

SEISMOLOGY

Tectonic strain in plate interiors?

Arising from: R. Smalley Jr, M. A. Ellis, J. Paul & R. B. Van Arsdale *Nature* 435, 1088–1090 (2005)

It is not fully understood how or why the inner areas of tectonic plates deform, leading to large, although infrequent, earthquakes. Smalley *et al.*¹ offer a potential breakthrough by suggesting that surface deformation in the central United States accumulates at rates comparable to those across plate boundaries. However, we find no statistically significant deformation in three independent analyses of the data set used by Smalley *et al.*, and conclude therefore that only the upper bounds of magnitude and repeat time for large earthquakes can be inferred at present.

The occurrence of earthquakes at the interior of tectonic plates — assumed to be rigid in conventional plate tectonic theory — indicates that stresses within plates accumulate on faults and are released during large, but rare, events. How this cycle relates to the slow deformation of plate interiors is unknown, posing significant difficulties for understanding the associated hazards. Stakes are high because several, now densely populated, intraplate areas have been struck in the past by large earthquakes, including in the central United States in 1811–12, in Basel, Switzerland, in 1356, and in Newcastle, Australia, in 1989. Geophysicists are now using the global posi-

tioning system (GPS) to quantify strain in plate interiors in the hope of relating it to stress build-up on seismogenic faults.

Smalley *et al.* report significant strain from GPS measurements in the New Madrid seismic zone (NMSZ) of the central United States. They interpret their findings as indicating deformation rates comparable to those observed at much more seismically active plate boundaries¹. If confirmed, this result could give insight into the processes that drive the occurrence of large earthquakes in plate interiors, and provide new quantitative information for seismic-hazard estimation in the New Madrid area¹.

However, independent analyses of the same data, performed by three independent groups using different analysis software and processing strategies, reveal no statistically significant site motions or strains (Fig. 1), with an average weighted misfit to a rigid-plate behaviour of 1.4 mm yr^{-1} (95% confidence). In particular, the shortening between sites RLAP and NWCC, used by Smalley *et al.*¹ as their primary argument for strain accumulation on the Reelfoot fault, is of marginal significance ($1.7 \pm 2.0 \text{ mm yr}^{-1}$; 95% confidence) and largely reflects an unexplained offset that

occurred between mid-2001 and early 2002 (Fig. 1, inset). The same analyses, using 156 GPS sites distributed throughout the central and eastern United States, find no spatially coherent deviation from rigid behaviour in the far field of the NMSZ either, apart from effects due to the removal of glacial loads, with an average weighted misfit to a rigid-plate model of 1.4 mm yr^{-1} (95% confidence) as well (further details are available from the authors).

Detecting motion depends critically on the assumed uncertainties of site velocities, which decrease as data span longer times. Hence the present data do not preclude the possibility that a statistically significant tectonic signal may emerge in the future. We shall then face the challenge of deciding whether the deformation represents strain accumulating for release in a future earthquake¹ or long-term relaxation after the 1811–12 earthquakes^{2,3}.

Is an upper bound of 1.4 mm yr^{-1} of motion across the NMSZ consistent with longer-term data from palaeo-earthquakes in the central United States?¹ Assuming that characteristic earthquakes repeat regularly in the NMSZ (probably an oversimplification, although it is one used in National Earthquake Hazard maps), this leads to a minimum repeat time of about 600–1,500 years, consistent with earlier estimates⁴ based on the palaeoseismic history⁵ if one assumes occurrence of earthquakes of magnitude 7, with 1–2 m of co-seismic slip⁴.

Although intraplate earthquakes indicate that tectonic stresses within plate interiors accumulate on faults and are released during large, infrequent events, deviations from rigid behaviour in the central United States and several other major plates^{6,7} are below the current resolution of GPS measurements and do not reflect this cycle — at least not on a timescale of a decade or less. Longer observation spans and further improvement of geodetic techniques are needed to understand where, why and how much strain concentrates in plate interiors.

E. Calais*, **G. Mattioli†**, **C. DeMets‡**,
J.-M. Nocquet§, **S. Stein||**, **A. Newman¶**,
P. Rydelek#

*Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907, USA

e-mail: ecalais@purdue.edu

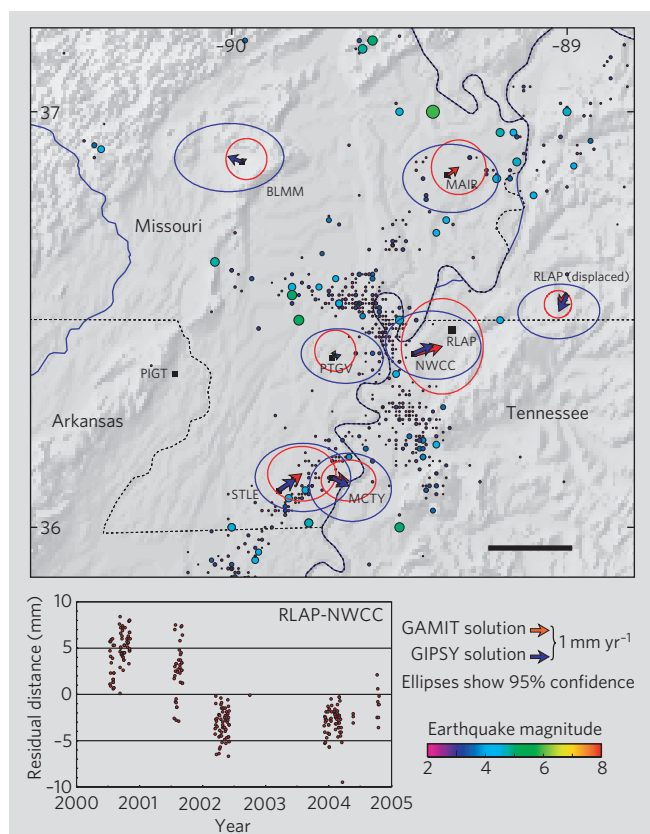
†Department of Geology, University of Arkansas, Fayetteville, Arkansas 72701, USA

‡Department of Geology and Geophysics, University of Wisconsin-Madison, Wisconsin 53706, USA

§CNRS, Geosciences Azur, 06560 Valbonne, France

||Department of Geological Sciences,

Figure 1 | Velocities and associated uncertainties (95% confidence) at continuous GPS sites in the New Madrid seismic zone. To perform these analyses, two different software packages (GAMIT and GIPSY) were used. Site velocities are within their error ellipses and hence show no statistically significant motion. Filled coloured circles show regional seismicity (United States Geological Survey catalogues; details of site names are listed in Table 1 of ref. 1, except BLMM). The different arrow types represent two independent solutions. Scale bar, 20 km. Inset, time series of daily baseline length estimates between sites RLAP and NWCC after removal of a mean. Error bars on daily estimates, omitted for the sake of clarity, are of the order of 2–3 mm.



Northwestern University, Evanston,
Illinois 0208-2150, USA
¶School of Earth and Atmospheric Sciences,
Georgia Institute of Technology, Atlanta,
Georgia 30332, USA
#Center for Earthquake Research, University of
Memphis, Memphis, Tennessee 38152, USA

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Smalley et al. reply

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The independent analyses of GAMA (global positioning system (GPS) array in mid-America) data by Calais et al.¹ demonstrate the difficulties in determining patterns of rational deformation within otherwise rigid plates. We are a long way from incorporating this type of information into seismic-hazard analysis, and we agree that longer time spans and improved spatial coverage with geodetic-quality data are required in order to gather the observations necessary to start modelling and understanding this enigmatic region.

The uncertainties in the analyses of Calais et al.¹ and in our own analysis² are reported at the 1-sigma level, but are shown at 95% confidence level on the maps (Fig. 2 of ref. 2 mistakenly identifies the uncertainties displayed on the map as 1-sigma rather than as their correct 95% confidence interval). There is no disagreement between the two sets of results^{1,2} for the far-field component of the array, where uncertainties in both are larger than surface velocities. The differences arise between analyses in the critical near-field sites, which straddle

the active faults. Velocity vectors and errors at these sites are remarkably close for the two GAMIT solutions: differences arise from the slightly larger uncertainty in the results of Calais et al.¹

Uncertainties in GPS analyses are poorly understood (see the differences between GIPSY and GAMIT analyses reported in refs 1, 2) and depend on the size of the array being considered and the pattern of deformation being sought. We illustrate this with a simple thought experiment: consider a least-squares fit to a straight line using a set of 150 points with a given error distribution, then add to this a second set of 10 points that span a limited range and for which the slope differs by 10%; it will be almost impossible, by statistical means, to distinguish the second set in the combined set. The statistics of the larger set will dominate the uncertainties of the smaller, and the only way to distinguish the two sets is to limit the data to reveal (perhaps serendipitously) the smaller and significant data set. This effect will be compounded if, in

an analysis of a GPS network, the station spacing is larger than the scale expected of local deformation, so that the large-array analysis will probably be aliased.

The illustrated recurrence interval¹, based on an assumed upper bound for fault slip of 1.4 mm yr⁻¹, is limited by the assumption that strain accumulation is linear over time (processes of this sort can be nonlinear), and by palaeoseismological evidence indicating an average recurrence (albeit limited by sparse data) of about 500 years (not 600–1,500 years¹) over the past 2,000 years². Such recurrence would, simplistically, require so-called fault-slip rates greater than 4 mm yr⁻¹. However, debating these few data in terms of a specific seismic hazard is risky (and we avoided it earlier²) because the source of such displacements is unknown²: they are snapshots of a potentially complex spatial and temporal pattern of fault-related displacements.

The relationship of our derived displacements and the well known active faults in the New Madrid region remain a compelling argument to us that the system is active, a conclusion borne out by a decade of geological results in the region². Neither we nor anyone else can so far explain this apparent local deformation — in the spirit of Galileo, “and yet it moves”.

R. Smalley Jr*†, M. A. Ellis*†, J. Paul*,
R. B. Van Arsdale†

*Center of Earthquake Research and Information,
†Department of Earth Sciences, The University of
Memphis, Memphis, Tennessee 38152, USA
e-mail: mellis@nsf.gov

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