**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 2000 years. We thus expected to see strain building up for a future large earthquake, but find none. Successive studies confirm this surprising result to 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.

Similar results are also emerging from structural and paleoseismic studies in the central U.S. and other continental interiors. It appears that in many places large earthquakes cluster on specific faults for some time and then migrate to other faults. Thus faults “turn on” and “turn off” on timescales of hundreds or thousands of years. Some faults that appear inactive today, such as the Meers Fault in Oklahoma, have clearly been active within the past 20,000 years. Hence large mid-continent earthquakes are episodic, clustered, and migrating.

We hypothesize that this spatio-temporal variability results from interactions between 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 explains why we have been unsuccessful to date in understanding them. We have focused on individual faults in isolation, whereas in a complex-system approach, the key is the interactions between 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 between 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. We have been puzzled for some time about why, given that the physics of fault rupture in these two environments is essentially the same, the spatio-temporal patterns of earthquakes in these two settings 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.
Because a plate boundary is rapidly loaded by the motion of neighboring plates, it typically acts almost like an isolated fault. In an ideal geometry, a through-going fault is loaded rapidly at rates of tens of millimeters per year. After a large earthquake, the steady plate motion reloads the fault quickly. 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 and so 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, there the fast plate motion dominates the loading process. In a mid-continent, however, loading is very slow, as shown by GPS data that to date cannot resolve any regional intraplate strain accumulation in North America. Hence after a large 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 between faults. This seems to be happening at New Madrid and other places such as North 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.

Plate boundary zones are intermediate between isolated faults and complex systems. Faults are reloaded at an intermediate rate - 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 most slowly, faults remain active for longer periods than within the plate interior, but seismicity sometimes migrates. For example, such migration seems to have occurred in the Great Basin 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. In such a view, New Madrid seismic zone is just the presently most active
one of the many recognized faults in the south-central U.S., and the lack of present deformation on it could indicate that the recent cluster of large earthquakes has ended. If so, the small earthquakes occurring in the area are aftershocks of the large ones in 1811-12, rather than foreshocks of an upcoming one. Rate-and-state friction models predict long aftershock sequences in situations where a fault is being loaded slowly. This is because it takes a long time after a large earthquake before far-field loading overwhelms the resulting small stress changes near the fault that cause aftershocks.

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, which are 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 the central and eastern US. 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 U.S. are dominated by quasi-periodic behavior of the New Madrid faults. However, if 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.

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 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 paleoseismic 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 transient release of strain that 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 accumulating 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.

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