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East meets Midwest: An earthquake in India helps hazard assessment in the Central United States

Why travel halfway around the world to study an earthquake?

Although geographically distant, the State of Gujarat in India bears many geological similarities to the Mississippi Valley in the Central United States. The Mississippi Valley contains the New Madrid seismic zone that, during the winter of 1811-1812, produced the three largest historical earthquakes ever in the continental United States and remains the most seismically active region east of the Rocky Mountains. Large damaging earthquakes are rare in ‘intraplate’ settings like New Madrid and Gujarat, far from the boundaries of the world’s great tectonic plates. Long-lasting evidence left by these earthquakes is subtle (fig. 1). Thus, each intraplate earthquake provides unique opportunities to make huge advances in our ability to assess and understand the hazards posed by such events.

On January 26, 2001, a M 7.7 earthquake struck the State of Gujarat in the northwest corner of India. Several teams of scientists traveled to the region to study what is now known as the Bhuj earthquake (named after the closest affected city). A few of these teams came from the Central and Eastern United States, with the specific objectives of learning lessons that they could apply directly to reducing earthquake hazards in their own cities and towns.

Figure 1. Close-up view of liquefaction taken several weeks after the Bhuj earthquake near the village of Umedpar. Shaking caused the saturated soils and sands to lose their strength and compact, raising the water pressure until water and sediment erupted on the surface as sandblows. As the salty water dries, a white salty crust is left behind. This part of the epicentral area, known as the Banni Plain, is adjacent to an inlet to the sea (the Great Rann of Kutch) that floods annually. The extremely flat topography suggests that the rates of geologic activity must be very low because high rates build mountains and other topographic relief. (Photo courtesy of Gary Patterson, Center for Earthquake Research and Information, Memphis, Tenn.)

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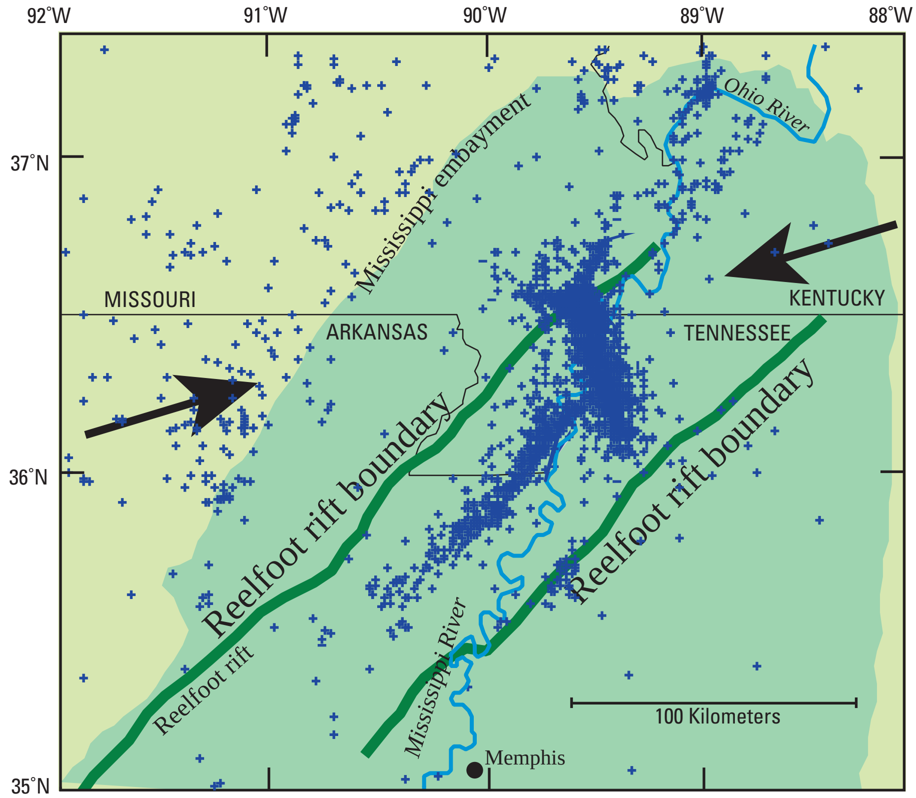
Figure 2. The New Madrid seismic zone is defined by a z-shaped pattern of earthquake epicenters (blue crosses). Many lines of evidence suggest that this pattern defines the major faults that broke during the 1811-1812 earthquakes. The vast majority of the earthquakes shown here are much too small to be felt and have been recorded by sensitive instruments deployed in the early 1970s. The earthquake activity roughly parallels the Reelfoot rift, an ancient break in the Earth's crust. Millions of years ago the crust began to pull apart, or rift, but failed to break completely as happens when new plate boundaries form. Instead, a long linear zone of intense faulting formed. Today the crust is being compressed in the direction shown by the arrows. Much of the seismic zone is buried beneath the Mississippi embayment (darker green area), a trough filled with sediments that may greatly amplify earthquake shaking.



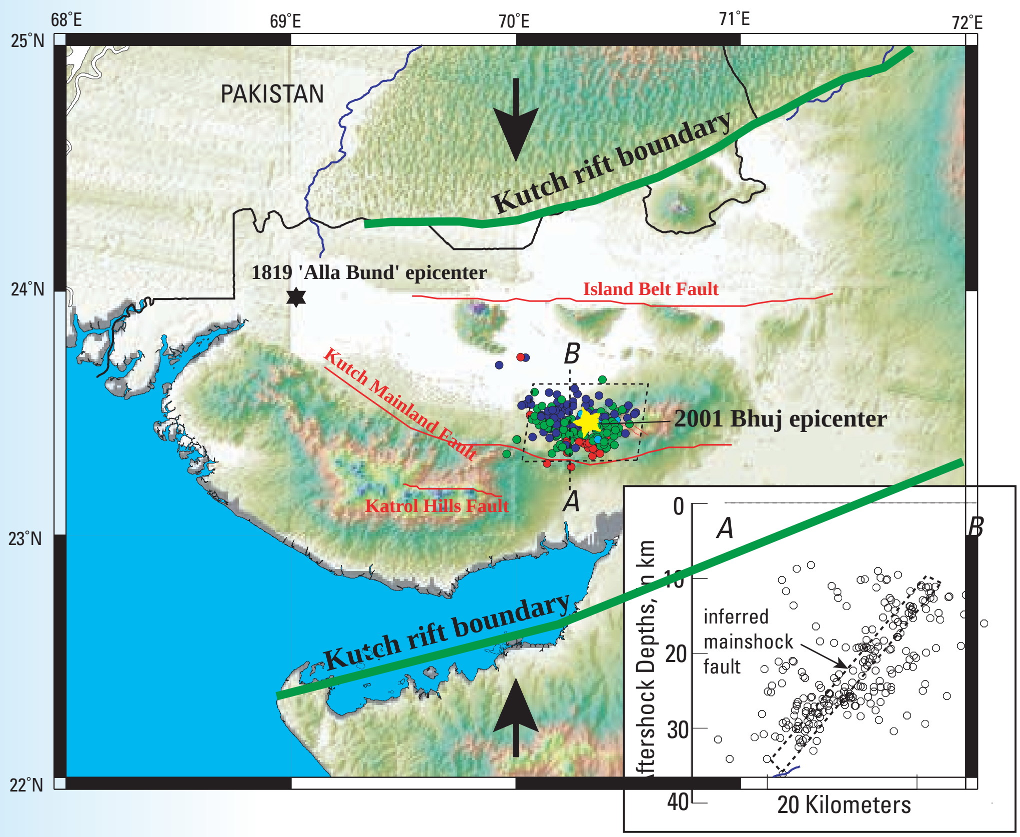


Figure 3. Shaded relief map of northwestern Gujarat, showing the locations of the 2001 M 7.7 Bhuj and the 1819 Alla Bund earthquakes, which probably were events of similar size (stars). Both earthquakes occurred in the Kutch rift, an example of a failed rift that is now affected by stresses (arrows) that act to compress it rather than pull it apart. Known faults are labeled. Like the New Madrid region, much of the region is blanketed by thick sediments. No earthquake monitoring network existed in Gujarat prior to the Bhuj event, but aftershocks were recorded by temporary networks. (Dots show aftershock locations; colors indicate aftershock depths: red, deep; green, intermediate; blues, shallow.) The extreme compactness of the inferred mainshock fault (dashed rectangle) contrasts with a typical earthquake on a plate edge, such as the recent M 7.6 1999 Taiwan earthquake, which raised the surface 8 m and broke the Earth's surface for almost 100 km (approximately the length of the Island Belt fault shown).

Inset: Aftershocks viewed in cross-section, along a line from A to B, reveal a southward dipping fault. If projected to the surface, the top of the fault (edge of the dashed rectangle on the map) does not correspond to any mapped fault. (Figure from Paul Bodin, Center for Earthquake Research and Information, Memphis, Tenn.)

What do the Central United States and Gujarat, India, have in common?

The geologic settings of the New Madrid and the Bhuj earthquakes are ancient failed-rift zones (figs. 2, 3). Although both formed under very different geologic circumstances than exist today, they are zones of relatively weaker crustal rocks where earthquake processes may cause faulting to occur more easily than in surrounding regions.

In both regions, large damaging earthquakes happen more frequently than scientists would expect based on the number of small and moderate earthquakes. In Gujarat, there was a major earthquake that broke a fault in 1819 and evidence of another one about 800 years earlier. In the Central United States, there is strong evidence of at least two prehistoric earthquake sequences similar to the 1811-1812 earthquakes, which shook the New Madrid region in about 1450 and 900 A.D. The geologically short time between large earthquakes (500 to 1,000 years) is surprising. Generally, such short times between large earthquakes are associated with more frequent small and moderate earthquakes than are observed in either Bhuj or New Madrid. In addition, neither region has the high topography that is a hallmark feature of regions elsewhere in the world that host frequent large earthquakes (figs. 4, 5).

The relationship of the New Madrid and Bhuj earthquakes to plate-tectonic motions remains a mystery. Although most earthquakes in the world occur in response to the relative motions of adjacent plates, both the New Madrid and Bhuj earthquakes occurred more than several hundred kilometers from the nearest plate boundaries. In New Madrid, sophisticated surveying techniques confirm a lack of relative motion across the region. Similar measurements are just being made in Gujarat, and preliminary evidence indicates that if there are relative motions, they are very, very slow. Thus, it seems that the energy released in these geologically frequent major earthquakes exceeds the energy supplied by plate-tectonic motions. We know that the level of stress in crustal rocks in intraplate regions is high, and it may be that these frequent earthquakes result from the release of energy from plate motions that has accumulated over long periods of geologic time.

The effects of earthquakes are better understood than why and how they occur. By far the greatest cause of damage is related to the ground shaking associated with seismic waves emitted by earthquakes. Thick, soft sediments and soils amplify ground shaking. Poorly cemented sediments many hundreds of meters thick blanket much of both the Gujarat and New Madrid regions. When water saturated, sediments are also highly susceptible to a phenomenon called liquefaction, in which shaking causes the sediments to become fluidlike; they lose their ability to support structures. Liquefaction also results in fountains of sand and water erupting to the surface (figs. 1, 5). Both the Bhuj and the New Madrid earthquakes were accompanied by widespread liquefaction.

Figure 4. Ground failure from the Bhuj earthquake most likely resulted from shaking, as the soil mass cracked and slid down the almost imperceptibly sloping ground surface. No permanent changes to the topography directly related to faulting have been identified. The flat terrain suggests that few shallow earthquakes have occurred here previously and (or) that the processes leading to frequent (geologically) large earthquakes have not been going on for very long.

What can we learn? What have we already learned?

Earthquakes affect much larger areas in the Central and Eastern United States than in the Western United States. Preliminary studies of the Bhuj earthquake show its reach to be very similar to those of the New Madrid earthquakes (background maps on page 1; modified from maps contributed by Susan Hough, 2001). This may reflect, in part, more efficient transmission of seismic waves in the colder, less faulted, older crust of plate interiors, relative to younger, hotter, and more fractured crust common along plate edges. However, a long-standing question is whether plate boundary and plate interior earthquakes themselves differ in some fundamental way, and whether these differences contribute to the profoundly greater extend of earthquake effects in plate interiors. Further study of data from modern seismic instruments for the Bhuj earthquake, which do not exist for New Madrid events, hold possible answers to these questions.

Figure 5. Sandblow deposits (light-colored spots) that erupted during the 1811-1812 earthquakes are still a common sight in farmers' fields of the upper Mississippi Valley. The interstate highway in the upper part of the photo provides scale. The flat topography resembles that in the epicentral area of the Bhuj earthquake (figs. 1, 4). Photo from S.F. Obermeier, 1998.

Figure 6. Collapsed houses in the town of Ratnal, in the epicentral region of the Bhuj earthquake. The almost total devastation may, in large part, be attributed to construction methods that have no resistance to earthquake shaking.

Astounding implications about the Bhuj mainshock have already been suggested from studies of its aftershocks (fig. 3). Researchers began deploying instruments to record aftershocks of the Bhuj earthquake almost immediately after the January earthquake. Aftershocks generally outline the fault that caused the mainshock, but Bhuj aftershocks reveal faulting deeper in the lower crust than generally thought possible. The fact that the aftershocks occur in a very compact volume suggests a highly concentrated source of stress. These results are key to understanding how earthquakes work in environments like Gujarat and New Madrid.

Surprisingly, faulting associated with the Bhuj earthquake stopped far below the ground surface, unlike most earthquakes of comparable magnitude. Although almost 200 years have passed since the 1811-1812 New Madrid earthquakes, most evidence indicates that they did not break the surface. The faults that cause large earthquakes typically rupture the surface of the Earth, forming a visible scarp. In addition to telling us about how earthquakes work, the depths over which a fault breaks determine the types of seismic waves radiated and thus, how the ground shakes. Further study of the Bhuj earthquake may reveal the reasons why faulting stopped before reaching the surface and how this relates to the pattern of shaking. Faults not visible on the ground surface make assessment of earthquake hazards especially challenging.

The need to prepare for earthquakes is vividly demonstrated by the human tragedy that resulted from the Bhuj earthquake. More than 20,000 people perished, in part because many lived in homes that had been built with no resistance to shaking (fig. 6). Structures in the United States, however, are generally better built and should better withstand earthquake shaking, even though most in the Central and Eastern United States were not designed with earthquakes in mind. The behavior of earthquakes in Gujarat and New Madrid makes preparedness a special challenge—infrequent small and moderate earthquakes give us a false sense of security that we are immune from the big earthquakes.

Reference:

Obermeier, S.F., 1998, Seismic liquefaction features: Examples from paleoseismic investigations in the continental United States: U.S. Geological Survey Open-File Report 98-488; available on the Internet as http://pubs.usgs.gov/openfile/of98-488/.

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