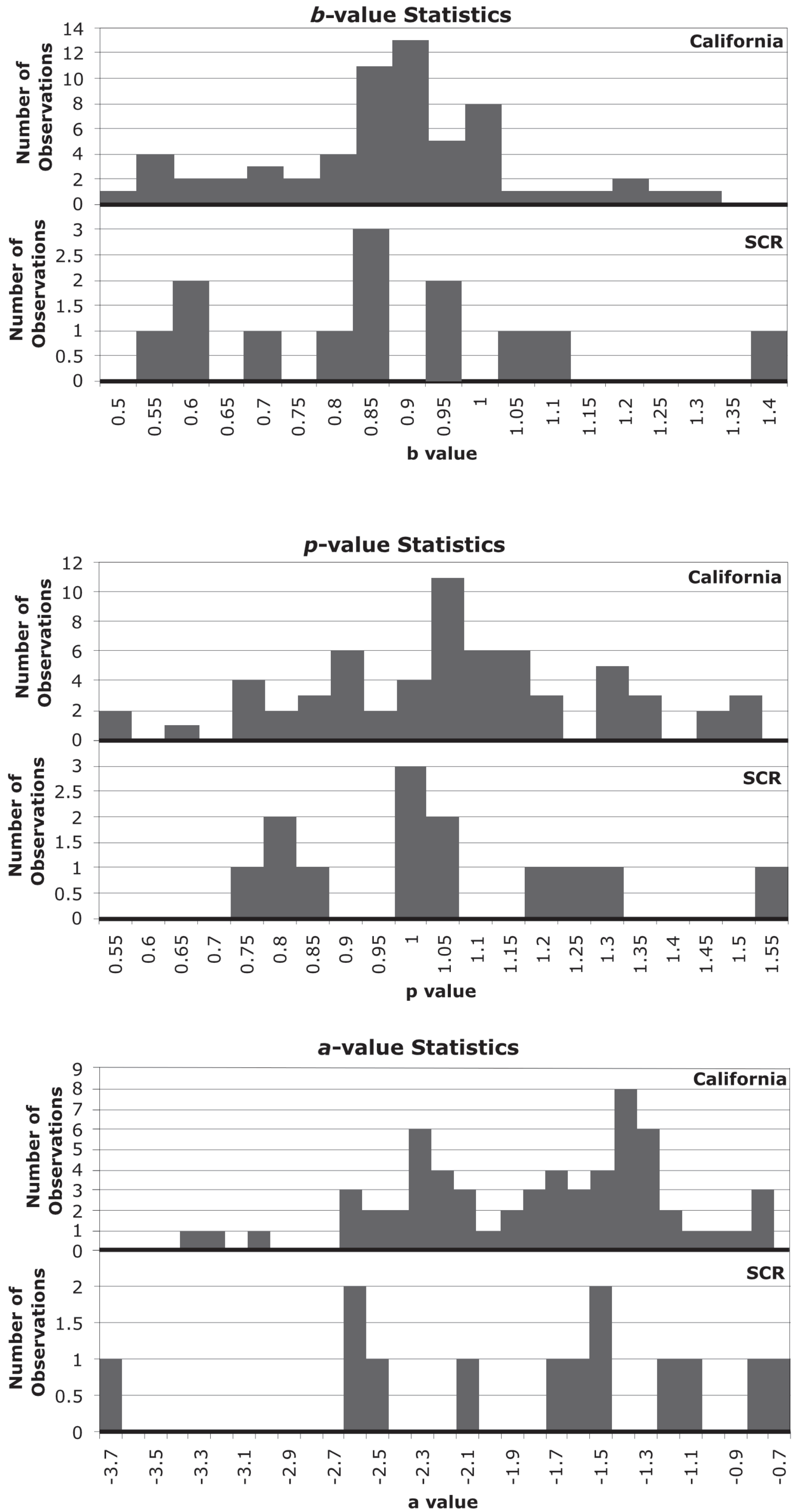
Figure 1 shows how the a, b, and p parameters found for the SCR events in this study compare to the distributions of those same parameters for California. For the b-value data, the mean values are 0.872 ± 0.171 for California and 0.865 ± 0.226 for the SCR data. The mean p values are 1.060 ± 0.221 for California and 1.046 ± 0.221 for the SCR data, and the mean a values are -1.800 ± 0.578 for California and -1.815 ± 0.821 for the SCR data. The 95% confidence intervals for the differences in the means (Mendenhall *et al.* 2009) between the California and SCR data for each Omori-law variable were computed using small-sample inference. In this statistical test, the null hypothesis is that there is no difference between the means of the two samples, while the alternative hypothesis is that the two samples have different means. The differences in the means and their corresponding 95% confidence intervals of the b value, p value, and a value are 0.006 ± 0.110, 0.014 ± 0.134, and 0.015 ± 0.380, respectively. In all three cases the 95% confidence intervals include the value 0, which means that the null hypothesis cannot be rejected for any of the variables. In a second test, the California and SCR b-value data, p-value data, and a-value data were each divided into equally spaced bins, the distributions each normalized to unit area, and a chi-square test (Mendenhall *et al.* 2009) of the match of the California and SCR distributions was conducted. The number of bins used for the b-value data, the p-value data, and the a-value data was seven, 10, and five, respectively. The null hypothesis in this test is that the California and SCR distributions are the same, while the alternative hypothesis is that the two distributions are different. For all three variables, the null hypothesis in this test has less than a 2% chance of being rejected. Thus, from both statistical tests I conclude that the distributions of the SCR Omori-law aftershock parameters cannot be distinguished from the distributions of those same parameters for aftershock sequences in California. This means that the generic California aftershock a, b, and p parameters ($a = -01.67$, $b = .91$, and $p = 1.08$) reported in the work by Reasenberg and Jones (1989) also can be used to describe generic SCR aftershock sequences.

APPLICATION OF THE RESULTS OF THIS STUDY TO AFTERSHOCK FORECASTING IN SCRs

This study suggests that the kind of aftershock forecasting that is currently carried out in California can be applied in the same way to stable continental regions on a global basis. As soon as a large SCR earthquake occurs, the generic California aftershock parameters can be used to make an initial estimate of the probabilities of the number of expected aftershocks above some minimum magnitude in the coming days. This can be the basis of an initial public forecast of the number of aftershocks that can be expected. In many cases, the aftershock activity within the first half to one day of a mainshock should be sufficient to update the Omori-law a parameter and to issue revised forecasts of the probabilities of aftershock activity at various magnitudes. If a large number of aftershocks are recorded, the b and p Omori-law parameters can be calculated for the aftershock sequence and the forecast aftershock probabilities can be further refined. Obviously, if a strong SCR earthquake takes place at a locality that is being monitored by a regional or local seismic network, then many aftershocks will likely be recorded and there will probably be sufficient data to update the a, b, and p parameters. Even if a strong SCR earthquake takes place at a locality where there is no regional or local seismic network monitoring, global monitoring of the larger aftershocks by agencies like the USGS NEIC may allow the a, b, and/or p parameters in Omori's law to be updated if a sufficient number of aftershocks are detected. Thus, even for poorly monitored SCR areas it may be possible to issue revised aftershock probability forecasts after some aftershock activity has been detected teleseismically.

In addition to forecasting the probabilities of numbers of events at different magnitude levels, the statistics in this study provide a basis for forecasting the possibilities of strong aftershocks. The largest aftershock is most likely about 1.3 magnitude units less than the magnitude of the mainshock. Based on the SCR data set analyzed in this study, the largest magnitude aftershock has about a 40% chance of occurring within five days of the mainshock and about a 70% chance of occurring within 60 days of the mainshock. However, about 30% of the time the largest SCR aftershock will occur more than 60 days, and perhaps as late as 1½ years, after the mainshock. Also, if the initial SCR event that triggers the forecast has $\mathbf{M} \geq 4.5$, then the statistics described above suggest that there is about a 5% chance that a comparable or stronger earthquake will take place near the same location during the subsequent 30 days.

The aftershock sequence of the 18 April 2008 **M** 5.2 Mount Carmel, Illinois, earthquake can be used to illustrate how aftershock forecasting might take place in the CEUS, a



▲ **Figure 1.** Distributions of the Omori-law parameters *b*, *p*, and *a* for California earthquakes from Reasenberg and Matthews (1990) and for the SCR earthquakes from this study.

stable continental region. Immediately after the Mount Carmel mainshock took place, an aftershock forecast could have been issued based on the generic California aftershock model of Reasenberg and Jones (1989). That forecast would have stated that about 29 aftershocks of **M** ≥ 2.0 could be expected during the next 24 hours, and about 43 aftershocks of **M** ≥ 2.0 could be expected during the next seven days. The largest aftershock expected would be about **M** 3.8, and there was about a 5% chance that an event larger than **M** 5.2 could take place. The first 24 hours after the mainshock yielded eight earthquakes of **M** ≥ 2.0, many fewer than the 29 that would have been initially forecast. This rate of aftershocks during the first day after the mainshock could have been used to find a revised a parameter in Equation 1, yielding the following revised Omori-law parameters: $a = -2.22$, $b = 0.91$, and $p = 1.08$. Based on these Omori-law parameters, a second forecast could have been issued exactly one day after the Mount Carmel mainshock, specifying that about two aftershocks of **M** ≥ 2.0 could be expected during the next 24 hours and about four aftershocks of **M** ≥ 2.0 could be expected during the next seven days. In fact, two aftershocks with **M** ≥ 2.0 were observed during the second day after the mainshock and eight aftershocks with **M** ≥ 2.0 were observed during the seven days after this second forecast would have been issued. The largest event observed during the aftershock sequence through 8 July 2008, was **M** 4.6. This is 0.6 magnitude units smaller than the mainshock and is almost one standard deviation greater than the mean mainshock-aftershock magnitude difference. However, this difference between the magnitude of the Mount Carmel mainshock and its largest aftershock is well within the range of our SCR data set, as documented in Table 2.

CONCLUSIONS

The results of this research provide a statistical basis, based on observations of past SCR events, for developing capabilities to issue aftershock and foreshock forecasts following the occurrences of large SCR events. As in California, the forecasts would need to be probabilistic in nature. They could inform the public about how many felt or strong aftershocks to expect, and they could warn the public of the potential that a larger earthquake might take place in the near future. Because of the wide variation in SCR aftershock behavior, from very productive aftershock sequences to mainshocks with almost no observed aftershocks, an initial aftershock forecast issued immediately after an SCR mainshock would have a large range of uncertainty. However, after just one day of aftershock monitoring, a revised aftershock forecast with a reduced level of uncertainty could be issued. The results of the analyses presented in this report can have a direct impact on reducing the losses from future earthquakes in stable continental regions. Forecasts of aftershock and foreshock probabilities would be useful for emergency managers, public officials, and search-and-rescue teams. Such forecasts would also help the public to understand the potential for future earthquake activity following the occurrence of a felt or damaging SCR earthquake.

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