# Dependence of Possible Characteristic Earthquakes on Spatial Sampling: Illustration for the Wasatch Seismic Zone, Utah


## Seth Stein
**Northwestern University**

## Anke Friedrich
**Universität Potsdam***

## Andrew Newman
**Los Alamos National Laboratory**


## INTRODUCTION

An important issue for regional tectonics and earthquake hazard estimation is whether large earthquakes are "characteristic", more frequent than would be inferred from the rates of smaller events. A challenge in resolving this question is that the rates of small earthquakes are typically determined from the seismologically recorded earthquake history, whereas the rates of large earthquakes are inferred from paleoseismic observations. As a consequence, different results from comparing the two can arise depending on the specific assumptions made and time and space sampling used.

In general, earthquake recurrences approximately follow a log-linear, *b*-value, or Gutenberg-Richter relation, $\log N = a - bM$, with $b \sim 1$, such that the logarithm of the annual number ($N$) of earthquakes above a given magnitude ($M$) decreases linearly with magnitude (Ishimoto and Iida, 1939; Gutenberg and Richter, 1944). Studies of specific areas, however, which commonly address the short history of seismological observations by combining seismological data for smaller earthquakes with paleoseismic data or geologic inferences for larger earthquakes, sometimes infer that large "characteristic" earthquakes occur more frequently than expected from the log-linear frequency-magnitude relation observed for smaller earthquakes (Schwartz and Coppersmith, 1984).

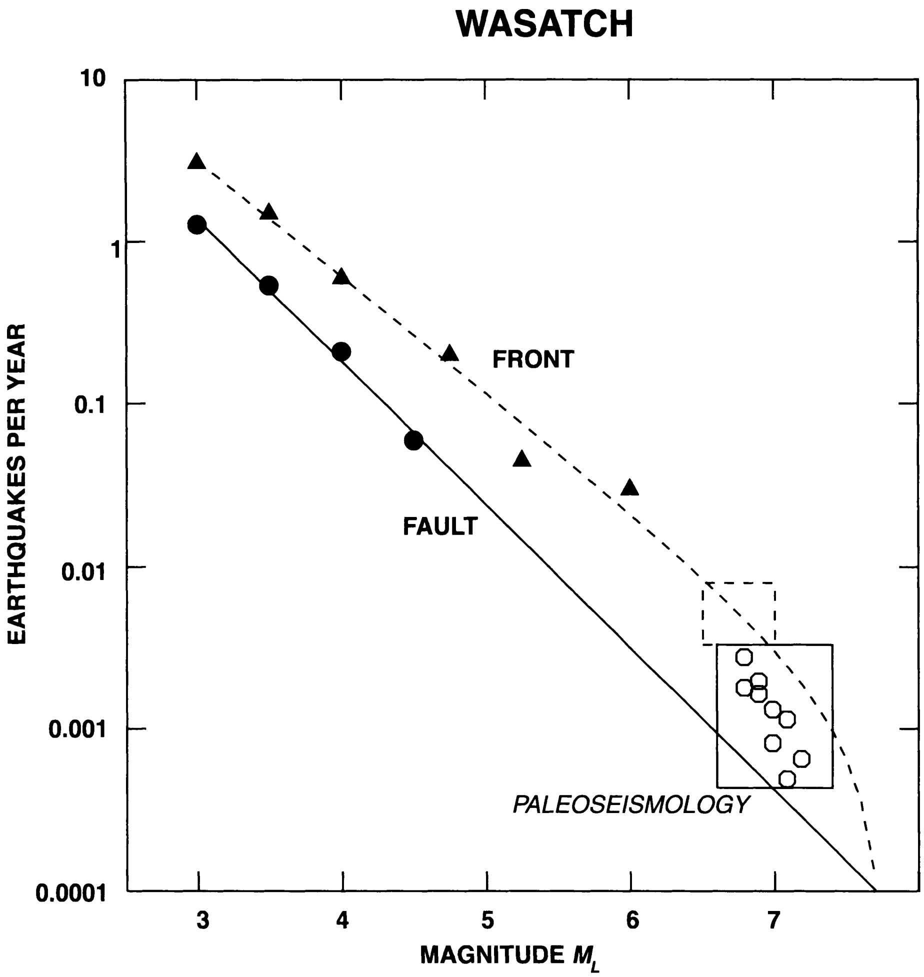
Whether characteristic earthquakes are real or apparent in any given region is an interesting question (Kagan, 1996; Wesnousky, 1996). A number of effects can give rise to apparent characteristic earthquakes or "uncharacteristic" earthquakes, ones that appear to occur less frequently than expected from the rates of smaller earthquakes (Stein and Newman, 2004). One bias can result from a short recorded earthquake history, in particular if its length is comparable to the mean recurrence time of large earthquakes predicted by a Gutenberg-Richter distribution. A second bias can result from errors in estimating the size or frequency of the largest earthquakes from the paleoseismic record (Stein and Newman, 2004; Street *et al.*, 2004). A third, which we consider here, is the spatial extent of the seismic zone under consideration.

## WASATCH SEISMIC ZONE

The Wasatch seismic zone is one of the first areas for which characteristic earthquakes were proposed (Schwartz and Coppersmith, 1984). Results from subsequent studies lead to opposing conclusions (Figure 1). Pechmann and Arabasz (1995) and Hecker (1993) found that the rate of present seismicity is consistent with that inferred from the sizes and dates of large paleoearthquakes inferred from fault scarps over the past 15,000 years. Hence, from these data no characteristic earthquakes need be postulated. In contrast, Chang and Smith (2002) found that the rate of present seismicity underpredicts the frequency of large paleoearthquakes, which would thus be characteristic earthquakes.

The linear frequency-magnitude relation (Figure 1) was derived for the Wasatch front area (Figure 2) from an earthquake catalog containing 61 events with local magnitudes 3–6 after declustering to remove foreshocks and aftershocks. Pechmann and Arabasz (1995) fit the recurrence with a truncated exponential relation:

*Now at Universität Hannover.

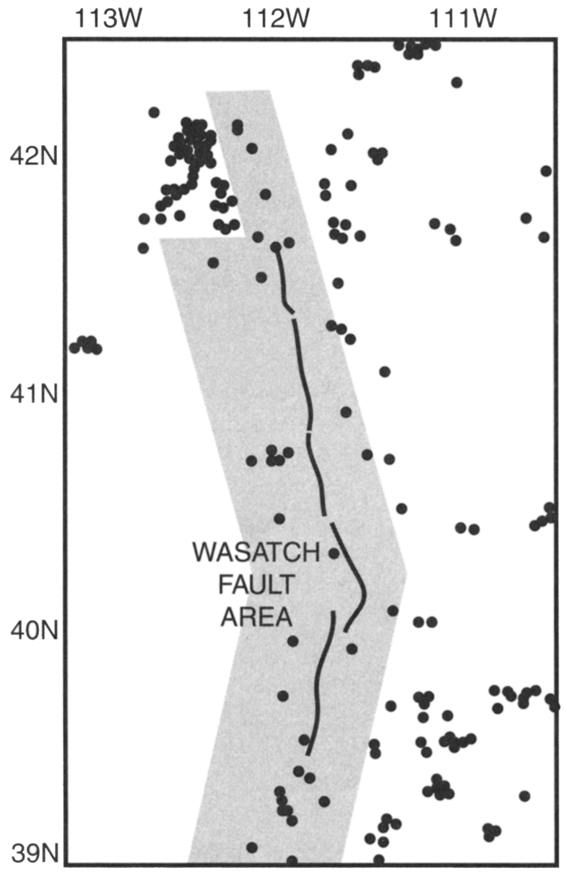



▲ **Figure 1.** Comparison of instrumental and paleoseismic earthquake recurrence rate estimates. For the Wasatch front, triangles are binned earthquake rates, dashed line is fit to them, and dashed box is estimated range from paleoearthquakes (Pechmann and Arabasz, 1995). For the Wasatch Fault, closed circles are binned earthquake rates (Chang and Smith, 2002 and personal communication), solid line is fit to them, closed circles are from paleoearthquakes, and solid box gives their range. Instrumental data for the front are consistent with the paleoseismic results and so do not imply the presence of characteristic earthquakes, whereas those for the fault underpredict the paleoseismic rate and so imply the presence of characteristic earthquakes.

$$N(M_L) = a10^{-b(M_L-3)} - c \,, \qquad (1)$$

with $a = 3.2$, $b = 0.72$, and $c = 1.2 \times 10^{-3}$, which is linear below about $M_L$ 6.5 and then decays to account for an assumed regional maximum magnitude of 7.75. These results were compared to an annual rate of surface-faulting earthquakes during the past 15,000 years inferred from paleoseismic data by Hecker (1993). These have an estimated magnitude range of $M_w$ (similar to $M_L$) 6.5–7.0 and recurrence interval of 125–300 years. Comparing the linear fit to the paleoseismicity, Pechmann and Arabasz (1995) concluded that extrapolating the rate of small instrumentally recorded earthquakes is consistent with the paleoseismically inferred rate of large earthquakes, as also noted by Hecker (1993) using earthquake recurrence data from Arabasz *et al.* (1992).

Figure 1 also shows a linear fit ($a = 2.78$, $b = 0.88$) to the recurrence of earthquakes in the Wasatch Fault area. The rates are for earthquakes with $M_L$ between 3–5 from the declustered catalog used by Chang and Smith (2002) and kindly provided to us. The 43 earthquakes (43, 18, 7, and 2 with magnitudes greater than 3, 3.5, 4, and 4.5, respectively) spanning 1962–1996 yield a lower recurrence rate because the Wasatch Fault area is only part of the Wasatch front (Figure 2). Chang and Smith (2002) compared the small earthquake data to an updated paleoseismic data set for the Wasatch Fault area, with paleoearthquake magnitudes inferred from the estimated rupture length and displacement (Wells and Coppersmith, 1994). Two rates can be inferred for several magnitudes because some fault segments may have ruptured simultaneously. The solid box shows a range ($M_w$ 6.6–7.4; recurrence interval 300–2,300 years) representing these results and an informal estimate of their uncertainty. This uncertainty reflects only that due to differences between single and multisegment rupture assumptions and in estimating magnitude using the Wells and Coppersmith (1994) relations for normal faults, which we estimate as about 0.2 units from




▲ **Figure 2.** Comparison of seismicity and paleoseismicity sampling areas for the Wasatch front (entire map area) and Wasatch Fault (gray area). Solid line denotes Wasatch Fault (after Chang and Smith, 2002).

the different values that emerge using either length or displacement (Mason, 1996). Other uncertainties include those in estimating fault length and displacement from geologic observations.

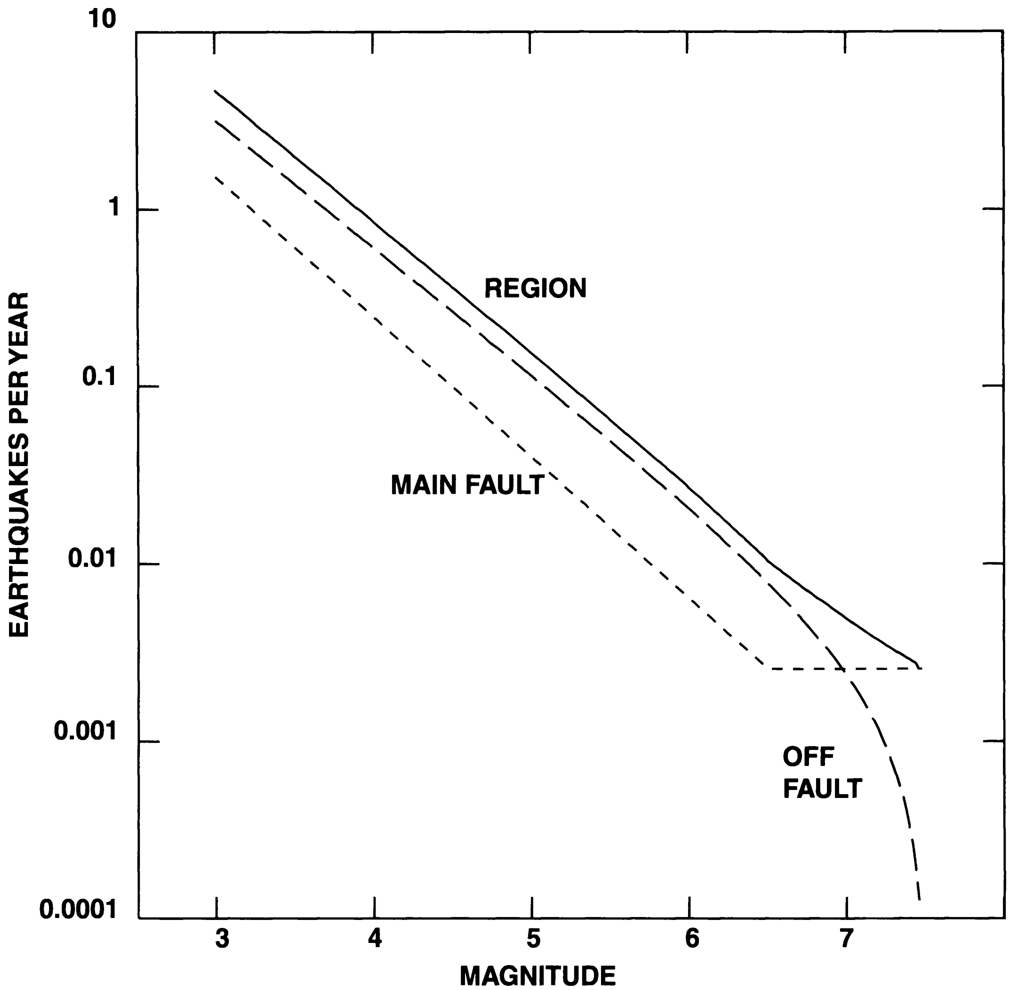
The earthquake and paleoseismic data used by Chang and Smith (2002) thus indicate that the rate of small earthquakes underpredicts that of large paleoearthquakes. Their interpretation seems plausible to us, although our figure differs from theirs in several ways. We plot $M_L$ as did Pechmann and Arabasz (1995), because the earthquake data are reported that way, whereas Chang and Smith (2002) converted the magnitudes using $M_w = 1.24\, M_L - 1.61$. This conversion would have some effect at low ($M_L$ 3, $M_w$ 2.1) and intermediate ($M_L$ 5, $M_w$ 4.6) magnitudes but little for the large ($M_L$ 7, $M_w$ 7.1) paleoseismic events, for which the difference is comparable to or less than the uncertainty in estimating the magnitude. Our $b$ value for $M_L$ (0.88) is consistent with theirs for $M_w$ (0.76). We plot Pechmann and Arabasz's (1995) values directly, whereas Chang and Smith (2002) scaled both their values and recurrence relation down by a factor of 0.17, reflecting the relative areas of the Wasatch Fault and front. Even so, their instrumental recurrence values appear to have been misplotted, and the recurrence equation given in their appendix for the Wasatch Fault is actually Pechmann and Arabasz's (1995) estimate for the Wasatch front. Nonetheless, we find that their catalog and paleoseismic estimates favor characteristic earthquakes on the Wasatch Fault.

Thus previous studies' results lead to different conclusions consistent with the assumptions those studies made. The crucial point is that Pechmann and Arabasz (1995) compare the recurrence of small earthquakes to that of paleoearthquakes in the entire Wasatch front region, whereas Chang and Smith (2002) compare the rate of paleoearthquakes on the Wasatch Fault to that of smaller earthquakes in an area around the Wasatch Fault. The fault area used by Chang and Smith (2002) is only 17% of the front area but contains about 50% of the paleoearthquakes (Hecker, 1993) considered by Pechmann and Arabasz (1995). For the curves in Figure 1, the paleoseismicity fraction is comparable to the ratio of seismicity rates on the fault and in the front for $M > 3$ (0.42) but higher than that for larger magnitudes (*e.g.*, 0.22 for $M > 5$), owing to the apparently higher $b$ value on the fault. Thus for these values, the fault area contains a higher fraction of the large paleoearthquakes than would be inferred from seismicity. As a result, the front region does not show characteristic earthquake behavior, whereas the fault region does. Whether this difference is real depends on how well the seismicity and paleoseismicity rates and hence differences between them can be estimated, which is not our focus here.

## DISCUSSION

We suspect that similar issues may arise in other seismic zones containing a major fault and a number of smaller ones. This situation is illustrated in Figure 3 for a hypothetical seismic zone in which seismicity on the main fault shows characteristic earthquakes, whereas seismicity off the fault obeys a truncated exponential relation. Adding the two recurrence relations gives that for the region as a whole, which for these values is essentially linear because at magnitudes above about 6.5 the seismicity off the main fault is less than predicted from linear recurrence, whereas that on the main fault is higher. This situation can be viewed as a specific case of Wesnousky's (1984) model in which regional seismicity shows Gutenberg-Richter behavior because it is a sum of many faults, each with a characteristic earthquake distribution whose largest magnitude is controlled by the length of the fault.

The Wasatch example thus illustrates the difficulty in identifying or excluding characteristic earthquake behavior. Such analyses typically involve comparing seismological and paleoseismic data, each with its own uncertainties, some of which reflect issues of temporal and spatial sampling. As we have seen, different spatial selections within a seismic zone can give different answers. It is not clear there is a right or wrong way to do this. In the example of Figure 3, analyses of regional seismic hazard might simply use the overall linear recurrence relation. Alternatively, one could divide the area into a main fault with characteristic earthquakes and an off-fault area with a truncated exponential relation.




▲ **Figure 3.** Recurrence relations for a hypothetical seismic zone. The main fault shows characteristic earthquakes, whereas seismicity off the fault obeys a truncated exponential relation. Adding the two recurrence relations gives an essentially linear relation for the region as a whole.

The toughest issue remains that of temporal sampling, because earthquake recurrence often seems quite irregular on different time scales. Friedrich *et al.* (2003) found that strain release in the Wasatch region has varied significantly over millions of years, with pulses of intense seismicity such as the present one occurring at periods of ~10,000 years. The Wasatch Fault paleoearthquakes considered in Figure 1 occurred within the past 6,000 years, whereas none was identified from about 15,500–6,000 ka (Chang and Smith, 2002). In contrast, the instrumental earthquake record samples less than 50 years. Hence even if the apparent characteristic earthquake behavior on the Wasatch Fault is not due to uncertainties in the instrumental and/or paleoseismic data, it is unclear whether one can interpret the discrepancy between the rates of large and small earthquakes as reflecting temporal sampling, real changes in rates of seismicity, or characteristic earthquake behavior due to the underlying physics of earthquake rupture. ◼

## ACKNOWLEDGMENTS

We thank Wu-Lung Chang and Robert Smith for helpful discussions and use of their earthquake catalog, and Walter Arabasz, James Pechmann, and Susan Hough for valuable comments. We also thank Giovanni Sella for graphic assistance and the Institute of Geosciences, University of Potsdam, for supporting Stein's visit. Manuscript is approved for unlimited public release by Los Alamos National Laboratory; LA-UR-05-0511.

## REFERENCES

Arabasz, W., J. C. Pechmann, and E. D. Brown (1992). Observational seismology and the evaluation of earthquake hazards and risk in the Wasatch front area, Utah, in P. L. Gori and W. W. Hays (editors), *Assessment of Regional Earthquake Hazards and Risk along the Wasatch Front, Utah,* U.S. Geological Survey Professional Paper 1500-A-J, D1–D36.

Chang, Wu-Lung and Robert B. Smith (2002). Integrated seismic-hazard analysis of the Wasatch front, Utah, *Bulletin of the Seismological Society of America* **92**, 1,904–1,922.

Friedrich, A. M., B. P. Wernicke, N. A. Niemi, R. A. Bennett, and J. L. Davis (2003). Comparison of geodetic and geologic data from the Wasatch region, Utah, and implications for the spectral character of Earth deformation at periods of 10 to 10 million years, *Journal of Geophysical Research* **108**, doi:10.1029/2001JB000682.

Gutenberg, B. and C. F. Richter (1944). Frequency of earthquakes in California, *Bulletin of the Seismological Society of America* **34**, 185–188.

Hecker, S. (1993). Quaternary tectonics of Utah with emphasis on earthquake-hazard characterization, *Utah Geological Survey Bulletin* **127**, 158.

Ishimoto, M. and K. Iida (1939). Observation sur les seismes enregistres par le microsismographe construit dernierement, *Bulletin of the Earthquake Research Institute, Tokyo University* **17**, 448–478.

Kagan, Yan Y. (1996). Comment on "The Gutenberg-Richter or characteristic earthquake distribution, which is it?" by Steven G. Wesnousky, *Bulletin of the Seismological Society of America* **86**, 274–285.

Mason, David B. (1996). Earthquake magnitude potential of the Intermountain seismic belt, USA, from surface-parameter scaling of late Quaternary faults, *Bulletin of the Seismological Society of America* **86**, 1,487–1,506.

Pechmann, J. C. and W. Arabasz (1995). The problem of the random earthquake in seismic hazard analysis: Wasatch front region, Utah, in W. R. Lunt (editor), *Environmental and Engineering Geology of the Wasatch Front Region: 1995 Symposium and Field Conference*, Utah Geol. Association, 77–93.

Schwartz, D. P. and K. J. Coppersmith (1984). Fault behavior and characteristic earthquakes: examples from the Wasatch and San Andreas fault zones, *Journal of Geophysical Research* **89**, 5,681–,698.

Stein, Seth and Andrew Newman (2004). Characteristic and uncharacteristic earthquakes as possible artifacts: applications to the New Madrid and Wabash seismic zones, *Seismological Research Letters* **75**, 170–184.

Street, Ron L., Robert A. Bauer, and Edward A. Woolery (2004). Short note: Magnitude scaling of prehistorical earthquakes in the Wabash Valley seismic zone of the central United States, *Seismological Research Letters* **75**, 637–641.

Wesnousky, Steven G. (1996). Reply to Yan Kagan's "Comment on 'The Gutenberg-Richter or characteristic earthquake distribution, which is it?' by Steven G. Wesnousky," *Bulletin of the Seismological Society of America* **86**, 286–291.

Wesnousky, Steven G. (1994). The Gutenberg-Richter or characteristic earthquake distribution, which is it?, *Bulletin of the Seismological Society of America* **84**, 1,940–1,959.



*Department of Geological Sciences*
*Northwestern University*
*Evanston IL 60208*
*(847)-491-5265;*
**seth@earth.northwestern.edu**
*(S.S.)*

*Institut für Geologie und Paläontologie*
*Universität Hannover*
*D-30167 Hannover*
*Germany*
**anke@mit.alum.edu**
*(A.F.)*

*Los Alamos National Laboratory*
*EES-9, MS D462*
*Los Alamos, NM 87545*
**anewman@lanl.gov**
*(A.N.)*