

Analysis of Transportable Array (USArray) Data Shows Earthquakes Are Scarce Near Injection Wells in the Williston Basin, 2008–2011

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ABSTRACT

We investigate possible links between seismicity and fluid injection in the Williston basin in the north-central United States, focusing on the region around the Bakken formation unconventional hydrocarbon play. Here, we show earthquakes are rarer near injection wells in the Williston basin than in the Fort Worth basin of Texas or in central Oklahoma. To identify earthquakes, we analyze seismograms collected by EarthScope USArray temporary stations, deployed on a grid with 70 km spacing. During the September 2008–May 2011 study period, we identified only nine regional earthquakes; of these only three were situated near injection wells. The reason why Williston basin earthquakes are so scarce is unclear. In both the Bakken and Barnett Shale play regions, injection volumes increased significantly in late 2007, and both areas have very low levels of natural seismicity. Oklahoma has experienced much higher rates of apparently induced seismicity than either region, possibly because injection volumes are higher in some wells in Oklahoma.

INTRODUCTION

It is well established that fluid injection into deep (~1–5 km) wells sometimes induces earthquakes (Suckale, 2009; Ellsworth, 2013; National Research Council, 2013). Since 2008 this has been investigated at several sites in the midwestern United States where there is wastewater disposal to support hydrofracturing operations (Frohlich *et al.*, 2011, 2014; Frohlich, 2012; Horton, 2012; Justinic *et al.*, 2013; Keranen *et al.*, 2013, 2014; Kim, 2013).

Over much of the midwestern United States, it can be difficult to assess whether detected earthquakes are natural or instead caused by regional petroleum production or fluid injection operations at nearby wells. This is because there are few continuously operating seismograph stations in the Midwest, and the U.S. Geological Survey's National Earthquake Information Center (NEIC) does not routinely detect and locate earthquakes smaller than approximately magnitude 2 (Ellsworth, 2013). Moreover, epicentral uncertainties are often as large as 10–15 km; this complicates the process of associating earthquakes with particular wells unless temporary seismo-

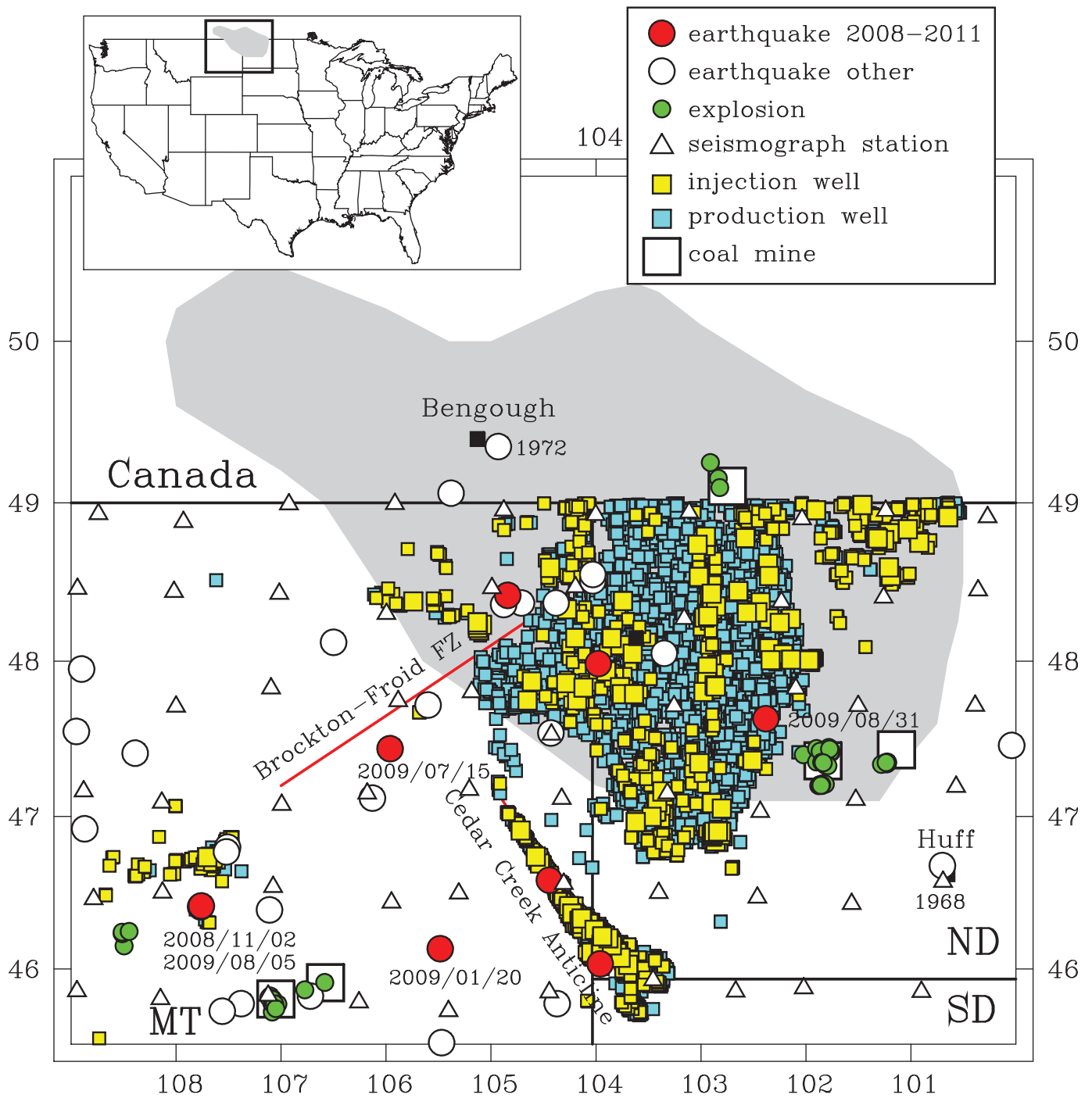
graph networks are deployed. However, for the two-year duration of deployments in the USArray program (Witze, 2013), high-quality seismograph stations operated continuously on a grid with 70 km spacing, making it possible to detect and locate earthquakes as small as M 1.5–2.0 with an epicentral accuracy up to 1–2 km (e.g., see Frohlich, 2012).

In the present study, we investigate the relationship between seismicity and injection/production in the Williston basin (Fig. 1), which recently has undergone a massive boom of production in one of its units, the Bakken formation (Fig. 2). The methods utilized in this study to analyze USArray data to identify and locate earthquakes are similar to those that we applied in surveys of three regions in Texas: the Barnett Shale play in northeast Texas (Frohlich, 2012), the Eagle Ford play of south central Texas (Frohlich and Brunt, 2013), and the Cogdell field in west-central Texas (Gan and Frohlich, 2013). We show the relationship between seismicity and injection is different in each of the four regions; of the four regions, there are the fewest apparently induced earthquakes in the Williston–Bakken region. Seismic activity is also considerably lower in the Williston–Bakken region than in Oklahoma (Keranen *et al.*, 2013, 2014) or Arkansas (Horton, 2012).

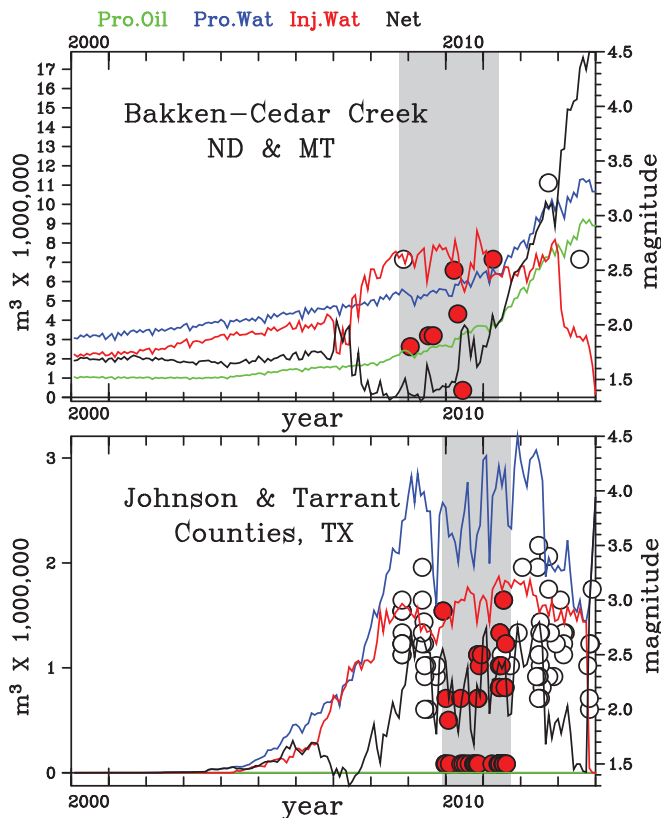
THE WILLISTON BASIN AND BAKKEN FORMATION

The Williston basin is a roughly circular depression covering about 500,000 km² across parts of North and South Dakota, Montana, Manitoba, and Saskatchewan. The deepest point, where the Precambrian basement depth is about 5 km, is near Williston, North Dakota. The Williston basin began to subside during the Ordovician and subsequently has undergone episodic subsidence (Pollastro *et al.*, 2013). Basin stratigraphic sequences record several cycles of marine transgression and regression. Petroleum production has been ongoing in the Williston basin since oil was discovered along the Cedar Creek anticline in the 1920s, with significant development phases occurring in the 1950s and then again in the 1970s.

The Bakken formation is currently the most commercially important stratigraphic sequence in the Williston basin (Pollastro *et al.*, 2013). The Bakken, which is upper Devonian and Lower Mississippian in age, is entirely in the subsurface with no



▲ **Figure 1.** Locations of earthquakes, injection wells, and production wells in the Bakken region. Red circles are earthquakes located in this study, white circles are other earthquakes reported by the National Earthquake Information Center (NEIC), and green circles are mine blasts. Coal mines are large white squares, labeled black squares are towns mentioned in the text, triangles are seismograph stations, injection wells are yellow squares, and production wells are blue squares. All plotted injection wells reported monthly injection volumes that exceeded $1600 \text{ m}^3/\text{mo}$ for one or more months since 2000; larger symbols are injection wells for which monthly injection volume exceeded $16,000 \text{ m}^3/\text{mo}$. Plotted production wells reported one or more monthly volumes exceeding $160 \text{ m}^3/\text{mo}$ since 2000. Grey region shows the extent of the Bakken formation. Labeled events are earthquakes mentioned in the text (see also Fig. 3). (MT, Montana; ND, South Dakota; SD, South Dakota)



▲ **Figure 2.** Regional monthly injection and production volumes (left axis) in two geographic regions. Monthly volumes are for (top) all Bakken–Cedar Creek wells in North Dakota (ND) and Montana (MT) and (bottom) all Johnson and Tarrant County wells in Texas (TX). Green and blue lines, respectively, are oil and water produced, the red line is water injected, and the black line is net volume (oil + water produced – water injected). Note that injection volumes in both regions experience significant increases in 2007. The gray-shaded area indicates the interval when the presence of USArray seismograph stations allowed detailed surveys of regional earthquake activity. Circles are times and magnitudes (right axis) of earthquakes reported by NEIC (white) and located by the authors (red). For the bottom graph, locations are as reported by [Frohlich \(2012\)](#) with undetermined magnitudes plotted at M 1.5.

surface outcrop. It has three members, an upper and lower black, organic-rich shale, separated by a dolomitic siltstone. Petroleum has been produced from the Bakken formation for more than 50 yrs; however, the application of hydraulic fracturing and horizontal drilling technologies has recently augmented Bakken oil and gas production, both of which have increased dramatically since 2006 (Fig. 2). As a result, by 2013 North Dakota was the second-largest petroleum-producing state in the United States, behind only Texas.

Historically, the largest earthquake reported in the Williston–Bakken region was assigned magnitude 5½ and occurred on 15 May 1909, with a reported epicenter that “could have been located in southern Saskatchewan, northeastern Montana, or northwestern North Dakota” ([Horner and Hasegawa,](#)

1978). Subsequently, the largest earthquakes were an M 4.4 on 8 July 1968 near Hough in North Dakota and an M 4.3 on 26 July 1972 near Bengough in Saskatchewan ([Horner et al., 1973](#)).

A second, roughly linear group of epicenters is situated in northern Montana and North Dakota. There are historical reports of earthquakes felt in Williston in 1915 and 1946, and instrumentally located epicenters occurred in 1975 (M 3.9), 1982 (M 3.3), 1998 (M 3.5), 2012 (M 3.3), and 2014 (M 4.1). Because of the absence of regional seismic stations, most of these locations are poorly determined but lie approximately along the southwest–northeast-trending Brockton–Froid fault zone. Dip and sense of movement on the fault zone are not well constrained. It shows evidence of Quaternary deformation, but it is not clear if it extends to the basement ([Wheeler, 1999](#)).

DATA AND METHODS

We identified seismic events for this study using data recorded by the three-component seismographs in the USArray temporary network, a National Science Foundation–supported program that deployed stations for intervals of two years on a grid with spacing ~70 km (Fig. 1). For the region surrounding the Bakken, USArray data were available between September 2008 and May 2011, allowing us to locate seismic events occurring during this period. At each station, we filtered the seismograms and identified candidate phase arrivals using a short-term/long-term average method; we ordered the candidate arrivals at all stations and grouped arrivals separated by 24 s or less from another arrival; and we further analyzed groups having phase arrivals identified at three or more stations. When this analysis indicated the arrivals were from a locatable regional event, we searched for arrivals at all stations surrounding the trial epicenter, including regional stations that weren’t part of the Transportable Array (e.g., DGMT in Dagmar, Montana).

We personally inspected the seismograms, reread *P* and *S* phases, and relocated all apparent regional earthquakes and representative mine blasts from each mine we identified. For most of the relocations, we only used phases recorded at stations within 1° of the epicenter; for the relocations, we arbitrarily fixed the depths of earthquakes at 5 km. To locate earthquakes, we utilized a standard iterated-least-squares approach to fit observed arrival times to times calculated for a flat-layered crustal model. The crustal model was based on [Morel-A-L’Huissier et al. \(1990\)](#) and consisted of layers having velocities of 3.6, 6.05, 6.5, 7.0, and 8.0 km/s, and layer thicknesses of 2.0, 8.0, 27, and 6.0 km over a half-space. In this study, with seismographs located on a 70 km grid, locations determined using five or more *P* phases and six or more *S* phases, azimuthal gaps of 110° or less, and root mean square residuals being 0.51 s or smaller (see Table 1), we estimate that the earthquake epicenters we determined are accurate to within ±2 km or less. All but one of the earthquakes reported in this study fit these criteria, with the exception of one event. The ±2 km accuracy corresponds to the discrepancy between our locations

Table 1
2010 Locations of Earthquakes Identified in This Study Using Fixed Focal Depth of 5 km

ID	Date (yyyy/mm/dd)	Time (hh:mm:ss.ss)	Latitude (°)	Longitude (°)	Magnitude	NP	NS	root mean square	Gap	Location
200	2008/11/02	22:49:19.48	46.410	-107.766	1.9	9	9	0.39	75	
360	2009/01/20	20:49:26.03	46.134	-105.484	1.8	8	7	0.21	107	
640	2009/07/15	05:14:7.15	47.439	-105.961	1.9	10	9	0.49	60	
680	2009/08/05	06:05:45.68	46.416	-107.760	1.9	9	9	0.36	76	
826	2009/08/31	01:24:22.78	47.632	-102.382	1.9	5	6	0.50	94	Bk
2090	2010/03/21	16:56:40.55	47.984	-103.978	2.5	9	9	0.27	72	Bk
2175	2010/04/27	05:07:58.84	46.585	-104.445	2.1	9	8	0.30	66	CC
2306	2010/06/14	07:58:3.46	46.034	-103.960	1.4	9	10	0.51	64	CC
2720	2011/04/06	11:23:49.39	48.418	-104.841	2.6	5	1	0.21	304	Bk

ID is identification number; NP and NS are number of *P* and *S* times used for relocation, respectively; and Gap is azimuthal gap. Events labeled Bk have epicenters within the shaded region in Figure 1, and events labeled CC are along the Cedar Creek anticline. Reported magnitudes are determined from peak-to-peak signal amplitude *A* and event-station distance *D* and estimated as magnitude $M = 0.6 \log_{10} A - 24 \text{ km}/D$.

of quarry blasts and the known locations of quarries in our previous investigations using USArray data in Texas (Frohlich, 2012; Frohlich and Brunt, 2013).

The information in this study concerning well locations and depths of production or injection, monthly volumes of oil produced, and water and gas produced and injected was from the database of IHS, Inc. It is a private company that compiles information about petroleum operations available from state regulatory sources and provides them by subscription to the public. The completeness and accuracy of these data are unknown but are likely to be as good as data from any publicly available source.

In the literature, the great majority of earthquakes reported as induced have epicenters within a few kilometers of an active injection well (Suckale, 2009). Exceptions at distances exceeding 10 km occurred in situations such as in Paradox Valley, Colorado, where injection has been ongoing for as much as 20 yrs (Block *et al.*, 2014), or in Oklahoma where injected volumes are extremely high (Keranen *et al.*, 2014). In the Bakken, widespread injection began increasing only in 2007; thus, in this study, we evaluate injection volumes primarily within 5 km of earthquake epicenters, or within 10 km when there are no wells with significant injection or production volumes within 5 km.

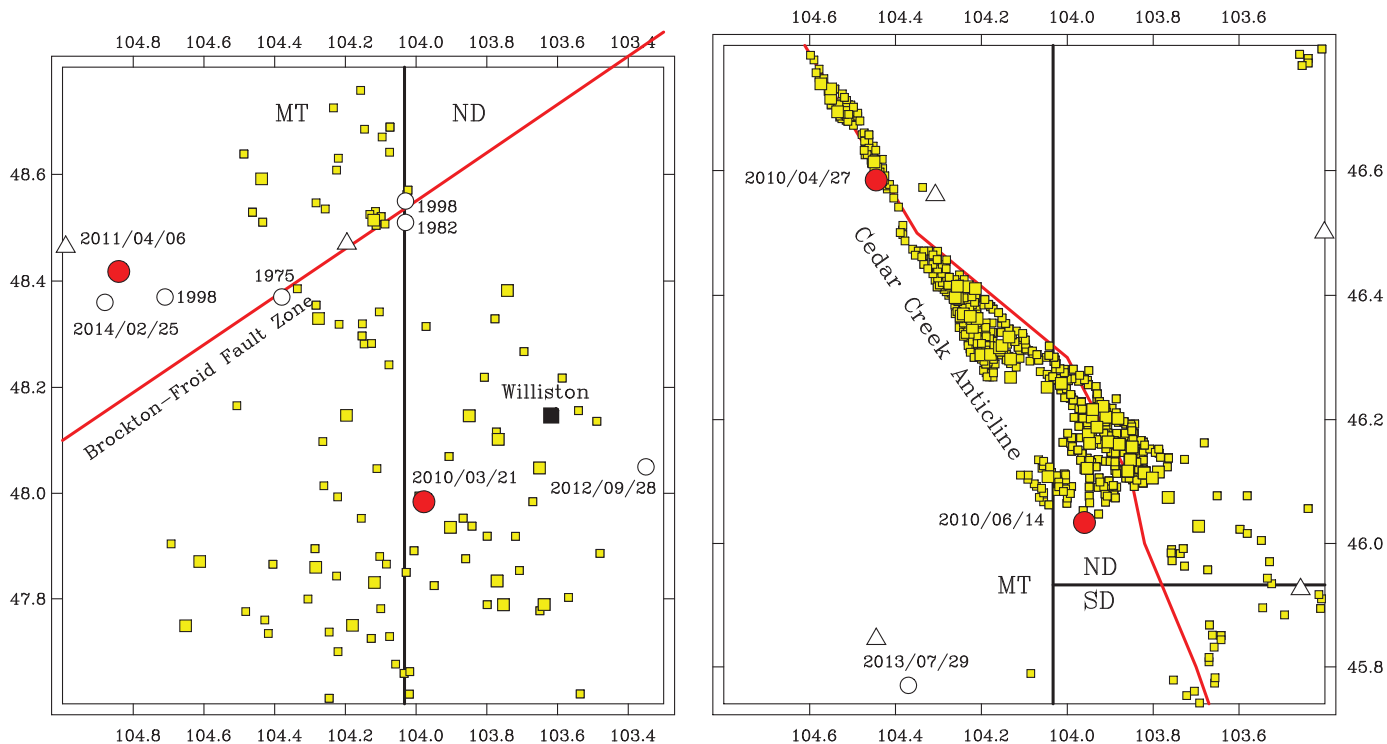
RESULTS

By far, the most abundant seismic signals recorded were mine blasts at regional strip mines that produce coal, mostly to be consumed by electric power plants. The 10 largest coal mines in the United States are in northeastern Wyoming (U.S. Energy Information Administration, 2013); some of these mines regularly generate explosions that are assigned m_b 3.5–4.0 by the NEIC.

Within the region mapped in Figure 1, our analysis of USArray data detected only nine earthquakes (Table 1) occurring between September 2008 and May 2011. Three of these epicenters lie within the mapped extent of the Bakken, two occurred south of the Bakken along the Cedar Creek anticline, and four were to the west of the Bakken in Montana.

Within the Bakken area, only one of the three earthquakes identified is probably induced or triggered. At wells within 5 km of the epicenter of the earthquake of 21 March 2010 southwest of Williston (Fig. 3, left), there had been a significant increase in oil and water production at the end of 2006 and a significant increase in injection near the end of 2008 (Fig. 4, top). In contrast, although the earthquake of 31 August 2009 (Fig. 1) was well recorded (so its location should be accurate), there were no active injection or production wells within 5 km. Similarly, there were no wells near the northeastern Montana earthquake of 6 April 2011 (Fig. 3, left). Moreover, it occurred in roughly the same area as apparently natural earthquakes associated with the Brockton–Froid fault zone that occurred in 1975, 1998, and 2014.

Further south, two earthquakes detected along the Cedar Creek anticline may be induced or triggered. The event of 14 June 2010 (Fig. 3, right) followed an overall increase in injection rates to about 150,000 cubic meters per month (m^3/mo) in mid-2009 at wells within a radius of 10 km (Fig. 4, middle). For the earthquake of 27 April 2010 (Fig. 3 right), injection volumes from 2003 onward averaged more than 100,000 m^3/mo at wells within 5 km of the epicenter (Fig. 4, bottom); however, volumes for extraction of water were approximately the same, so the net volume of fluid extracted was considerably less. For Bakken–Cedar Creek injection wells, the injection rates are relatively high for the wells near both the 14 June 2010 and 27 April 2010 earthquakes; since 2000, only 11 Bakken or Cedar Creek wells reported any monthly injection volumes exceeding 100,000 m^3/mo .



▲ **Figure 3.** Detailed maps of the earthquakes and injection wells investigated in this study: (left) the region near Williston and the Brockton–Froid fault zone and (right) the area along the Cedar Creek anticline. Symbols are as in Figure 1, without production wells.

It is implausible that injection triggered any of the four remaining earthquakes we detected, all located in eastern Montana (Fig. 1). There are no injection or production wells within 10 km of the earthquakes of 20 January 2009 or 15 July 2009. For the earthquakes of 2 November 2008 and 5 August 2009, which had nearly identical epicenters, there were no nearby injection wells; however, since 2000 there have been producing wells within 5 km that regularly extract water at rates of $\sim 15,000 \text{ m}^3/\text{mo}$.

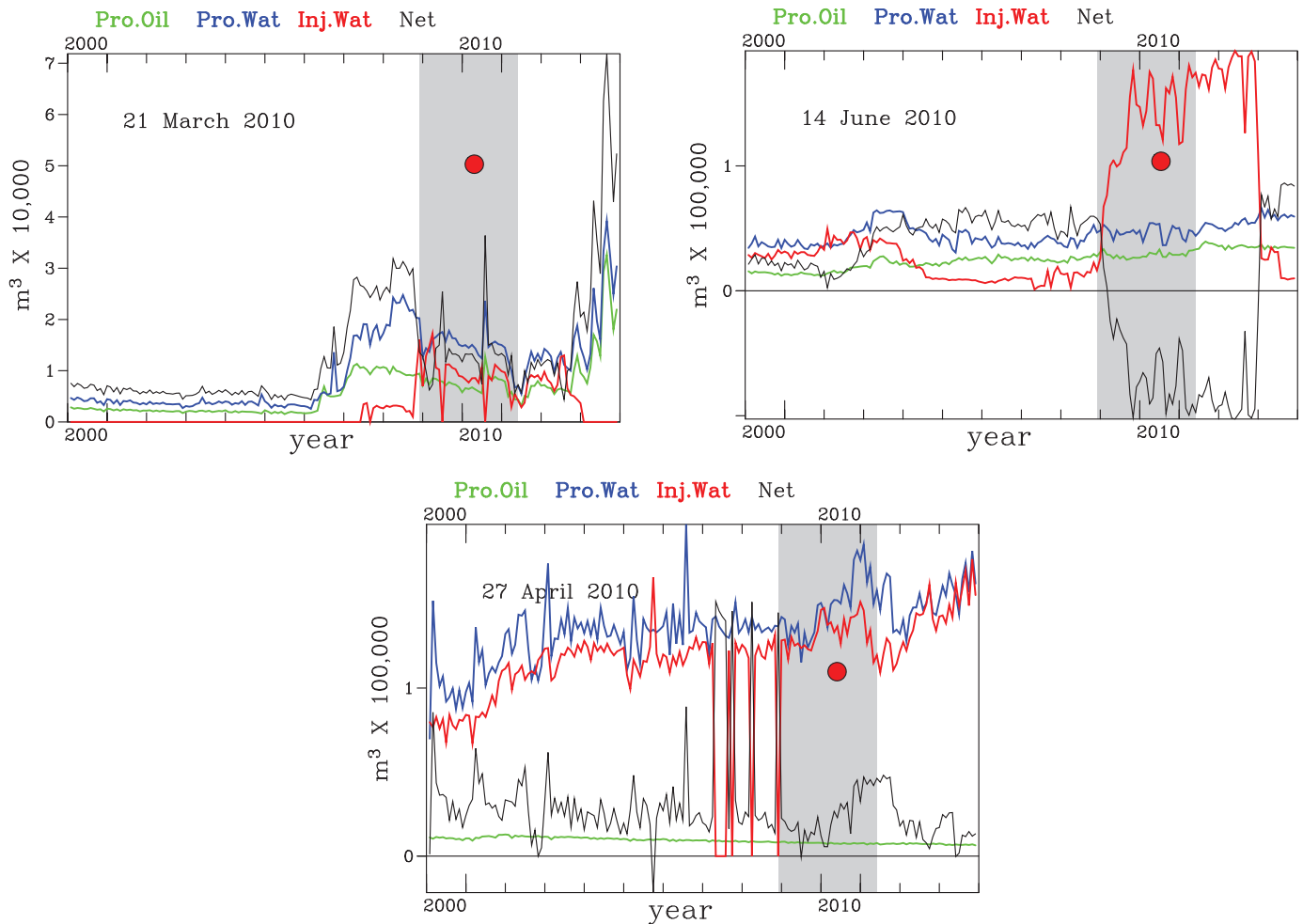
DISCUSSION

The principal result of this study is that an intensive search finds significantly fewer injection-caused earthquakes in the Bakken region than identified in a similar search in the Barnett Shale region of Texas (Frohlich, 2012) or as reported by NEIC in central Oklahoma (Keranen *et al.*, 2013, 2014). Within the Bakken and along the Cedar Creek anticline, comprising an area of $\sim 100,000 \text{ km}^2$, we identified only five earthquakes during the 2008–2011 study period (Table 1 and Fig. 2). In contrast, our study of the Barnett Shale in Texas (Frohlich, 2012) used similar methods and found 55 earthquakes within Johnson and Tarrant Counties, comprising an area of $\sim 5000 \text{ km}^2$. There is no directly comparable study of Oklahoma. However, within 150 km of Oklahoma City, with an area of $71,000 \text{ km}^2$, the NEIC has reported between 90 and 280 earthquakes each year between 2010 and 2013; in 2014 they reported more than 1500 earthquakes. In the Bakken–Cedar Creek and Johnson–Tarrant County regions,

the NEIC reported 5 and 35 earthquakes between 2010 and 2014, respectively.

Why are rates of recent seismic activity different among these areas? In Oklahoma, especially near Oklahoma City, injection volumes are massive at some wells, with four high-volume injection wells within 20 km of the reported earthquake activity, including two where injection rates exceeded a million barrels per month ($160,000 \text{ m}^3/\text{mo}$). Within the Barnett Shale of Texas, earthquake activity associated with injection was concentrated in a few areas, notably in Johnson and Tarrant Counties, and elsewhere there were few or no earthquakes even in counties where injection wells were numerous. Yet, the time history of injection in the Bakken and Barnett regions are similar, with both experiencing significant increases in injected volumes since 2006 (Fig. 2).

Triggered earthquakes are thought to occur when injected fluids reduce the normal stress and thus friction across faults, allowing them to slip in response to regional tectonic stress (Zoback and Townend, 2001; National Research Council, 2013). To assess the likelihood of fault reactivation, one needs knowledge of the *in situ* stress state, orientation of pre-existing faults, and changes in fluid pressure. In the Williston basin, Zhou *et al.* (2008) argue that maximum stress is vertical; the Bakken formation is overpressured (Burrus *et al.*, 1996), but otherwise the stress profile relates simply to depth and density with a gradient of 1 psi/ft (Zhou *et al.*, 2008). The horizontal stresses are poorly constrained, but Williams-Stroud and Billingsley (2010) note the low-stress anisotropy and comment that this produces a wider range of fracture orientations than



▲ **Figure 4.** Injection and production volumes for wells near the earthquakes of (top) 21 March 2010, (middle) 14 June 2010, and (bottom) 27 April 2010. The red circles indicate the time when each earthquake occurred, and the gray-shaded area indicates the time interval of USAArray seismograph station deployment. Green and blue lines indicate the oil and water produced, the red line is water injected, and the black line is net volume (oil + water produced – water injected). Volumes plotted are for all wells within 5 km of the epicenter (top and bottom) and within 10 km (middle). The data suggest that changes in production or injection may have triggered the earthquakes in the top and middle panels; for the 21 March 2010 earthquake, production volumes increased significantly in 2006, and then injection volumes increased in 2008; for the 14 June 2010 earthquake, injection increased significantly in 2009. For the 27 April 2010 earthquake, injection and water production volumes were consistently high in the decade prior to the earthquake, but there are no unusual changes in 2009 or 2010.

would be found in basins where the differential stress is higher. The World Stress Map (Heidbach *et al.*, 2009) shows one data point in Saskatchewan with maximum horizontal stress oriented north–south. Ling (2014) show highly variable orientations in North Dakota, with northeast–southwest predominant.

The Bakken play and neighboring regions are remarkable for their low level of historical seismicity. This may be partly because of the absence of felt seismicity, due to historically low populations densities coupled with the near absence of regional seismograph stations. The occurrence of regional earthquakes with M 5½ in 1909 and M 4.4 in 1972 suggests higher natural seismic activity than occurs in the Fort Worth basin of northeast Texas, where no natural historical earthquakes with magnitudes this large have occurred (Frohlich and Davis, 2002;


Frohlich *et al.*, 2011). If the 1909 estimate of magnitude M 5½ is accurate, the maximum historically observed earthquake size for the Bakken region is more comparable with Oklahoma, where the largest natural historical earthquakes (in 1882 and 1952) had magnitudes of ~5.7.

An important result of this and our previous surveys is that the relationship between seismicity and injection/production activities varies considerably in different geographic areas. In the Williston basin and western counties of Texas' Fort Worth basin (Frohlich, 2012), there is very little seismic activity near injection wells. In Oklahoma (Keranen *et al.*, 2013, 2014), Arkansas (Horton, 2012), in Johnson and Tarrant counties in the Fort Worth basin (Frohlich *et al.*, 2011; Frohlich, 2012; Justinic *et al.*, 2013), and near Timpson in east Texas (Frohlich *et al.*, 2014), there are earthquakes associated

with high-volume injection wells. In the Eagle Ford play region of Texas, earthquakes are associated primarily with production (not injection; Frohlich and Brunt, 2013). In the Cogdell field of Texas, increased seismic activity since 2006 coincided with a massive CO₂ gas injection program to enhance production (Gan and Frohlich, 2013).

Two unresolved questions are raised by these investigations: (1) Why does injection or production enhance seismic activity near some wells and fields and not others? and (2) What differences in geology and/or in injection/production practices explain the difference responses of the various regions? This variability in response to injection complicates efforts to come up with sensible uniform policies and regulations to mitigate potential seismic hazards associated with injection practices. At a minimum, it suggests that within any particular geographic region it is important to survey the relationship between seismicity and injection before considering possible policy responses or regulations.

DATA AND RESOURCES

All seismograms evaluated in this study are archived at the **10** Incorporated Research Institutions for Seismology Data Management Center and are freely available. Information about injection well locations, volumes, etc., was obtained by subscription from IHS, Inc., a private company that compiles information about petroleum operations available from public sources. 

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