The New Madrid Seismic Zone: Not Dead Yet

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The extent to which ongoing seismicity in intraplate regions represents long-lived aftershock activity is unclear. We examined historical and instrumental seismicity in the New Madrid central U.S. region to determine whether present-day seismicity is composed predominantly of aftershocks of the 1811–1812 earthquake sequence. High aftershock productivity is required both to match the observation of multiple mainshocks and to explain the modern level of activity as aftershocks; synthetic sequences consistent with these observations substantially overpredict the number of events of magnitude ≥ 6 that were observed in the past 200 years. Our results imply that ongoing background seismicity in the New Madrid region is driven by ongoing strain accrual processes and that, despite low deformation rates, seismic activity in the zone is not decaying with time.

Seismic hazard is not isolated to tectonic plate boundaries, as evidenced by earthquakes that occur in stable continental regions. Intraplate earthquakes, which are related to the internal deformation of plates rather than motion at plate boundaries, can be large and damaging, as with the 2001 Bhuj earthquake (*1*). In this work, we study the 1811–1812 New Madrid sequence, which is of paramount importance for understanding intraplate seismogenesis and for probabilistic seismic hazard assessment in the central and eastern United States and other midcontinental regions. The sequence included four events that were widely felt throughout the central and eastern United States, conventionally regarded as three primary mainshocks and the large dawn aftershock following the first mainshock. Magnitude estimates for these events have varied widely, from a low of magnitude (M) ≈ 7 for the largest mainshocks (*2*) to values over 8 in magnitude (*3*).

Aftershocks of the 1811–1812 sequence have been considered in two ways. Several studies have used archival accounts of large aftershocks and/or tallies of felt earthquakes to estimate magnitudes for large aftershocks and consider the overall magnitude distribution of early aftershocks [e.g., (*4*, *5*)]. Two studies have considered the long-term rate of seismicity in the New Madrid Seismic Zone (NMSZ) and concluded that it is well characterized as a long-lived aftershock sequence (*6*, *7*). It is important to note, however, that these latter two studies do not show a fit, from 1811 to present, to traditional Omori decay (*8*, *9*). Such direct evidence has been observed for the classic long-lived aftershock sequence following the 1891 Nobi earthquake, for which an Omori decay can be seen for 100 years (*10*). In the New Madrid case, however, a direct fit is not possible given uncertainties in the early New Madrid catalog. In this study, we reconsider the long-lived aftershock hypothesis using rigorous tests assuming an Epidemic Type Aftershock Sequence (ETAS) model (*11*). ETAS modeling allows us to determine probabilities of observing robust features of the New Madrid catalog, should the long-lived aftershock hypothesis be true.

The ETAS model, developed on the premise that all earthquakes potentially trigger their own aftershocks, successfully explains the empirical Omori decay law, which, so far as is known, universally describes the temporal decay of aftershocks. The ETAS model explains observed foreshock rates and multiplets (*12*) and has been shown to accurately characterize seismicity, including both short- and long-term aftershock sequences [e.g., (*13*)], and is now a widely used short-term earthquake clustering model (*14*). The model has been used to characterize and forecast seismicity rates in a wide range of tectonic environments, including intraplate regions and regions characterized by swarmy activity (*15*, *16*). In this work, we use ETAS modeling in an attempt to generate synthetic catalogs that match well-constrained features of the New Madrid earthquake sequence (see materials and methods in the supplementary materials).

To test the long-lived aftershock hypothesis, we identified three robust observational constraints that are not dependent on particular contentious magnitude values. Our first imposed constraint

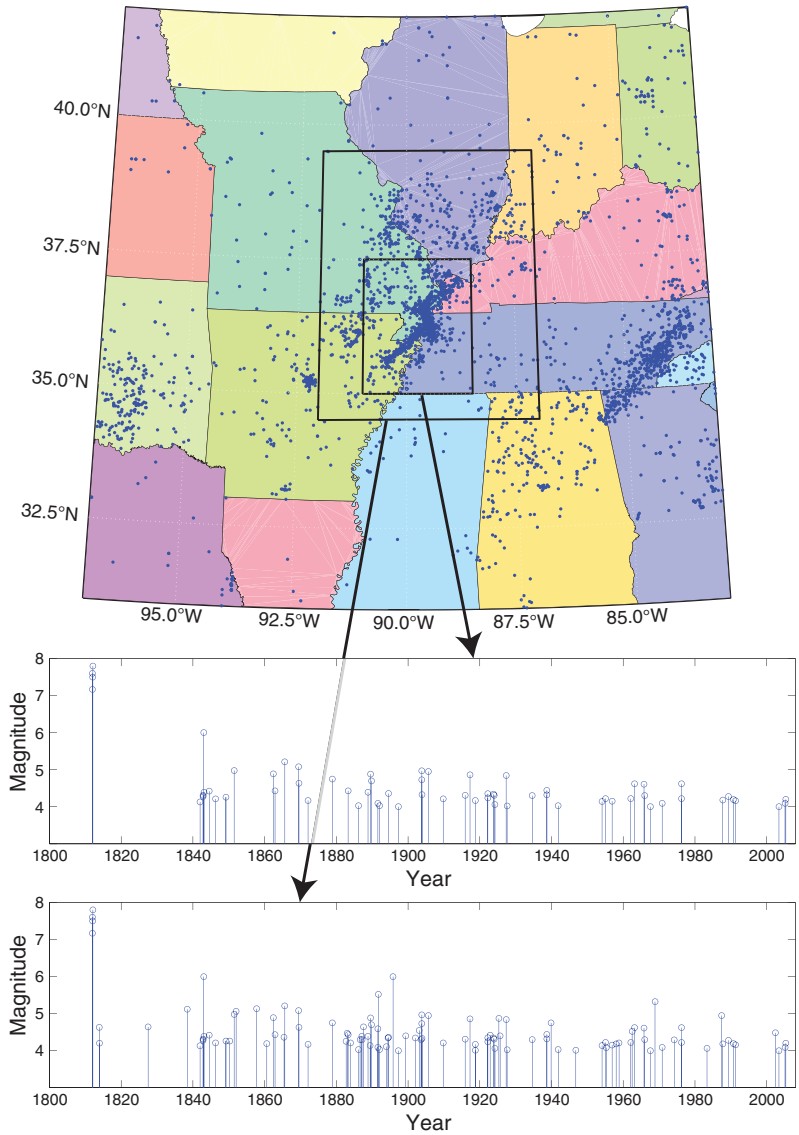

Fig. 1. Seismicity in the New Madrid region (CEUS catalog, 1800–2008, $M \geq 4$). Note that the early catalog is not complete to $M4$.

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is that the sequence included four principal events of comparable magnitude, separated by no more than 0.7 magnitude units. This is based on the range in event magnitudes inferred by different studies (*2*, *3*, *17*). Although the absolute magnitudes of these earthquakes remain a subject for debate, the relative magnitudes are much more reliably determined. Analysis of prehistoric sandblows in the NMSZ shows that protracted sequences, with multiple large mainshocks, are apparently the norm for this region (*18*).

The second constraint is on the recent rate of moderate-sized ($M \geq 4$) earthquakes. Because using different catalogs and box sizes produce different estimates, we used the most conservative estimate of three $M \geq 4$ earthquakes over 10 years (Fig. 1), taken from the Central and Eastern United States Seismic Source Characterization (CEUS-SSC) catalog (*19*) (see materials and methods).

The third constraint is the number of moderate ($M \geq 6$) events in the NMSZ after the initial cluster in the first year. The CEUS-SSC catalog (*19*) includes two such events, the 1843 Marked Tree, Arkansas, and 1895 Charleston, Missouri, earthquakes, both with preferred magnitudes of 6.0. Although a recent reinterpretation of macroseismic effects of the 1843 earthquake (*20*) estimates a lower preferred magnitude of 5.4, we assume, for conservatism, that the sequence produced no more than two $M \geq 6$ late events (see materials and methods).

We generated synthetic ETAS catalogs, searching for a single set of subcritical, direct Omori parameters that matched the three robust observational constraints described above. The fraction of stochastic catalogs that are consistent with both early clustering behavior and recent seismicity in the New Madrid region are shown in Fig. 2, A and B, respectively. These two constraints reduce the possible ETAS phase space to a small region (Fig. 2C). Synthetic catalogs produced in this region of the ETAS phase space are very productive both early and late in the sequence. We find that synthetic sequences that are active enough to match observed New Madrid–style early clustering behavior and current seismicity rates contain many more $M \geq 6$ events at intermediate times than have been observed (table S1). At 95% confidence, no set of direct Omori parameters is consistent with all three of our constraints: early

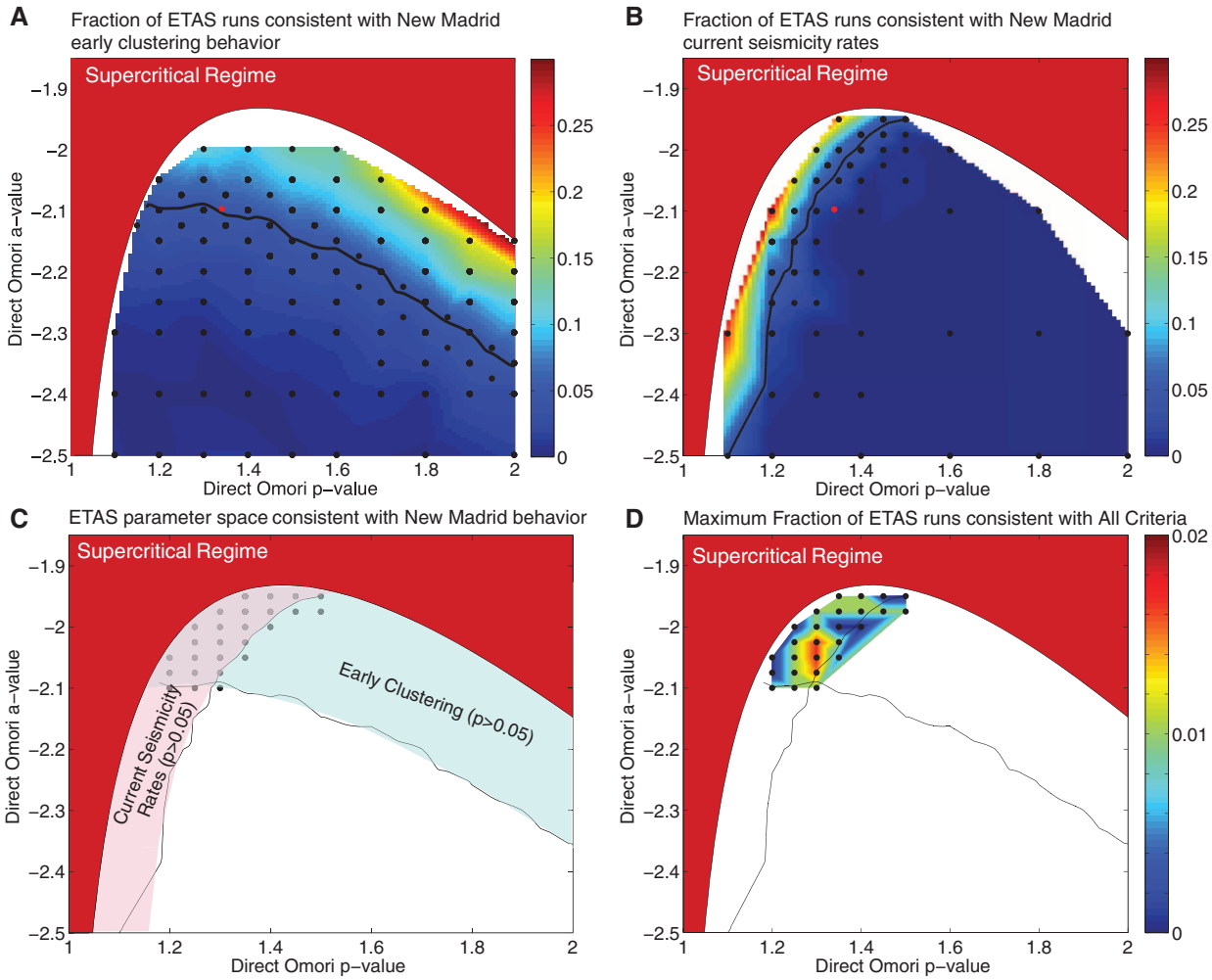

Fig. 2. Regions of ETAS parameter space consistent with New Madrid behavior. The unphysical, supercritical regime (see materials and methods) is shown in red. (**A**) ETAS simulations within the subcritical regime are sampled at the black points; colors show a linear interpolation of the fraction of synthetic sequences for which the four largest shocks in the first 2 months are within 0.7 magnitude units of each other, as was seen in the New Madrid sequence. Above the black line (which theoretically is smooth but has small irregularities due to sampling error), at least 5% of synthetic sequences are consistent with New Madrid clustering behavior; below this line, the early behavior is less productive than observations. The red dot shows average California parameters (*25*) for reference. (**B**) The fraction of synthetic sequences that have a late (200 years post-mainshock) aftershock rate that matches current New Madrid seismicity rates. (**C**) The parameter space consistent with both early clustering and current seismicity rates is confined to a small region; we sample sequences at the points shown and find that sequences with parameters in this region typically produce a much higher rate of *M*6 earthquakes after the first year than that observed. (**D**) The maximum fraction, over all mainshock magnitudes, that is consistent with early clustering, current seismicity rates, and the rate of $M \geq 6$ earthquakes after the first year, linearly interpolated between sampling points. Although some variation in this plot is due to sampling error, all points have been sampled sufficiently to determine that the fraction is less than 5%, at 95% confidence (see table S1).

clustering, current seismicity rates, and the rate of $M \geq 6$ events after the first year (Fig. 2D). Among sequences sampled that were consistent with New Madrid early clustering behavior and current seismicity rates, the mean number of $M \geq 6$ earthquakes from 1 year to 200 years post-mainshock was 135. At best, at some points in ETAS phase space ~1.7% of the sequences are consistent with our criteria. Results using a stricter criteria that includes the observation that no $M \geq 6$ earthquakes occurred in the region in the past 100 years (table S1) show that we can reject the long-lived aftershock hypothesis at even higher confidence.

Based on our statistical analysis, the hypothesis that current seismicity in the New Madrid region is primarily composed of aftershocks from the 1811–1812 sequence fails. This is because a sequence active enough at late times to produce the seismicity rates observed today and active enough at early times to produce the short-term clustering observed in the first few months would be highly likely to produce too many aftershocks in the intermediate times. If current seismicity in the New Madrid region is not composed predominantly of aftershocks, there must be continuing strain accrual. This is in agreement with recent work finding nonzero strain measurements in the region that are consistent with ongoing interseismic slip of about 4 mm/year (*21*), in contrast to earlier studies [e.g., (*22*)]. The spatial distribution of the stress pattern driven by this model would be generally consistent with the stress change caused by an earthquake on the Reelfoot fault. This could explain how ongoing microseismicity is not part of an aftershock sequence but is still consistent with the predicted stress change associated with the 1811–1812 sequence (*23*). If ongoing microseismicity does result from ongoing strain accrual, this suggests that the region, along with the neighboring Wabash Valley where nonzero strain has also been observed (*24*), will continue to be a source of hazard.

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Supplementary Materials

www.sciencemag.org/content/343/6172/762/suppl/DC1
Materials and Methods
Fig. S1
Table S1
References (*26–30*)

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Evolutionarily Dynamic Alternative Splicing of *GPR56* Regulates Regional Cerebral Cortical Patterning

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The human neocortex has numerous specialized functional areas whose formation is poorly understood. Here, we describe a 15–base pair deletion mutation in a regulatory element of *GPR56* that selectively disrupts human cortex surrounding the Sylvian fissure bilaterally including "Broca's area," the primary language area, by disrupting regional *GPR56* expression and blocking RFX transcription factor binding. *GPR56* encodes a heterotrimeric guanine nucleotide–binding protein (G protein)–coupled receptor required for normal cortical development and is expressed in cortical progenitor cells. GPR56 expression levels regulate progenitor proliferation. *GPR56* splice forms are highly variable between mice and humans, and the regulatory element of gyrencephalic mammals directs restricted lateral cortical expression. Our data reveal a mechanism by which control of *GPR56* expression pattern by multiple alternative promoters can influence stem cell proliferation, gyral patterning, and, potentially, neocortex evolution.

Although most mammals have elaborate and species-specific patterns of folds ("gyri") in the neocortex, the genetic and evolutionary mechanisms of cortical gyrification are poorly understood (*1–3*). Abnormal gyrification, such as polymicrogyria (too many small gyri), invariably signals abnormal cortical development, so regional disorders of gyrification are of particular interest, because they highlight mechanisms specific to cortical regions. The human cortex contains dozens of cortical regions specialized for distinct functions—such as language, hearing, and sensation—yet it is unsolved how these cortical regions form and how human cortical regions evolved from those of prehuman ancestors.

Examination of >1000 individuals with gyral abnormalities identified five individuals from three

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