Artificial seismic acceleration

To the Editor — In their 2013 Letter, Bouchon *et al.*[1] claim to see a significant acceleration of seismicity before magnitude ≥6.5 mainshock earthquakes that occur in interplate regions, but not before intraplate mainshocks. They suggest that this accelerating seismicity reflects a preparatory process before large plate-boundary earthquakes. We concur that their interplate data set has significantly more foreshocks than their intraplate data set; however, we disagree that the foreshocks indicate a precursory phase that is predictive of large events in particular. Acceleration of seismicity in stacked foreshock sequences has been seen before[2,3] and has been explained by the cascade model, in which earthquakes occasionally trigger aftershocks larger than themselves[4]. In this model, the time lags between the smaller mainshocks and larger aftershocks follow the inverse power law common to all aftershock sequences, creating an apparent acceleration when stacked (see Supplementary Information).

A fundamental problem is that the catalogues used by Bouchon *et al.* — seismicity recorded in a 50-km radius prior to each mainshock — do not contain all earthquakes down to their chosen magnitude of completeness threshold of $M = 2.5$ (Supplementary Information), either in individual sequences or when combined. As a result, we argue the statistical analysis of the data, such as their finding that the Gutenberg–Richter value $b = 0.63$, and simulations based on that analysis are flawed (see Supplementary Information).

Bouchon and colleagues compare their data with simulations that use the cascade-model-based epidemic type aftershock sequence (ETAS) model[5]. The individual data sets are too small to constrain the ETAS parameters, so Bouchon *et al.* combine them. However, stacking incomplete sequences does not correct for the missing events. Bouchon and colleagues use a joint maximum-likelihood inversion to simultaneously determine ETAS parameters. Although common, this technique often leads to an erroneously low α value[6] — the value that determines the relative aftershock productivity between small and large mainshocks (see Supplementary Information). In simulations, this low value causes high rates of secondary aftershocks, slow sequence decay, and a weakening of the apparent acceleration due to foreshocks. We show that ETAS parameters, fit to earthquake catalogues from California, can produce acceleration comparable to the data used by Bouchon *et al.* (Supplementary Information). Although the ETAS parameters for California may not be applicable to other regions that are part of the data set used by Bouchon *et al.*, they demonstrate the existence of reasonable parameters that produce different behaviour than the simulations in Bouchon *et al.*

Bouchon and colleagues also compare the acceleration seen before the mainshocks with activity seen before nearby smaller earthquakes. The cascade model predicts that these stacks should be statistically identical. Unfortunately, Bouchon and colleagues only use a single set of smaller controls that are of unknown interplate or intraplate origin, and again the analysis uses an incomplete data set. We cannot determine the interplate versus intraplate origin of the small earthquakes, but using more controls and a higher completeness threshold brings the mainshocks and controls into agreement (Fig. 1).

In summary, we find that the tests performed by both Bouchon *et al.* and by us do not provide compelling evidence for precursory activity that could be used to predict large earthquakes at

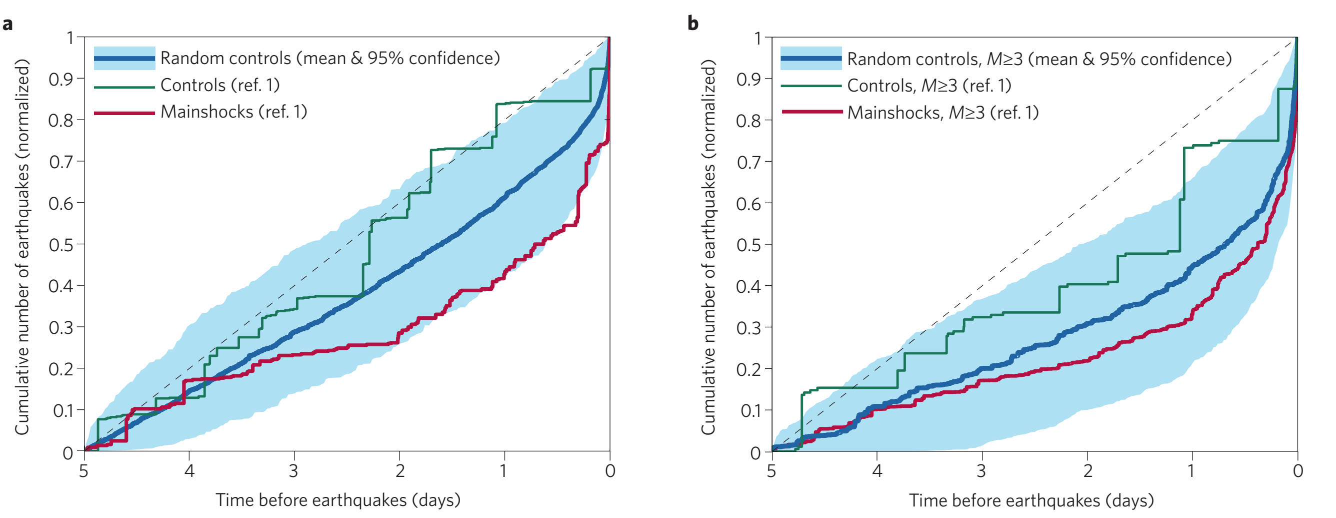

Figure 1 | Stacked earthquakes prior to the mainshocks discussed by Bouchon *et al.* compared with stacked earthquakes prior to randomly selected earthquakes. **a**, The mean of the randomized controls (blue) with 95% confidence bounds in grey (determined by Monte Carlo sampling random subsets the size of the data set compiled by Bouchon *et al.*), compared with the mainshocks from Bouchon *et al.* (red). More strict control earthquakes defined by Bouchon and colleagues (see text) are shown in green. **b**, Same asleft panel, but using only earthquakes with $M \geq 3$. While the mainshocks discussed by Bouchon *et al.* are marginally consistent with the random controls at $M \geq 2.5$, at $M \geq 3$ they are much more consistent.

plate boundaries. Although some large earthquakes may be preceded by slow slip and/or migration of seismicity, these processes have not been shown to be precursory for interplate $M \geq 6.5$ events in particular. For example, the foreshocks of the 2011 $M = 9.0$ Tohoku-Oki earthquake in Japan and the 2014 $M = 8.1$ Iquique earthquake in Chile abutted the mainshock hypocenter[7,8], thus aseismic slip is not required to connect the foreshocks and mainshocks. We therefore suggest that the seismic acceleration observed prior to interplate earthquakes can be explained by normal foreshock processes. ❐

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Additional information
Supplementary information is available in the online version of the paper.

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Reply to 'Artificial seismic acceleration'

Bouchon *et al.* reply — In our study[1], we show that most large magnitude $M \geq 6.5$ interplate earthquakes are preceded by an acceleration of seismic activity. The Correspondence from Felzer *et al.* questions our interpretation of this acceleration. It has long been recognized that one characteristic of seismic events is their natural tendency to cluster both in space and time, as evidenced by the presence of aftershocks following an earthquake. The debate raised by Felzer *et al.* is whether foreshocks result only from this tendency to cluster, that is, a first shock triggers others and eventually one of them triggers a large earthquake by something akin to a random throw. Felzer and colleagues advocate this interpretation. Alternatively, foreshocks may indicate an underlying mechanical process, such as slow fault slip, in which the foreshocks are simply the seismically visible signature — an interpretation we claim our observations favour.

Felzer and colleagues mostly question our calculation of two curves in our original Fig. 4a,b (shown in blue) and in Supplementary Fig. S15. These curves are intended to give an estimate of the acceleration of seismic activity expected from the clustering tendency of seismicity. They are based on a widely used statistical description of the temporal evolution of a sequence of seismic events — the epidemic type aftershock sequence (ETAS) model[2]. We are aware of the limited accuracy of these curves because they are based on statistics of a data set that is inherently limited. However, we disagree that a parameterization based on data from the Californian catalogues used by Felzer *et al.* is better than one based on the actual catalogues from the specific regions we studied. Regarding catalogue completeness, our hypothesis is that we can invert the ETAS parameters by mixing all the earthquake sequences because ETAS is a linear model. We suggest that this linearity justifies the inference of one magnitude of completeness for the set of sequences. Imposing a magnitude cut-off of $M = 3.0$, as Felzer and colleagues advocate, would eliminate the majority of foreshocks.

Felzer *et al.* also suggest that our value for the productivity parameter α is too low. However, inversions of ETAS parameters based on a likelihood function systematically provide values lower than $\alpha = 2.3$ obtained by Felzer *et al.* using the weakly constrained Bath's Law, a statistical law relating the magnitudes of the main shock and largest aftershock. For example, Zhuang *et al.*[3] analysed the Japanese catalogue, which covers an important part of the subduction zone we analysed, and obtained α values in the range 1.33 to 1.36. Similarly, in their study of worldwide seismicity, Chu *et al.*[4] obtained an α value of 0.89 for subduction zones. Finally, even seismicity in southern California[5] is found to be characterized by an α value of 1.03, similar to our estimates of 1.04. The α value used by Felzer and colleagues is thus likely to be too large.

It is regrettable that their Correspondence puts so much emphasis on the ETAS calculation. The ETAS model is inherently biased because it imposes a temporal-only description to a process that, in reality, involves the clustering of events both in time and in space. The observations we reported show that most of the foreshocks in our subduction data set, which makes up the majority of our database, do not cluster near the main shock hypocentre or near each other, but instead are spread over a broad area. Because these foreshocks cluster in time but do not cluster in space, as the ETAS model implicitly assumes, the ETAS model cannot provide a correct description of them. Indeed, the simple observation of the non-spatial clustering of many foreshocks (Fig. 4e in ref. 1) demonstrates, independently of the use of any model, that foreshocks are not generally the result of the tendency of seismic events to cluster both spatially and temporally. In physical terms, this means that many foreshocks are too distant from each other and too distant from the main shock hypocentre to trigger one another. ❐

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Artificial seismic acceleration

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I. HOW THE CASCADE MODEL EXPLAINS ACCELERATION IN STACKED FORESHOCK SEQUENCES

In the cascade model a large earthquake preceded by a foreshock is simply a large aftershock of a small mainshock. The events leading up to the large aftershock should follow an inverse power law decay with time, like any other aftershock sequence. It is this inverse power law decay in the individual sequences that leads to the appearance of acceleration when the sequences are stacked, as illustrated in Figure S1. Note that this model only explains acceleration seen in stacks of foreshock sequences and does not predict acceleration in individual foreshock sequences. To our knowledge no one has ever documented that clear routine acceleration is a common feature in individual foreshock sequences.

II. COMPLETENESS THRESHOLDS AND MAGNITUDE-FREQUENCY DISTRIBUTIONS

The Bouchon *et al.* dataset[1] consists of 50-km-radius regions surrounding mainshocks in well-instrumented areas around the Pacific Rim, each sampled for a year. Bouchon *et al.* assume that all of the regions have a completeness magnitude (M_c) of 2.5 and a Gutenberg-Richter b parameter of 0.63. This b-value is significantly lower than the value of 1.0 that is found by most global studies[2,3] and does not agree with what can be observed in the different regions individually (Figures S2, S3). To check this assertion, we determine the b-value and its uncertainty, assuming $M_c = 2.5$, for each of their 31 interplate earthquake catalogs (Figure S3). One region did not have enough data to analyze. Of the remainder 10 catalogs were within one standard deviation of 0.63, 15 were with two standard deviation, and 21 were within 3 standard deviations, with 9 catalogs being over 3 standard deviations away. If the Bouchon *et al.* model were a good description of the individual catalogs then we would have expected 29 to be within 2 standard deviations and only 1 to be over 3 standard deviations. We further determine that many of the regions are not complete to $M_c = 2.5$ (Figure S2), which is likely part of the reason they appear so heterogeneous and one of the reasons why the b-value that Bouchon *et al.* determine for the compilation was so low; differences in the JMA magnitude scale is another likely factor. Using a completeness threshold that is too low for many parts of the data set is problematic when solving for

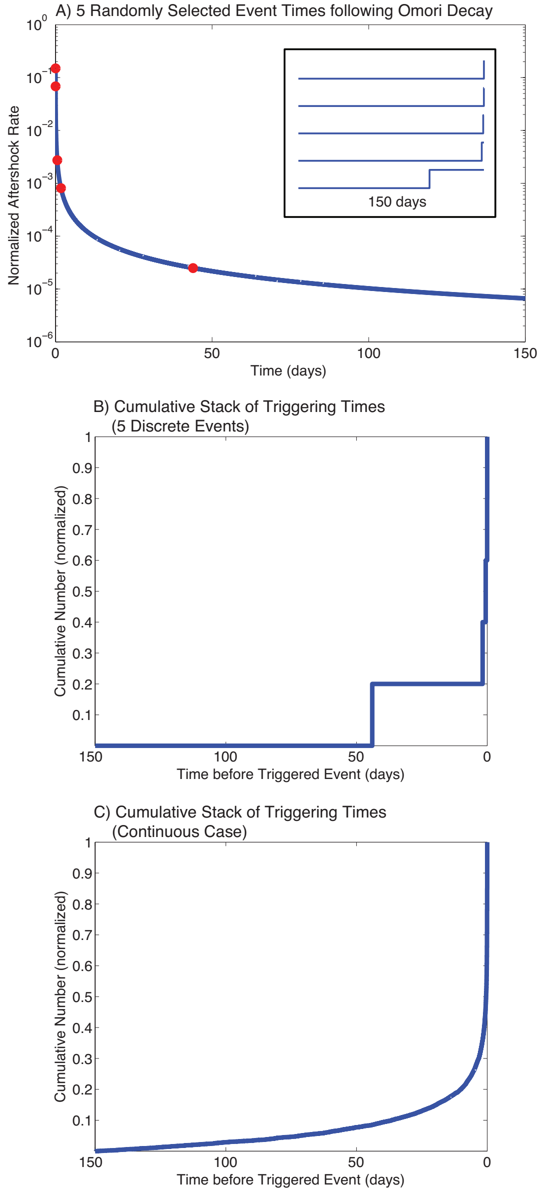

FIG. S1. Visual explanation of the origin of the inverse Omori law. (A) A simulated aftershock sequence following inverse power law decay (Omori's Law). The red dots are randomly selected aftershocks in the sequence, illustrating representative times that a mainshock could be triggered in a foreshock sequence. Note that because aftershock sequences have the vast majority of their activity at short times, most of the randomly selected shocks are at short times after sequence initiation. The inset shows the single step function at the time of each red dot; summing these step functions leads to plot (B), which shows a normalized stack of the 5 events. It can be seen that the preponderance of short mainshock to aftershock times leads to to the appearance of pre-mainshock acceleration. (C) Continuous model of (B).

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parameters as it will result in assigning inaccurate aftershock counts to many earthquakes. It also means that plots of statistical features of the data are likely to be inaccurate.

III. ETAS MODELING AND THE α PARAMETER

To solve for ETAS parameters, Bouchon *et al.* perform a maximum likelihood inversion on the data within 50 km of the epicenter and between 365 and 60 days prior to each mainshock. By not including the aftershocks of the largest events, they may have denied themselves the data best able to constrain the ETAS parameters. Perhaps more importantly, they also combine data from all of the mainshock regions. There is a clear desire to combine the data sets as many of them are so small individually that solving for sequence-specific ETAS parameters would be impossible. Nonetheless if the regions have heterogeneous characteristics the parameters solved from the composite data set will be inaccurate. In addition to the low b-value discussed above, the productivity parameter α found by Bouchon *et al.* is also quite low.

In ETAS aftershock modeling the parameter α determines relative aftershock productivity as a function of mainshock magnitude. In Bouchon *et al.* notation, the mean number of aftershocks triggered by an earthquake of magnitude M is proportional to $e^{\alpha M}$. Lower values of α result in higher aftershock production by smaller mainshocks, and hence to higher secondary aftershock production as aftershocks produce more aftershocks of their own. This in turn leads to slower total aftershock sequence decay. In the ETAS model a shallower inverse power law following mainshocks leads to a less pronounced inverse power law when foreshock sequences are stacked. In fact, the aftershock decay produced by the Bouchon *et al.* aftershock parameters is so slow that if we run simulations with a Gutenberg-Richter magnitude frequency distribution of simulated earthquakes we get super-critical sequences that never decay. If we run the simulations only sampling from magnitudes that are reported in the catalog, as instructed by Bouchon *et al.* (personal communication), the sequences remain sub-critical but have a low average decay constant, or indirect Omori p-value, of 0.23 (measured over a year following a $M7$ mainshock).

Bouchon *et al.* use a very low value of α in part because they solve for α using the standard MLE joint parameter inversion. This method is commonly used in the literature but routinely results in values that are too low. This issue is discussed by Helmstetter *et al.*[7]

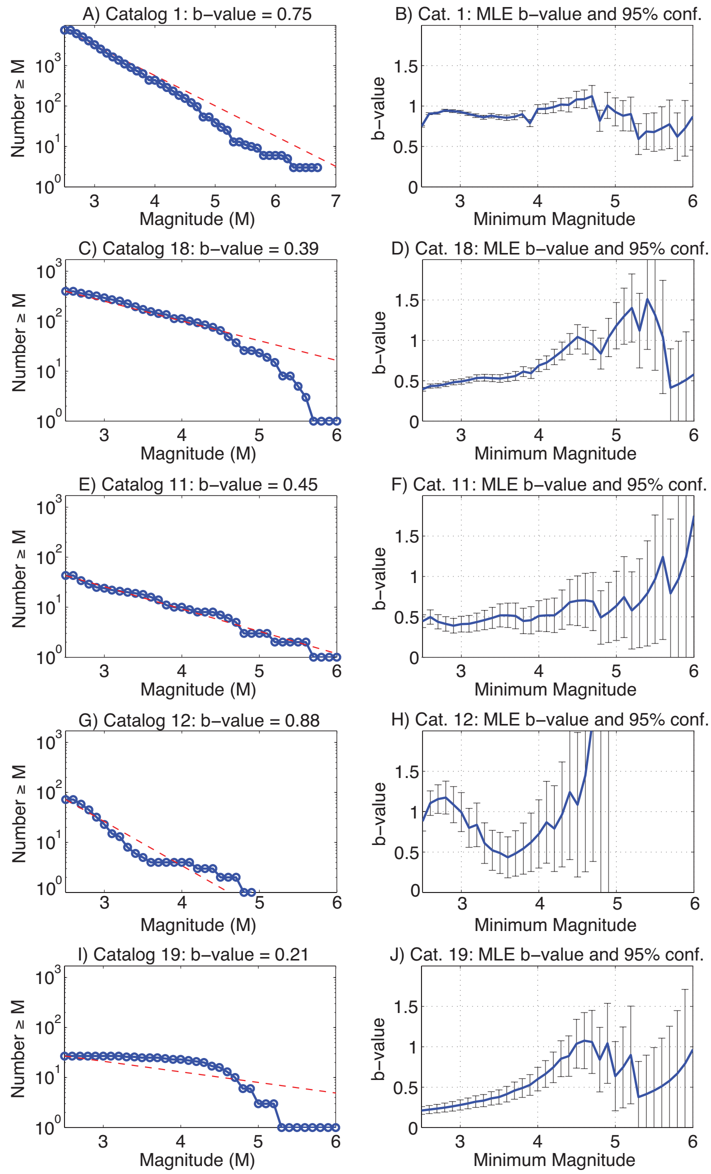

FIG. S2. Magnitude-frequency and b-value vs. minimum magnitude plots for representative Bouchon *et al.* interplate catalogs. The catalog numbers come from Bouchon *et al.* Table S1. Red dashed lines show the MLE (maximum likelihood estimate) b-values[4,5] estimated assuming a minimum completeness magnitude of 2.5. Some catalogs (A,B) show a fairly consistent b-value (in this case, for $M \geq 2.6$), while others show a much lower b-value at M 2.5 that in some cases (C,D) increases with magnitude and in other cases is stable (E,F). Some catalogs have quite volatile b-value estimates depending on the minimum magnitude assumed (G,H). Still other catalogs (I,J) show clear catalog incompleteness at low magnitudes that results in an extremely poor b-value fit if a completeness magnitude of 2.5 is assumed.

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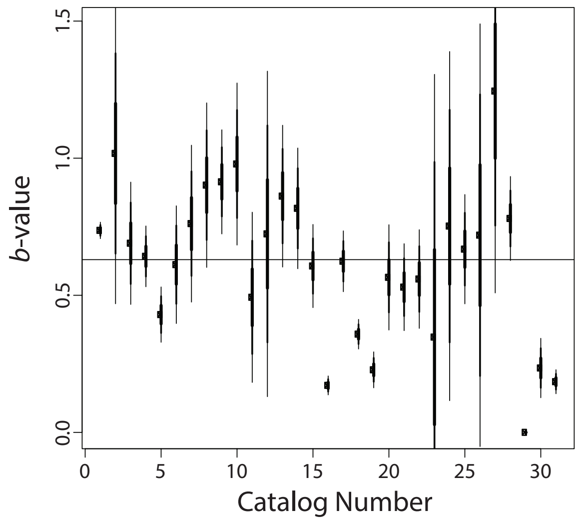

FIG. S3. The b-value of the Gutenberg-Richter distribution for the 31 interplate catalogs from the Bouchon *et al.* dataset. The catalog numbers come from Bouchon *et al.* Table S1. The b-values and uncertainties were determined using the maximum-likelihood method[4,5] corrected for binning[6]. The 1, 2, and 3 standard deviation uncertainties are plotted as the thickest to thinnest lines with the circle showing the maximum-likelihood value. The horizontal line is $b = 0.63$, the value solved for the union of these 31 catalogs by Bouchon *et al.* Note that the individual catalogs have heterogeneous b-values rather than showing a central tendency around $b = 0.63$. Thus, a model using $b = 0.63$ will not be a good representation of these catalogs.

(see page 4) and Kagan[8]. The reasons given by these authors for the problem include strong tradeoffs between the different ETAS parameters when they are solved for jointly, temporal variance in catalog completeness following larger earthquakes that is rarely modeled, and the fact that the standard MLE solution assumes an isotropic, circular pattern of aftershocks around mainshock epicenters when in fact the aftershocks of large earthquakes are actually distributed along fault planes. Helmstetter *et al.*[7] consider the last to be the most important issue, which results in many direct aftershocks of the mainshock being improperly assigned as aftershocks of other aftershocks. This in turn leads to the assignment of inaccurately high productivities to small earthquakes.

In fact, α does not need to be solved for as part of a joint inversion. Since the parameter simply reflects the mean relative number of aftershocks produced as a function of mainshock magnitude, we can hold the aftershock counting time and the aftershock area as a function of mainshock magnitude fixed and then find the best fit to a scatter plot of mainshock magnitude vs. total number of aftershocks, where the aftershocks are carefully counted above the completeness threshold of each sequence and the counts are corrected for the use of different completeness thresholds. Using this method Felzer *et al.*[9] found α to be very close to 2.3 (using Bouchon *et al.* notation; this is 1.0 if productivity is written in base 10 rather than base e), much higher than the base e value of 1.0 found by Bouchon *et al.*

The accuracy of $\alpha = 2.3$ can further be demonstrated with examples from the catalog. For example, using the UCERF3 catalog for California[10], we find 100 $M \geq 4$ earthquakes in the Landers aftershock zone in the week following the mainshock. The Landers sequence was certainly not an inactive one for California, and our ETAS modeling indicates that it had a roughly average activity rate for the state. It did, however, produce a largest aftershock in the first seven days of $M6.5$ rather than the mean Bath's Law expectation of $M6.1$, therefore it could be argued that it was possibly 2.5 times more active than an average sequence. We can take the Landers productivity rate, and an α value of 2.3 to project the mean aftershock productivity of an $M4$ mainshock in California. If we assume that Landers did indeed have an average activity rate, then it follows that $M4$ earthquakes in California should produce 0.05 $M \geq 4$ aftershocks on average; if we assume that Landers is 2.5 times more active than average this results in 0.02 $M \geq 4$ aftershocks/mainshock. The standard USGS California aftershock statement, based on observations, is that earthquakes have a 5% to 10% chance of triggering an aftershock equal to or larger than themselves, so the first value is in agreement with observations. Doing the same calculation with $\alpha = 1.0$, as solved for by Bouchon *et al.* implies that a $M4$ earthquake in California should produce, on average, 1.4 to 3.6 $M \geq 4$ aftershocks. That is, each $M4$ and smaller earthquake should routinely be triggering multiple aftershocks larger than itself, which is in clear conflict with observations. Again using $\alpha = 1$ we also get that each $M5$ in California is expected, on average, to trigger 0.5 to 1.0 additional $M \geq 5$ events, again clearly in conflict with the observations. The same exercise can be run with other large/small earthquake pairs as long as the catalog completeness for each aftershock sequence is appropriately accounted for and the fact is noted that the number of aftershocks produced by small earthquakes tends to be quite variable, so a number of small mainshocks should be averaged together for the best accuracy.

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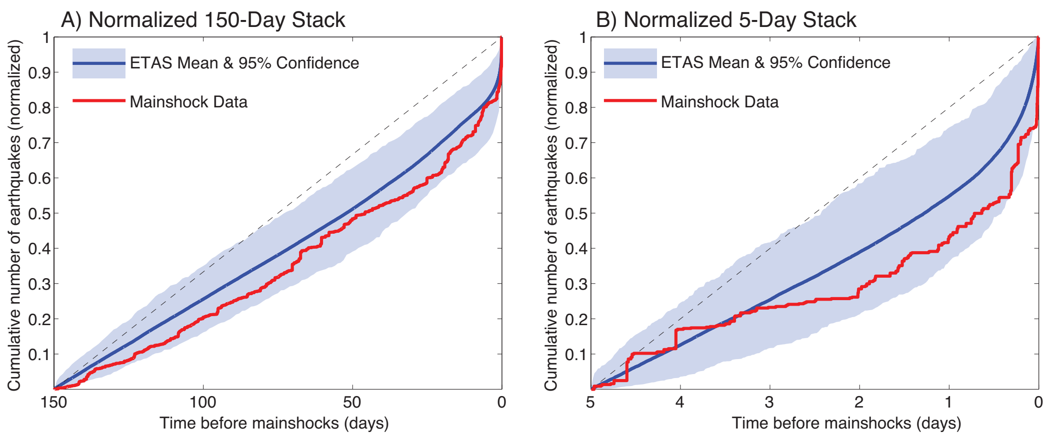

FIG. S4. Stacked sequences of foreshocks from ETAS simulations using the California parameters solved by Hardebeck *et al.*[11] (A) Normalized stacked seismic activity for 150 days preceding the mainshocks and (B) normalized stacked seismic activity for 5 days preceding the mainshocks. The blue line gives the average of the simulations and the gray area gives the 95% confidence zone. The red lines give the real data before the mainshocks identified by Bouchon *et al.*

IV. ALTERNATIVE ETAS SIMULATIONS

We would like to recreate the Bouchon *et al.* ETAS simulations with more accurate parameters, but the variable and ill-constrained catalog completeness and limited data set size in each region make it very difficult to solve for accurate ETAS parameters in the Bouchon *et al.* regions. Therefore for demonstration purposes only we run proxy simulations with published ETAS parameters for California[11] to get a general idea of how simulations with one set of feasible parameters compares with the data. Our simulations with the California parameters show far more stacked seismicity acceleration than the Bouchon *et al.* ETAS simulations (Figure S4). Clearly this is not a rigorous test since we know that the California parameters are not exact matches for the seismicity in all the Bouchon *et al.* regions, but California is a subset of the regions investigated by Bouchon *et al.* Furthermore, this test is a simple proof of concept that parameters that are a closer fit to real data do produce significant acceleration in ETAS simulations.

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