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The debate on the prognostic value of earthquake foreshocks: A meta-analysis

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The hypothesis that earthquake foreshocks have a prognostic value is challenged by simulations of the normal behaviour of seismicity, where no distinction between foreshocks, mainshocks and aftershocks can be made. In the former view, foreshocks are passive tracers of a tectonic preparatory process that yields the mainshock (i.e., loading by aseismic slip) while in the latter, a foreshock is any earthquake that triggers a larger one. Although both processes can coexist, earthquake prediction is plausible in the first case while virtually impossible in the second. Here I present a meta-analysis of 37 foreshock studies published between 1982 and 2013 to show that the justification of one hypothesis or the other depends on the selected magnitude interval between minimum foreshock magnitude m_{min} and mainshock magnitude M. From this literature survey, anomalous foreshocks are found to emerge when $m_{min} < M - 3.0$. These results suggest that a deviation from the normal behaviour of seismicity may be observed only when microseismicity is considered. These results are to be taken with caution since the 37 studies do not all show the same level of reliability. These observations should nonetheless encourage new research in earthquake predictability with focus on the potential role of microseismicity.

Foreshock occurrence has for many years been considered as the most promising phenomenon to predict earthquakes; but while at least two successful evacuations based on foreshock observations have been claimed, for the 1975 Haicheng, China earthquake[1,2] and the 1995 Kozani-Grevena, Greece earthquake[3], numerous earthquakes show no precursory signal (e.g., the 2004 Parkfield, California earthquake had no fore-shocks or precursory deformation despite the dense instrumentation)[4]. The lack of systematic precursory patterns questions the prognostic value of foreshocks, although their non-systematic appearance may be due to a combination of aleatory and epistemic uncertainties on the rupture process[5]. Foreshocks observed prior to a larger earthquake may correspond to a triggering process[6,7], which is part of the normal behaviour of seismicity[8], or to a tectonic loading process associated to aseismic slip[5,9,10,11], representing a deviation from the normal behaviour (Fig. 1).

The normal behaviour of seismicity is well described by the Epidemic-Type Aftershock Sequence (ETAS) model[8], in which each event can trigger aftershocks (Fig. 1a). Aftershock generations, which follow the modified Omori time diffusion law, are superposed on a constant background rate. The event frequency-magnitude distribution is described by the Gutenberg-Richter (GR) law. This model implicitly assumes that any transient change in the seismicity is due to the triggering of an earthquake by another one. While any earthquake can produce numerous aftershocks of smaller magnitudes, there is a non-zero probability that it will also trigger a larger earthquake[12,13]. This GR-based statistical view forms the basis of current operational earthquake forecasting methods[14–16]. However, the probability of having for instance a $M = 6$ mainshock following a $m = 4$ foreshock in the next week is only $\Pr(M \mid m, \Delta t) = 0.8‰$[12], which is of limited use for general evacuations[16]. This low value reflects the fact that foreshocks are virtually non-informative in ETAS since the mainshock magnitude is independent of the foreshock pattern[6]. This view is in agreement with the concept of Self-Organized Criticality (SOC)[17] in which any event could cascade into a larger one[13].

Earthquake prediction theories relate foreshock occurrence to tectonic loading due to aseismic slip[5,9–11] (Fig. 1b). In earthquake nucleation theories[9–11], foreshocks are due to premonitory slow-slip within the nucleation zone of the mainshock. In the recently proposed Non-Critical Precursory Accelerating Seismicity Theory (N-C PAST)[5,18], foreshocks are due to the cumulated effects of constant loading on the fault that hosts the mainshock. These theories are supported by seismic and geodetic measurements[19] and are consistent with observations of repeating events in foreshock sequences[20,21] and tectonic tremors[22]. In the loading view, foreshocks are the passive tracers of the preparatory process of the mainshock and therefore carry information on the upcoming event. In this view, some large earthquakes are potentially predictable (i.e., potentially forecasted with a relatively high probability) even if in practice, no probabilistic model is yet available.
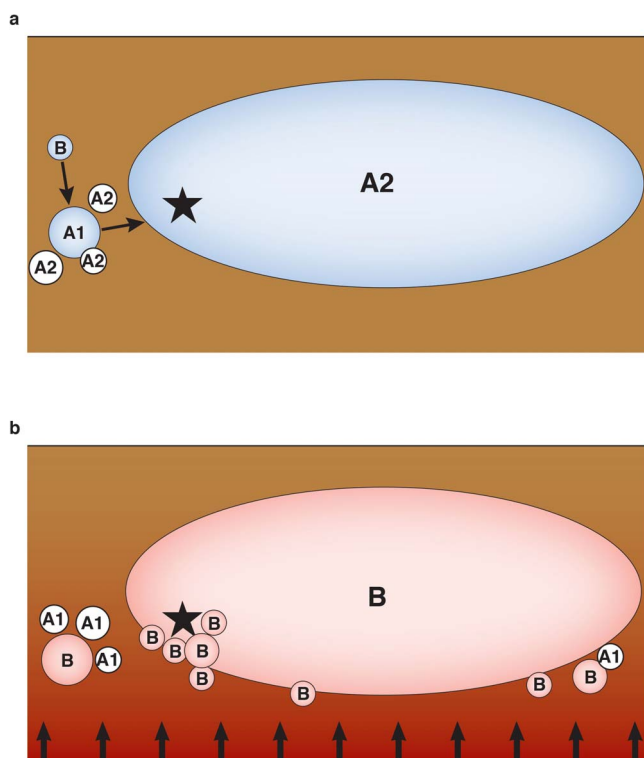
Figure 1 | Schematic depiction of the two main conflicting earthquake foreshock theories. Event magnitudes correlate to ellipse sizes. Arrows represent causal effects. The largest ellipse represents the mainshock and the star its hypocentre. Smaller coloured circles represent foreshocks. Aftershocks of the mainshock are not shown. **a,** Earthquake triggering process, as described by the ETAS model[6,7] or by Self-Organized Criticality[17]. Background events (B) can trigger aftershocks (A1), which in turn can trigger their own aftershocks (A2). There is a non-zero probability of an aftershock being larger than the trigger event[12]. **b,** Loading process by aseismic slip, as described by earthquake nucleation models[9–11] or by the N-C PAST[5]. The mainshock is due to constant tectonic loading on the hosting fault (red area, upward arrows). Foreshocks correspond to the part of background seismicity that is influenced by the same loading process. Some of the models predict a concentration of foreshocks at the location of the future mainshock hypocentre.

In this study, I consider that foreshocks correspond to any increase in seismic activity compared to past activity, in particular short-term foreshocks that are observed over seconds to days and within a fault length from the mainshock[23], and accelerating seismic release observed over weeks to months within several fault lengths from the mainshock[18]. It has recently been claimed that both types of foreshocks are undistinguishable from the ETAS process when using a relatively high minimum magnitude cutoff, for instance $m_{min} = 4.0$[24,25]. These results are however contradicted by investigations of well-recorded foreshock sequences based on $m_{min} \ll 4.0$[1,5,20,21,26–28] that suggest that aseismic slip is at the origin of foreshocks. This basic observation suggests that data selection may be the main reason for contradictory foreshock theories.

I present a meta-analysis of 37 studies published between 1982 and 2013 (Supplementary Table S1) to determine if the conflicting claims are correlated to the use of specific foreshock and mainshock magnitude ranges. Here I use as metric the mainshock magnitude M and minimum foreshock magnitude m_{min} (Fig. 2). For studies based on stacking, I consider the minimum mainshock magnitude M_{min} instead of M. Only studies in which foreshocks are observed, and their possible origin explained, are taken into account. Three types of arguments are considered: heuristic, statistical, and physical (i.e.,

static stress transfer theory). Most published studies select one of the two possible origins by verifying or disproving the earthquake triggering origin, which is better established than the loading origin, and can thus be considered as the null hypothesis. In these cases, loading by aseismic slip is proposed as corollary when earthquake triggering is rejected. Direct arguments for loading are mostly based on heuristic considerations, such as foreshocks distributed over large areas or foreshocks as repeating events, which are observations difficult to explain by earthquake triggering. However, heuristic approaches may be considered less reliable than statistical or physical ones. Of the 41 results provided in the 37 analyzed manuscripts, 23 support loading (i.e., 56%) and 18 triggering (i.e., 44%) (Table S1). This represents a reasonably homogeneous dataset. It should be noted that the data points presented in Figure 2 are based on the conclusions of the different peer-reviewed studies, whether they really do or do not represent the true foreshock process. No attempt has been made to rank the studies by the quality of their analyses. All 37 studies are considered equally valid. Studies that infer one theory or the other based on changes of the slope of the GR law, on power-law time-to-failure fitting, or on event migration, are not considered in our meta-analysis since these patterns can be explained indiscriminately by both theories[5,6,18].

In Figure 2, studies supporting loading by aseismic slip are represented in red, and earthquake triggering in blue. A correlation between the choice of M and m_{min} and the proposed origin of foreshocks is found. The emergence of an anomalous foreshock behaviour (i.e., due to loading by aseismic slip, Fig. 1b) is observed once microseismicity is included in the analysis, roughly with $m_{min} < M - 3.0$; otherwise foreshocks are best explained by the normal behaviour of seismicity (i.e., earthquake triggering, Fig. 1a). Overall, 25% of the data points (19 out of 77) diverge from the observed correlation. Looking only at the case $m_{min} < M - 3.0$, only 6% of the data points (2 out of 36) diverge from the correlation. These anomalies (no. 13 in Fig. 2 and Table S1 - for the 1999 $M = 7.1$ Hector Mine mainshock and $m_{min} = 2.0$; no. 33 for the 2011 $M = 9.0$ Tohoku mainshock and $m_{min} = 1.2$) suggest a triggering origin of foreshocks when using a criteria $m_{min} < M - 3.0$. However in the case of the Hector Mine mainshock, the claim is only based on "circumstantial evidences" and is in disagreement with another study investigating the same foreshock sequence (no. 16). In the case of the Tohoku mainshock, the seismicity is driven by the aftershock sequence of an $m = 7.3$ foreshock, which occurs only 2 days before the mainshock (confirmed by pers. comm., David Marsan, 2013). Another study (no. 31) claims a loading origin of the foreshocks preceding the Tohoku mainshock.

Additional trends derived from the meta-analysis (Table S1) are shown in Figure 3. I find that statistical approaches employing stacking methods (large data set analysis) tend preferentially towards an earthquake triggering origin of foreshocks. Arguments for loading are mostly based on the study of individual foreshock sequences (Fig. 3a). Second, when investigating the studies chronologically, I find that the popularity of the triggering view has increased over time in parallel to the development of statistical approaches based on stacking methods. Since the 2000's, there is no clear preference for any given theory of foreshock origin, showing that the debate continues (Fig. 3b).

The observed correlation between the choice of M and m_{min} and the proposed origin of foreshocks suggests that data selection is a possible reason for conflicting foreshocks theories. The debate on whether foreshocks have a prognostic value (loading by aseismic slip view) or not (earthquake triggering view) cannot however be solved solely based on the correlation shown in Figure 2. A proponent of the triggering view would argue that a higher m_{min} is required to reach completeness over a large data set and that only a systematic robust statistical analysis of a large population of mainshocks provides reliable results (Fig. 3). A proponent of the loading view, on the other
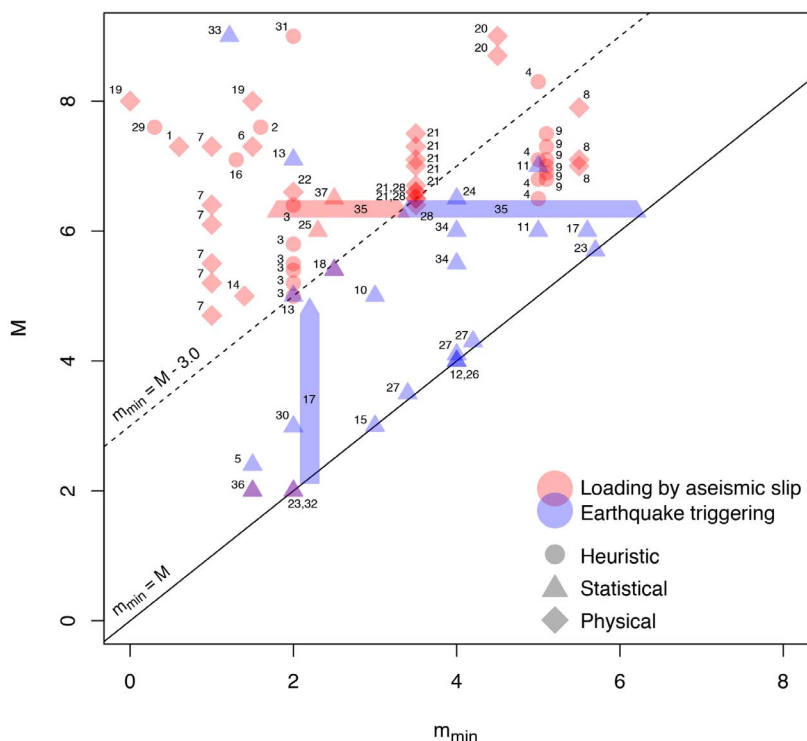
Figure 2 | Meta-analysis of 37 published studies in which the origin of observed foreshocks is determined. Mainshock magnitude M versus minimum foreshock magnitude m_{min}. Arguments are based on heuristic, statistical or physical considerations. Numbers (from 1 to 37 - not to be confounded with reference numbers in the main text) correspond to the different studies considered in chronological order from 1982 to 2013. Matching between number and reference is given in Supplementary Table S1. A same study may include different values of M and m_{min}, yielding a total of 77 data points. The emergence of an anomalous foreshock behaviour (i.e. loading process due to aseismic slip) is observed once microseismicity is included in the analysis, roughly with $m_{min} < M - 3.0$; otherwise foreshocks are best explained by the normal behaviour of seismicity (i.e. earthquake triggering process).
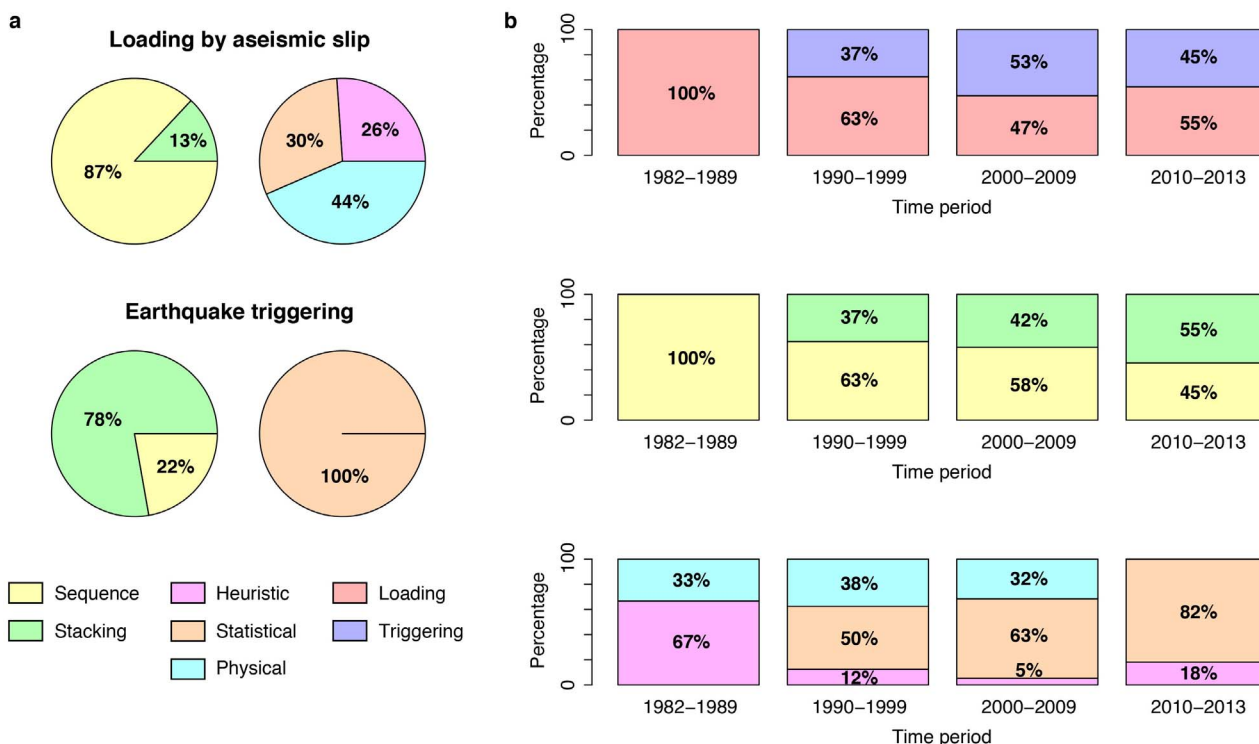
Figure 3 | Other statistics derived from the meta-analysis. a. Differences in methods employed to argue in favour of loading by aseismic slip or in favour of earthquake triggering. Statistical approaches with use of stacking methods (large data set analysis) tend preferentially towards an earthquake triggering origin of foreshocks. Arguments for loading are mostly based on the study of individual foreshock sequences. b. Evolution of thoughts and methods through time. Popularity of the triggering view has increased over time with the development of statistical studies based on stacking methods. Since the 2000's, there is no clear preference for any given theory of foreshock origin, showing that the debate continues.
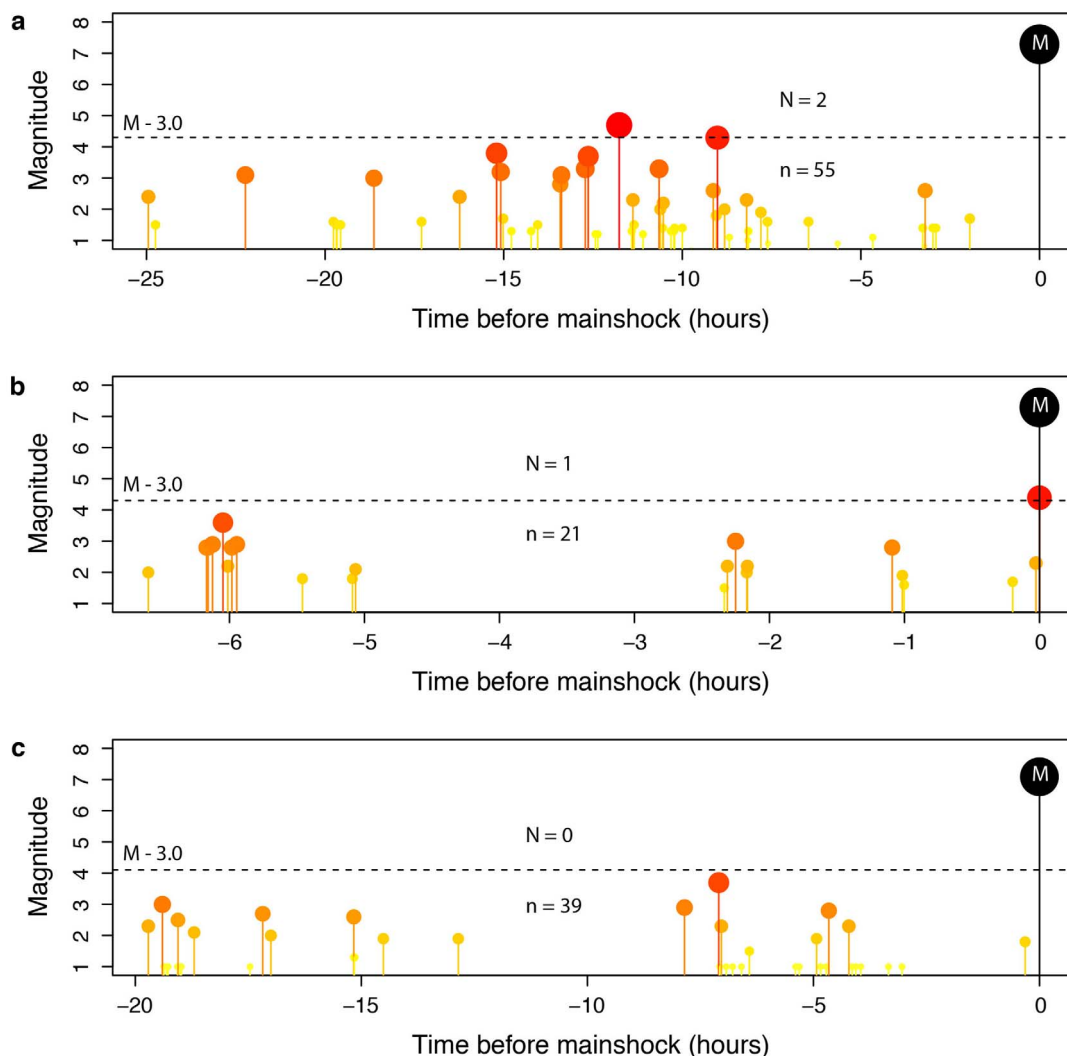
Figure 4 | Examples of relocated foreshock sequences. Observed prior to the **a**, 4 February 1975 $M = 7.3$ Haicheng, China earthquake[1] (study no. 1, see Fig. 2 and Table S1), **b**, 28 June 1992 $M = 7.3$ Landers, California earthquake[26] (study no. 6) and **c**, 16 October 1999 $M = 7.1$ Hector Mine, California earthquake[27] (study no. 16). N and n are the numbers of foreshocks above and below the $M - 3.0$ lines, respectively. Almost all foreshock magnitudes are below $M - 3.0$. An aseismic slip origin of foreshocks is suggested in the three cases[1,26,27]. The Haicheng earthquake has been successfully predicted based on foreshock information[2]. The three studies imply that far fewer events are observed prior to the foreshock sequences above m_{min}.

hand, would indicate that the use of a relatively high m_{min} leads to under-sampling of potentially existing foreshock sequences. For illustration purposes, Figure 4 shows three examples of relocated foreshock sequences observed prior to the 4 February 1975 $M = 7.3$ Haicheng, China earthquake[1] (study no. 1), the 28 June 1992 $M = 7.3$ Landers, California earthquake[26] (study no. 6) and the 16 October 1999 $M = 7.1$ Hector Mine, California earthquake[27] (study no. 16). With N and n the numbers of foreshocks above and below $M - 3.0$, respectively, I find $0 \leq N \leq 2$ and $21 \leq n \leq 55$. While this result is a direct consequence of the GR law statistics, the three studies considered (nos. 1, 6 and 16) imply that far fewer events are observed at proximity of the mainshock epicentre prior to each foreshock sequence above m_{min}. It means that a spatiotemporal anomaly becomes apparent only when $m_{min} < M - 3.0$. It should be noted that the information shown in Figure 4 is however insufficient to prove or disprove any of the two theories.

I conclude that the debate on the origin of earthquake foreshocks might be resolved in the future by combining the statistical robustness of large dataset analyses to datasets containing microseismicity from which anomalous foreshocks seem to emerge. The fact that since 2010 82% of studies are statistical in nature and 55% based

on stacking methods, while still 55% of the analyses support the loading view (Fig. 3b), indicates that this shift in methodology is in progress. Based on the empirical result of Figure 2, I recommend using $m_{min} < M - 3.0$ in any foreshock analysis to get more reliable results, preferentially with $m_{min} = M_c$, the completeness magnitude of the dataset. For the case $M_c > M - 3.0$, a better knowledge of microseismicity is necessary, which can be done by better assessing issues of data completeness at low magnitudes[29] and/or by improving existing seismic networks to decrease M_c[30].

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Author contributions

A.M. performed the literature survey and the meta-analysis, wrote the manuscript and prepared all the figures.

Additional information