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. ❐

References

1. Bouchon, M., Durand, V., Marsan, D., Karabulut, H. & Schmittbuhl, J. *Nature Geosci.* **6,** 299–302 (2013).
2. Papazachos, B. C. *Bull. Seis. Soc. Am.* **96,** 389–399 (1973).
3. Jones, L. M. & Molnar, P. *J. Geophys. Res.* **84,** 3596–3608 (1979).
4. Helmstetter, A., Sornette, D. & Grasso, J-R. *J. Geophys. Res.* **108,** 2046 (2003).
5. Ogata, Y. *J. Am. Stat. Assoc.* **83,** 9–27 (1988).
6. Helmstetter, A., Kagan, Y. Y. & Jackson, D. D. *J. Geophys. Res.* **110**, B05S08 (2005).
7. Kato, A. *et al. Science* **335,** 705–708 (2012).
8. Yagi, Y. *et al. Geophys. Res. Lett.* **41,** 4201–4206 (2014).

Additional information

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

Karen R. Felzer[1], Morgan T. Page[1]* and Andrew J. Michael[2]

[1]US Geological Survey, Pasadena, California 91106, USA. [2]US Geological Survey, Menlo Park, California 94025, USA.

*e-mail: pagem@caltech.edu

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. ❐

References

1. Bouchon, M., Durand, V., Marsan, D., Karabulut, H. & Schmittbuhl, J. *Nature Geosci.* **6,** 299–302 (2013).
2. Felzer, K. R., Page, M. T. & Michael, A. J. *Nature Geosci.* **8,** 82–83 (2015).
2. Ogata, Y. *J. Am. Stat. Assoc.* **83,** 9–27 (1988).
3. Zhuang J., Ogata, Y. &Vere-Jones, D. *J. Geophys. Res.* **109**, B05301 (2004).
4. Chu A., Schoenberg, F. P., Bird, P., Jackson, D. D. & Kagan, Y. Y. *Bull. Seism. Soc. Am.* **101,** 2323–2339 (2011).
5. Veen A. & Schoenberg, F. P. *J. Am. Stat. Assoc.* **103,** 614–624 (2008).

Michel Bouchon[1]* and David Marsan[2]

[1]Centre National de la Recherche Scientifique and Université Joseph Fourier, ISTerre, BP53, 38041 Grenoble, France. [2]Université de Savoie, ISTerre, 73376 Le Bourget du Lac, France.

*e-mail: Michel.Bouchon@ujf-grenoble.fr