USGS Award No.: 01-HQ-GR-0061

GPS CONSTRAINTS ON PRESENT-DAY STRAIN IN THE U.S. MIDCONTINENT

Final Technical Report

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Keywords: GPS-Campaign, Geodesy, Seismotectonics, Tectonic Structures

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Non-Technical Summary

Observations from a new high-precision GPS geodetic network in the southern Illinois Basin provide evidence for present-day tectonic strain in the Wabash Valley seismic zone, an area associated with a concentration of historical and instrumentally recorded earthquakes, paleoseismic evidence of repeated, large-magnitude earthquakes, and possible Quaternary faulting. The GPS network consists of 56 sites distributed over a 100,000 km^2 area of Illinois, Indiana, and Kentucky, augmented by a dense 24-station geodetic array in the Shawnee National Forest of southernmost Illinois. The results reported here are based on a five GPS campaigns, conducted from 1997-2003, and suggest statistically significant horizontal motions at 28 of the sites surrounding the Wabash Valley seismic zone. The inferred velocities are highly variable, presumably influenced by systematic and random geodetic errors, as well as significant non-tectonic deformation sources, such as mine- and solution-related subsidence. Nonetheless, the individual site velocities, as well as a formal inversion for tectonic strain, suggest a systematic pattern of shear strain that may be interpreted either as sinistral shear along the NNE-trending Wabash Valley Fault System or as dextral shear along the NE-trending Commerce Geophysical Lineament. The shear strain rate estimated for the area surrounding the Wabash Valley Fault System is estimated at 2.3 ± 0.8 x 10^{-9} yr^{-1}, in a similar direction, but at a significantly smaller magnitude than previously measured rates in the New Madrid seismic zone.

Investigations Undertaken

The Wabash Valley region (Figure 1) has become the focus of increasing scientific interest over the past several years. This development has been sparked by a number of important discoveries, including newly acccumulating evidence for large, prehistoric earthquakes in the region [e.g., Obermeier et al., 1991; Munson et al., 1997], evidence for Cenozoic faulting [Sexton et al., 1986, 1996; McBride et al., 2002a; Bear et al., 1997], the presence of large geophysical anomalies [Braile et al., 1982; Hildenbrand & Ravat, 1997; McBride et al., 2002b], and a significant concentration of seismicity in the Wabash Valley area [Nuttli, 1979; Braile et al., 1982; Pavlis et al., 2002]. These observations are coupled with the occurrence of several sizeable earthquakes in the past several years [e.g., Taylor et al., 1989; Stauder & Nuttli , 1970] and growing concerns about seismic hazard in the urban areas of southern Indiana and Illinois. Reflecting this growing attention, the NEHRP program identified the Wabash Valley seismic zone as a key target area for geological and geophysical investigations in the Central U.S. over the past several years.

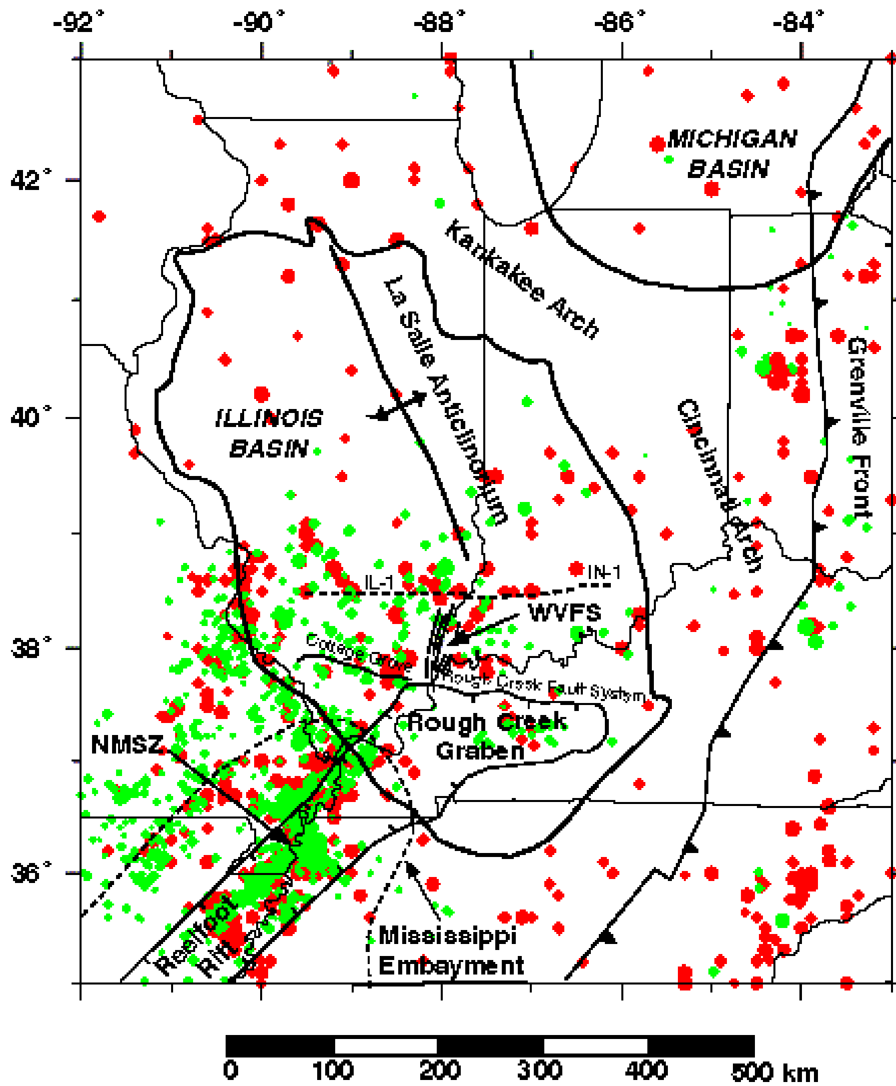


Figure 1*. Structural features and seismicity of the central U.S. Note the location of the Wabash Valley Fault System (WVSZ) near the center of the Illinois Basin. The WVFS may represent a northern extension of the New Madrid Seismic Zone (NMSZ). Green circles represent earthquakes located by the University of Memphis and St. Louis University seismic networks. Red circles represent epicenters of historical earthquakes reported by Nuttli (1979). Circle size scales with earthquake magnitude. Adapted from Bear et al. (1997).*

This project seeks to assess present-day deformation of the Wabash Valley seismic zone using high-precision geodetic measurements using the Global Positioning

System (GPS). In the past several years, a number of groups have initiated GPS geodetic measurements in the central U.S. These measurements have focused primarily on the New Madrid seismic zone [Liu et al., 1992; Snay et al., 1994; Weber et al., 1997; Newman et al., 2002]. Because the existing GPS networks in the Central U.S. extend only to the very southern edge of the Illinois Basin, our project has succeeded in extending this network to the northeast to envelop the Wabash Valley seismic zone [Hamburger et al., 2002].

Results

In this grant period, we have focused on analysis of existing GPS measurements at a new geodetic network surrounding the Wabash Valley seismic zone. The GPS network, shown in Figure 2, consists of 56 geodetic sites extending over an area of 100,000 km2 in southern Indiana (20 sites), southern Illinois (23 sites), and western Kentucky (13 sites). The network includes 28 existing geodetic sites that are part of the National Geodetic Survey (NGS) network of first-order triangulation and/or leveling benchmarks. Campaign measurements were made in the summers of 1997, 1998, 2000, 2002, and 2003. Locations of network sites are shown in map form in Figure 2 and tabulated as Table 1.

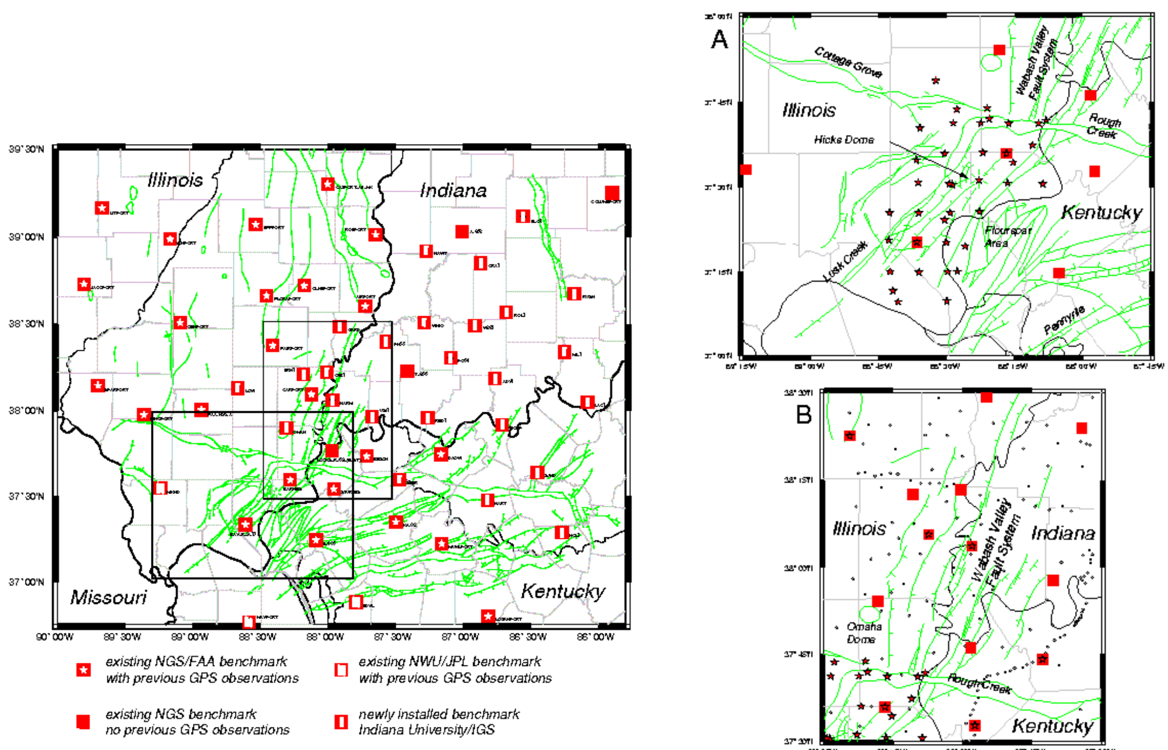


__Figure 2.__ (Left) Southern Illinois Basin geodetic network. Large symbols show bench-marks observed during the 1997-2002 GPS campaigns. Structural features from Bear et al. [1997]. Rectangles show areas of possible densification in the maps shown at right. (Right) Areas of proposed densification of the regional GPS network: (A) Hicks Dome/Fluorspar district of southern Illinois; (B) Wabash Valley area of southern Indiana/Illinois. Squares indicate locations of stations in our regional GPS network; stars indicate sites with previous GPS observations; small diamonds indicate first-order triangulation or leveling sites.

Data from field stations were downloaded to field computers, quality checked and reduced to standard RINEX format. The full data set has been transferred to the UNAVCO data archive, where they will be made available for use by other researchers working in the area. The GPS data in this paper were analyzed using the GIPSY/OASIS II software (release 6) developed at the Jet Propulsion Laboratory (Zumberge et al., 1997). Raw GPS data collected in the field were analyzed in 24-hour daily solutions along with regional and well-distributed globalcontinuous sites. We used fixed orbits obtained from JPL's submission to the IGS. Each daily solution was then transformed into the ITRF97 reference frame. Finally, the individual daily GPS solutions in the ITRF97 reference frame were combined together to determine site positions at epoch 1998.0 and site velocities. For more details aout the strategy, refer to Larson et al. (1997) and Freymueller et al. (1999, 2000); in this survey, we used a 'local' frame of reference, fixed with respect to our base station BLO1, which is presumed, based on the distribution of seismicity, to lie outside the most actively deforming area. Formal errors in coordinates and velocities were estimated from the coordinate covariance matrices. Because these formal errors frequently under-represent the true observational errors (e.g., Larson and Agnew, 1991), they were then scaled to match the 95th percentile (χ^2) of the repeatability of the daily site coordinate estimates. Estimated site velocities are shown in Fig. 3.

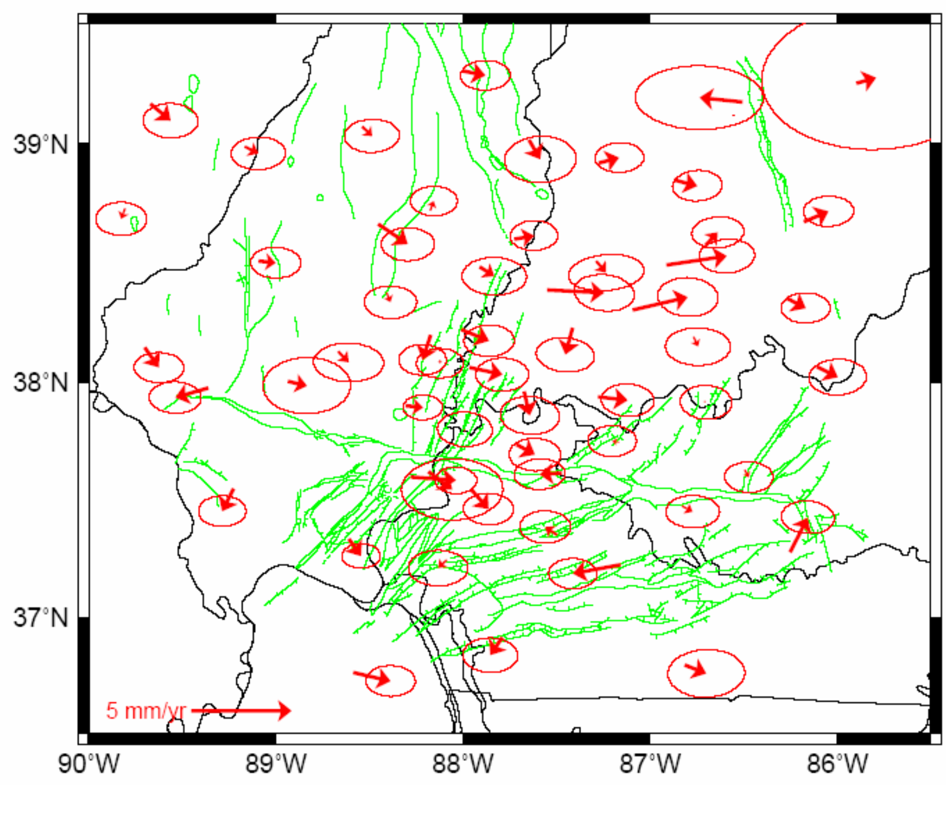


Figure 3. *Preliminary results from the Wabash Valley GPS network, 1997-98. Solid dots indicate locations of GPS sites, as shown in Table 1 and Figure 2. Vector arrows indicate velocities of relative motion of benchmarks with respect to the base station, BLO1, which was occupied continuously during both campaigns. Ellipses show estimated errors in velocity determinations at the 95% confidence level.*

Table 1. WABASH VALLEY GPS NETWORK SITE LOCATIONS

Station Name	Code	Latitude (° ' " N)	Longitude (° ' " E)	Height (m)	Station Location
ADY1	ADY1	38 11 30.326334	-86 46 05.265736	111.7285	Adyeville, IN
AIRPORT	AIRP	38 36 10.416700	-87 43 29.577112	98.2612	Mt. Carmel, IL airport
BARNES	BARN	37 35 55.472055	-88 16 46.033148	176.5458	Harrisburg, IL (USFS)
BAY R 9 17	BAYI	37 20 11.021745	-88 36 32.893717	75.5570	Harrisburg, IL (USFS)
BESCH	BESC	37 44 11.666179	-87 42 44.465045	105.7199	Corydon, KY
BLO1	BLO1	39 07 09.996037	-86 33 24.112475	187.2007	Bloomington, IN
BRN1	BRN1	38 12 02.389326	-88 10 19.207250	118.1276	Centerville, IL
CARPORT	CARP	38 05 41.197454	-88 07 21.609494	85.6950	Carmi, IL airport
CASPORT AZ MK	CASP	39 18 14.776365	-88 00 05.462557	165.3021	Casey, IL airport
CENPORT	CENP	38 30 39.584917	-89 05 32.498736	128.5188	Centralia, IL airport
COLUMBPORT	COLU	39 15 09.563311	-85 53 50.296488	163.4369	Columbus, IN airport
CRA1	CRA1	38 51 02.593719	-86 52 07.366340	192.2266	Crane Naval Weapons Ctr
DAOW	DAOW	37 44 46.740029	-87 09 50.676114	90.6136	Owensboro, KY airport
EDVL	EDVL	36 54 54.756077	-87 47 21.994878	105.7884	Eddyville, KY
EFFPORT	EFFP	39 04 23.026033	-88 32 20.113519	144.5456	Effingham, IL airport
FAA H96 A	FAAI	38 00 19.676254	-88 56 05.078920	102.4289	Benton, IL
FAIRPORT	FAIR	38 22 38.026809	-88 24 26.109685	93.6072	Fairfield, IL airport
FLORAPORT	FLOR	38 39 54.093245	-88 27 09.133561	109.0807	Flora, IL airport
GARD	GARD	38 29 11.131010	-87 54 40.992854	117.0721	Gard's Point, IL
GOSP	GOSP	37 55 09.997200	-86 42 38.770137	161.6831	Cannelton, IN
HARM	HARM	38 03 43.984105	-87 57 58.917399	83.4850	Harmonie St. Park, IN
HART	HART	37 28 36.183044	-86 49 43.014824	145.2389	Hartford, KY
HAWT	HAWT	38 55 14.328542	-87 16 23.331176	145.7867	Hawthorn Mine, IN
JACOPORT	JACO	38 43 51.234987	-89 48 15.983636	111.7420	St. Jacob, IL airport
KY 02	KY02	37 21 12.406280	-87 29 49.452580	124.1268	Madisonville, KY
LAC1	LAC1	38 04 01.978058	-86 06 35.836640	161.9448	Laconia, IN
LITPORT	LITP	39 10 01.564186	-89 40 11.213718	177.4236	Litchfield, KY airport
LOCKS R 69 EAST	LOCK	37 47 36.089817	-87 59 25.128912	78.6951	Uniontown locks & dam
LOGANPORT	LOGA	36 47 51.934211	-86 48 54.162240	177.3800	Logan Co., KY airport
LOVI	LOVI	38 07 49.118001	-88 40 00.853271	119.7405	Lovilla, IL
MAYPORT	MAYP	36 45 54.923955	-88 35 05.539885	128.8532	Mayfield, KY airport
MIL1	MIL1	38 21 23.139842	-86 16 11.655468	148.8320	Milltown, IN
MKND	MKND	37 32 58.894305	-89 13 29.336513	177.4544	Makanda, IL
MUHLPORT	MUHL	37 13 31.948466	-87 09 29.107531	95.9068	Greenville, KY airport
NOL1	NOL1	37 16 46.937698	-86 15 03.227672	145.3904	Nolin Dam, KY
OLNEPORT	OLNE	38 43 18.011356	-88 10 24.761998	110.4865	Olney, IL airport
OMAH	OMAH	37 54 07.539013	-88 18 23.055124	88.7330	Omaha, IL
OTB1	OTB1	38 13 20.823312	-88 00 28.181120	91.5980	Grayville, IL
PC64	PC64	38 18 19.807515	-87 05 30.980712	132.1459	Pike City, IN
PINCPORT	PINC	37 58 36.176940	-89 21 38.788339	88.8046	Pinckneyville, IL airport
PK65	PK65	38 23 20.648882	-87 32 58.379677	103.5225	Patokah, IN
RED1	RED1	37 56 20.545295	-87 16 39.507464	108.3498	Red Bush, IN
ROBPORT	ROBP	39 00 57.854851	-87 38 46.796308	104.8416	Robinson, IL airport
ROL1	ROL1	38 34 32.289420	-86 42 07.873418	146.6043	Roland, IN
RUSH	RUSH	38 40 31.993291	-86 10 39.855876	198.4413	Rush Creek, IN
SAND	SAND	37 37 45.291088	-86 29 35.674029	217.4843	Sand Knob, KY
SEBR	SEBR	37 37 01.490107	-87 28 16.162050	104.4264	Sebree, KY
SPARPORT	SPAR	38 08 49.159114	-89 41 58.987801	128.8679	Sparta, IL airport
STURGIS	STUR	37 32 44.461392	-87 57 21.678843	81.8124	Sturgis, KY airport
T 356	T356	38 13 45.319210	-87 24 51.950860	111.3289	Buckskin, IN
USI1	USI1	37 57 40.533238	-87 40 19.396074	107.2073	Univ. S. Indiana
VANPORT	VANP	38 59 23.907556	-89 09 57.904952	129.4106	Vandalia, IL airport
W231	W231	38 29 37.506288	-86 54 48.066120	118.0481	Haysville, IN
WHIO	WHIO	38 30 37.197043	-87 17 16.367532	102.6353	Petersburg, IN
Z 405	Z405	37 14 45.614851	-88 05 14.191236	147.2283	Crayne, KY

Our preliminary results, based on a one-year measurement interval, from 1997-98, were reported by *Hamburger et al.* [2002]. They indicated statistically significant horizontal motions at 28 of the sites surrounding the Wabash Valley seismic zone. The inferred velocities are highly variable, presumably influenced by systematic and random geodetic errors, as well as significant non-tectonic deformation sources, such as mine- and solution-related subsidence. Nonetheless, the individual site velocities, as well as a formal inversion for tectonic strain, suggest a systematic pattern of shear strain that may be interpreted either as sinistral shear along the NNE-trending Wabash Valley Fault System or as dextral shear along the NE-trending Commerce Geophysical Lineament. While most of our strain estimates remain statistically indistinguishable from zero, the averaged shear strain for the entire network is estimated at 12.7 ± 6.0 x 10^{-9} yr^{-1}. The shear strain rate estimated for the area surrounding the Wabash Valley Fault System is estimated at 3.6 ± 4.8 x 10^{-9} yr^{-1}, in a similar direction, but at a significantly smaller magnitude than previously measured rates in the New Madrid seismic zone. Additional observations conducted in 2000, 2002, and 2003 were used to improve measurement precision and to extend the observational base. We have also revised the entire suite of GPS position measurements using the GIPSY-OASIS GPS analysis software. Results are compatible with those reported above, with a downwardly revised strain estimate of 1.8 ± 1.2 x 10^{-9} yr^{-1} (max. compressional strain, oriented 128.2° ± 10.4°). Strain estimates from the Shawnee network are compatible, but still within the margin of their larger error estimates. The maximum compressional strain is estimated at 17.5 ± 16.7 x 10^{-9} yr^{-1}, oriented 96.8° ± 21.2°.

Table 1. Tensor Strain and Rotation Rates in the southern Illinois Basin

Subregion[a]	Number of sites	$\dot{\epsilon}_1^b$ *nstrain/yr*	$\dot{\epsilon}_2^b$ *nstrain/yr*	Azimuth[c] deg	$(\dot{\epsilon}_2 - \dot{\epsilon}_1)/2$ *nstrain/yr*	$\dot{\omega}$ *nrad/yr*	$\Delta = (\dot{\epsilon}_1 + \dot{\epsilon}_2)$ *nstrain/yr*	Reduced χ^2
Entire network	74	-1.7±1.2	2.8±1.0	130.6±9.4	2.3±0.8	-0.9±0.8	1.0±1.5	1.31
Shawnee network	22	-26.9±26.1	4.9±8.9	107.2±26.3	15.9±14.8	7.2±12.4	-22.0±25.4	1.00
South WVSZ	20	-2.9±3.9	1.9±2.1	105.1±27.7	2.4±2.3	-0.1±2.1	-1.0±4.2	1.47
North WVSZ	7	-15.4±7.0	1.4±5.3	56.8±14.1	8.4±4.7	-10.8±4.7	-14.0±7.9	1.09
West WVSZ	10	-6.0±3.5	5.3±2.4	122.1±10.6	5.6±2.4	3.0±2.3	-0.7±3.7	0.91
East WVSZ	11	-1.4±2.0	18.4±5.7	173.3±6.4	9.9±2.9	-4.1±2.3	16.9±6.2	1.74
Big Shawnee	24	-27.4±14.2	5.1±4.5	107.0±13.9	16.3±8.0	7.6±6.5	-22.3±13.8	0.95

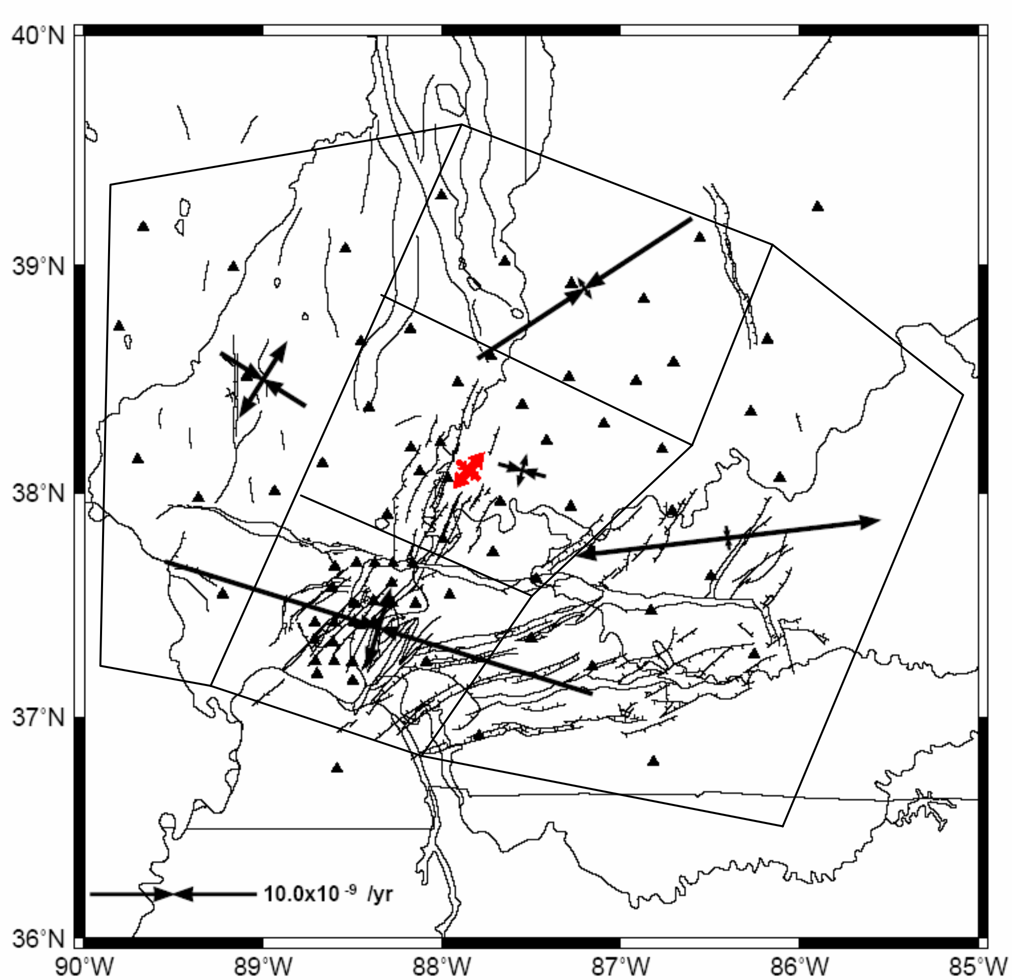


Figure 4. *Inverted strain field, based on observed velocities from Figure 3. Estimated strains are summarized in Table 2. Solid symbols represent orientations and magnitudes of principal strain components for each grid area. Large strain rates along margins of study area result from limited sampling along the periphery of the network. Colored symbols represent the average principal strain rates for the entire study area, assuming uniform strain.*

The Wabash Valley GPS network is expected to provide an important resource for crustal deformation studies in the U.S. midcontinent. It will provide a baseline against which future geodetic measurements may be compared. The next remeasurement of the network, is expected to provide a further test of these first estimates of present-day strain across the southern portion of the Illinois Basin, and densification of this regional network is planned for areas of possible high strain accumulation. All data collected as part of this experiment have been archived at the UNAVCO GPS data archive, and will be made available for collaborative regional studies of crustal deformation. Data can be accessed via the internet from http://www.unavco.ucar.edu/data/.

The June, 2002 Darmstadt, Indiana earthquake

The June 18, 2002, m_b 5.0 Evansville earthquake occurred in an area of diffuse intraplate activity on the northern periphery of the New Madrid seismic zone called the Wabash Valley Seismic Zone (WVSZ). The WVSZ has been the site of at least seven historical events with M>5.0, and as many as seven prehistoric events with M>6.0. The Wabash Valley Fault System, a NNE-trending series of Paleozoic normal faults located along the Wabash River valley, is rooted in a series of basement-penetrating, high-angle transtensional faults, with normal displacements reaching >600m, and possible sinistral strike-slip displacements of 2-4 km. The area is also the site of a significant concentration of low-magnitude earthquakes, as recorded by a temporary seismic array deployed in the WVSZ in 1995-1996. GPS measurements from a regional geodetic network indicate statistically significant velocities for a number of sites in the WVSZ, and possible evidence for sinistral shear strain associated with the fault system. We analyzed GPS data collected approximately one month after the mainshock to improve uncertainties on strain rates and to test for possible coseismic displacements associated with the Evansville event. The earthquake was well recorded by the PEPP educational seismology network, which operates broadband seismographs at educational institutions around the region. The network was augmented by a temporary network of ten portable seismic instruments operated within 15-20 km from the mainshock. We report on analysis of seismicity and seismotectonic observations associated with the earthquake.

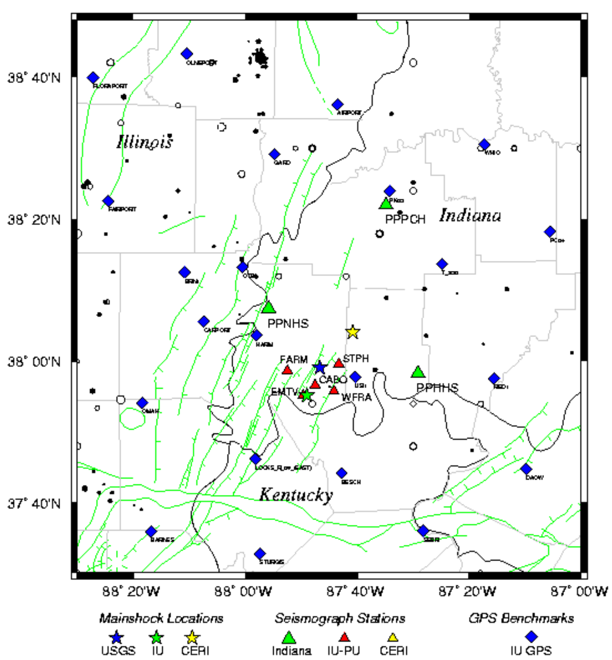
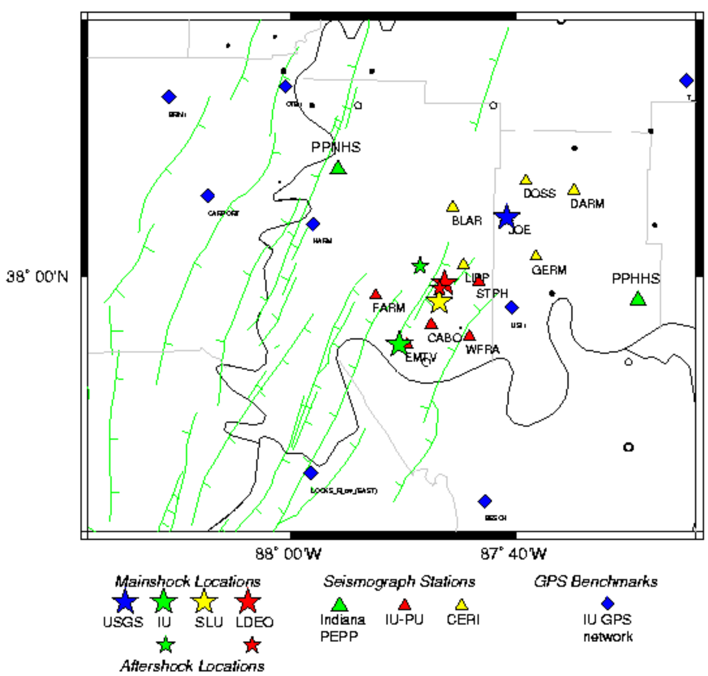


Figure 2. Seismotectonic setting of the 2002 Darmstadt, Indiana earthquake. Stars show estimated location of the mainshock; triangles show positions of recording seismograph stations, including permanent stations of the IU-PEPP seismograph network and temporary stations deployed by Indiana University/ Purdue University (red) and the University of Memphis' Center for Earthquake Research and Information (yellow); blue diamonds show positions of GPS stations in the vicinity of the mainshock. Faults of the Wabash Valley Fault system are shown by hachured lines, adapted from Bear [1997].

Observations from the PEPP regional seismic network were critical for constraining the location and depth of the event at 14-18 km. The temporary seismic network recorded only one probable aftershock with M~2, which occurred only 3 hours after the mainshock. A moment-tensor inversion for the Darmstadt mainshock source indicates a nearly pure strike-slip mechanism, with P-axis oriented ENE-WSW, similar to those of other intraplate events in the region and subparallel to the absolute motion of the North American Plate. The location of the earthquake and its hypocentral depth (14-18 km) suggest ongoing deformation along reactivated Precambrian and Paleozoic basement structures, in a zone of recurring seismic activity, and in an area of possibly heightened neotectonic strain.



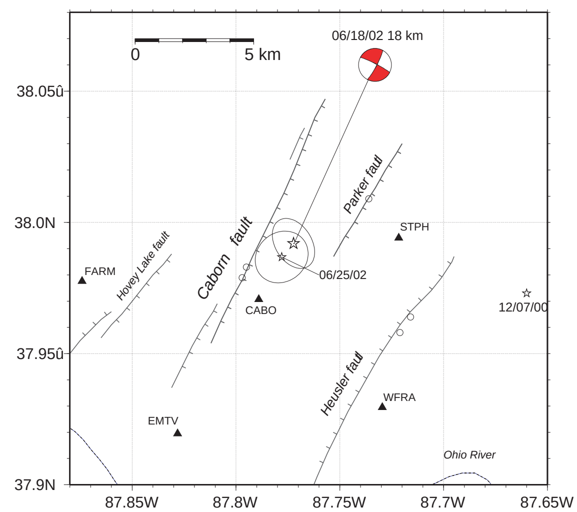


Figure 2. Revised mainshock and aftershock location (left) and earthquake source mechanism (right) for 2002 Darmstadt earthquake. Mechanism is from Kim [2003].

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