FORUM

Space Geodesy and the New Madrid Seismic Zone

PAGE 256

One of the most contentious issues related to earthquake hazards in the United States centers on the midcontinent and the origin, magnitudes, and likely recurrence intervals of the 1811–1812 New Madrid earthquakes that occurred there. The stakeholder groups in the debate (local and state governments, reinsurance companies, American businesses, and the scientific community) are similar to the stakeholder groups in regions more famous for large earthquakes. However, debate about New Madrid seismic hazard has been fiercer because of the lack of two fundamental components of seismic hazard estimation: an explanatory model for large, midplate earthquakes; and sufficient or sufficiently precise data about the causes, effects, and histories of such earthquakes.

Background

The important knowns, ordered roughly by the confidence with which they are held as true, are as follows:

1. In the winter of 1811–1812, three large earthquakes occurred in the New Madrid region. Together, they liquefied more than 3700 square kilometers of the surrounding region [*Fuller*, 1912; *Tuttle*, 2001, 1999; *Tuttle and Schweig*, 1995], with liquefaction occurring out to epicentral distances of more than 240 kilometers [*Johnston and Schweig*, 1996; *Street and Nuttli*, 1984]. Regardless of the earthquakes' magnitudes, the conterminous United States had never historically, or since, been so widely and vigorously shaken by earthquakes.

2. Paleoseismic evidence—such as multiple generations of well-dated liquefaction covering more than 10,000 square kilometers [*Tuttle*, 2001, 1999; *Tuttle and Schweig*, 1995] and various tectono-geomorphic features—points to the occurrence of at least three earthquakes prior to 1811–1812, approximately 500 years apart, since 300 A.D., and at least one earthquake that occurred at approximately 2350 B.C. [*Kelson et al.*, 1996; *Tuttle et al.*, 2002, 2005].

3. Recent geological investigations find paleoliquefaction features, of currently unknown origin, 75–240 kilometers southwest of the New Madrid region, from 700, approximately 5500, and approximately 6800 years ago [*Cox et al.*, 2004, 2006; *Al-Shukri et al.*, 2005; *Tuttle et al.*, 2006].

4. A number of factors—microseismicity [e.g., *Chiu et al.*, 1992]; geomorphology [*Russ*, 1979]; the development of the Lake County uplift (covered by modern Mississippi River meanders); development over the Reelfoot thrust fault of both the Tiptonville Dome and within the past 2500 years, the Reelfoot Scarp [*Van Arsdale*, 2000]; and constraints offered by numerical models [e.g., *Gomberg and Ellis*, 1994]—indicate a complex, three-dimensional fault structure, with two northeast trending, right-lateral strike-slip faults connected across a compressional step by the Reelfoot thrust fault.

Recent Contribution of GPS Geodesy

The estimation of modern deformation rates using geodetic GPS measurements has progressed over the past 20 years from campaign [*Liu et al.*, 1992] to continuous measurements, with the precision and understanding of uncertainties improving markedly. The most recent geodetic results [*Smalley et al.*, 2005a] reveal the first hint of a statistically significant sensible pattern and rate of active deformation consistent with fault geometry, Holocene-based repeat-time, and recent explanatory tectonic models [e.g., *Kenner and Segall*, 2000].

The *Smalley et al.* [2005a] GPS results generated significant controversy, due principally to the treatment of uncertainties [*Calais et al.*, 2005; *Smalley et al.*, 2005b; *Stein*, 2007; *Newman*, 2007]. *Stein* [2007] repeats the arguments of *Newman et al.* [1999] that GPS results suggest seismic hazard estimates for the region that are greatly exaggerated. We reiterate that while continuous GPS measurements have not yet reached the precision where there is general agreement that New Madrid seismic zone (NMSZ) deformation has been detected, none of the GPS results to date unequivocally argue for changes to the independently and geologically estimated seismic hazard.

Newman [2007] raises interesting issues about modeling deformation, but he misses the main point, the detection of deformation, of *Smalley et al.* [2005a]. Strain around a finite fault is inhomogeneous and cannot be characterized by a single value; it is dangerous to base models on a single strain measurement. Detection of a strain rate of the order of 10^{-7}–10^{-8} per year in the immediate region of the New Madrid faults, even by only two pairs of stations, is nevertheless an important observation that should not be dismissed.

Smalley et al. [2005a] suggest that deformation may represent interseismic strain accumulation or various viscoelastic or poroelastic postseismic processes. *Rydelek* [2007] takes issue with a tectonic origin of the strain but misses an important distinction between elastic stress accumulation and postseismic stress evolution.

The key is that the strain reservoirs for the two processes are different. Strain accumulates in the elastic crust, the earthquake releases strain, and the process starts over. In a coupled elastic-viscoelastic system, an earthquake sheds strain stored in the elastic layer into the viscoelastic reservoir, and the viscoelastic reservoir feeds strain back into the elastic layer as it relaxes. Such a model can generate geologically rapidly repeating sequences of earthquakes without requiring additional energy from the tectonic far field during the sequence [*Kenner and Segall*, 2000]. Earthquake magnitudes will wane over time due to energy loss in the viscous reservoir. Postseismic viscoelastic effects can therefore significantly affect the whole earthquake cycle, and the term "relaxation" may be misleading with respect to the viscoelastic contribution to seismic activity.

Stein [2007] suggests that seismicity may be temporally clustered, that present activity is shutting down, and that there will be no large earthquakes for many hundreds to thousands of years. At timescales longer than the Holocene, this is not unreasonable. Seismic stratigraphy across the Reelfoot thrust fault suggests that geologically averaged rates of displacement are very slow [*Van Arsdale*, 2000]. Regardless of the controversy surrounding the GPS results presented by *Smalley et al.* [2005a], the quality and rapidly increasing quantity of geological evidence make the conclusions of *Stein* [2007], based on geophysical models rather than on geologic evidence, both premature and a risky basis for pursuing public policy related to New Madrid earthquake hazard.

Improving geological, geophysical, and geodetic data provide an increasingly more enigmatic picture, indicating that processes responsible for earthquakes in continental plate interiors may behave quite differently from, and require a more complex description than, those at plate boundaries. Seismicity in eastern North America is also concentrated in zones containing fossil structures related to the opening and closing of ocean basins associated with the past few Wilson cycles. How these regions respond to stresses transmitted through continental plates is poorly understood. The challenge is to develop models for continental intraplate earthquakes that consider all available data and can be used with societal risk criteria to formulate responsible public policy.

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MEETING

Cold Regions Hydrology and Water Management: Bridging the Gap

Prediction of Water Resources in Mountain and Northern Canada: What is Needed, What Can be Done—An IP3 Users/Stakeholders Community Workshop; Canmore, Alberta, Canada, 18–19 March 2008

PAGE 256

Improved Processes and Parameterisation for Prediction in Cold Regions (IP3) is a research network funded by the Canadian Foundation for Climate and Atmospheric Sciences (http://www.usask.ca/ip3). With more than 80 members across Canada, the United States, and Europe, IP3 is devoted to the study and prediction of surface water, weather, and climate systems in cold regions, particularly Canada's Rocky Mountains and western Arctic. IP3 contributes to better understanding of ungauged basin streamflow, snow and water supplies, Arctic Ocean freshwater inputs, and sustainable management of mountain and northern water resources. These issues are important to agriculture, recreation, industrial development, regional planning, policy making, streamflow forecasting, and environmental conservation in the Canadian Rockies, prairies, and north.

In response to feedback from our 2007 annual workshop (report at http://www.usask.ca/ip3/download/ws2/report.pdf), IP3 developed a users' community workshop to facilitate the application of cold regions hydrological science to water management. The meeting attracted 60 participants and was sponsored by Indian and Northern Affairs Canada, Canadian Society for Hydrological Sciences, Western Watersheds Climate Research Collaborative, Bow River Basin Council, and Northwest Territories Power Corporation.

At the meeting, water managers presented their institutional needs for hydrological data, information, and modeling tools and how IP3 could help meet those needs. The importance of siting observational networks in headwater locations and improving prediction of streamflow in small to medium basins at daily timescales was emphasized. Other observations of interest to the participants included solar radiation, stream temperature, snowpack, groundwater, and soil thaw. Canadian hydrometeorological observational networks have shrunk over the years, so this strong interest in observations is an opportunity for scientists and water managers to work together to strategically expand and enhance existing monitoring networks.

For cold regions prediction, water managers need to know when a snowpack will melt and when and how much will run off to rivers. Models need to fully incorporate observations, be user friendly, and be accompanied by training and clearly written user manuals. Participants also asked that they be made aware of available data and tools because most users do not know all that is currently available and applicable to their operations.

Along with its 18-member Users' Advisory Committee, IP3 scientists are beginning to address these and many other needs expressed during the workshop. To assist with users' modeling needs, IP3 is organizing training workshops on its Cold Regions Hydrological Model (CRHM; see http://www.usask.ca/hydrology/crhm.htm). To continue the dialogue between IP3 scientists and potential users of our data and tools, IP3 plans to increase its outreach activities (through public events/seminars, written materials, data/model analysis, online graphical presentation, etc.) and will continue to involve water managers in scientific meetings.

Relationships between scientists, users, and policy makers who live in or interact with northern and mountain communities are crucial links that drive application of cold regions hydrological science. IP3 is committed to developing these relationships and encouraging community involvement so that water managers and other stakeholders have the information and tools needed to make well-informed decisions that protect and benefit our critical water resources.

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