

Mid-Continent Earthquakes as a Complex System

Niels Bohr once observed: “How wonderful that we have met with a paradox. Now we have some hope of making progress.” This situation is happening in the long-frustrating effort to understand large earthquakes in continental interiors.

The paradox arises from a series of GPS studies across the New Madrid seismic zone (NMSZ). Large (magnitude >7) earthquakes felt across the Midwest occurred here in 1811 and 1812, small earthquakes occur today, and paleoseismic records show evidence of large earthquakes about 500 years apart in the past 2,000 years. We thus expected to see strain building up for a future large earthquake, but found none. Successive studies confirm this surprising result with progressively higher precision. The most recent analysis shows that present-day motions within 200 km of the NMSZ are indistinguishable from zero and less than 0.2 mm/yr (0.2 mm is the thickness of a piece of fishing line).

The NMSZ is thus deforming far more slowly—if at all—than expected if large earthquakes continue to occur as they have. Hence the high strain rates required by paleoearthquakes in the NMSZ must have been transient and have ended. This observation is consistent with the absence of fault-related topography, the small deformation that has accumulated over the fault system’s long life, and the jagged nature of the faults thought to have broken in 1811 and 1812. All of these indicate that the cluster of large-magnitude events in the past few thousand years does not reflect the faults’ long-term behavior.

Such variable fault behavior is being widely recognized in continental interiors. In many places large earthquakes cluster on specific faults for some time and then migrate to others. Some faults that appear inactive today, such as the Meers fault in Oklahoma, have clearly been active within the past few thousand years. Thus mid-continental faults “turn on” and “turn off” on timescales of hundreds or thousands of years, causing large earthquakes that are episodic, clustered, and migrating.

We hypothesize that this spatio-temporal variability results from interactions among the faults in a region. The faults form a complex system, in the sense that the system’s evolution cannot be understood by considering an individual fault.

Complex systems arise in many branches of the physical, biological, and social sciences, as reviewed in the April 2, 1999 issue of *Science*. In complex systems, the whole behaves in a fashion more complicated than can be understood from analysis of its component parts. As a result, such systems can evolve in many different ways. Studying them requires moving beyond the traditional reductionist approach, in which we focus on the

system’s simplest component, understand it in detail, and generalize it for the entire system. Instead, the system should be viewed as a totality, such that local effects in space and time result from the system as a whole.

Thinking of mid-continent faults as a complex system may explain much of why we have been unsuccessful in understanding them. To date we have focused on individual faults in isolation, whereas in a complex-system approach, the key is the interactions among faults.

An ideal isolated fault behaves relatively simply. Earthquakes occur when stress on the fault exceeds its frictional strength. When stress reaches the critical value, the fault slips in an earthquake, releasing the accumulated elastic strain, and the cycle repeats. An isolated fault acted on by constant or slowly varying forces thus produces quasi-periodic earthquakes because the forces steadily build up stress.

This process becomes more complicated due to interactions among faults. A large earthquake not only releases stress on the hosting fault, but also changes the stress on other segments of that fault or nearby faults by instantaneous (elastic) stress transmission and transient stress migration related to viscous relaxation in the lower crust. Furthermore, long periods of mechanical locking (absence of earthquakes) or clusters of repeated earthquakes on one fault can affect the loading rate on neighboring faults. In such a system the rate of strain accumulation on a given fault is not constant. Instead, it varies depending on the forces acting within the plate, the geometry of the fault system, and the rheology of both the faults and the material between them. As a result, the locations of large earthquakes vary in space and time.

This view explains why mid-continent earthquakes and ones at plate boundaries behave differently. Because the physics of fault rupture in these two environments is essentially the same, we have been puzzled about why the spatio-temporal pat-

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terns of earthquakes in the two environments are so different. This difference arises from the relative role of fault interaction, which primarily controls earthquake patterns in a complex system but is less significant at plate boundaries where seismicity is primarily controlled by steady loading from relative plate motion.

A plate boundary is rapidly loaded at rates of tens of millimeters per year by the motion of neighboring plates. As a result, a simple boundary containing a major through-going fault typically acts almost like an isolated fault. After a large earthquake, the steady plate motion quickly reloads the fault. This reloading dominates all other stress effects including those due to earthquakes on other faults. As a result, fault segments produce quasi-periodic earthquakes that continue for long times. Because this system is steady, the average time between these earthquakes can be predicted from the plate motions and geologic history, and geodetic data show the strain building up that will be released in the next earthquake.

In contrast, mid-continental faults are loaded slowly, as illustrated by GPS data that to date cannot resolve any regional intraplate strain accumulation in the central United States. Hence mid-continental faults act like a complex system. In many cases, a complicated set of faults with different orientations and sizes is loaded slowly—at rates less than one mm/yr—by a combination of processes. These can include the stresses imparted by neighboring plates and generated within the plate, tractions from mantle flow, regional loads such as glacial isostatic adjustment, and local effects such as sedimentation or denudation. Although these stresses also act on plate boundary faults, the fast plate motion there dominates the loading process. However, after a large mid-continental earthquake, stress reaccumulates very slowly—if at all—on the fault that broke. Instead, stress changes due to fault interactions can give rise to earthquakes on other faults after a long quiescence, during which stress has slowly accumulated to a critical value. As a result, seismicity can migrate among faults. This seems to be happening at New Madrid and other places such as northern China, where the historically active seismicity in the Shanxi graben has shut down in the past 200 years and may be migrating eastward to the North China Plain.

This process is reminiscent of the game “Booby-Trap” (Figure 1), which consists of a box with a spring bar pushing on many small pieces. When one piece is removed, some of the others slide around in a complicated way, as illustrated in <http://www.earth.northwestern.edu/people/seth/Educational/boobytrap.html>.

Plate boundary zones such as southern California, where the plate motion is spread over a broad region, are intermediate between isolated faults and complex systems. The primary boundary fault takes up much of the motion, and other faults are reloaded at an intermediate rate—typically a few mm/yr—by the fraction of the plate motion not taken up on the primary

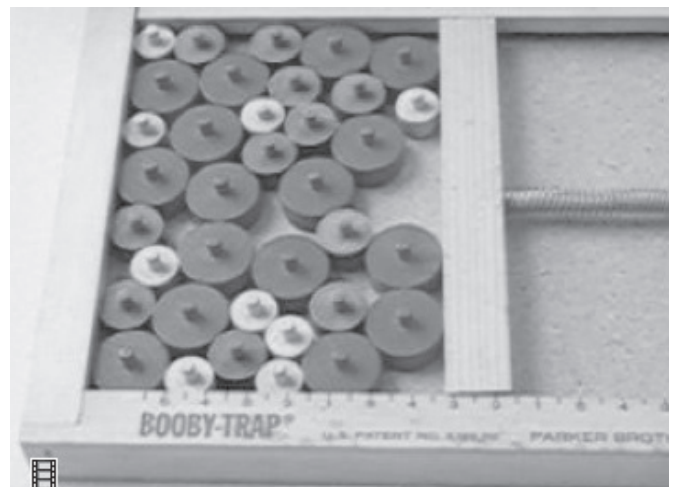
boundary and by regional effects such as the boundary-related topography. Because these stress sources change at best slowly, faults remain active for longer periods than within the plate interior, but seismicity sometimes migrates. Such migration is thought to have occurred in the Basin and Range province since the Quaternary and between the San Andreas and San Jacinto faults in the past 100,000 years.

A complex-system view offers an alternative way of thinking about mid-continent earthquakes. For example, in this view, the New Madrid faults that broke in 1811–1812 are just the presently most active of the many recognized faults in the south-central United States, and the lack of present deformation on them could indicate that the recent cluster of large earthquakes has ended. Most of the small earthquakes in the area seem likely to be aftershocks of the large ones in 1811–12, rather than foreshocks of an upcoming one. The longer duration of aftershocks in continental interiors

relative to plate boundaries probably reflects the differences in loading rates, because it takes much longer after a large earthquake for fault reloading to overwhelm the small postseismic stress changes on and near the fault that cause aftershocks. As a result, it has been suggested that many concentrations of mid-continental seismicity may be aftershocks of large past earthquakes, such as the 1663 Charlevoix event. Improved uniform datasets for mid-continental earthquakes from programs like USArray should be helpful in exploring this possibility.

We have conducted a pilot study using a simple finite-element model to explore earthquakes in a system of interacting fault zones. The model assumes uniform physical properties of the faults subject to uniform forces acting on the continent’s margins. As the model evolves over time, it replicates general aspects of the complexity of earthquakes that we observe in

Spatio-temporal variability results from interactions between faults in a region that form a complex system whose evolution cannot be understood by considering an individual fault.



▲ **Figure 1.** The game Booby-Trap is an analogy for the way mid-continental earthquakes migrate in space and time among a network of interacting faults.

the central and eastern United States. An earthquake on one fault changes the stress on others and so can cause seismicity to migrate. If a fault weakens following a large earthquake, repeated large earthquakes occur on this fault before migrating to another. Hence although the actual earthquake hazard in the model is uniform in space, assessments based on short time snapshots are biased.

This view of mid-continent fault systems has major implications for earthquake hazard policy. Present policy assumes that earthquake hazards in the central United States are dominated by quasi-periodic behavior of the New Madrid faults. However, because large earthquakes migrate among faults, hazard assessments based only on the recent earthquake record can overestimate the risks in regions of recent large earthquakes and underestimate them where seismicity has been recently quiescent.

Although this complex-system view of mid-continent earthquakes has many attractive features, it is only a general concept at present. The question is whether it will give us useful new insights. An approach that seems worth pursuing is to develop realistic models to explore the dynamic interplay of the mechanical properties of mid-continent areas, the forces acting on the fault systems, and the faults' physical properties. Such models should be able to replicate the known historic and paleoseismic faulting histories and the geodetic observations. They would allow exploration of unresolved issues. One is under what conditions earthquakes will occur in temporal clusters and under what conditions such clusters end. At present how this happens is unclear. Two possibilities are that faults weaken with time, or that what appear to be clusters in the paleoliquefaction record in fact occurred on different nearby faults. Another important question is when the absence of geodetically observed deformation can indicate that an earthquake cluster is ending, rather than indicating transient release of strain accumulated over a time much longer than the time between large earthquakes. Finally, if co- and post-seismic stress transfer controls earthquake migration and clustering, the question of what causes the initial event in a cluster remains open. Because

long-term far-field stress loading by plate motions is very slow, processes that may have a minor role at plate boundaries, such as flexural loading or unloading due to ice or sediments, may play a significant role, provided that they act at a time scale that is short compared to the relaxation time of the lithosphere.

Such models are likely to give insights into aspects of the past earthquake history that have not yet been recognized. They should also give testable predictions for the possible evolution of the system, including where to expect strain accumulation that will be released in future earthquakes. These predictions can then be tested using GPS data and—if successful—incorporated into improved earthquake hazard models and used to develop cost-effective seismic hazard mitigation policies.



Because large earthquakes migrate between faults, hazard assessments based only on the recent earthquake record can overestimate the risks in regions of recent large earthquakes and underestimate them where seismicity has been recently quiescent.

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