Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake

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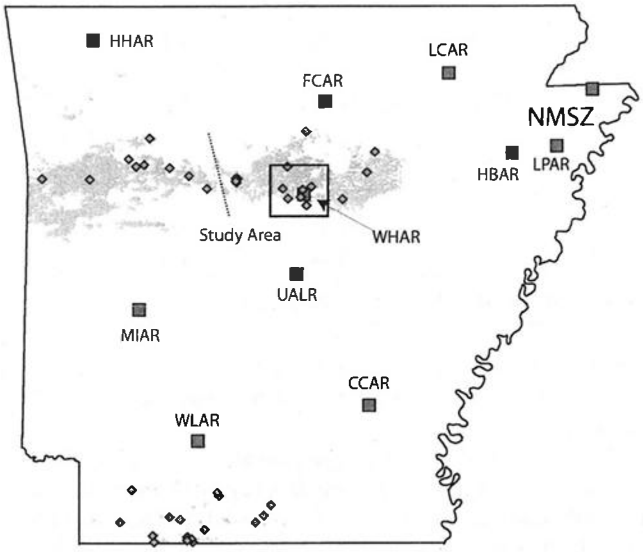
INTRODUCTION

Only a handful of the thousands of waste disposal wells across the United States have been linked to induced or triggered earthquakes. Still, two well-documented cases—Rocky Mountain Arsenal, Colorado, in the 1960s (Healy *et al.* 1968) and Paradox Valley, Colorado, in the 1990s (Ake *et al.* 2005)—demonstrate that fluid injection into the subsurface can trigger earthquakes. The largest event at Rocky Mountain Arsenal was **M** 5.2, and the largest event at Paradox Valley was **M** 4.3. The U.S. Environmental Protection Agency provides Underground Injection Control (UIC) regulations administered by the states to protect underground sources of drinking water. However, the UIC does not limit the proximity of waste disposal wells to active seismic zones or to critical facilities (*e.g.*, hospitals, schools, or nuclear power plants) based on the potential to induce or trigger earthquakes.

Over the last several years, hydraulic fracturing (hydrofracking), a technique used to enhance natural gas recovery, has become widely used in north-central Arkansas (Figure 1). Wastewater, a byproduct of the hydrofracking process, is being injected under pressure into subsurface rocks at eight waste disposal wells (Table 1) in the study area. Since the first waste disposal well became operational in April 2009, the study area has experienced an increase in the rate of magnitude ≥ 2.5 earthquakes, with one in 2007, two in 2008, 10 in 2009, 54 in 2010, and 157 in 2011. The study area has a long history of seismic activity including earthquake swarms in the early 1980s (Chiu *et al.* 1984) and 2001 (Rabak *et al.* 2010), so the current earthquake-rate increase may simply reflect another peak in a natural cycle. However, 98% of the recent earthquakes occurred within 6 km of one of three waste disposal wells after the start of injection at those wells. This close spatial and temporal correlation supports the hypothesis that the recent increase in earthquake activity is caused by fluid injection at the waste disposal wells.



▲ **Figure 1.** The state of Arkansas with permanent broadband seismic stations (dark gray squares) and saltwater disposal wells (gray diamonds) shown. The study area is outlined. Gray shading indicates areas of active gas wells. In north-central Arkansas the Fayetteville Shale gas play areas coincide with the gas wells; conventional reservoir gas play to west separated by dotted line from unconventional gas play to east employing horizontal drilling and hydrofracking of the Fayetteville Shale. Locations of gas wells and disposal wells are from the Arkansas Oil and Gas Commission (AOGC).

The start of injection on 18 August 2010, at well #5 (Figure 2), presented a unique opportunity to investigate this hypothesis. At well #5 fluid is injected into the Ozark aquifer between 2.38 and 3.34 km depth. Well #5 actually cuts the Enders fault (Figure 2), thus providing a relatively short and direct conduit to the depth of 6–7 km where possible induced earthquakes had occurred in a prior study (Horton and Ausbrooks 2010) in 2009 near well #2. During the first week of September 2010, Scott Ausbrooks of the Arkansas Geological Survey (AGS) and

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TABLE 1
Class 2 UIC wells permitted in the study area. See Figure 2 for well location. Volume and pressure are peak values observed during injection period. Peak volume and injection pressure at Rocky Mountain Arsenal (RMA) and Paradox Valley (PV) are included for comparison.

Well	Permit	Volume (m^3/month)	Pressure (MPa)	Start Stop (dd/mm/yy)	Injection Depth (m)	Aquifer
1	43266	62,662	11.8	07/07/10 03/03/11	1,821 1,969	Springfield/Ozark
2	41079	54,058	15.8	15/04/09 20/06/11	1,982 2,009	Springfield
3	39487	23,435	20.3	15/06/09 27/07/11	2,365 3,231	Springfield/Ozark
4	42981	29,573	5.1	15/01/10 15/10/10	1,713 1,926	Springfield/Ozark
5	36380	19,580	19.6	16/08/10 03/03/11	2,379 3,344	Ozark
6	42989	18,629	3.2	05/04/10 NA	678 706	*
7	43177	37,997	14.5	15/01/10 NA	1,383 1,859	Ozark
8	43979	41,280	1.8	15/01/11 NA	647 864	*
RMA		37,857	7.2	08/02/62		Precambrian
PV		53,148	34.5	22/07/96		

* Western Interior Plains confining system.

I installed an array of seismometers in the vicinity of well #5. The array also surrounds well #1, which began injection on 8 July 2010.

In late September 2010, a continuous swarm of small- to moderate-size (**M** ≤ 4.7) earthquakes began to illuminate a previously undetected fault. By 4 March 2011, when well #5 and well #1 ceased fluid injection, nearly 1,000 earthquakes revealed a fault approximately 13 km in length between the towns of Guy and Greenbrier, Arkansas (Figure 2). The earthquakes align along a nearly vertical fault striking about N30E at depths between ~3 and ~7 km. In cross-section, a rectangle 13 km in length and 3.2 km in width dipping 11° to the southwest captures most of the observed seismicity (Figure 3). The seismicity migrates in time, with activity concentrated on the north end of the fault during the fall and early winter. Then, following a midwinter lull, intense seismic activity during a two-week period in late February illuminated the southern end of the fault. The Guy-Greenbrier fault (named for the first time in this report) cuts the top 2 or 3 km of the Precambrian basement rock extending up into the Paleozoic sedimentary rock (and the Ozark aquifer) on the northern end.

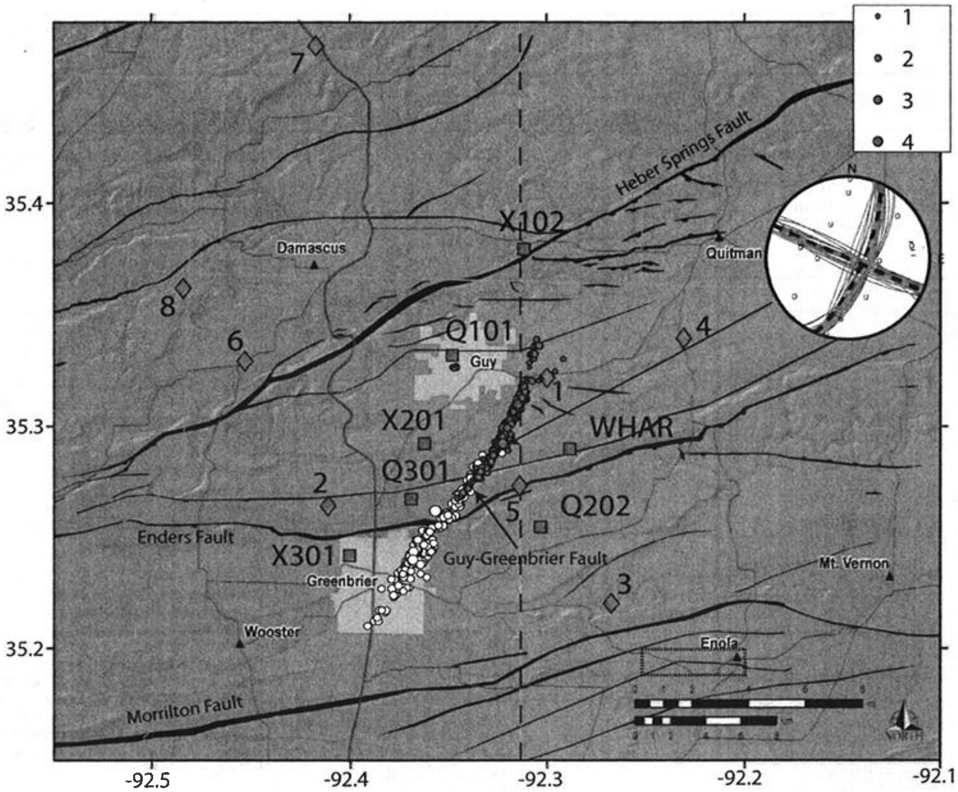
GEOHYDROLOGY

The study area is located in the eastern Arkoma basin just north of the Ouachita Mountains frontal faults (Schweig *et al.* 1991). A stratigraphic section for the study area (Figure 4) modified from Caplan (1954) shows Precambrian basement overlain by a thick sequence of Paleozoic sedimentary rocks. The earthquakes in this study occur largely in the Precambrian crystalline basement whereas wastewater is injected into the Paleozoic sedimentary rock. The geohydrology and structural geology of the study area contribute to the hydraulic connection between the waste disposal well injection depths and the earthquake depths.

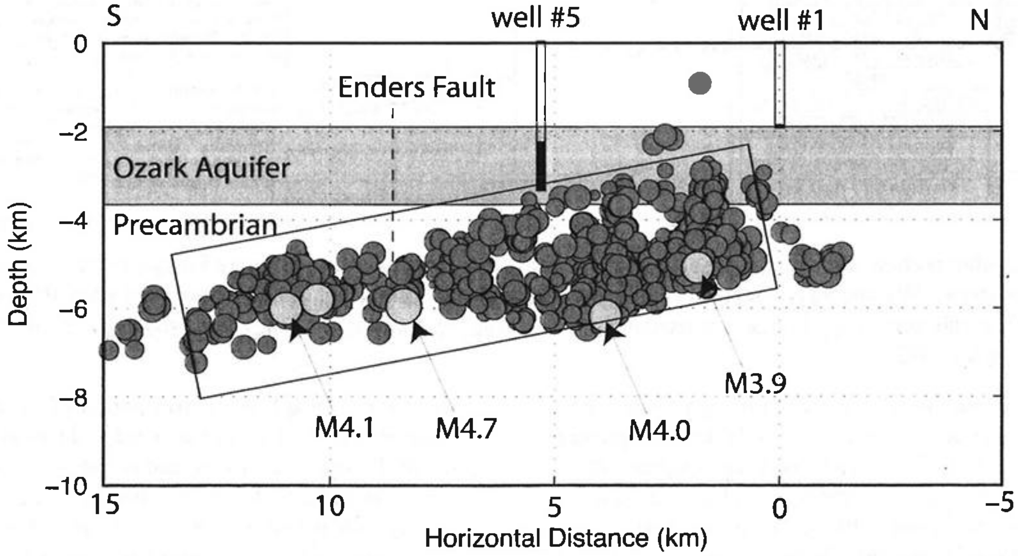
Two major geohydrologic systems (Figure 4) exist in the study area (Imes and Emmett 1994). The upper several kilometers are termed the Western Interior Plains confining system. The rocks consist of alternating sequences of shale (low permeability) and sandstone, limestone, and coal (variable permeability). Permeable zones exist locally, but vertical and lateral groundwater flow is restricted because low permeability rocks dominate the system. Two UIC wells in the study area inject into this unit.

The Ozark Plateaus aquifer system underlies the Western Interior Plains confining system (Imes and Emmett 1994). The system is made up of alternating aquifers and confining units (Figure 4). They are:

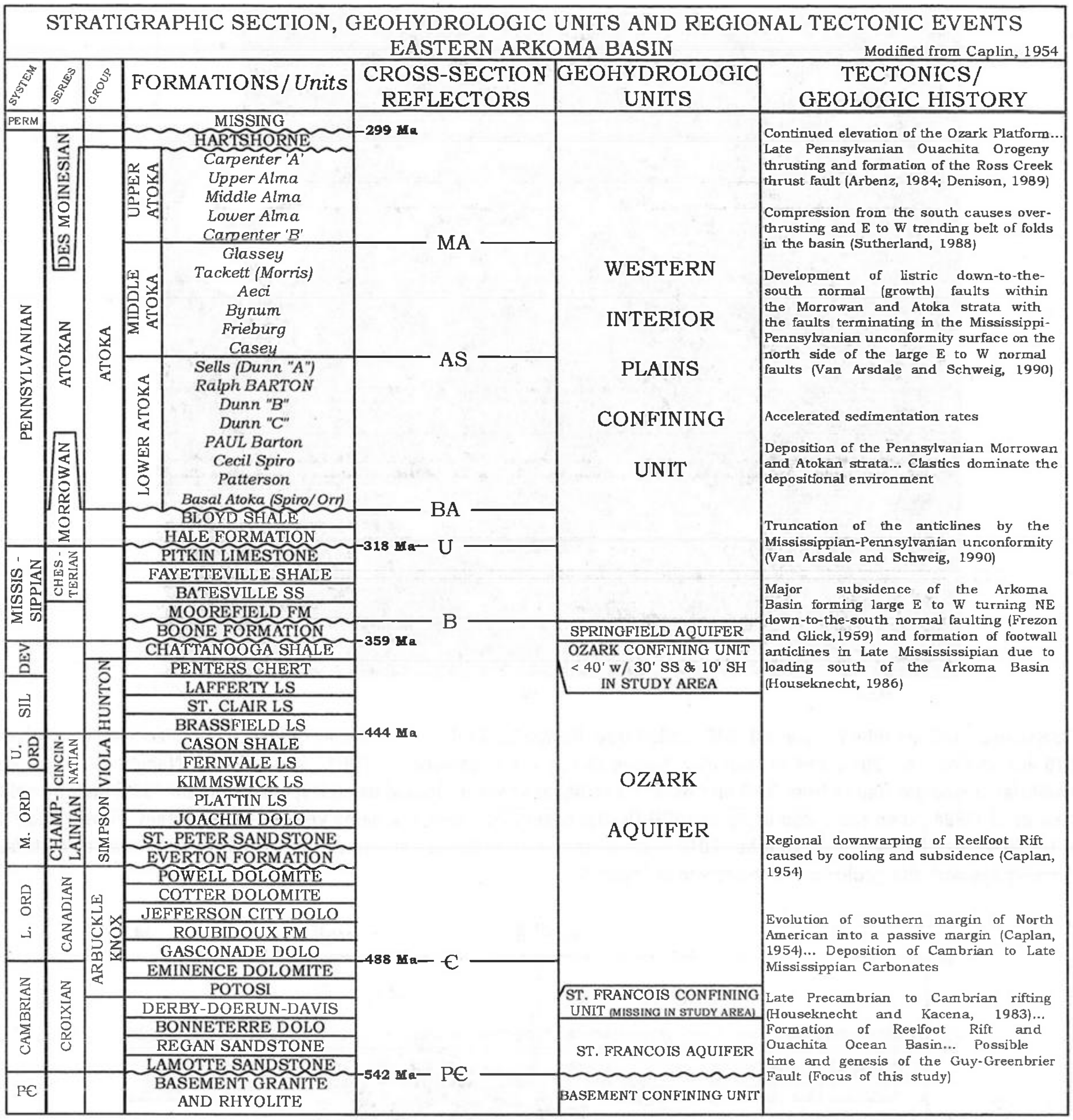
1. The Springfield Plateau aquifer is limestone (the Boone Formation in the study area) with relatively low intrinsic porosity. In northern Arkansas its permeability is enhanced because of dissolution of limestone along fractures and bedding planes.



▲ **Figure 2.** Seismic stations (black squares), UIC wells (gray diamonds, Table 1), earthquakes (dark gray filled circles) between 1 October 2010 and 15 February 2011, and earthquakes (white filled circles) between 02/16/11 and 03/08/11. Named faults penetrate to the Precambrian basement (faults from AGS and AOGC). Earthquakes were located using HypoEllipse (Lahr 1999) and the velocity model of Chiu *et al.* (1994), then relocated using hypoDD (Waldhauser 2001) with the same velocity model. Inset: First-motion focal mechanism for **M** 4.0 earthquake on 11 October 2010 is consistent with right-lateral strike-slip on a NE oriented fault. North/south dashed line coincides with the geologic cross-section in Figure 4.



▲ **Figure 3.** Cross-section showing earthquake hypocenters looking N60W. Rectangle is 13 × 3.2 km and dips 11°. Shaded rectangle indicates the approximate vertical extent of the Ozark aquifer with the bottom boundary depth determined in well #5 and the top boundary depth determined in well #1. Solid black portion of each well indicates the interval where fluid is injected. The dashed line indicating the Enders fault is approximate. The larger earthquakes (light gray circles) rupture the deeper portions of the fault.

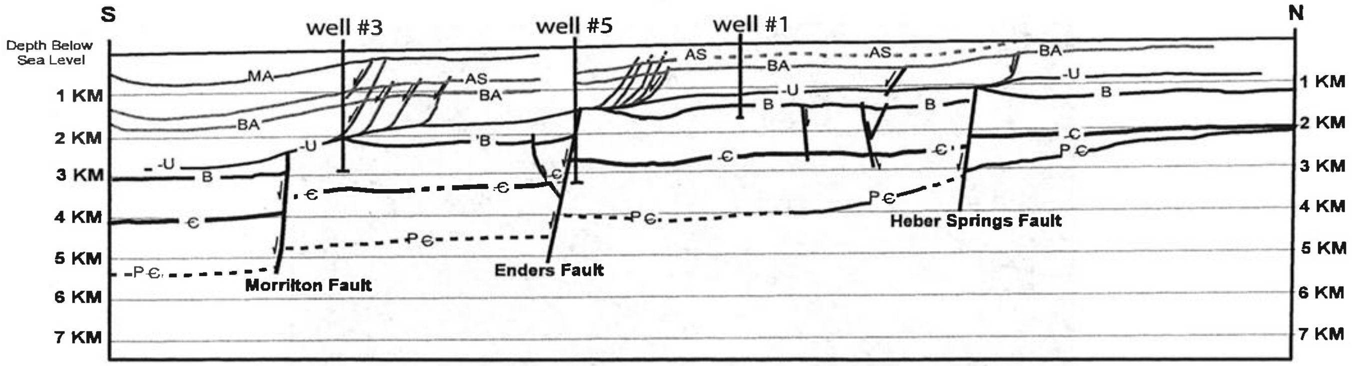


STRATIGRAPHIC SECTION, GEOHYDROLOGIC UNITS AND REGIONAL TECTONIC EVENTS
EASTERN ARKOMA BASIN
Modified from Caplin, 1954

SYSTEM	SERIES	GROUP	FORMATIONS/ *Units*		CROSS-SECTION REFLECTORS	GEOHYDROLOGIC UNITS	TECTONICS/ GEOLOGIC HISTORY
PERM				MISSING		WESTERN INTERIOR PLAINS CONFINING UNIT	
PENNSYLVANIAN	DES MOINESIAN			HARTSHORNE	299 Ma		Continued elevation of the Ozark Platform... Late Pennsylvanian Ouachita Orogeny thrusting and formation of the Ross Creek thrust fault (Arbenz, 1984; Denison, 1989)
	ATOKAN	ATOKA	UPPER ATOKA	*Carpenter 'A'*			
				Upper Alma			
				Middle Alma			
				Lower Alma			Compression from the south causes overthrusting and E to W trending belt of folds in the basin (Sutherland, 1988)
				Carpenter 'B'			
			MIDDLE ATOKA	*Glassey*	MA		
				Tackett (Morris)			Development of listric down-to-the-south normal (growth) faults within the Morrowan and Atoka strata with the faults terminating in the Mississippi-Pennsylvanian unconformity surface on the north side of the large E to W normal faults (Van Arsdale and Schweig, 1990)
				Aeci			
				Bynum			
				Frieburg			
				Casey			
			LOWER ATOKA	*Sells (Dunn "A")*	AS		
				Ralph BARTON			
				Dunn "B"			
				Dunn "C"			Accelerated sedimentation rates
				PAUL Barton			Deposition of the Pennsylvanian Morrowan and Atokan strata... Clastics dominate the depositional environment
				Cecil Spiro			
				Patterson			
	MORROWAN			*Basal Atoka (Spiro/Orr)*			
				BLOYD SHALE	BA		Truncation of the anticlines by the Mississippian-Pennsylvanian unconformity (Van Arsdale and Schweig, 1990)
				HALE FORMATION			
MISSIS - SIPPIAN	CHES - TERIAN			PITKIN LIMESTONE	318 Ma U		
				FAYETTEVILLE SHALE			
				BATESVILLE SS			Major subsidence of the Arkoma Basin forming large E to W turning NE down-to-the-south normal faulting (Frezon and Glick,1959) and formation of footwall anticlines in Late Missississipian due to loading south of the Arkoma Basin (Houseknecht, 1986)
				MOOREFIELD FM			
				BOONE FORMATION	B	SPRINGFIELD AQUIFER	
DEV				CHATTANOOGA SHALE	359 Ma	OZARK CONFINING UNIT < 40' w/ 30' SS & 10' SH IN STUDY AREA	
		HUNTON		PENTERS CHERT		OZARK AQUIFER	
SIL				LAFFERTY LS			
				ST. CLAIR LS			
				BRASSFIELD LS			
U. ORD	CINCIN- NATIAN	VIOLA		CASON SHALE	444 Ma		
				FERNVALE LS			
M. ORD				KIMMSWICK LS			
	CHAMP- LAINIAN	SIMPSON		PLATTIN LS			
				JOACHIM DOLO			
				ST. PETER SANDSTONE			Regional downwarping of Reelfoot Rift caused by cooling and subsidence (Caplan, 1954)
				EVERTON FORMATION			
L. ORD	CANADIAN	ARBUCKLE KNOX		POWELL DOLOMITE			
				COTTER DOLOMITE			
				JEFFERSON CITY DOLO			Evolution of southern margin of North American into a passive margin (Caplan, 1954)... Deposition of Cambrian to Late Mississippian Carbonates
				ROUBIDOUX FM			
				GASCONADE DOLO			
CAMBRIAN	CROIXIAN			EMINENCE DOLOMITE	488 Ma Є		
				POTOSI			Late Precambrian to Cambrian rifting (Houseknecht and Kacena, 1983)... Formation of Reelfoot Rift and Ouachita Ocean Basin... Possible time and genesis of the Guy-Greenbrier Fault (Focus of this study)
				DERBY-DOERUN-DAVIS		ST. FRANCOIS CONFINING UNIT (MISSING IN STUDY AREA)	
				BONNETERRE DOLO		ST. FRANCOIS AQUIFER	
				REGAN SANDSTONE			
				LAMOTTE SANDSTONE			
PЄ				BASEMENT GRANITE AND RHYOLITE	542 Ma PЄ	BASEMENT CONFINING UNIT	

▲ **Figure 4.** Stratigraphic section of rocks in study area with cross-section reflectors used in Figure 5, regional hydrological units, and tectonic history. The large E-W trending normal faults cut through Mississippian and older strata, offsetting the top of the Precambrian basement. The St. Francois confining unit does not exist in the study area, so the Ozark aquifer essentially lies atop the Precambrian. Used by permission of the AGS.

2. The Ozark confining unit is the Chattanooga Shale. The hydraulic connection between the overlying Springfield Plateau aquifer and the underlying Ozark aquifer can vary significantly with local lithologic and structural differences (Imes and Emmett 1994). In the study area the confining unit is relatively thin, being composed of ~10 m of sandstone and only ~3 m of shale.
3. The Ozark aquifer is the thickest aquifer in the study area. Dolostone is the dominant rock type in the Ozark aquifer with some limestone and sandstone formations. The dolostone has relatively low intrinsic porosity (~4–6%), but permeability is enhanced in fractured and faulted areas.
4. The St. Francois confining unit is composed of clastic and carbonate rocks with variable shale content. This unit has not been identified in Arkansas (Caplan 1960). A review of well logs and drill cuttings from well #5 indicates that the St. Francois confining unit is absent (Ausbrooks, personal communication 2011), so there is no impermeable unit to stop fluid infiltration from the Ozark aquifer into the St. Francois aquifer and the Precambrian basement.



▲ **Figure 5.** Interpreted geologic cross-section modified from Van Arsdale and Schweig (1990) by the AGS. Reflectors are identified in Figure 4. Used by permission of the AGS.

5. The St. Francois aquifer consists of the moderately permeable Bonneterre Dolomite and the Lamotte Sandstone. It is absent in the study area (Caplan 1960).
6. The Precambrian confining unit is composed of generally low permeability crystalline rock. Faults and fractures provide conduits for fluid movement.

As mentioned, the St. Francois confining unit is absent in the study area (Caplan 1960). Therefore, no impermeable unit exists to stop fluid infiltration from the Ozark aquifer into the St. Francois aquifer to the top of the Precambrian. At well #1 wastewater is injected into two distinct depth intervals. The upper injection interval is in the Mississippian age Boone Formation at depths between 1.84 and 1.87 km. The injection occurs over ~30 m in the Springfield aquifer. The lower interval is the Silurian-Devonian age Hunton Group at depths between 1.89 and 1.92 km. This injection occurs over ~30 m in the top of the Ozark aquifer. These two intervals are separated by ~14 m of the Chattanooga Shale. Wastewater at well #5 is injected into the Ordovician age Arbuckle/Knox Group at depths between 2.38 and 3.34 km. The injection interval spans 960 m of the Ozark aquifer. Wastewater at well #2 is injected into the Boone Formation at depths between 2.084 km and 2.109 km. Injection spans ~25 m in the Springfield aquifer.

In the study area most wells inject into carbonate rocks with relatively low intrinsic porosity (4–6%), so the higher-volume wells are sited where the structural geology (fractures, joints, and faults) enhances the porosity and permeability. Normal faulting found in the eastern Arkoma basin includes steep basement faults down to the southeast, which are continuous from the Precambrian basement upward through the Mississippian (Van Arsdale and Schweig 1990). They terminate at the base of the Pennsylvanian ("U" in Figures 4 and 5). These faults trend east-northeast subparallel to the principal compression axis of the present-day stress field in the midcontinent (Zoback and Zoback 1991) and are nonseismic. There are three of these deep basement faults in the study area (Figures 2 and 5): the Morrilton fault, the Enders fault, and the Heber Springs fault. These faults may act as fluid conduits both laterally and vertically (Ake *et al.* 2005).

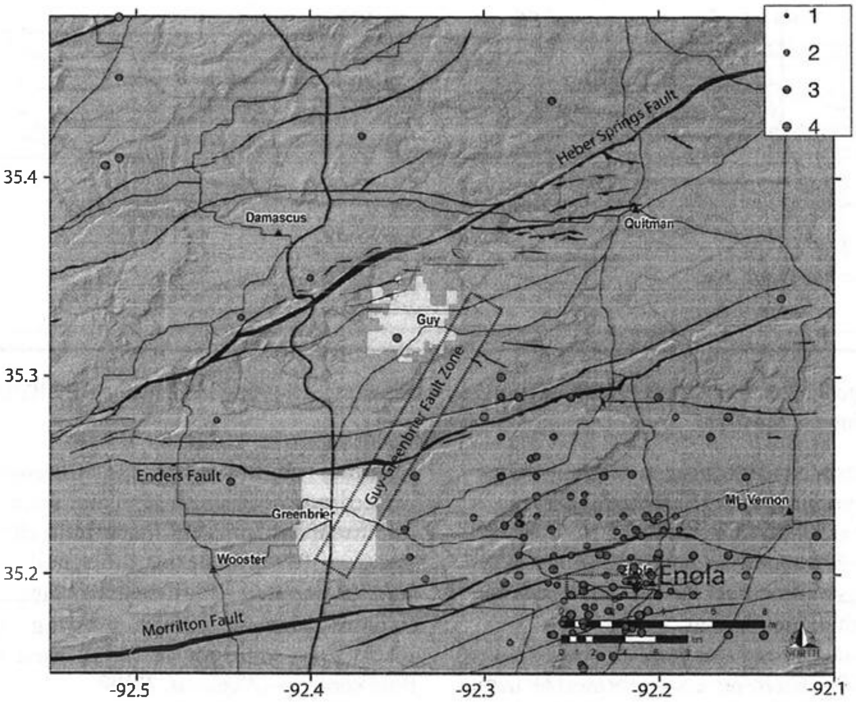
A platewide extensional event in the early Cambrian (Burke and Dewey 1973) that formed the northeast trending Reelfoot rift underlying the Mississippi Embayment likely caused northeast-southwest (and northwest-southeast) trending basement faults and fractures in the study area (Imes and Emmett 1994). Repeated differential movement across weak zones associated with these basement faults created faults and fracture zones in younger overlying consolidated Paleozoic rocks (Imes and Emmett 1994). These faults may also act as fluid conduits (Ake *et al.* 2005).

SEISMICITY

Arkansas has a history of earthquakes. The New Madrid seismic zone (NMSZ) lies in the northeast corner of the state (Figure 1). Three large earthquakes occurred in the NMSZ during the winter of 1811–1812. Paleoliquifaction evidence suggests five to nine magnitude 7+ earthquakes have occurred in the NMSZ in the last 1,100 years (Tuttle *et al.* 2002). The NMSZ is traditionally considered to be the most seismically active area east of the Rocky Mountains.

Diffuse seismic activity surrounds the NMSZ. In central Arkansas, this diffuse activity is composed of both scattered, isolated earthquakes and two intense swarms of earthquakes near Enola in 1982 and 2001. Enola is ~15 km southeast of the recent earthquakes. In Figure 6 the Enola swarm area is shown along with seismicity between January 1976 and April 2009. It is unclear whether the distribution of earthquakes is real or produced by uncertain earthquake locations related to significant potential timing errors inherent in recording and interpreting older "smoked paper" seismic records. Where earthquakes were recorded locally with digital instruments, the swarm activity occurred in compact, elongated, ~east-west trends at depths from 3 to 7 km (Chiu *et al.* 1984; Rabak *et al.* 2010).

We first considered the possibility that earthquakes may be caused by fluid injection at waste disposal wells in Arkansas in the fall of 2009 after eight earthquakes (2.4 ≤ magnitude ≤ 3.0) occurred within 5 km of well #2 (Figure 7). At that time the closest existing seismic station, UALR, was ~54 km south of well #2. Therefore earthquake locations from the Cooperative New Madrid Seismic Network (CNMSN) had large uncertainty (mean horizontal error 3.0 km and vertical 4.5 km). Scott Ausbrooks of the AGS and I deployed a three-



▲ **Figure 6.** Earthquakes (gray circles) located in study area between 1 January 1976 and 1 April 2009. Enola swarm earthquakes from studies using digital recorders (Chiu *et al.* 1984; Rabak *et al.* 2010) were confined within the dotted square at depths between 3 km and 7 km. The future Guy-Greenbrier fault area is shown. No clustering of earthquakes is observed along the Guy-Greenbrier fault. No waste disposal wells operated in the study area before or during this time. The first disposal wells became operational in April 2009.

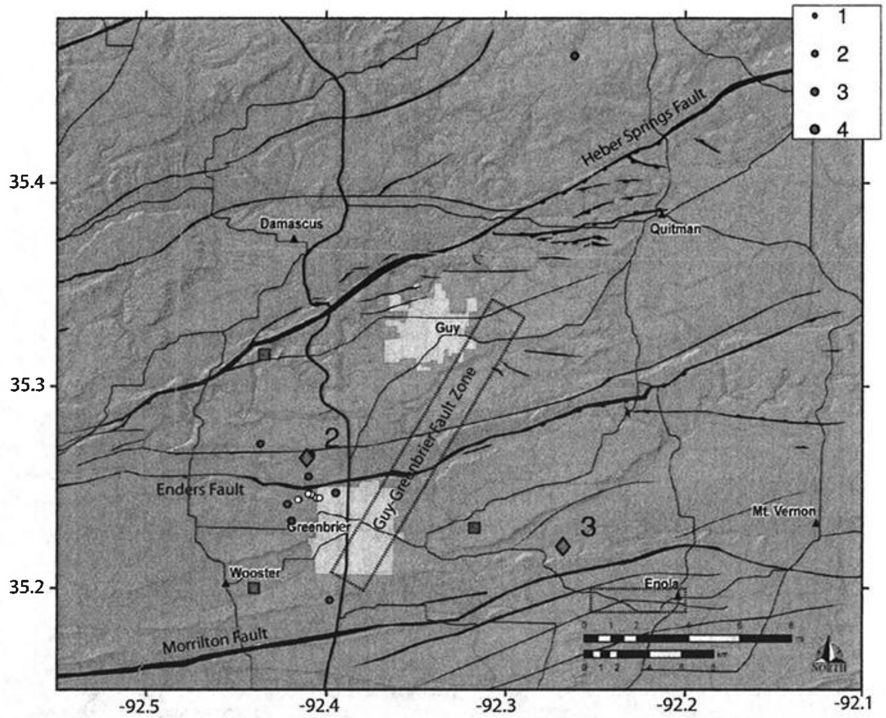
station seismic array for ~six weeks and detected hundreds of small earthquakes located in a tight cluster about 2 km south of the well (Figure 7). These well-located earthquakes (mean horizontal error ~0.5 km and vertical ~1.0 km) occurred at depths between 6.7 and 7.6 km whereas fluid was injected at a depth ~2.4 km at well #2. A large E-W trending normal fault (the Enders fault) occurs about 2 km south of well #2. The Enders fault cuts the Springfield aquifer (into which fluid is injected) and underlying rocks, and it offsets the top of Precambrian crystalline rock in which the earthquake cluster was located.

Scattered activity continued within several kilometers of well #2 in 2010 (Figure 8). Seismic activity also started occurring east of well #3. Temporary seismic stations were deployed near Enola from June through August 2010. Using the temporary stations, we were able to obtain precise earthquake locations (Figure 8). The events were tightly clustered in a slightly east-west elongated trend. Similarity in waveforms between these well-located earthquakes and previous events indicates some of the previous events were poorly located. Both well #3 and the well-located earthquakes are along the Morrilton fault. Seismic activity also started occurring off the Heber Springs fault northeast of well #6 during this period. No earthquakes occur along the Guy-Greenbrier fault prior to the start of injection at well #1 on 7 July 2010.

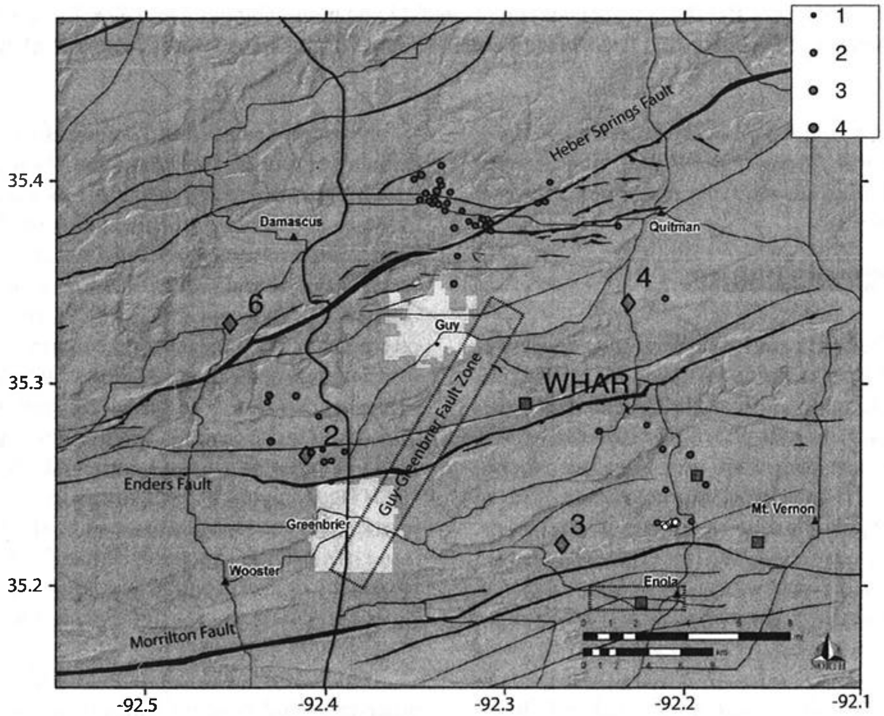
After injection started at well #1, scattered events start to occur within a radius of ~5 km from the well. The first earthquakes occurred along the Guy-Greenbrier fault 28 days (08/04/10) following the initiation of injection (Figure 9). Fluid injection started at well #5 on 18 August 2010. During the first week of September 2010, Ausbrooks and I installed an array of seismometers in the vicinity of the two recently activated wells. The local array augments regional seismic stations and provides increased earthquake detection and improved resolution of location.

Starting ~23 September 2010, a swarm of hundreds of small to moderate earthquakes (Figure 9) began southwest of well #1. **M** 4.0 and **M** 3.8 earthquakes on 11 and 15 October 2010, and an **M** 3.9 earthquake on 20 November 2010, were felt widely across northern Arkansas and southern Missouri. A ~N30E striking fault around 5 to 6 km long was illuminated by the seismicity by December. The earthquakes aligned along a nearly vertical fault at depths between 3 km and 7 km. This fault is consistent with slip on the NE-trending nodal plane of the focal mechanism of the **M** 4.0 earthquake (Figure 2 inset). At that time we estimated a maximum credible earthquake magnitude of 5.7 based on the fault area of 24 km^2 (Horton and Ausbrooks 2011).

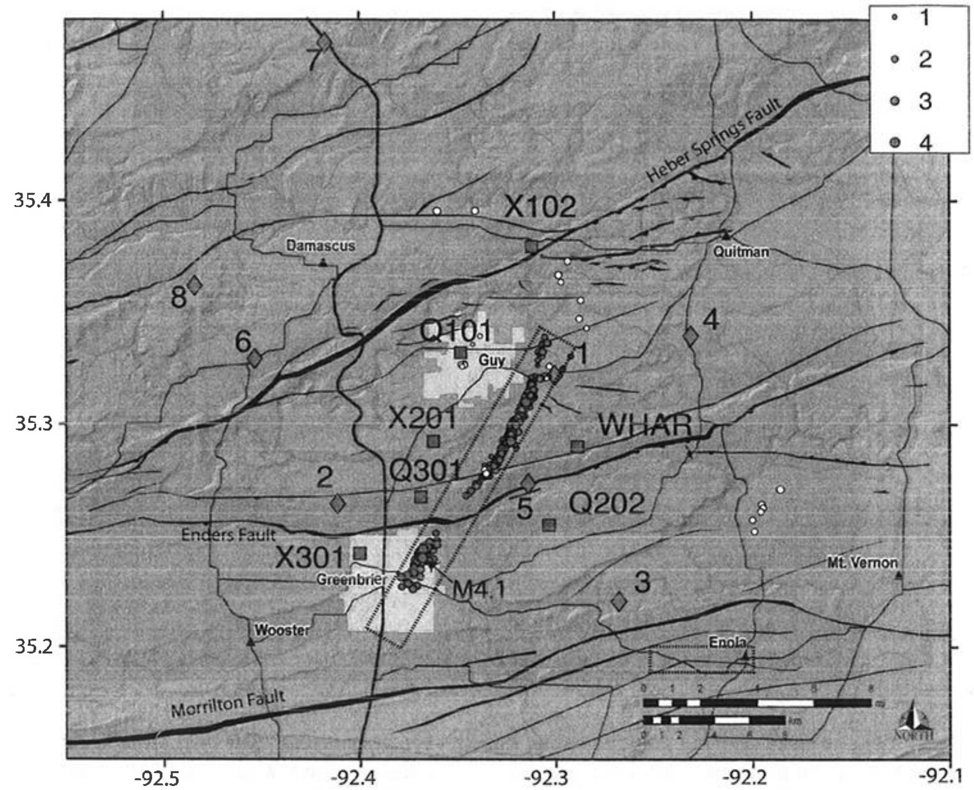
Intense swarm activity during the fall was followed by a relative lull in activity in mid-winter. Intense earthquake swarm activity began again on 16 February along the same trend as before but several kilometers to the south, leaving a clear gap on the upthrown side of the Enders fault that crosscuts the Guy-Greenbrier fault on its southern end between the fall 2010 swarm activity and the spring 2011 activity (Figure 9). The **M** 4.1 event on 18 February occurred in this southern



▲ **Figure 7.** Earthquakes (gray circles) located in study area by regional seismic network stations, CNMSN, between 1 April 2009 and 31 December 2009. Three temporary stations (squares) were deployed in October and November 2009 after earthquakes near well #2 happened. White circles are earthquakes located using temporary stations (Horton and Ausbrooks 2010). The Enders fault lies between these well-located earthquakes and well #2. Two waste disposal wells were operating in the study area by October 2009.



▲ **Figure 8.** Earthquakes (gray circles) located in study area by regional seismic network stations, CNMSN, between 1 January 2010 and 6 July 2010. Three temporary stations (unnamed squares) were deployed June through August 2010. The permanent station WHAR was completed by 1 March 2010. White circles are well-located earthquakes using temporary stations and WHAR. Four waste disposal wells were operating in the study area by April 2010.



▲ **Figure 9.** Earthquakes between 7 July 2010 and 18 February 2011. White circles denote earthquakes between 7 July 2010 and 1 September 2010. Gray circles are earthquakes recorded between 1 September 2010 and 18 February 2011. The first earthquakes in the Guy-Greenbrier fault zone occur after the start of injection at well #1 and before injection at well #5. The earthquakes south of the Enders fault all occur between 15 February 2011 and 18 February 2011. Eight waste disposal wells were operating in the study area by February 2011.

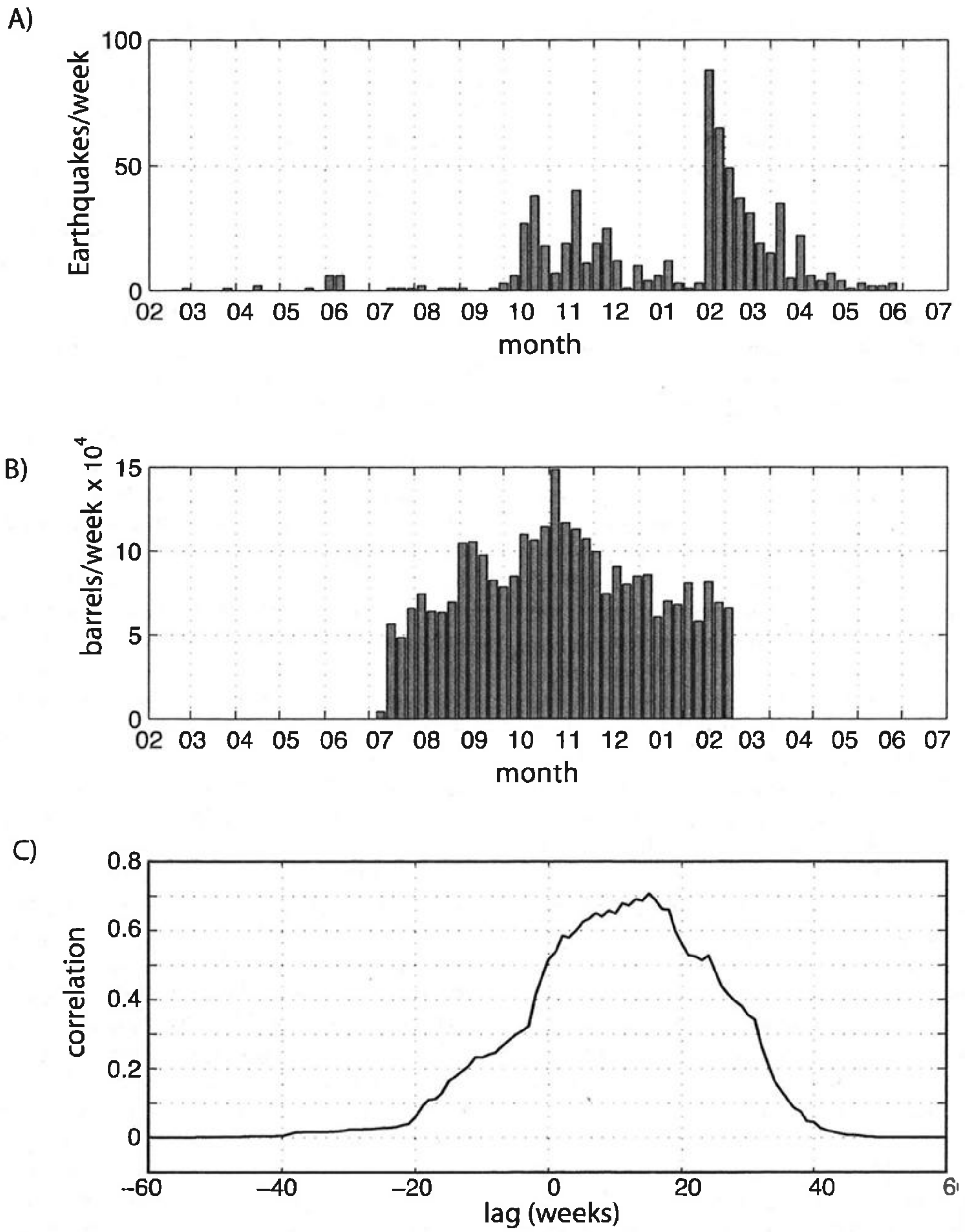
area. The gap was filled by the **M** 4.7 on 27 February and later events. During a two-week period, the known fault length more than doubled in length to ~13 km, causing concern and anticipation of larger events.

DISCUSSION AND CONCLUSIONS

Injection of fluids was halted at well #1 and at well #5 shortly in advance of an emergency shut-down order issued by the Arkansas Oil and Gas Commission (AOGC), the state regulator for these wells on 4 March 2011. The Guy-Greenbrier earthquake swarm did not stop with the shutdown of the two waste disposal wells (Figure 10A), but the rate and size of earthquakes steadily dropped during the three months following shutdown. The pore pressure buildup from months of injection would require time to return to the pre-injection level. At Rocky Mountain Arsenal the largest earthquake (**M** 5.2) happened more than a year after pumping had ceased. At the end of July 2011, well #1, well #2, and well #5 were permanently shut-in and plugged voluntarily by their operators. The AOGC also required well #4 to shut down based on potential public safety issues at that time. Only six earthquakes have occurred on the Guy-Greenbrier fault in the six months following the permanent shutdown.

Numerous faults and fractures in the study area provide avenues of groundwater movement through Precambrian crystalline rock that otherwise has low permeability (Imes and Emmett 1994). Many of these faults in the Precambrian basement connect with faults and fracture zones in the younger, overlying Paleozoic rocks (Imes and Emmett 1994). The Guy-Greenbrier fault appears to be exactly this type of fault. It extends from the Precambrian basement up into the Paleozoic sedimentary rock (Figure 3), providing a hydraulic connection between the Ozark aquifer—both well #1 and well #5 inject into the Ozark aquifer—and the earthquakes in the middle and northern end of the fault. Well #5 also cuts the Enders fault (Figures 2 and 5), providing a hydraulic connection to the earthquakes at the southern end of the fault. Well #2 injects into the Springfield aquifer about 2 km north of where the Enders fault cuts through the aquifer. So, the Enders fault may hydraulically connect well #2 with the southern end of the Guy-Greenbrier fault.

The hydrologic properties of the Guy-Greenbrier fault and other fault and fracture zones in the Precambrian basement of the study area are unknown. However, at Rocky Mountain Arsenal, transmissivity (1.08×10^{-5} m^2/s) in fractured Precambrian crystalline basement was determined from the observed long-term decline in fluid levels in the injection well



▲ **Figure 10.** Cross-correlation of earthquake frequency and combined injection volume at well #1 and well #5. (A) Number of earthquakes with m ≥ 2.0 per week is plotted for the entire study area. The start time coincides with the completion of installation of the Arkansas Seismic Network (see Figure 1) on 26 February 2010. (B) Combined injection volume at wells #1 and #5 per week. Injection at both wells ceased on 3 March 2011. (C) Normalized cross-correlation coefficient with peak 0.7 and lag of 15 weeks.

after injection ceased (Hseih and Bredehoeft 1981). Using this transmissivity in combination with the estimated storage coefficient (1.0×10^{-5}), a pore pressure buildup over time exceeding 0.1 MPa out to ~20 km from the well was predicted for fluid injected into a long, narrow reservoir spanning a depth interval from 3.7 to 7 km (Hseih and Bredehoeft 1981). Earthquakes on the Guy-Greenbrier fault span a similar depth range of the Precambrian basement. The peak monthly volume at well #1 (<2 km from the northern end of the fault) and well #2 (<6 km from the center of the fault) exceeds the peak volume at Rocky Mountain Arsenal (Table 1), and the peak injection pressure is considerably higher at all three wells. Due to the relatively high volume and pressure of injection at the wells surrounding the Guy-Greenbrier fault, significant pore pressure buildup would occur over time within the Ozark aquifer. Because of the hydraulic connection between the Ozark aquifer and the Guy-Greenbrier fault, pore pressure should also increase in the fault zone. The injected fluid does not need to travel the entire distance; only the pore pressure buildup needs to expand into the fault zone.

Increased pore pressure in the fault zone reduces frictional resistance to shear failure that can trigger earthquakes (Healy *et al.* 1968). In the presence of pore fluids, the Mohr-Coulomb criterion for slip (earthquake) on a pre-existing plane of weakness (fault) is

$$|\tau| = S_0 + \mu(\sigma - P)$$

where τ is the shear stress on the surface, S_0 is the cohesion of the surface, μ is the coefficient of friction, σ is the normal stress, and P is pore pressure. As long as the shear stress promoting slip is less than frictional resistance to slip (right side of equation), slip will not occur.

Earthquake triggering by the pore pressure mechanism requires that the rocks in the fault zone are critically stressed—stressed to near their breaking strength—before injection starts (Healy *et al.* 1968). Zoback and Townend (2001) suggest that intraplate regions like Colorado and Arkansas are in a state of failure equilibrium because ductile creep in the lower crust and upper mantle—driven by forces applied to the lithosphere at the plate boundaries—concentrates stress in the upper crust, loading suitably oriented faults to the point of failure over geologic time (Zoback and Townend 2001). A vertical fault striking ~N30E is suitably oriented with respect to the ENE orientation of the principal compression axis of the present-day stress field in the mid-continent (Zoback and Zoback 1991) for (strike-slip) failure. This is also the orientation of the northern strike-slip segment of the NMSZ (300 km to the east-northeast) and many focal mechanism nodal planes from the Enola earthquake swarm sequences ~15 km to the southeast (Chiu *et al.* 1984; Rabak *et al.* 2010).

At Rocky Mountain Arsenal, a strong correlation was observed between the number of observed earthquakes and the volume (Evans 1966) and pressure (Healy *et al.* 1968) of fluid injected at the well over about four years. Figure 10 shows a strong positive correlation between the frequency of earthquakes ($m \geq 2.0$) in the study area and the combined volume of injection at wells #1 and #5. We show combined volume, but a similar correlation exists for each independent well. The correlation peak is rather broad because the overall period of injection shifted by a couple of months coincides with the period of intense seismic activity on the Guy-Greenbrier fault. There is not a strong short-term correlation of individual peaks in injection with peaks in earthquake frequency. In part this may be due to the fact that up to four wells may contribute to the pore pressure in the fault zone.

Whether the recent earthquakes along the Guy-Greenbrier fault were naturally occurring or triggered by fluid injection, the fault must have been critically stressed prior to the earthquakes because loading the fault by natural means takes time. Therefore, the Mohr-Coulomb criterion must have been changed incrementally (naturally or by human activity) shortly before or coincident with the earthquakes. The earthquakes along the Guy-Greenbrier fault began after the start of injection at well #1 with intense seismic activity following the start of injection at well #5. The earthquake frequency in the study area shows a strong correlation with the volume of injection at well #1 and well #5 (Figure 10). The injection of fluids increased pore pressure in the Ozark aquifer, and because of the hydraulic connection between the Ozark aquifer and the Guy-Greenbrier fault, pore pressure could also have increased in the fault zone. Given the strong spatial and temporal correlation between the two wells and seismic activity on the fault, it would be an extraordinary coincidence if the recent earthquakes were not triggered by the fluid injection. For these reasons, I conclude that fluid injection triggered the recent seismicity on the Guy-Greenbrier fault.

Empirical relationships (Wells and Coppersmith 1994), determined from a global dataset of earthquake magnitudes and the corresponding fault dimensions, predict the Guy-Greenbrier fault is capable of an **M** 5.6 earthquake (based on fault area = 41 km^2) or **M** 6.0 earthquake (based on subsurface rupture length = 13 km). An event of that size would require rupturing the entire (estimated) fault surface, and the likelihood of such an earthquake is unknown. However, it is clear that a large and growing area of the fault was being affected by the combined injection of fluids at nearby wells in early March 2011. Since the **M** 4.7 earthquake only ruptured a small part (<4 km^2) of the fault, it is reasonable to assume the Guy-Greenbrier fault is capable of generating a larger earthquake ($4.7 < \mathbf{M} < 6.0$). Therefore continued injection of fluids at the surrounding wells could trigger a potentially damaging earthquake.

Hydrofracking and the concomitant wastewater disposal industries are expanding across the United States. Earthquakes (magnitude ≤ ~4.0) that are potentially associated with hydrofracking waste disposal have recently been reported in several states including Texas (Frohlich *et al.* 2011), Oklahoma (Holland and Gibson 2011), Arkansas (Horton and Ausbrooks 2010), and West Virginia (*Charleston Daily Mail*, "Studying link between earthquakes and wells," 8 September 2010). The number of disposal wells (and the associated earthquakes) will likely increase dramatically when the price of natural gas increases to a level at which production actually becomes profitable. As this happens the lack of regulations limiting the proximity of UIC wells to active seismic zones or to critical facilities (*e.g.*, hospitals, schools, or nuclear power plants) based on the potential to induce or trigger earthquakes may become a problem in many areas of the country. For example, a waste disposal well is currently operating within 12 km of the cooling tower of Arkansas Nuclear One. I have not observed earthquakes near this well, but UIC wells can function in a wide range of localities. Limiting the proximity of UIC wells to nuclear power plants and other critical structures seems sensible.

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