LETTERS

Space geodetic evidence for rapid strain rates in the New Madrid seismic zone of central USA

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In the winter of 1811–1812, near the town of New Madrid in the central United States and more than 2,000 km from the nearest plate boundary, three earthquakes within three months shook the entire eastern half of the country and liquefied the ground over distances far greater than any historic earthquake in North America[1,2]. The origin and modern significance of these earthquakes, however, is highly contentious[3]. Geological evidence demonstrates that liquefaction due to strong ground shaking, similar in scale to that generated by the New Madrid earthquakes, has occurred at least three and possibly four times in the past 2,000 years (refs 4–6), consistent with recurrence statistics derived from regional seismicity[7]. Here we show direct evidence for rapid strain rates in the area determined from a continuously operated global positioning system (GPS) network. Rates of strain are of the order of 10^{-7} per year, comparable in magnitude to those across active plate boundaries, and are consistent with known active faults within the region. These results have significant implications for the definition of seismic hazard and for processes that drive intraplate seismicity.

Current models for generating crustal earthquakes require a means of generating and replenishing strain energy in the Earth's crust, a process that readily occurs along the boundaries of rigid tectonic plates[8]. Large, frequent earthquakes therefore require rapid accumulation in the crust of a significant amount of strain energy. Such strain accumulation is typically observed as differential velocities measured at the Earth's surface via space geodetic surveys. Before the establishment of the permanent GPS array in mid-America (GAMA), space-based geodesy had failed to yield significant differential surface velocities in the New Madrid seismic zone[9,10]. These earlier results, despite large uncertainties of up to $\pm 5\,\mathrm{mm\,yr^{-1}}$, were interpreted to mean that levels of seismic hazard in the central USA should be revised downwards[10].

Table 1 | Locations, velocities, and standard uncertainties of GAMA sites

Station	Longitude	Latitude	V_E	V_N	σ_E	σ_N	Corr
RLAP	270.66	36.47	−1.13	−0.81	0.32	0.32	0.040
MAIR	270.64	36.85	0.27	0.54	0.32	0.32	0.067
NWCC	270.54	36.42	0.89	1.01	0.32	0.28	0.048
CVMS	270.36	35.54	0.40	−0.35	0.32	0.32	0.021
PTGV	270.30	36.41	−0.07	0.64	0.32	0.32	0.073
MCTY	270.30	36.12	0.44	0.28	0.32	0.32	0.070
STLE	270.14	36.09	0.57	0.89	0.28	0.28	0.069
PIGT	269.83	36.37	0.72	−0.18	0.53	0.49	0.016
GODE	283.17	39.02	−0.52	0.79	0.35	0.32	0.242
NLIB	268.43	41.77	−0.52	0.30	0.32	0.32	0.202
MDO1	255.99	30.68	0.53	0.42	0.28	0.28	0.476
PIE1	251.88	34.30	−0.35	0.54	0.32	0.32	0.561

The top eight stations are GAMA sites shown in Fig. 1; the lower four are stations used to define a stable North America. Velocities (V) and uncertainties (σ) are in $\mathrm{mm\,yr^{-1}}$ and are derived from four years of data collection. Corr is the correlation between uncertainties in the N and E directions.

GAMA was installed in the mid- to late 1990s and currently comprises 11 permanent geodetic monuments that both surround and straddle active faults within the New Madrid seismic zone. GAMA sites in the Mississippi embayment use a 'strong' monument consisting of a ~20-m-long, 36-cm-diameter H-beam driven vertically into the ground with a ~1-m mast permanently mounted on the top of the H-beam. A 'strong' monument is one where stability against small soil movements relies on the strength of the monument,

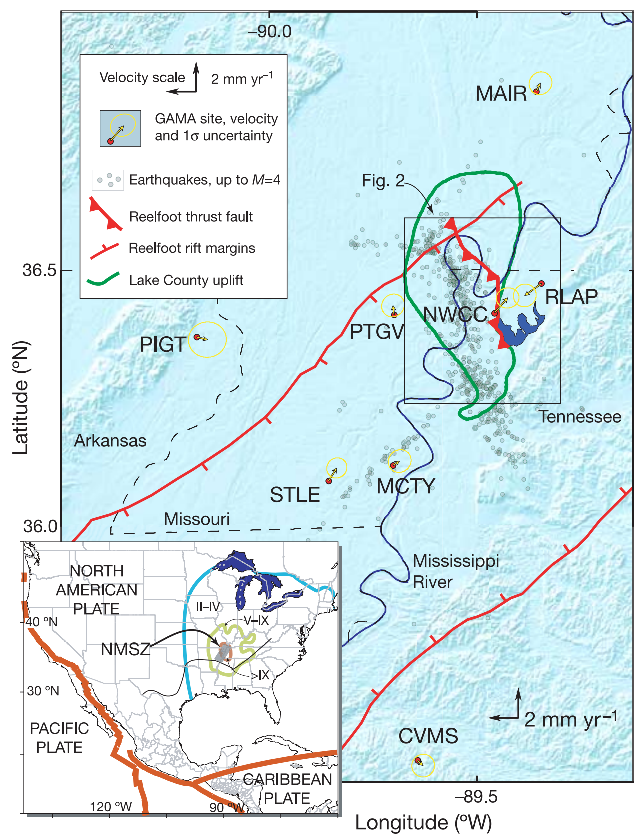

Figure 1 | Velocities and associated uncertainties of GAMA sites in the New Madrid seismic zone (NMSZ). Regional setting of the NMSZ (inset), where plate boundaries (red lines), are clearly remote. The significance of the 1811–1812 and similar earthquakes over the past 10,000 years is shown by reference to contours of intense ground-shaking, quantified by the modified Mercalli intensity scale (Roman numerals). The thick grey line under the region of highest shaking intensity is Reelfoot rift, a failed arm of the Precambrian rifted margin of North America, which is largely coincident with the interior extent of the Paleozoic Appalachian–Ouachita mountain belt (thin black line).

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in this case the H-beam. This is in contrast to a braced monument, which depends on a set of braces to stabilize an otherwise 'weak' monument. Drilled braced monuments are typically constructed of ~2.5-cm-diameter stainless steel rods, which are strong in compression but weak with respect to bending. Both kinds of monument typically reach depths of 10 to 15 m. (We are collaborating in a monument stability test whereby a drilled braced monument is installed within 10 m of the H-beam monument at two of the GAMA sites.) To prevent very shallow surface effects, such as frost heaving, from affecting the position of the monument the top ~1 m of the H-beam is decoupled from the shallow soil with a PVC pipe. A choke-ring antenna with radome is mounted on this mast. GAMA sites outside the embayment are mounted directly in rock outcrop using a ~3 m steel mast, the bottom ~2 m of which is cemented into the rock.

Velocities are derived from processing up to four years of continuous GPS data that includes the GAMA stations and additional stations in central and eastern North America (Table 1). Time-series data were processed using the GAMIT/GLOBK software package by the three-step method described by ref. 11. Formal errors are scaled by the square root of the residual chi-square per degrees of freedom to obtain the standard 1-σ uncertainty of GPS velocities[12], and a random walk of 1 mm $yr^{-1/2}$ was assumed to account for possible monument instability[13].

Two features of the distribution of surface velocities are particularly significant. First, sites close to active faults (near-field) show statistically significant motions consistent with the expected sense of displacement (Fig. 1). Two sites, NWCC and RLAP, straddle the Reelfoot thrust fault-scarp across a fault-normal distance of ~11 km, and show a relative convergence of $\sim 2.7 \pm 1.6$ mm yr^{-1} (Fig. 2). The Reelfoot fault-scarp separates a region of relatively higher elevations in its hanging wall (the Lake County Uplift) from the submerged swamps of Reelfoot Lake in its footwall (Fig. 3)[14]. Active convergence across this fault is consistent with independent evidence for deformation associated with the fault during the third and largest of the 1811–1812 New Madrid earthquakes and for earlier Holocene activity[15–17]. (It was displacement across this fault that notoriously caused part of the Mississippi River to flow temporarily backwards[2].)

Two other sites, STLE and MCTY, face each other across the southern right-lateral fault, highlighted by a prominent northeast-trending and vertical zone of microseismicity and right-lateral earthquake focal mechanisms (Fig. 1). These sites are separated by a fault-normal distance of ~7 km and show a relative fault-parallel right-lateral velocity of ~1 mm yr^{-1}. In each case, the relative velocities yield current strain rates of the order of 10^{-7} yr^{-1}. These rates are comparable to those found along plate margins, such as the San Andreas fault in California[8].

The second significant result is that surface velocities at distances beyond a few fault dimensions (far-field) from active faults do not differ significantly from zero (Fig. 1, Table 1). If the New Madrid seismic zone accumulates strain in the same manner as do plate boundaries, we should expect to see significant surface velocities in the far-field as well as the near-field; this is the signal pattern of one rigid region moving past another.

The apparent absence of far-field velocities suggests one of two possibilities. First, the driving force for New Madrid style earthquakes is local rather than regional. This is a fundamentally different boundary condition than typically inferred from geodetic observations along plate boundaries, in which the lateral and relative motion of plates across a relatively thin zone of deformation provides a means of accumulating strain energy. A local driving force is likely to be related to the release of gravitational potential energy, increasingly recognized as a critical source of energy in the process of building mountains within the interior of continents (for example, ref. 18). Two models have been proposed to provide a local source of energy: deformation of a low-viscosity body within the lower crust[19] or the incremental sinking of a rift-pillow[20], each possibly triggered by the last deglaciation[21]. In each case, however, deeper motion would be expected to yield a radial surface displacement field, for which we see no current evidence.

It is also possible that the observed pattern of surface velocities represent a long-term postseismic process following the 1811–1812 earthquakes. This explanation is consistent with patterns of postseismic deformation following, for example, the 1999 moment magnitude $M_w = 7.1$ Hector Mine[22] and the 2002 $M_w = 7.9$ Denali[23] earthquakes; in each case, near-field surface velocities are significantly larger than those in the far-field. Interpretations of these patterns differ, and include any or a combination of poroelasticity decay, viscous relaxation, or afterslip across the main rupture plane. Current theoretical models are unable to distinguish among these possibilities, largely because of significant uncertainties in earth model parameters (for example, rheology, layer thicknesses,

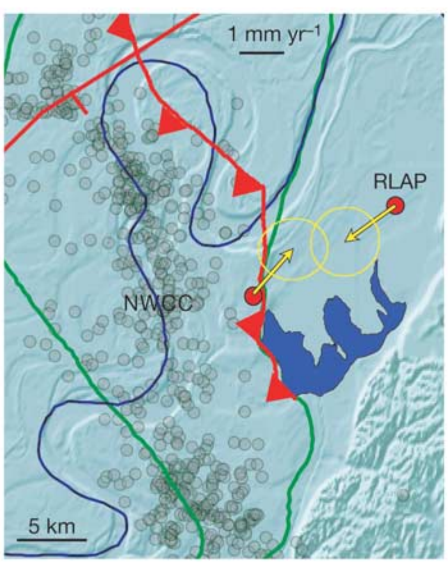

Figure 2 | Velocities of two GAMA sites, RLAP and NWCC, that straddle the active Reelfoot thrust fault. Standard 1-sigma uncertainties (see text) are shown as yellow ellipses. The thrust fault dips at ~30° to the southwest and west and is shown by the red-barbed line. Other symbols as in Fig. 1.

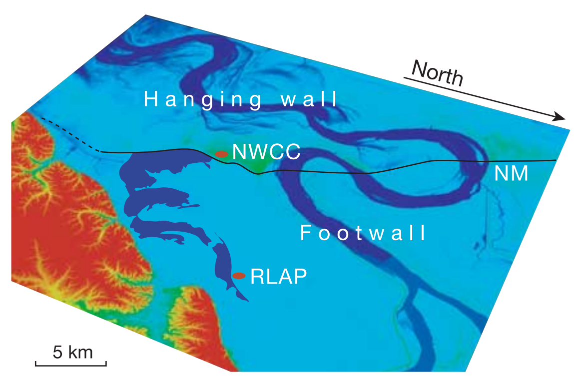

Figure 3 | An oblique view of high-resolution (10 m) digital topography associated with the Reelfoot thrust-fault. View is to the southwest and shows the relative position of the converging GAMA sites seen in Fig. 2. Surface expression of the thrust fault is shown by the black line, dashed where uncertain. The Mississippi River cuts through the clearly visible emerging hanging-wall of the Reelfoot thrust fault, and the town of New Madrid (NM) lies immediately in the footwall of the fault. The Reelfoot fault hanging wall is nowhere more than 10 m above the surrounding region and slopes gently towards the southwest.

boundary conditions) and because observational data are generally too sparse[24]. For this reason, we have intentionally chosen not to model these data, taking the view that at this stage, modelling is premature, offering a deceptively simple and attractive solution to a complex problem. What we can say with some certainty, however, is that whatever the driving force behind the current surface velocities, whether related to 1811–1812 postseismic processes or to the accumulation of a locally sourced strain, aseismic slip is almost certainly required across faults (or shear zones) within the upper few kilometres of the surface.

A process of postseismic afterslip associated with the 1811–1812 New Madrid earthquakes is appealing, despite the relatively long time span since the events. If coseismic slip was largely confined to the subsurface, as in the analogous $M_w = 7.7$ Bhuj earthquake in Gujarat, India, in 2001, slip may be propagating into the upper few kilometres of the crust and, perhaps significantly, into relatively unconsolidated and weakly confined embayment sediments.

The new results presented here should significantly inform the discussion on the nature of deformation in the New Madrid region. Despite the large uncertainties of the earlier campaign surveys[9,10], those results were taken to indicate a significantly reduced level of seismic hazard in the New Madrid region. This interpretation was strongly debated[3,6,25–29], largely because of the extensive and unequivocal evidence for repeated large earthquakes over the past 2,000 years. Geological evidence now exists for widespread and intense liquefaction, similar in size to that generated by the 1811–1812 sequence, in AD 1450 ± 100 yr, AD 900 ± 100 yr, AD 300 ± 200 yr, and in 2350 BC ± 200 yr, and for each event, earthquakes induced more than one episode of liquefaction[4–6,30]. We emphasize here that regardless of the geodetic results, the challenge remains to reconcile the geodetic observations with the detailed geological evidence available for repeated large earthquakes within the central USA. How such earthquakes happen inside a plate interior is not understood.

Received 4 February; accepted 11 April 2005.

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Acknowledgements We thank the NSF Mid-America Earthquake Center and the US Geological Survey for supporting this work. We thank colleagues, particularly A. Johnston, at CERI and E. Schweig at the USGS for discussions.

Author Contributions R.S. and M.A.E. jointly wrote the paper and designed, constructed, and maintained the GAMA network. J.P. performed the GPS data analysis, and R.B.V.A. contributed to the interpretations.

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