LETTERS

Long aftershock sequences within continents and implications for earthquake hazard assessment

Seth Stein[1] & Mian Liu[2]

One of the most powerful features of plate tectonics is that the known plate motions give insight into both the locations and average recurrence interval of future large earthquakes on plate boundaries. Plate tectonics gives no insight, however, into where and when earthquakes will occur within plates, because the interiors of ideal plates should not deform. As a result, within plate interiors, assessments of earthquake hazards rely heavily on the assumption that the locations of small earthquakes shown by the short historical record reflect continuing deformation that will cause future large earthquakes[1]. Here, however, we show that many of these recent earthquakes are probably aftershocks of large earthquakes that occurred hundreds of years ago. We present a simple model predicting that the length of aftershock sequences varies inversely with the rate at which faults are loaded. Aftershock sequences within the slowly deforming continents are predicted to be significantly longer than the decade typically observed at rapidly loaded plate boundaries. These predictions are in accord with observations. So the common practice of treating continental earthquakes as steady-state seismicity overestimates the hazard in presently active areas and underestimates it elsewhere.

The disastrous magnitude-7.9 earthquake in Sichuan, China, in May 2008 was a surprise because it occurred on a fault that had had little recent seismicity. Such surprises occur often for earthquakes within continents. In contrast to plate boundaries where large (magnitude $M > 7$) earthquakes occur at expected locations along the boundary faults, continental interiors like Sichuan or the central and eastern United States contain many old faults, most of which show little seismicity over the past hundred years for which we have seismological data. Hence, we are uncertain of the times and locations of future large earthquakes. Present earthquake hazard assessments typically assume that recent small earthquakes indicate the location of large future earthquakes. But what if some of these recent earthquakes are instead aftershocks of earlier large events?

Large earthquakes are typically followed by aftershock activity that decays to a lower level interpreted as 'normal' background seismicity[2]. This transition is difficult to identify precisely, because defining it depends on the area treated as the aftershock zone and the criterion used. For the majority of large earthquakes, which occur at plate boundaries, the transition generally occurs less than a decade after the main shock, as shown by both studies of individual events[3–5] and a large global compilation[6] (Fig. 1a). This duration is therefore regarded as the norm. In contrast, aftershock sequences can be much longer in other tectonic settings. In diffuse plate boundary zones such as the Basin and Range, aftershocks often continue for fifty years or more[7–10] (Fig. 1b). Within continental interiors, aftershocks may continue for hundreds of years after the main shock. Seismicity in the areas of past large earthquakes, including those in New Madrid, Missouri (1811–1812), Charlevoix, Quebec (1663), and Basel, Switzerland (1356), may be aftershocks[11]. In the New Madrid seismic zone, the best-studied of these areas, seismicity delineates the areas thought to have ruptured in the main shocks, appears to be decreasing (Fig. 1c) and the largest earthquakes are at the ends of the presumed ruptures; all three observations are often found in aftershock studies[12].

For most aftershock sequences, the number of earthquakes decreases approximately hyperbolically with time after the mainshock, following the empirical Omori's Law. Hence the aftershock durations may be estimated, using the change in seismicity rates from decaying aftershocks to background seismicity, which can be directly measured for short aftershock durations[2,5,6]. However, identifying this

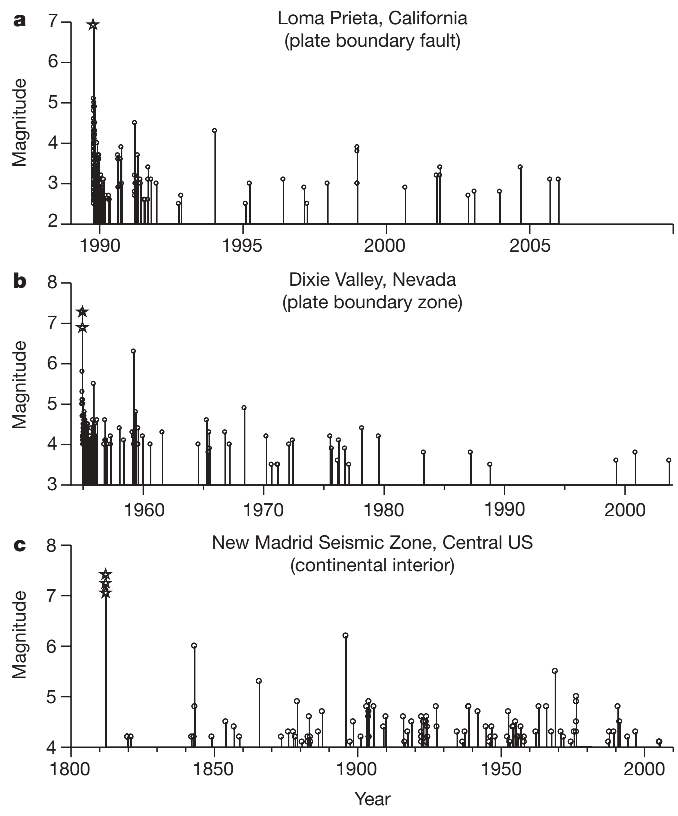

Figure 1 | Aftershock sequences following large earthquakes in different tectonic settings. **a**, The Loma Prieta earthquake ($M = 6.9$) on the San Andreas Fault on 17 October 1989. **b**, The Dixie Valley and Fairview Peak earthquakes ($M = 7.1$ and $M = 6.8$) in Nevada in December 1954. **c**, The New Madrid earthquakes ($M = 7.0$–7.4) in the central USA, that occurred December 1811–February 1812. Note the different time and magnitude scales for each panel. Stars are mainshocks. Data sources are given in Supplementary Information.

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transition becomes difficult and then impossible as the aftershock duration approaches and then exceeds the length of the short earthquake record (Fig. 1). For historic earthquakes, further problems arise from incomplete and nonuniform catalogues. Nonetheless, bounds on the duration of some aftershock sequences can be inferred. A lower bound comes from treating today's earthquakes as aftershocks, and an upper bound comes where there is paleoseismic evidence of large (probably magnitude greater than 7) earthquakes but little seismicity today.

Figure 2 shows aftershock durations for selected events from three tectonic settings: plate boundary faults, broad plate boundary zones, and continental interiors. Despite the uncertainties in estimating both the duration and the rate at which tectonic slip loads the faults, the data indicate an inverse relationship between the aftershock durations and the slip rates. Faults at plate boundaries that are loaded by the rapid (typically faster than 10 mm yr^{-1}) plate motion show aftershock durations of about ten years[3–6]. Faults within broad plate boundary zones but off the main boundaries move at only a small fraction of the plate motion (a few millimetres per year[7–9]) and have longer aftershock durations. Aftershocks continue today following the 1952 Kern County, California, and 1959 Hebgen Lake, Montana, earthquakes, and have a typical duration of about 100 years in the Central Nevada seismic belt[10]. Such a duration is consistent with the absence of aftershocks from large earthquakes on the Wasatch fault, the most recent of which occurred about 600 years ago[9].

The longest aftershock sequences occur within continental plate interiors, which deform at rates typically less than a millimetre per year[13–15]. Today's New Madrid and Charlevoix seismicity give lower duration bounds. Upper bounds come from the absence of seismicity at sites of past earthquakes such as the Reelfoot Rift's eastern margin[16] in the New Madrid area and the Meers fault in Oklahoma[17]. Thus, within continents, aftershock sequences can last hundreds of years or longer.

It is reasonable that within continents aftershocks should continue long after large earthquakes. Aftershocks result from changes of stress and fault properties induced by the main shock. At a plate boundary, steady plate motion quickly reloads the fault after a large earthquake and overwhelms the effects of the main shock. Within continents, however, the faults are reloaded much more slowly, allowing aftershocks to continue much longer.

This inverse correlation between aftershock durations and fault loading rates is consistent with the rate-and-state model of fault friction, which predicts changes in fault properties after earthquakes, and is commonly used for aftershock studies[3–6,18]. This model predicts an aftershock duration $t_a = A\sigma/\dot{\tau}$, where $\dot{\tau}$ is the rate of shear stressing on the fault, σ is the normal stress, and A is a constitutive parameter[3]. Although the stressing rate is hard to measure, it can be estimated from the relative velocity (loading rate) across the fault. For a simple geometry[19] in which $\dot{\tau} = \mu v/\pi w$, where μ is the rigidity, v is the loading rate, and w is the vertical extent of the seismogenic fault, $t_a = A\sigma\pi w/\mu v$. Using $A = 0.01$, $\sigma = 15$ MPa, $\mu = 30$ GPa and $w = 20$ km, we can predict $t_a = 314/v$ for t_a in years and v in millimetres per year. This t_a–v relation is generally consistent with observations spanning a wide range of loading rates and aftershock durations (Fig. 2).

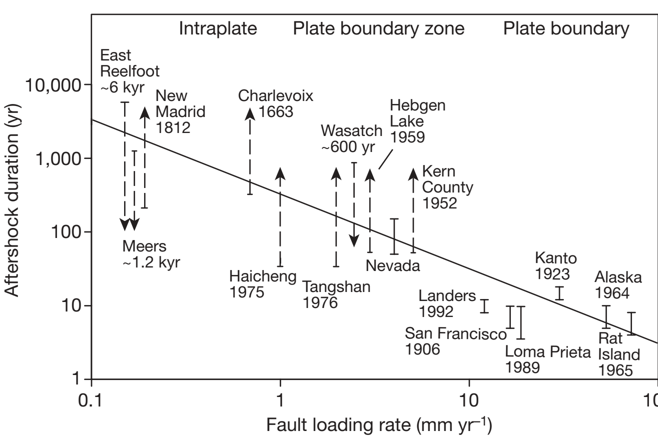

Figure 2 | Aftershock durations and fault loading rates for selected large earthquakes in different tectonic settings. The solid line is the model prediction. Aftershock durations have bars showing the span of published estimates. One-sided constraints have bars at the known value and arrows indicating the open value. For example, the New Madrid aftershocks span at least 200 years, but the upper bound is unconstrained. Similarly, the Wasatch aftershocks span less than 600 years, but the lower bound is unconstrained. Data and sources for this plot are in the Supplementary Information. 1 kyr = 1,000 years.

Both the data and the model used here are simplifications of complicated systems. The aftershock durations are inferred by several techniques, and include both aftershocks on the fault plane itself and ones in the surrounding area triggered by stress transfer[4,6,20]. The model treats all faults as having the same geometry and physical properties, and differing only in loading rate. Hence the single line shown represents a trend about which we expect scatter.

Although long aftershock sequences within continents are more easily identifiable because of low background seismicity, the systematic increase in aftershock durations for lower loading rates indicates that this variation reflects the physics of faulting. This variation can be explained by the rate-and-state model that attributes aftershocks to changes in fault friction after the main shock. Alternatively, aftershocks have been interpreted as resulting from stress disturbances. One such process is viscous relaxation in creeping fault segments surrounding the rupture zone[21]. This process occurs primarily within the upper crust for a few years after the main shock. However, large earthquakes can significantly load the viscous lower crust and upper mantle, which then transfer stress back to the seismogenic upper crust over a much longer time, as indicated by geodetic data[22]. This process would last longer within continents than near plate boundaries because of the more viscous lower crust and upper mantle, and so could also contribute to long aftershock sequences. The resulting exponential decay in seismicity would be similar to that predicted by Omori's law.

Recognizing such long aftershock sequences is crucial for seismic hazard assessment within continents. The observation that the locations of small continental earthquakes tend to be the sites of many future ones[23] is consistent with many of these events being part of long aftershock sequences. In this case, the locations of these small earthquakes may not indicate the timing or the locations of future large earthquakes, which are often episodic, temporally clustered, and migrate between faults over thousands of years[13,24–28]. A striking example of this variability is in North China, where large ($M > 7$) earthquakes have been frequent, but not a single pair has occurred in the same place since 1300 AD. Several effects presumably contribute to these complex spatiotemporal patterns. Temporal clustering of earthquakes arises in various tectonic settings owing to stress transfer caused by earthquake interactions[29]. The slow tectonic loading within continents causes stress transfer to have a greater effect than at rapidly loaded plate boundaries[27,28]. The spatial migration of large earthquakes is probably related to fault interaction over multiple timescales[27]. Because the tectonic loading is slow and is accommodated by a network of faults, factors such as the heterogeneity of lithospheric rheology, fault properties and geometry, and the earthquake history of each fault may all contribute to the complex spatiotemporal patterns.

The complex spatiotemporal patterns of large earthquakes, and the long durations of their aftershocks, make assessing earthquake hazards within continents difficult. In the short term much of the seismic hazard results from aftershocks, which can be damaging, and thus should not be removed in attempts to infer earthquake recurrence and hazards. In the longer term, relying unduly on recent seismicity to predict the locations of future large earthquakes will overestimate the hazard in some places and lead to surprises elsewhere.

Improved assessments of earthquake hazard require treating the networks of faults within continents as complex systems and developing a better understanding of how such systems behave in time and space[28]. This is being done by combining the seismological record with palaeoseismic studies that provide a longer earthquake history, and high-precision Global Positioning System (GPS) measurements that show whether deformation continues. Taken together, these data can show whether recent seismic events in a region are aftershocks or indicate future large earthquakes. One example is the New Madrid area, where palaeoseismic data show a cluster of large earthquakes in the past millennium[25,30] but two decades of GPS measurements show no deformation, so the cluster of large earthquakes there appears to have ended[13,14].

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions S.S. developed the friction-based model and much of the data set. M.L. developed the Chinese data and the viscous relaxation model. Both authors discussed the results and participated in the writing.

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Lasting earthquake legacy

Tom Parsons

Earthquakes occur within continental tectonic plates as well as at plate boundaries. Do clusters of such mid-plate events constitute zones of continuing hazard, or are they aftershocks of long-past earthquakes?

Early on the morning of 16 December 1811, an earthquake of about magnitude 7 shook the centre of the United States around a small town on the Mississippi called New Madrid. By 7 February 1812, it had triggered three more shocks of similar magnitude[1]. The earthquakes broke a set of faults along the Arkansas, Missouri and Tennessee state boundaries, apparently reactivating an ancient rift in the interior of a continental tectonic plate[2].

On 31 August 1886, a magnitude-7 shock struck Charleston, South Carolina; low-level activity continues there today. One view of seismic hazard is that large earthquakes will return to New Madrid and Charleston at intervals of about 500 years[3]. With expected ground motions that would be stronger than average[4], that prospect produces estimates of earthquake hazard that rival those at the plate boundaries marked by the San Andreas fault and Cascadia subduction zone[3,4]. The result is two large 'bull's-eyes' on the US National Seismic Hazard Maps (Fig. 1) — which, for example, influence regional building codes and perceptions of public safety.

But what if earthquakes are not always going to return to mid-continental locations such as New Madrid or Charleston? From data on activity at New Madrid and elsewhere in the world, Stein and Liu (page 87 of this issue)[5] identify a global inverse correlation between aftershock duration and tectonic deformation rates. They argue that localized high rates of mid-continental activity, taken to reflect steady-state plate deformation, may instead be very long-lived aftershock sequences.

As first noted by Omori[6] in 1894, and now known as Omori's law, aftershock rates

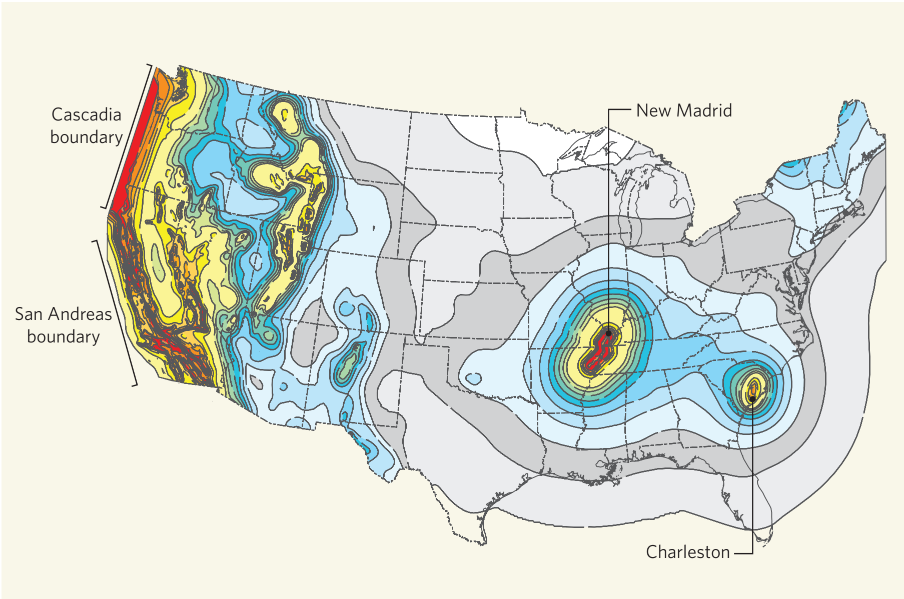

Figure 1 | Probabilistic assessment of seismic hazard in the United States[3]. Warm colours show regions with the highest probability of strong shaking, which tend to be located near, or influenced by, major plate boundaries. Earthquake clustering in mid-continental areas such as New Madrid and Charleston is here interpreted to reflect continuing deformation sufficient to produce frequent large earthquakes. This expectation, combined with the anticipated ground response, produces hazard estimates that rival those for plate-boundary zones on the west coast. Stein and Liu[5], however, suggest that low-level, mid-continental seismic activity can be attributed to a long-lived sequence of aftershocks.

are highest immediately after a mainshock, and then decay as a function of inverse time (Fig. 2). Stein and Liu[5] demonstrate that aftershocks decay very slowly where there is little tectonic deformation, and can persist for hundreds of years. By contrast, aftershock rates at fast-deforming plate boundaries return to the background level within about ten years.

Rate-and-state friction theory holds that fault failure depends on competition between initially very slow slip speed (rate) and the evolving duration (state) of a population of contact points in a fault. Stein and Liu's observations confirm a major prediction of that theory — that the aftershock decay period on a fault should depend directly on the rate at which tectonic stress accumulates[7]. Declining aftershock sequences at New Madrid and Charleston, along with little steady-state deformation, would mean that earthquake hazard rates are declining as well.

We have independent methods of assessing whether plate deformation is continuing. On the one hand, palaeoseismology — a kind of forensic seismology that reads geological clues left by prehistoric earthquakes — has been used to interpret quake clusters that occurred around AD 900 and AD 1450 at New Madrid[8]. When combined with the 1811–12 series, the upshot of this analysis was the estimate of a 500-year recurrence interval used for hazard mapping[3]. On the other hand, space geodesy — the use of a space-based reference frame to monitor current crustal movements — reveals present-day deformation rates in the New Madrid zone that are indistinguishable from those of the rest of the continental interior, and that have been interpreted as New Madrid shutting down[9]. Digging deeper into the palaeoseismic record indicates temporal earthquake clusters that are followed by millennia of quiescence[10], a finding that reconciles these contrasting observations if we are now entering a quiet period.

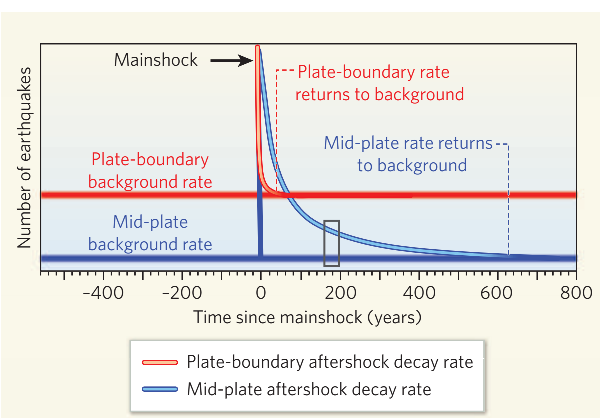

Figure 2 | Comparison of aftershock decay rates from plate-boundary and mid-plate regions. Mainshocks cause temporarily heightened earthquake rates of a duration controlled by the rates of tectonic deformation[5]. The black box shows the modern instrumental observation window on a long-lived decay sequence of mid-plate aftershocks. That window has been open for only about 40 years, illustrating the difficulties in distinguishing aftershocks from the lower, steady-state background rate of earthquake occurrence.

This is where geological time versus human time comes in. Meteorologists have the benefit of having watched hundreds of seasonal cycles to support their weather forecasts. Earthquake forecasters, however, have not yet witnessed a complete seismic cycle in slowly deforming continental interiors anywhere on Earth. The task is akin to predicting a full-year's weather based on watching one week in January. Stein and Liu's study[5] inevitably suffers from this problem; it is difficult to accurately calculate a long aftershock decay trend from a brief observation time. A limited view of earthquake history can actually be dangerous: despite the huge shocks that recently caught many by surprise in Sumatra and in Wenchuan, China, there is still a tendency to place undue emphasis on known past events in hazard assessments when trying to see the future.

A better understanding of mid-continental seismicity, one that avoids excessive influence from events in the recent past, will require that historically unbroken crustal weak points are not overlooked. Fault mapping and palaeoseismology at unconventional locations may be required to find out if places such as New Madrid and Charleston are special. At the same time, we must discriminate between the signals of steady-state deformation and the slowly fading legacy of historical earthquakes.

The large uncertainties arising from our brief glimpse into mid-continental earthquake cycles are unavoidable. Forecasters will thus have to follow multiple possibilities, including those with Omori-law time-decaying hazard estimates, through a logic-tree structure. With that approach, there is the prospect of arriving at a practical solution that properly balances the available resources for earthquake mitigation and the distribution of earthquake-resistant building structures in mid-continental regions. ■

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News

Aftershocks can last for centuries

Why earthquakes might happen in unexpected places.

Jane Qiu

Some tremors may be aftershocks of bigger earthquakes that occurred hundreds of years ago, researchers say.

There were precious few warning signs before the 2008 Sichuan earthquake hit. *M. Ralston/AFP/Getty Images*

Scientists assess earthquake risks mainly by looking at fault movements and seismic activity along the boundaries of tectonic plates, where most quakes take place. But at the plate interior, "we have little idea where the next fault rupture will happen on the continent and every major quake came as a surprise", says Mian Liu, a geophysicist at the University of Missouri in Columbia, and an author of a study in *Nature* looking at aftershocks[1].

Indeed, the magnitude-7.9 Sichuan earthquake in China in 2008 caught scientists off guard because it occurred in an area that had been experiencing little seismic activity (see '**Seismology: The sleeping dragon'**).

In contrast, the seismic zone near New Madrid in Missouri has seen frequent earthquakes in recent years but studies using Global Positioning System (GPS) measurements have shown little strain accumulation due to ground motion across the fault[2].

Lasting effects

Liu and Seth Stein, a geophysicist at Northwestern University in Evanston, Illinois, noticed that the frequency and magnitude of these New Madrid quakes had declined since 1811-12, when four earthquakes of magnitude 7–7.5 shook the town.

"These are patterns of aftershocks," says Liu. But aftershocks were thought to be felt for no more than a decade after the initial quake.

Stein and Liu, however, suspected that the duration of aftershocks, which take place as the crust around the fault plane adjusts to the effects of the main shock, could be related to the rate at which the fault moves. At fast-moving faults, such as the San Andreas fault, aftershocks would die out quickly.

But with the New Madrid fault, which moves over 100 times more slowly than the San Andreas fault, it could take hundreds of years for the effects of a major earthquake to fade away.

Using a simple model of the changes in fault property after an earthquake, the researchers verified the relationship. Moreover, they found that data from 16 major earthquakes around the world are

Fault scarp left by a 1959 magnitude 7.5 earthquake in Montana. Aftershocks of the earthquake continue today. *Seth Stein*

consistent with their work.

"It is interesting that, with the same seismic history, we can come up with completely opposed predictions of where the next quakes are most likely to occur." says Ross Stein, a geologist at the US Geological Survey in Menlo Park, California, who was not involved with the work. "We may have been fooled by the seismic activity [along the New Madrid fault], assuming that it represents the build-up of the next major earthquake."

Liu stresses, however, that the study has just looked at one aspect of a very complicated problem. "We are just trying to correct the part of the practice that isn't working," he says. "Recent seismic activity can be misleading for assessing earthquake hazards."

Whacking a mole

Liu says that the study also suggests that seismic models based on studies at plate boundaries may not work for predicting earthquakes in the interior of plates. At the boundaries, tectonic stress builds up at a constant rate, leading to fairly regular cycles of earthquakes. In the interiors, however, such constant stress-loading processes do not occur.

"Predicting big quakes based on small quakes is like the 'whack-a-mole' game: you wait for the mole to come up where it went down," says Seth Stein. "But we now know that big earthquakes can pop up somewhere else."

Indeed, detailed earthquake catalogues in China, which go back more than 2,000 years, show that large earthquakes have never struck in the same place twice. "So the mole never came up from the same hole twice," says Liu.

To further test his hypothesis, Liu is leading a US–China collaboration to study earthquakes in northern China. In the past 700 years, there have been three earthquakes of magnitude 8 or greater — including the Huaxian earthquake in 1556, the most deadly earthquake in human history which killed more than 830,000 people — and a dozen of magnitude 7 or more along the Shanxi graben, a depressed block of land between parallel faults, in Shanxi province.

But the Shanxi graben has been dormant for the past 200 years, whereas the seismic activity seems to be increasing in the North China Plain to its east, resulting in large earthquakes such as the magnitude 7.8 Tangshan earthquake in 1976.

Liu and his colleagues now plan to use seismological methods to map the distribution of fault zones in the region as well as their movements and underlying structure; they will use GPS stations to measure strain accumulation along active faults and dig trenches to establish the history of ancient earthquakes.

"Hopefully, these multiple approaches will be able to test our aftershock hypothesis and advance our understanding of earthquakes," says Liu.

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