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 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,

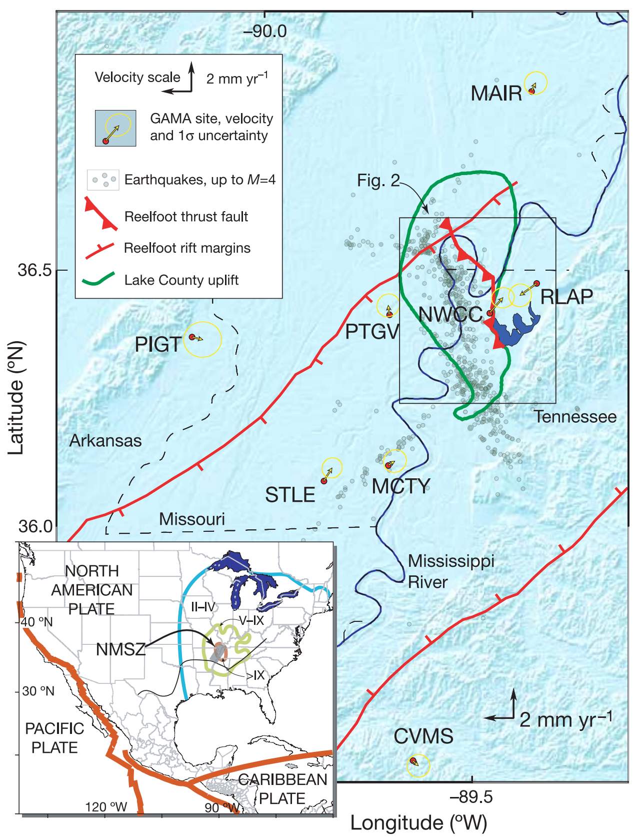

Figure 1 | Velocities and associated uncertainties of GAMA sites in the New Madrid seismic zone (NMSZ). Regional setting of the NMSZ (inset), where plate boundaries (red lines), are clearly remote. The significance of the 1811–1812 and similar earthquakes over the past 10,000 years is shown by reference 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 ~2.7 ± 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,

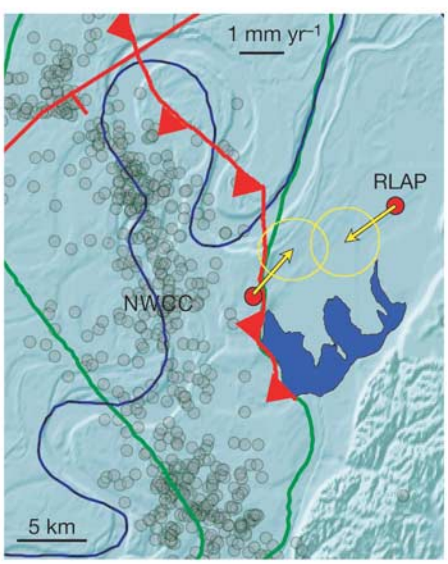

Figure 2 | Velocities of two GAMA sites, RLAP and NWCC, that straddle the active Reelfoot thrust fault. Standard 1-sigma uncertainties (see text) are shown as yellow ellipses. The thrust fault dips at ~30° to the southwest and west and is shown by the red-barbed line. Other symbols as in Fig. 1.

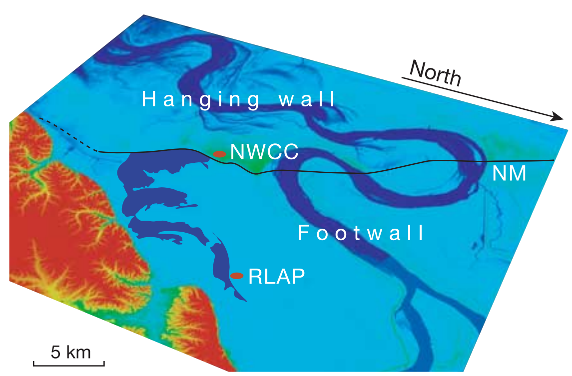

Figure 3 | An oblique view of high-resolution (10 m) digital topography associated with the Reelfoot thrust-fault. View is to the southwest and shows the relative position of the converging GAMA sites seen in Fig. 2. Surface expression of the thrust fault is shown by the black line, dashed where uncertain. 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.

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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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mation processing[7,8]. Grandmother cells are the theoretical limit of sparseness, where the representation of an object is reduced to a single neuron.

Quiroga and colleagues[3] report what seems to be the closest approach yet to that limit. They recorded neural activity from structures in the human medial temporal lobe that are associated with late-stage visual processing and long-term memory. The structures concerned were the entorhinal cortex, the parahippocampal gyrus, the amygdala and the hippocampus, and the recordings were made in the course of clinical procedures to treat epilepsy.

The first example cell responded significantly to seven different images of Jennifer Aniston but not to 80 other stimuli, including pictures of Julia Roberts and even pictures of Jennifer Aniston with Brad Pitt. The second example cell preferred Halle Berry in the same way. Altogether, 44 units (out of 137 with significant visual responses) were selective in this way for a single object out of those tested.

The striking aspect of these results is the consistency of responses across different images of the same person or object. This relates to another major issue in visual coding, 'invariance' (Fig. 1). One of the most difficult aspects of vision is that any given object must be recognizable from the front or side, in light or shadow, and so on. Somehow, given those very different retinal images, the brain consistently invokes the same set of memory associations that give the object meaning. According to 'view-invariant' theories, this is achieved in the visual cortex by some kind of neural calculation that transforms the visual structure in different images into a common format[9–11]. According to 'view-dependent' theories, it is achieved by learning temporal associations between different views and storing those associations in the memory[12–14].

Quiroga and colleagues' results[3] set a new benchmark for both sparseness and invariance, at least from a visual perspective. Most of the invariant structural characteristics in images of Jennifer Aniston (such as relative positions of eyes, nose and mouth) would be present in images of Julia Roberts as well. Thus, any distributed visual coding scheme would predict substantial overlap in the neural groups representing Aniston and Roberts; cells responding to one and not the other would be rare. The clean, visually invariant selectivity of the neurons described by Quiroga *et al*. implies a sparseness bordering on grandmotherliness.

However, as the authors discuss, these results may be best understood in a somewhat non-visual context. The brain structures that they studied stand at the far end of the object-representation pathway or beyond, and their responses may be more memory-related than strictly visual. In fact, several example cells responded not only to pictures but also to the printed name of a particular person or object. Clearly, this is a kind of invariance based on learned associations, not geometric transformation of visual structure, and these cells encode memory-based concepts rather than visual appearance.

How do you measure sparseness in conceptual space? It's a difficult proposition, requiring knowledge of how the subject associates different concepts in memory. The authors did their best (within the constraints of limited recording time) to test images that might be conceptually related. In one tantalizing example, a neuron responded to both Jennifer Aniston and Lisa Kudrow, her co-star on the television show *Friends*. What seems to be a sparse representation in visual space may be a distributed representation in sitcom space! In another example, a neuron responded to two unrelated stimuli commonly used by Quiroga *et al.* — pictures of Jennifer Aniston with Brad Pitt and pictures of the Sydney Opera House. This could reflect a new memory association produced by the close temporal proximity of these stimuli during the recording sessions, consistent with similar phenomena observed in monkey temporal cortex[15].

Thus, Quiroga and colleagues' findings may say less about visual representation as such than they do about memory representation and how it relates to visual inputs. Quiroga *et al.* have shown that, at or near the end of the transformation from visual information about object structure to memory-related conceptual information about object identity, the neural representation seems extremely sparse and invariant in the visual domain. As the authors note, these are predictable characteristics of an abstract, memory-based representation. But I doubt that anyone would have predicted such striking confirmation at the level of individual neurons. ■

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EARTH SCIENCE

New Madrid in motion

Martitia P. Tuttle

A new network of geodetic field stations has greatly improved monitoring of relative motion across a seismic zone in the central United States. It seems that rapid deformation is occurring across this fault system.

The New Madrid seismic zone lies 50–200 km from Memphis, Tennessee, and was the site of devastating earthquakes in 1811 and 1812. These earthquakes included three mainshocks and many aftershocks, with the largest earthquake having an estimated[1,2] magnitude of 7.4–8.1. Historically, New Madrid has been the most seismically active region in central and eastern North America — what hazard might it pose today?

This question has been the subject of vigorous debate in the Earth science and earthquake engineering communities[3,4]. The report by Smalley *et al.* (page 1088 of this issue)[5] will enlighten that debate. From high-precision Global Positioning System (GPS) measurements, made with a newly installed network of field stations, they conclude that the New Madrid seismic zone is rapidly deforming at rates of the same order of magnitude as those at the boundaries of tectonic plates. This result contradicts earlier estimates of low rates of deformation or strain accumulation[6], but is consistent with geological evidence for the occurrence of repeated 1811–1812-type (New Madrid) events in the past 2,000 years[7,8].

During the past 12 years, geologists found a record of New Madrid events in the form of earthquake-related features, known as sand blows (Fig. 1, overleaf). The sand blows formed as a result of liquefaction, a process by which water-saturated sandy sediment below the surface is liquefied and vented on the ground in response to strong earthquake shaking. Detailed study of hundreds of sand blows, some of which are associated with Native American archaeological sites, led to the interpretation that they formed during three, possibly four, New Madrid events of magnitude 7.6 or greater in the past 2,000 years[8].

In the 1990s, geophysicists undertook GPS measurements using a network of field

50 & 100 YEARS AGO

NATURE

50 YEARS AGO

"Personal Factors in Accident Proneness." Dr. J. A. Smiley... has made full use of his position as medical adviser to an aircraft-manufacturing company to study the accident histories of 6,450 men, and to examine in detail 87 men classified as accident prone... His thesis may briefly be stated — accident-prone individuals are usually emotionally disturbed, with associated hypothalamic misfunction which, it is tentatively suggested, produces minor imbalance of adrenalin and acetylcholine with concomitant behaviour disturbance... [they] also show 'anxiety' sweating in interview, albumin in the urine specimens collected during medical examination, a seven-fold increase in peptic ulcer incidence and a more than four-fold increase in incidence of other medical symptoms... The problem remains, however, whether these men may adequately be described as accident prone... the main conclusion to be drawn is that proneness to report minor injury can be added to the list of other known clinical signs of emotional disturbance.

From *Nature* 25 June 1955.

100 YEARS AGO

Prof. E. Wiedemann, of Erlangen, sends us a short statement of observations described in his work on electric discharges... He agrees with Mr. Jervis-Smith as to the action of ozone, and advises persons who work for a long while with influence machines not to have these machines situated in the working room. "Ozone belongs to the poisonous gases, and is the more dangerous, since the injurious effects are not manifest at the time; on the contrary, breathing the gas produces at first a feeling of exhilaration, but afterwards it has a depressing effect on the nervous system... During my observations I have suffered somewhat severely from nervous disturbance (hyperesthesia of the feet) due to breathing ozone. These lasted for one or two years. Moreover, I always experience discomfort after performing experiments in my lectures on Tesla discharges."

From *Nature* 22 June 1905.

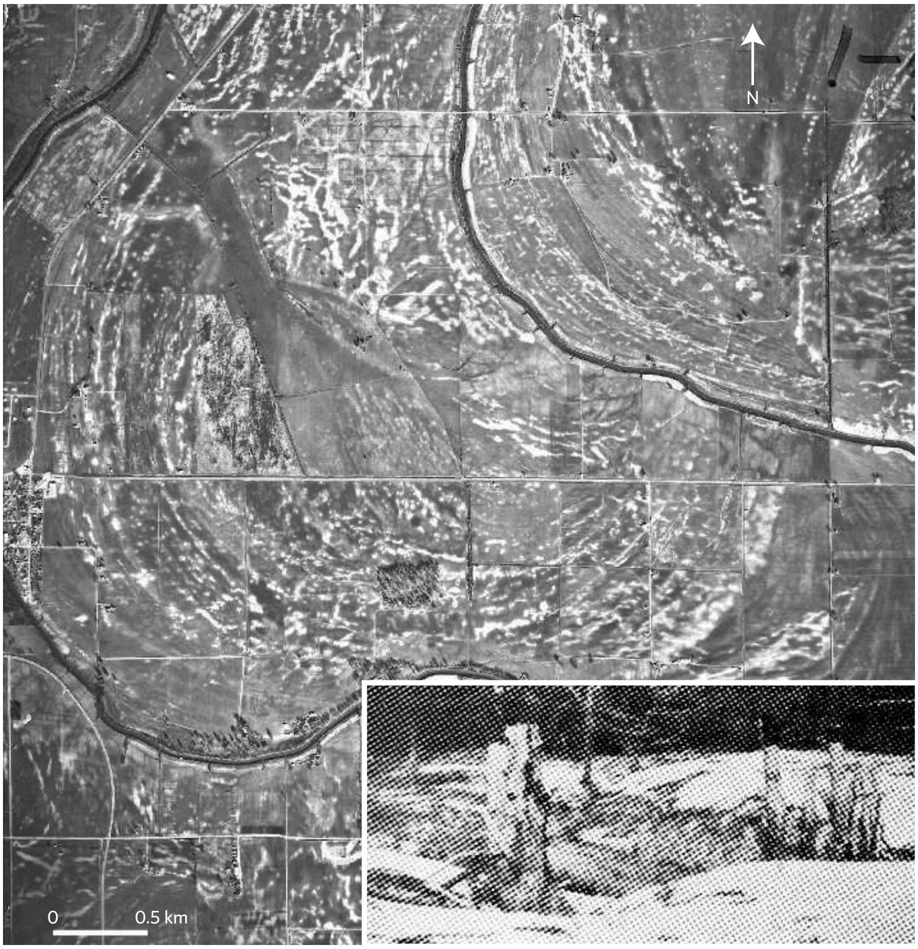

Figure 1 | Earthquake evidence. This aerial photograph, taken in 1964, shows light-coloured sand blows near the Little River in northeastern Arkansas. The inset is a ground view, taken about 100 years ago, of trees killed by the sand deposits. Some of the sand blows were produced by the New Madrid earthquakes of 1811–12; others were formed in prehistoric times. Smalley and colleagues' analyses[5] are consistent with the finding of fairly frequently repeated New Madrid events surmised from this geological record.

stations spanning the New Madrid region to ascertain the rate at which the seismic zone is deforming in response to tectonic forces[6]. Measurements were collected for several days in 1991, 1993 and 1997, the upshot being estimated relative motion across the seismic zone of 1.4 mm yr^{-1} with uncertainties of ±3 mm yr^{-1}. These motions were interpreted to be indistinguishable from zero, and therefore indicative of low rates of strain accumulation. Given that earthquake frequency is related to the build-up and release of strain energy, it was concluded that the New Madrid seismic zone produces either magnitude 8 earthquakes every 5,000–10,000 years or magnitude 7 earthquakes every 1,000 years[6]. This finding differed from that of the geological studies.

In the late 1990s, a network of permanent GPS stations was installed in the New Madrid region. The new network included many improvements; for example, stations were located close to and on both sides of major New Madrid faults, and strong H-beams were used that are less susceptible to non-tectonic movements than the 1-inch-diameter steel rods used in the previous network[5]. Because the new stations are permanent and collect data continuously, the repeated setting up of field stations, which introduced measurement errors in the previous studies, could be avoided.

Smalley *et al.*[5] have analysed four years of continuous measurements from the new network. They calculate relative motions across the seismic zone that are similar (1–2.7 mm yr^{-1}) to those measured during the 1990s but with much smaller uncertainties — at most 25% of those of the previous studies. Smalley *et al.* point out that in the earlier GPS data the tectonic signal was lost in the noise, and interpret their results to indicate high rates of strain in the New Madrid seismic zone.

They also find relative motions across the seismic zone that are consistent with expected fault movements as inferred from present-day seismicity[9] and recent fault studies[7]. For example, relative motion indicates that bedrock slips over itself along a major northwest-oriented fault, known as the Reelfoot thrust fault, that is inclined towards the southwest (see Fig. 2 on page 1089). The new findings are persuasive because they help to explain the geological observations of frequent New

Madrid earthquakes, and they make sense in terms of the active faulting in the region.

One of the most interesting results is that motions in the surrounding region are low compared with motion in the seismic zone itself. This unusual behaviour differs from that at plate boundaries, raising questions about the driving forces and earthquake processes within plates. Post-seismic afterslip — a process by which fault displacements at depths of several kilometres are expressed at the surface for a period of time following an earthquake[10] — seems a reasonable explanation for the regional pattern of motions. However, there is currently insufficient information about the physical properties of the Earth in the New Madrid region to test this and competing models.

Smalley and colleagues' results are consistent with the findings of geological studies that the seismic zone produced earthquakes about every 500 years of magnitude 7.6 or greater. As such, they provide scientific justification for the adoption of stricter earthquake provisions in the building codes for Memphis and other cities in the central United States[4]. Looking ahead, installation of additional field stations close to known faults would help to define their extent and further quantify their strain rates. One of the most daunting challenges will be to develop and test models that can explain how such large and frequent earthquakes are produced in the New Madrid region, and to see if the models also apply to other intraplate regions. ■

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EVOLUTIONARY BIOLOGY

Island of the clones

Thomas N. Sherratt and Christopher D. Beatty

The discovery of an all-female population of damselflies in the Azores archipelago provides a novelty for entomologists. It also highlights the unique selection pressures faced by species that colonize islands.

Tucked away in the journal *Odonatologica* comes a paper by Cordero Rivera and colleagues[1] that will surprise many entomologists, and will exercise biologists studying evolution on islands and the mechanisms of sex determination. Cordero Rivera *et al.* have discovered that a species of damselfly on the Azores reproduces parthenogenetically (Fig. 1). This form of reproduction, in which females produce eggs that develop without fertilization by males[2], has been recorded in almost all insect groups. But until now it was not known to occur in any natural populations of damselflies or dragonflies (the Odonata)[3].

The Azores archipelago lies 1,500 km from the coast of Europe. Inspired by a report[4] that only females of the damselfly *Ischnura hastata* had ever been found there, Cordero Rivera and his team visited 15 localities on six of the islands. Although more than 330 adult specimens of *I. hastata* were examined, none of them was male. To test whether the species was parthenogenetic, a sample of larvae was reared to adulthood in the laboratory — more than 1,900 females were produced over nine generations, but no males.

Ischnura hastata is common in North and South America, yet it occurs in these regions as a classically sexual species with both males and females. The concept of 'geographic parthenogenesis'[5] proposes that the parthenogenetic forms of a species are more likely to occur in certain areas — such as higher latitudes and altitudes, and on islands — because of the different selection pressures that organisms face under these conditions[6,7]. One possibility, therefore, is that certain damselfly species can include both sexual and parthenogenetic forms, and that on arriving on a remote island it is the parthenogenetic form that is favoured, at least initially, owing to the difficulty of finding mates.

One might wonder why standard sexual reproduction does not kick in once the population builds up in size, but perhaps local conditions continue to favour parthenogenesis. Indeed, *I. hastata* frequents temporary or recently established habitats[4], and Cordero Rivera *et al.* note that there is anecdotal evidence of local extinctions of pond populations. Furthermore, chance may play a role in the establishment and maintenance of parthenogenesis: *I. hastata* is also found on the Galapagos Islands, but the population contains both males and females[8].

In at least some odonates, there may be a degree of predisposition to parthenogenesis; for example, there is evidence that unfertilized eggs of the dragonfly *Stylurus oculatus* can be artificially induced to develop[9]. Moreover, certain parasites that are inherited only in the female line can manipulate their insect host into producing predominantly (or only) female offspring[10]. Cordero Rivera and colleagues are testing whether any microbial agents are responsible for driving the absence of males in *I. hastata*, but they have ruled out one potential bacterial parasite, *Wolbachia*, which infects a range of other insect groups[10]. If parthenogenesis in *I. hastata* is parasite mediated, then the microbial agent might have had a beneficial effect on its host in the initial phases of colonization, allowing individuals to reproduce without mates.

There have also been intriguing accounts of other damselfly species on remote archipelagos. In particular, on the islands of Fiji, it seems that females of the damselfly *Nesobasis rufostigma* actively defend territories over aquatic habitats, whereas the males, which are infrequently encountered, reside some distance from the stream[11]. This phenomenon has been dubbed 'sex-role reversal'[11] and, if confirmed, would be the first example in an odonate. If males are in short supply, then this unusual mating system might be explained by female competition for access to males[12]. Furthermore, males of two rarer Fijian damselflies (*N. flavostigma* and *N. caerulescens*) have

Figure 1 | Reproduction without fertilization in a damselfly. A female *Ischnura hastata* lays eggs in a pond on the island of Pico, Azores. (Courtesy of A. Cordero Rivera, Univ. Vigo.)

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 positioning 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 boundaries[1]. 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 area[1].

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 ± 2.0 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 earthquake[1] 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 estimates[4] based on the palaeoseismic history[5] if one assumes occurrence of earthquakes of magnitude 7, with 1–2 m of co-seismic slip[4].

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.

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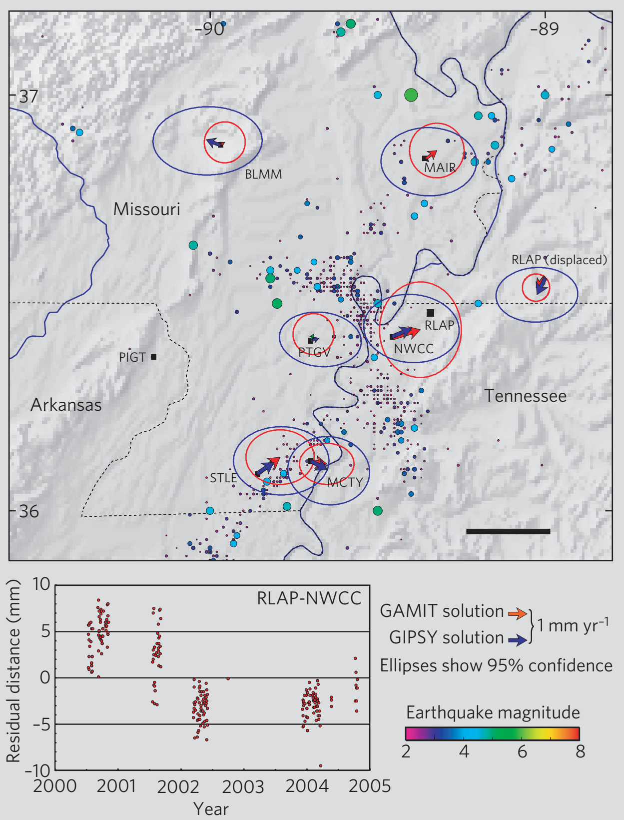

Figure 1 | Velocities and associated uncertainties (95% confidence) at continuous GPS sites in the New Madrid seismic zone. To perform these analyses, two different software packages (GAMIT and GIPSY) were used. Site velocities are within their error ellipses and hence show no statistically significant 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.

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SEISMOLOGY

Smalley et al. *reply*

Replying to: E. Calais *et al*. *Nature* 438, doi:10.1038/nature04428 (2005)

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 analysis[2] 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 interval[1], 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 years[1]) over the past 2,000 years[2]. 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 earlier[2]) because the source of such displacements is unknown[2]: 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 region[2]. Neither we nor anyone else can so far explain this apparent local deformation — in the spirit of Galileo, "and yet it moves".

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Time-Variable Deformation in the New Madrid Seismic Zone

Eric Calais[1] and Seth Stein[2]

At plate boundary faults, a balance is achieved over <1000 years between the rates at which strain accumulates and is released in large earthquakes. Whether this steady-state model, which forms the basis for seismic hazard estimation, applies to continental plate interiors, where large earthquakes are infrequent, is unresolved. The New Madrid Seismic Zone (NMSZ, Fig. 1A) in North America is a focus for this issue. Large-magnitude ($M > 7$) earthquakes in 1811 and 1812 make hazard estimation a priority. Recent geodetic results have shown motions between 0 to 1.4 mm year^{-1}, allowing opposite interpretations (*1*) (Fig. 1B). The upper bound is consistent with steady-state behavior, in which strain accumulates at a rate consistent with a repeat time for magnitude ~ 7 earthquakes of about 600 to 1500 years, as seen in the earthquake record. However, the lower bound cannot be reconciled with this record, implying that the recent cluster of large-magnitude events does not reflect long-term fault behavior and may be ending.

New analysis including 3 additional years of Global Positioning System (GPS) data and three additional sites (*2*) shows root mean square (RMS) velocities relative to the rigid interior of North America of less than 0.2 mm year^{-1} (Fig. 1C). These residual velocities are below their uncertainties at 95% confidence (Fig. 1A). A simulation shows that even these residuals can be explained as nontectonic artifacts (*2*), so the observations do not require motions different from zero during this time. Our results correspond to strain rates lower than 1.3×10^{-9} year^{-1}, less than predicted by a model in which large earthquakes occur because the NMSZ continues to be loaded as a deeper weak zone relaxes (*3*).

At steady state, a rate of 0.2 mm year^{-1} implies a minimum repeat time of 10,000 years for low $M = 7$ earthquakes with ~2 m of coseismic slip and one longer than 100,000 years for $M = 8$ events (Fig. 1D). In contrast, the geologic data show a series of large earthquakes between 300 ± 200 Common Era and present and an additional cluster between 2200 and 1600 Before the Common Era (*4*). This implies an average repeat time of at most 900 years over that interval, much shorter than the geodetic data imply. Strain in the NMSZ over the past several years has therefore accumulated too slowly to account for seismicity over the past ~5000 years, hence excluding steady-state fault behavior.

Elsewhere throughout the plate interior, GPS data also show average deformation less than 0.7 mm year^{-1} (*5*), and paleoseismic records show earthquake migration and temporal earthquake clustering (*6*).

These data imply that fault loading, strength, or both vary with time in the North American continental interior. Time variations in stress could be due to local loading and unloading from ice sheets or sediments or after earthquakes on other faults. Alternatively, midcontinent faults may be loaded at a constant rate too small to be detected geodetically yet but sufficient to accumulate strain released in clustered events. In this hypothesis, clustering and migration could reflect time variations in fault strength (*7*).

Earthquake hazard estimates assuming that recent seismicity reflects long-term steady-state behavior may thus be inadequate for plate interiors and may overestimate the hazard near recent earthquakes and underestimate it elsewhere.

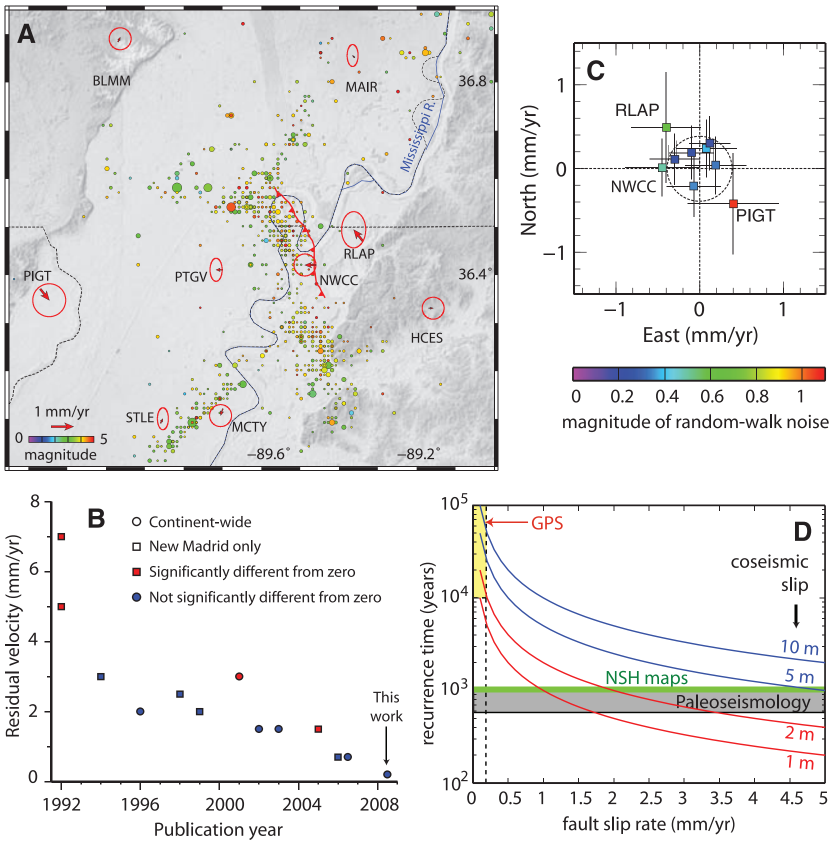

Fig. 1. (**A**) GPS site velocities in the NMSZ relative to North America and uncertainties (95% confidence). Circles show earthquake epicenters since 1974. Red line shows the Reelfoot fault. BLMM, HCES, MAIR, MCTY, NWCC, PIGT, PTGV, RLAP, and STLE indicate the names of the continuous GPS stations used in this work (*2*). (**B**) Maximum permissible deformation rates in the NMSZ as a function of publication year. References are listed in (*2*). Circles show continent-wide studies; squares show NMSZ studies. Red are publications claiming rates significantly different from zero; blue are upper bounds for publications claiming rates not significantly different from zero. The decrease in rates as a function of time reflects more-precise site velocity estimates because of both more precise site positions and the longer time span of observations. (**C**) Scatter plot of residual velocities. Sites are color-coded by the level of noise in their position time series. Bars show 95% error in velocities. Dashed circle shows 1-σ RMS of the data set. Note that sites with the largest noise have the largest residuals. (**D**) Earthquake recurrence interval as a function of slip rate across the fault in a steady-state model, with two end-member values of coseismic slip for magnitude 7 (red curves) and magnitude 8 (blue curves) earthquakes. The GPS and paleoseismology domains do not overlap. NSH indicates National Seismic Hazard maps.

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Supporting Online Material

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Materials and Methods
Fig. S1
References and Notes

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