much longer—hundred of years or more—to resolve. This situation would have delighted Mark Twain, who piloted steamboats through the area only 50 years after the 1811–1812 earthquakes. In his words, "There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact."

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—SETH STEIN, Department of Earth and Planetary Sciences, Northwestern University, Evanston, Ill.; E-mail: seth@earth.northwestern.edu

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Earthquake Risk From Strain Rates on Slipping Faults

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Discrete geodetic measurements made near active faults may capture only small bits of a relatively complex field of deformation surrounding a fault, making it difficult to accurately describe the nature of ongoing activity along the fault. This difficulty is compounded when geodetic measurements are reported as strain rates, which involve differences in the displacement between two or more sites over time. As a result, very low displacement rates can be quoted as very high strain rates, which may lead to incorrectly inferring high seismic risk. As an example, I look at a recent deformation study across the New Madrid Seismic Zone (NMSZ). The NMSZ, located in east central United States and away from rapidly deforming plate boundaries, is best known for its series of three large earthquakes ($M > 7$) in the early 1800s, and continues today with numerous small earthquakes (Figure 1).

A recent study by *Smalley et al.* [2005] used two GPS sites within a larger continuous network to identify rapid strain accumulation across the central thrust segment of the NMSZ. Using the limited subset of data, *Smalley et al.* [2005] inferred that the strain rate measured at the NMSZ is comparable to rates along the San Andreas and other active faults, in apparent contrast to an earlier campaign GPS study that showed less than 2 millimeter per year of overall deformation [*Newman et al.*, 1999]. It has been argued that the new results do not require motion statistically different from zero, reflecting differences in processing techniques and random noise [*Calais et al.,* 2005]. However, here I consider a separate larger and more general issue. This is the validity of using simple strain measurements across a fault for implying earthquake recurrence and seismic hazards. The difficulty is that the small displacement rates can be quoted as high strain rates.

Of the eight sites in a network surrounding the NMSZ, *Smalley et al.* [2005] found that only two sites, which were 11 kilometers apart, showed potentially significant deformation of

2.7 ± 1.6 millimeters per year (Figure 1). Using the simple linear relation for strain rate,

$$\dot{\varepsilon} = \frac{\Delta \dot{u}}{l}$$

where $\Delta \dot{u}$ is the change in velocity over the distance l between measurements, they find a strain rate of approximately 10^{-7} per year. Unfortunately, this resultant strain rate alone does not yield useful information about the true strain accumulation across a slipping fault. That is because for a given
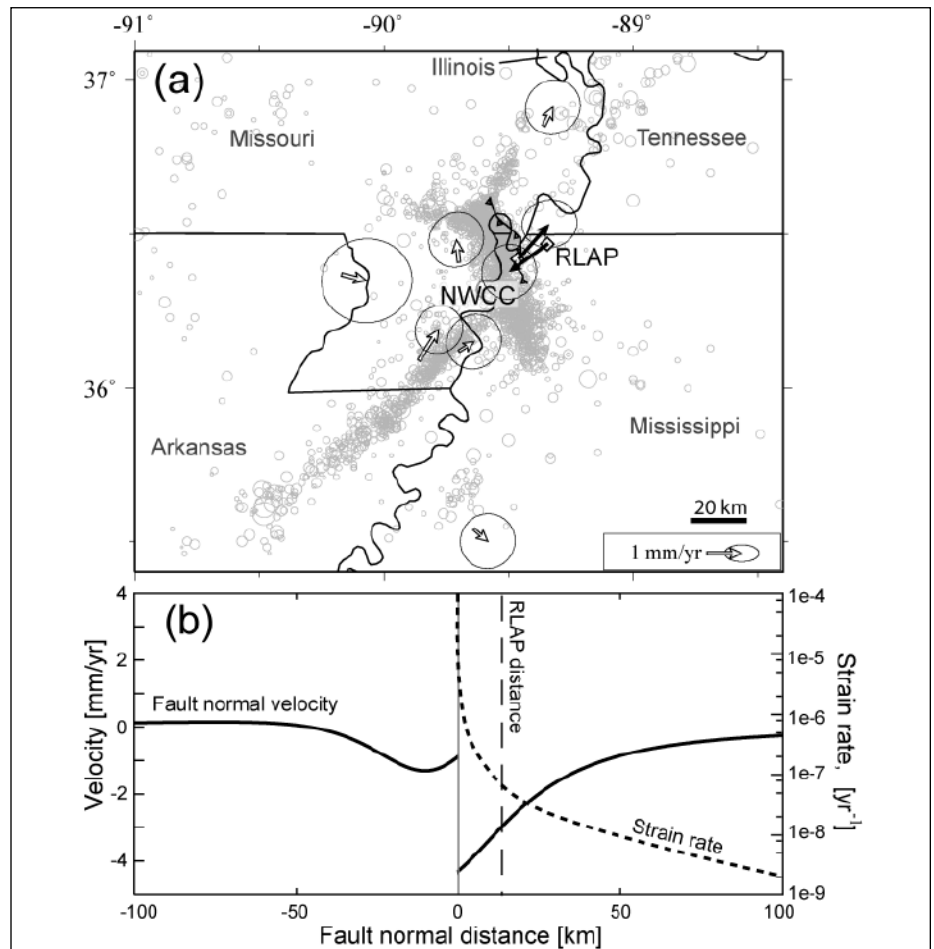

*Fig. 1. (a) New Madrid seismicity since 1974 (grey circles), GPS horizontal site velocities and 2σ errors (arrows and ellipses [*Smalley et al., 2005*]), and approximate surface location of the Reelfoot thrust fault (thick toothed line). Solid arrows are site velocities nearest the thrust and were used to infer strain rates of 10^{-7} per year at the distance of site RLAP. (b) Predicted fault-normal displacements and strain rates (thick dark solid and dashed lines) for ongoing slip across a simple thrust assuming a 60-kilometer-long, 70° west dipping fault extending to 20 kilometer depth (approximating the Reelfoot thrust) using the analytic model of Mansinha and Smylie [1971]. Slip is scaled to approximate that reported by Smalley et al. [2005], 11 kilometers from the fault (thin vertical dashed line). The resulting strain rate is not constant, but instead increases rapidly near the fault.*

fault slip rate, the strain rate is directly dependent on the distance between the two sites across the fault. In the NMSZ, ongoing earthquake activity along the Reelfoot fault (Figure 1) suggests that this is the case near the two sites used in the Smalley paper.

To better illustrate the issue, the model curves in Figure 1 show fault-normal shortening and the resulting strain rate for a simplified fault analogous to the Reelfoot thrust. Slip is scaled to approximate the 10^{-7} per year strain rate at two sites about 5 kilometers from the fault, inferred by *Smalley et al.* [2005]. However, depending on changes in the measurement distance, strain rates decrease dramatically away from and increase rapidly very near the fault. Specifically, when measurements are made 100 kilometers from the fault, the resultant strain rate decreases by 2 orders of magnitude. However, as measurements are made right up to the fault, strain rates become infinitely large, as the distance between measurements goes to zero. Thus, it is clear that a direct comparison of strain rates alone from different fault systems is not useful for describing relative activity along faults, let alone their seismic hazard. It is

better to either directly compare relative velocities at certain distances or compare the best models that describe such activity. In this case, the measured convergence suggests that there is active slip along the fault, consistent with ongoing microseismicity.

A significant consideration to be made here is whether or not ongoing active slip along a fault suggests increased seismic hazard, as has been suggested by *Smalley et al.* [2005]. It has generally been observed that along active faults, the regions that are not actively slipping are instead locked and thus able to build strain energy for possibly catastrophic release. These locked regions, identifiable by significant far-field and little to no near-field strain, have the greatest potential for moderate to large earthquakes [e.g., *Scholz,* 2002]. Thus, ongoing slip on a fault may suggest lower immediate danger because the fault is accumulating little if any strain energy for future events. In the NMSZ, if the relative motion is real, it may be due to postseismic relaxation within the asthenosphere due to past earthquakes [*Rydelek*, this issue], which causes transient motions near the fault rather than accumulating slip for future earthquakes.

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—ANDREW NEWMAN, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta; E-mail: anewman@gatech.edu

New Madrid Strain and Postseismic Transients

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A crucial issue for the assessment of earthquake hazard in the New Madrid Seismic Zone (NMSZ) of the central United States is whether the small motions inferred from geodetic measurements are actually the result of strain accumulation that will eventually be released in damaging earthquakes. The interpretation of these measurements has led to an ongoing debate over the associated seismic risk and hazard assessment in the NMSZ [*Zoback,* 1999; *Schweig et al.,* 1999; *Newman et al.,* 1999a, 1999b; *Stein et al.,* 2003]. The gist of the debate is whether or not models of high seismic hazard in this region are supported by the geodetic data and historic earthquake data.

A recent report by *Smalley et al.* [2005] on GPS measurements across the Reelfoot fault suggested a relatively high strain rate, of the order of 10^{-7} per year, comparable to that normally associated with convergence at plate boundaries. To some, these measurements seemingly ended the debate since they were taken to be the result of rapid strain accumulation that could unleash a large, devastating earthquake, which in turn prompted a general public warning from a top U.S. Federal Emergency Management Agency (FEMA) official [*Brown,* 2005]. Others, however, believe that the debate is not yet settled [*Calais et al.,* 2005]; it has been argued that these GPS measurements show no statistically significant motion and instead

reveal a puzzling offset in one of the GPS time series [*Calais et al.,* 2006].

Smalley et al. [2005] offered several explanations for their observations, one of which was long-term postseismic relaxation following the 1811–1812 sequence of three large earthquakes that occurred in this seismic zone. Clearly, relaxation is fundamentally different from accumulation. Postseismic relaxation is due to the coupling of the rigid elastic crust to the underlying viscoelastic asthenosphere. An earthquake generates stresses that are relieved by both an immediate elastic response (coseismic effect) and a long-term viscoelastic relaxation (postseismic effect) that will persist for many decades because of the enormous value of the viscosity of the asthenosphere, on the order of 10^{20} pascal seconds. The long-term effects of postseismic relaxation were found to include migrations in seismicity [*Rydelek and Sacks,* 2001] and triggering or inhibition of remote seismicity [*Rydelek and Sacks,* 1990; *Pollitz and Sacks,* 1997; *Rydelek and Sacks,* 2003].

It is odd that *Smalley et al.* [2005] did not pursue the possibility of postseismic effects, since it was previously shown by *Rydelek and Pollitz* [1994] that a large-magnitude strike-slip earthquake in 1811 along the Bootheel lineament in the NMSZ could generate a localized high rate of strain in the present day. This rate may resemble some features of the Reelfoot GPS measurements if that observation were indeed the result of steady strain deformation.

To investigate postseismic effects specific to a large thrust earthquake, model calculations [*Pollitz,* 1992] were done for a $M_w = 7.8$ event in 1812 along the Reelfoot fault shown in Figure 1 and with fault parameters given in Table 1. This earthquake was the last, and largest, of the three events that occurred in the winter of 1811–1812. A viscoelastic Earth model [*Rydelek and Pollitz,* 1994] believed to be appropriate for this region of the central United States was used, and the calculations were run to span the time interval 2000–2005, that is, results for 5 years of postseismic viscoelastic relaxation that correspond to the times and regions of the GPS measurements of *Smalley et al.* [2005].

Figure 1 shows the model results for the engineering strain $\gamma = \varepsilon_{EE} - \varepsilon_{NN}$, where ε_{EE} and ε_{NN} are the compressional components of the strain tensor. Calculated strain rates of order 10^{-7} per year are found in the vicinity of the Reelfoot fault, and the corresponding

Table 1. Fault model parameters for 1812 Reelfoot Earthquake. Uniform slip on the fault plane is assumed.

Latitude =	36.64°
Longitude =	-89.55°
Strike =	158°
Length =	58 km
Width =	27 km
Dip =	40°
Rake =	90°
Slip =	11.0 m
M_w =	7.8 (computed from fault parameters)