SEISMOLOGY

Oklahoma's recent earthquakes and saltwater disposal

10.1126/sciadv.1500195

F. Rall Walsh III* and Mark D. Zoback

Over the past 5 years, parts of Oklahoma have experienced marked increases in the number of small- to moderate-sized earthquakes. In three study areas that encompass the vast majority of the recent seismicity, we show that the increases in seismicity follow 5- to 10-fold increases in the rates of saltwater disposal. Adjacent areas where there has been relatively little saltwater disposal have had comparatively few recent earthquakes. In the areas of seismic activity, the saltwater disposal principally comes from "produced" water, saline pore water that is coproduced with oil and then injected into deeper sedimentary formations. These formations appear to be in hydraulic communication with potentially active faults in crystalline basement, where nearly all the earthquakes are occurring. Although most of the recent earthquakes have posed little danger to the public, the possibility of triggering damaging earthquakes on potentially active basement faults cannot be discounted.

INTRODUCTION

The number of small- to moderate-sized earthquakes in much of the central and eastern United States began to increase markedly around 2009 (*1*). As noted by a number of authors (*2*–*7*), some of this seismicity appears to be associated with increases in saltwater disposal that originates as "flow-back" water after multistage hydraulic fracturing operations (*8*). Because flow-back water is usually quite saline (and can contain other contaminants), it is often disposed of through injection into regulated class II underground injection control (UIC) wells (*9*). Class II UIC wells are also used to inject "produced" water, saline water that was produced from water-bearing oil reservoirs. In general, produced water is either reinjected into the oil producing formation as part of water-flooding enhanced oil recovery (EOR) operations or disposed of in dedicated saltwater disposal (SWD) wells where it is usually injected into saline aquifers, sedimentary formations with relatively high porosity and permeability.

The fact that increased pore pressure at depth resulting from fluid injection can trigger slip on preexisting, already-stressed faults is well documented (*9*–*13*), and the mechanisms by which triggered fault slip occurs are generally well known (*9*). Simply put, increased fluid pressure decreases the effective normal stress on a fault. The effective normal stress resists fault slip by acting perpendicular to the fault, in a sense clamping the fault. Because an increase in pore pressure reduces the effective normal stress, it acts to unclamp a fault, potentially triggering the release of accumulated strain energy on a preexisting fault that is already close to failure (*9*). Such faults are often referred to as critically stressed faults. An earthquake on a critically stressed fault caused by fluid injection is referred to as a triggered earthquake when a relatively small perturbation triggers the release of already stored energy in an earthquake (*9*, *13*, *14*). Strain energy (or stress) on a fault accumulates over time as a natural geologic process. The pressure change resulting from fluid injection simply triggers its release. Injection-related seismicity has been discussed in a variety of contexts in which large volumes of fluid have been, or might be, injected into subsurface formations (*14*, *15*).

No state has experienced a more significant increase in seismicity in recent years than Oklahoma. As shown by the red circles in Fig. 1, numerous $M \geq 2.5$ earthquakes have occurred throughout much of the central part of the state in the past 5 years (*16*). The yellow circles in the figure show earthquakes of similar magnitudes occurring over the 34-year period ending in 2008. The increase in seismicity is not an artifact of improved seismic detection capabilities because there has been a marked increase in the number of earthquakes in Oklahoma at all magnitudes. For example, the rate of widely felt $M \geq 4$ earthquakes has gone from about one per decade before 2009 (going all the way back to 1882) to 24 in 2014 alone (*17*), roughly a 200-fold increase. Throughout the central and eastern United States, the likelihood of missing $M \sim 3$ earthquakes has been negligible for at least the past 25 years (*18*). In Oklahoma, there was about one $M \geq 3$ event per year during the 34-year period from 1974 (the onset of modern seismic recording) to 2008, but more than 100 $M \geq 3$ events per year in 2013 and 2014.

The upper part of Fig. 2 shows the cumulative number of $M \geq 2.5$ earthquakes in Oklahoma as a function of time. The times of occurrence and magnitudes of individual earthquakes are shown as red dots in the lower part of the figure. It can be seen that the rate of earthquake occurrence began to increase in 2009 and has continued to increase since then. Figure 2 also shows the aggregate monthly injection volume from ~7000 UIC wells reporting in any given month. The earliest time for which comprehensive injection data are currently available is 1997 (*19*). Although the seismicity data are available through the end of 2014, injection data in the state are currently only available through 2013. Three types of injection wells are shown—EOR wells, SWD wells, and wells of unknown type because the type of injection well is not listed before 2011 in the available data. The locations of 5644 wells that injected more than 30,000 barrels (~4800 m^3) in any month in 2011–2013 are mapped in Fig. 1.

As can be seen in Fig. 2, the aggregate monthly injection volume in the state gradually doubled from about 80 million barrels/month in 1997 to about 160 million barrels/month in 2013, with nearly all of this increase coming from SWD not EOR. Most of the SWD in central Oklahoma is occurring into the Arbuckle Group that is close to crystalline basement (*20*). A number of entries in the UIC database had obvious errors, either in the listed monthly injection rates or in the well locations. For example, some wells appeared multiple times in the database. In other cases, either the locations of the wells were not reported or the reported latitude and/or longitude placed the wells outside of Oklahoma. Fortunately, the cumulative volume of injection associated with these wells is only about 1% of the statewide injection in recent years.

Department of Geophysics, Stanford University, Stanford, CA 94305, USA.
*Corresponding author. E-mail: frwalsh@stanford.edu

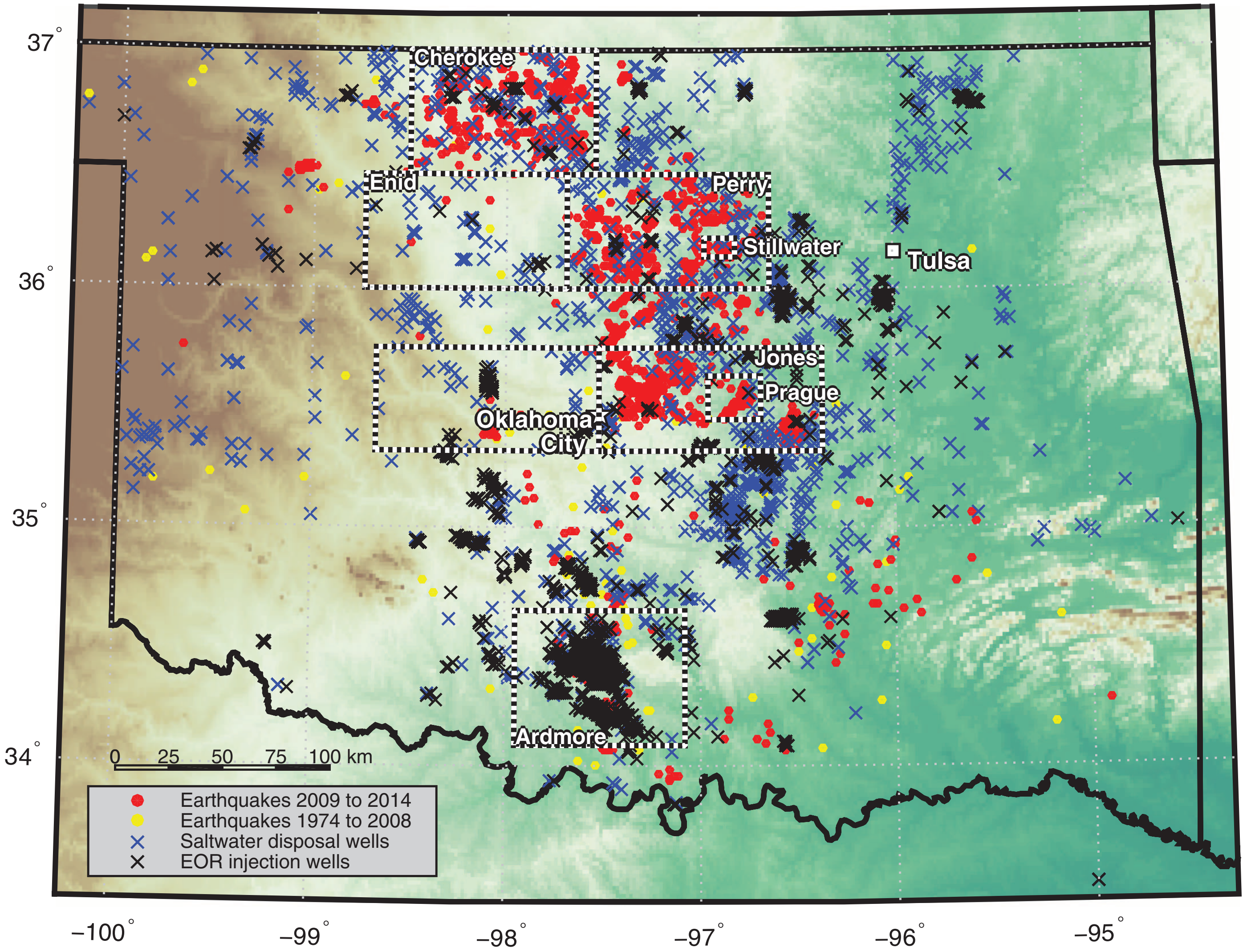

Fig. 1. Earthquakes and injection wells in Oklahoma. The map shows the locations of recent earthquakes (2009–2014 as red dots), historical earthquakes (1974–2008 as yellow dots), and EOR wells (black x's) and SWD injection wells (blue x's) that injected more than 30,000 barrels (~4800 m^3) in any month in the most recent 3 years of data. Eight study areas are outlined, each named for a nearby town, and are presented in Figs. 3 to 5.

Unreasonably large monthly injection volumes in the database were corrected by fixing obvious typographical errors or taking the median of five adjacent months of data. Fewer than 100 monthly injection volumes (out of more than 1.5 million) were corrected in this way. In general, the most recent injection data are more reliable than the older data.

Whereas the volume of injection has steadily doubled over the past ~17 years, the seismicity increased abruptly in 2009 (Fig. 2). Moreover, whereas injection wells are located throughout the state, the recent seismicity is mostly occurring in north central Oklahoma (Fig. 1). To investigate whether there are spatial and temporal relationships between injection and seismicity, we have defined special study areas that are outlined in Fig. 1. Each of the six main study areas is 5000 km^2. Three of these study areas discussed below account for 71% of the $M>3$ earthquakes that have ever been recorded in Oklahoma, but are just 8% of the total area of the state. They contain 17% of the SWD wells and 27% of the total volume injected in SWD wells in the state. Figure 3 shows the monthly aggregate injection (by well type) in the three most seismically active study areas, as well as the magnitudes and times of occurrence of the recent earthquakes in each area. A detailed map showing the locations of the earthquakes and all injection wells in each area is also shown.

RESULTS: SPECIAL STUDY AREAS

We first consider an area encompassing the town of Cherokee in north central Oklahoma. In this area, the Mississippi Lime, a carbonate formation with a high ratio of produced water to hydrocarbons (*21*), is being developed with large volumes of saline produced water being disposed of into the deeper Arbuckle Group. As can be seen in the upper panel of Fig. 3, disposal rates in the Cherokee area began to increase in 2005, but rapidly accelerated in 2010. Although several small earthquakes occurred in 2011 and 2012, the onset of the marked increase in seismicity early in 2013 closely follows the sharp increase in SWD. Note that the rate of SWD in 2013 is more than 10 times higher than it

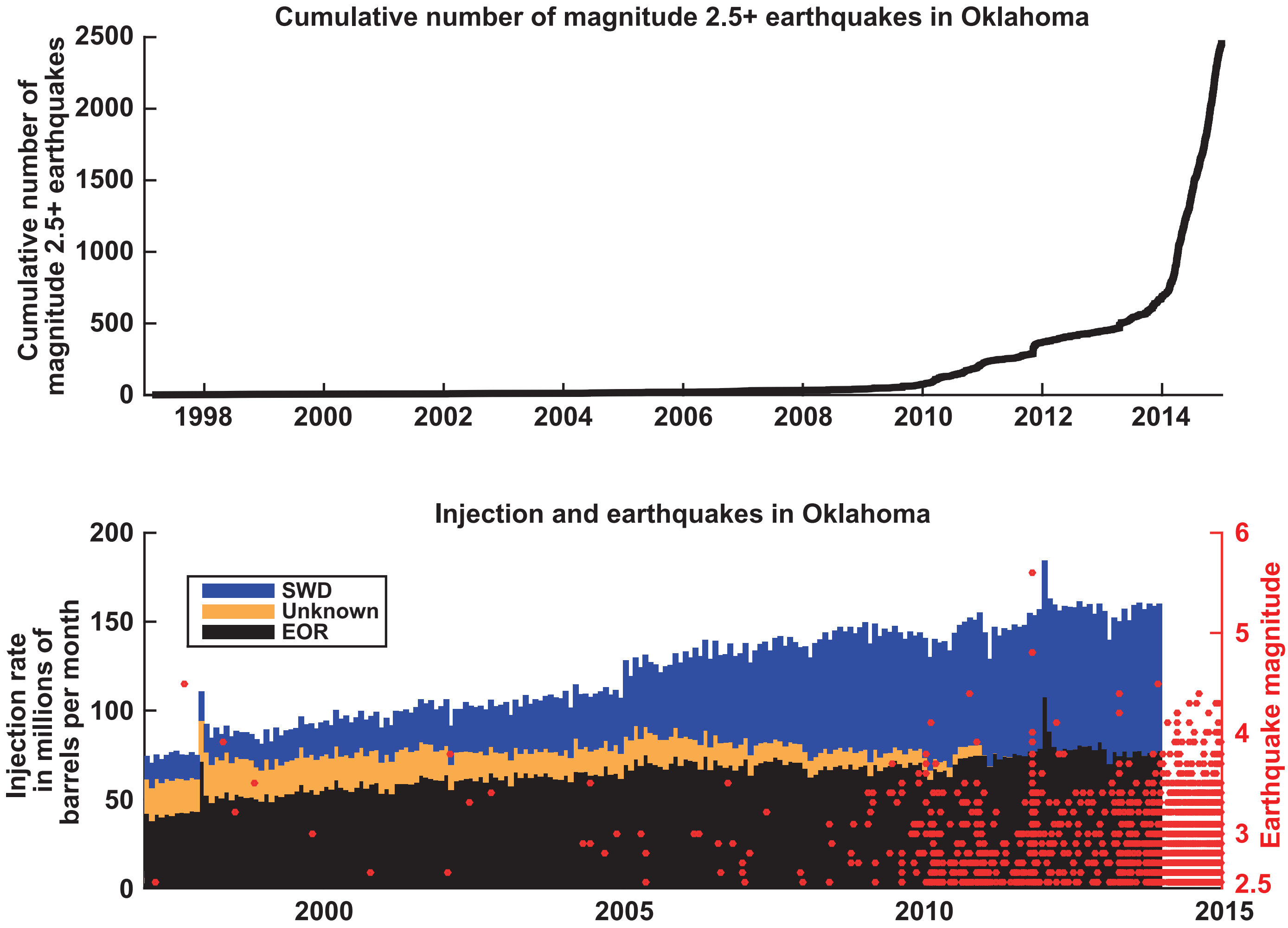

Fig. 2. Statewide injection and earthquakes. (**Top**) Cumulative number of *M*2.5 or greater earthquakes in Oklahoma since 1997. (**Bottom**) The left axis shows the total combined injection rate of all UIC wells in Oklahoma by type (see the text). The right axis shows all earthquakes in the state by magnitude through time in the state. Earthquake data are complete through 2014. The injection data are only available through 2013.

was in the early 2000s. The high rate of seismicity in this area continued into 2014. The rate of SWD was continuing to increase through the end of 2013 when the available injection data ended. The location accuracy of the earthquake epicenters in these study areas is about ±5 km. Thus, even considering the location uncertainty of the individual earthquakes, it is clear in the detailed map of the Cherokee area in Fig. 3 that both the earthquakes and injection wells are widely dispersed.

Although the Mississippi Lime development extends into southern Kansas, monthly saltwater injection data are not available for individual wells in Kansas. Thus, it is not possible to extend our analysis into the state, even though there has been appreciable recent seismicity in the area, including a *M*4.8 earthquake that occurred in November 2014 near Conway Springs, Kansas, about 30 km north of the Oklahoma border.

The middle panel of Fig. 3 shows the Perry study area, southeast of the Cherokee area, where SWD rates started to increase around 2005. A few earthquakes occurred in 2009, but a marked increase in seismicity followed a rapid increase in injection rates in 2013. Injection rates are about five times higher in 2013 than in the early 2000s. As in the Cherokee area, the map of Perry shows that the locations of the earthquakes and injection wells are distributed throughout the area.

The Jones area (the lower panel of Fig. 3) is an area of appreciable seismic activity just to the north and east of Oklahoma City. Numerous *M*~4 earthquakes occurred in 2013 and 2014 that have been felt throughout the Oklahoma City metropolitan area. SWD in this area began gradually increasing in 1999. Earthquakes began to occur in the area in 2007 when the rate of injection reached a maximum of about 12.5 million barrels/month, about 10 times the rate in the late 1990s. Although the aggregate injection rate slowly decreased between 2007 and 2010, it has remained relatively high compared to the levels in the late 1990s.

A recent study determined precise locations and focal plane mechanisms for many recent earthquakes in parts of central Oklahoma where additional seismometers had been deployed (*22*). As the sedimentary rocks in this area extend to 2 to 3 km, nearly all the earthquakes are occurring in crystalline basement at an average depth of between 5 and 6 km (fig. S1). Thus, the time lag between the onset of SWD and seismicity in the areas seen in Fig. 3 is not unexpected. In the case of seismicity triggered by reservoir impoundment, it is typical for there to be several years between impoundment of the reservoir and earthquake occurrence because of the time it takes for pore pressure

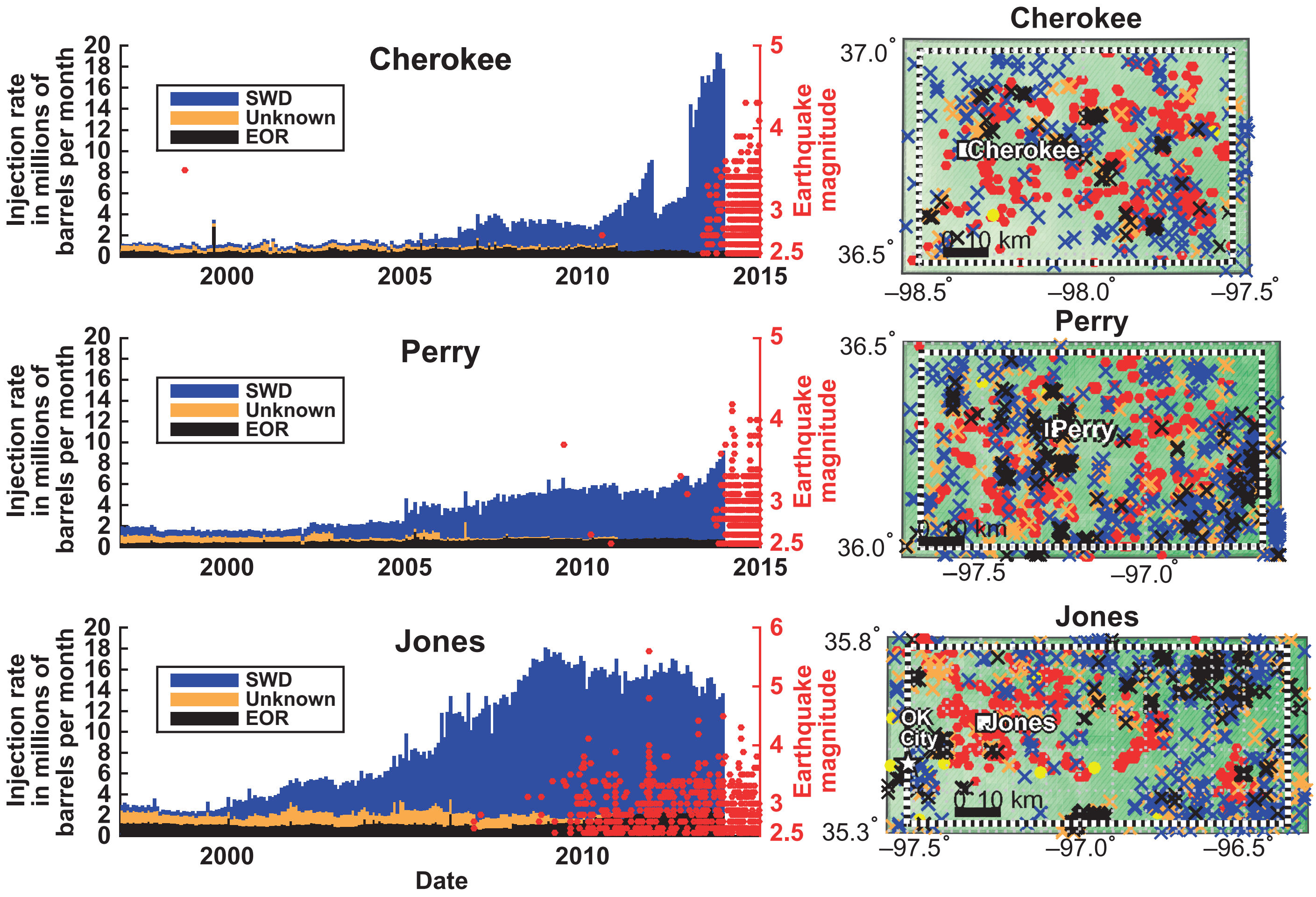

Fig. 3. Injection and earthquakes in three study areas. Monthly injection rates from EOR, SWD, and unknown wells within the Cherokee, Perry, and Jones study areas, as well as the times and magnitudes of earthquakes in each area. Detailed maps of each study area are also shown. The symbols for earthquakes and injection wells on the maps are the same as in Fig. 1. Note that the vertical scale is the same for each study area in this figure. Each study area is 5000 km^2.

to propagate to depth (*23*). The time between injection and seismicity seen in Fig. 3 depends on the location of the potentially active faults with respect to the injection wells, the rates of injection, the permeability of the relevant strata, and the proximity of the fault to failure (*24*).

To further illustrate the fact that the areas of increased seismicity are correlative with areas of large amounts of SWD, Fig. 4 shows injection and seismicity in three areas adjacent to those in Fig. 3 of equal size but with little seismicity. As shown in Fig. 1, the Enid study area is to the west of Perry and south of Cherokee, and the Oklahoma City area is just west of Jones. The three areas in Fig. 4 have much less SWD and many fewer earthquakes than those in Fig. 3. Although there appears to be a year of unusually high EOR injection in the Oklahoma City area in 2005, this does not affect the observation that there is relatively little SWD in this area and comparatively few recent earthquakes.

The lower part of Fig. 4 shows the Ardmore area, where relatively few earthquakes have occurred during the past 5 years but where appreciable injection (more than 40 million barrels/month, note changed injection scale in Fig. 4) has been going on for 15 years. Because nearly all of the injection is occurring into EOR wells (that is, the injection is back into shallower producing formations), one would not expect a pressure buildup that could affect critically stressed basement faults.

Figure 5 zooms in on two smaller areas of recent seismicity. The Prague area (upper panel) includes the November 2011 Prague earthquake sequence that included a *M*5.7 mainshock that occurred on a splay of the north-northeast trending Wilzetta fault (*25*) in central Oklahoma. There was a *M*~5 foreshock and many aftershocks, the largest of which was also *M*~5. Many of the aftershocks clearly occurred on faults extending into crystalline basement (*25*). In a relative sense, injection rates in the Prague area increased rapidly in 2000 and gradually decreased afterward, but it should be noted that the area shown and injection rates are far less than those shown in either Fig. 3 or Fig. 4. Injection into the Wilzetta disposal well [located at the northeastern end of the NE-SW lineation of aftershocks (*25*)] shows a similar pattern of injection rates that have decreased slowly since 2000. Thus, there is no clear temporal correlation between changes in SWD and the time of occurrence of the Prague sequence in late 2011 at this scale. Several studies (*25*–*28*) have suggested that injection into the Wilzetta and nearby UIC wells was the probable cause of at least the first of the three *M*5+ earthquakes in the Prague sequence. It is difficult to know if the Prague sequence was (i) triggered by an increase in pressure at depth from the Wilzetta (and nearby) wells, (ii) triggered by injection into the other wells in the general area, or (iii) a naturally occurring earthquake

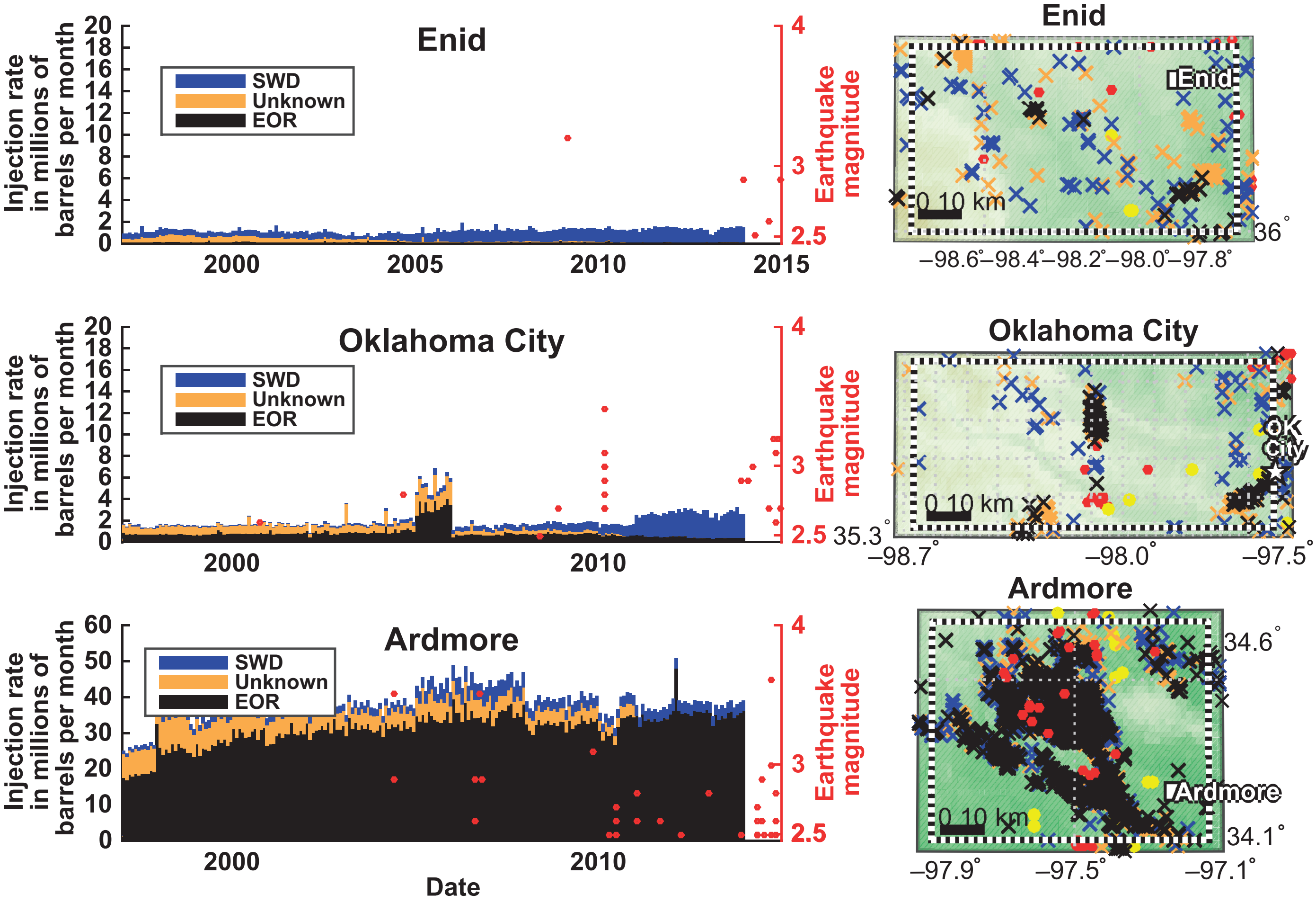

Fig. 4. Injection and earthquakes in three additional study areas with fewer earthquakes and less SWD. In contrast to those in Fig. 3, here are three comparable areas with comparatively few earthquakes. The vertical scales in the Enid and Oklahoma City study areas are the same as in Fig. 3. The Ardmore area has a different vertical axis because of the very large volumes of EOR injection.

sequence. With thousands of injection wells in the state, it is likely that some naturally occurring earthquakes would occur in the vicinity of disposal wells. Moreover, relatively large earthquakes are not unknown in Oklahoma. For example, there is paleoseismic evidence of a M~7 earthquake that occurred on the Meers fault in southwestern Oklahoma about 1100 years ago (*29*).

The three study areas with appreciable recent seismicity (Cherokee, Perry, and Jones) all show a clear increase in SWD rates and a subsequent increase in seismicity (Fig. 3). The Jones area shows an elevated rate of earthquake occurrence that follows an increase in SWD by several years.

Several recent studies have suggested possible links between individual injection wells and triggered seismicity in the Prague and Jones areas (*25*, *30*). There are indeed cases where individual SWD wells appear to be triggering earthquakes in their proximity. For example, the lower panel of Fig. 5 shows an injection well (magenta diamond) located near the town of Stillwater within the Perry special study area. Injection in that well increased to about 500,000 barrels/month in 2013 from nearly nothing. Earthquakes occurred in the immediate area surrounding the well soon after the injection rate began to increase and continued into 2014. Such close correlations in time and space exist but are relatively rare.

DISCUSSION: A CONCEPTUAL MODEL FOR OKLAHOMA SEISMICITY

In three of the six study areas defined above, marked increases in seismicity follow significant increases in SWD. The Arbuckle Group is the predominant formation used for SWD in central Oklahoma (*21*, *31*). Because it appears to be in hydraulic communication with the underlying crystalline basement, pressure changes resulting from SWD in the Arbuckle can propagate to depth. In the context of modeling by previous workers (*24*, *30*), a relatively simple conceptual model is starting to evolve, namely, that the significant increases in SWD increase pore pressure in the Arbuckle Group, which spreads out away from the injection wells with time, eventually triggering slip on critically stressed faults in the basement. Both the SWD wells and the earthquakes are widely distributed throughout the seismically active study areas (Fig. 3). As noted above, a delay between increases in SWD and seismicity, as

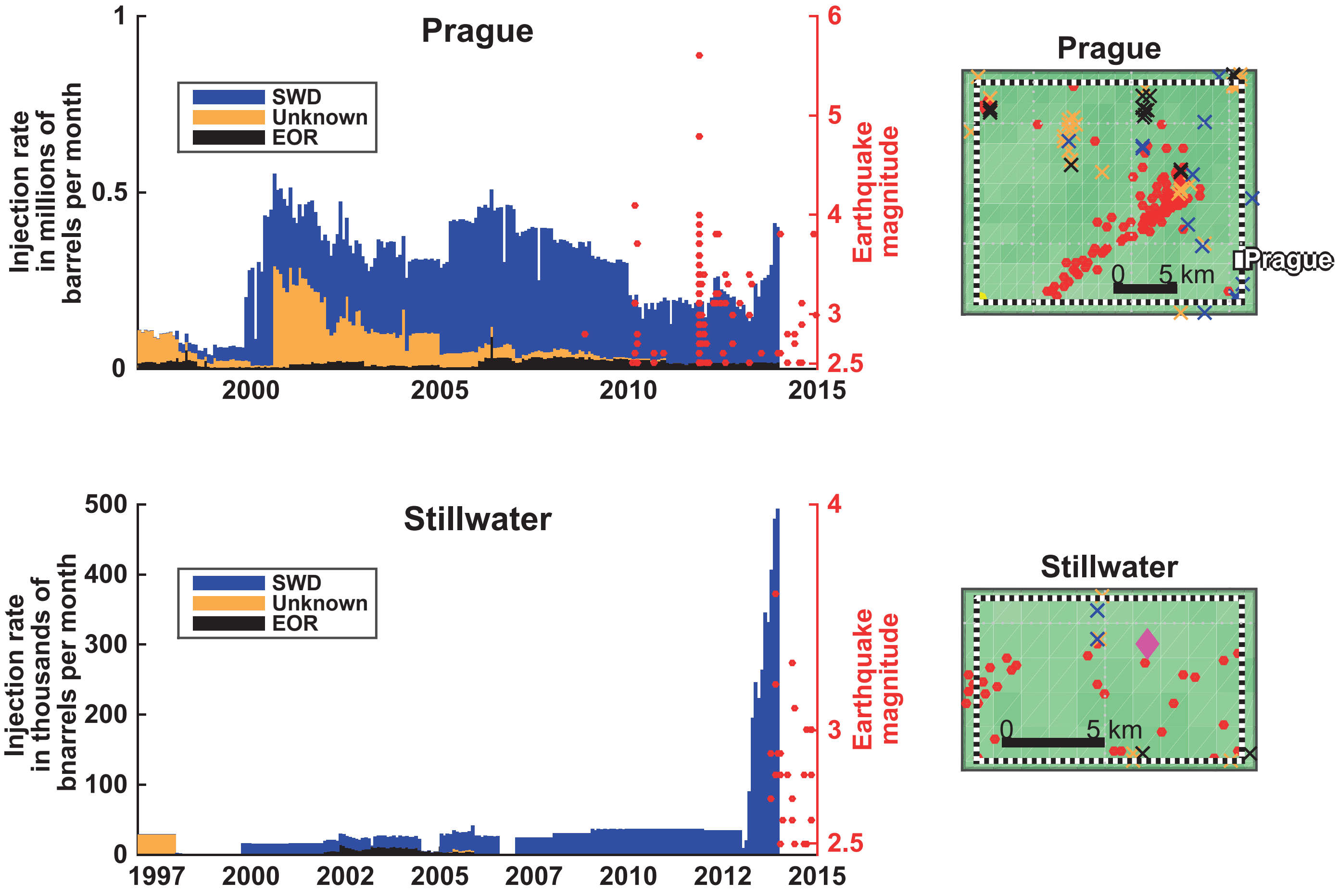

Fig. 5. Injection and earthquakes in two areas within the Prague and Jones study areas. These show monthly injection rates and locations of EOR, SWD, and unknown wells as well as earthquakes. The symbols for earthquakes and injection wells are the same as in the maps in Fig. 3. Note that the vertical scale is different for each area, as are the sizes of the study areas.

well as a separation between the locations of the injection wells and the earthquakes, is expected. In addition, there may be stratigraphic controls on the time delay between injection rate increases and the onset of seismicity. If injection is directly into the relatively high permeability lower Arbuckle Group in northern Oklahoma (*32*), pressure changes would be expected to spread out more quickly from the injection wells. This might explain the increase in seismicity closely accompanying the increase in injection rates in 2013 observed in the Cherokee and Perry areas in Fig. 3.

To better understand this conceptual model, there are three characteristics of faults in crystalline basement rocks that should be recognized. First, only a subset of the faults found in crystalline basement are potentially active in the current stress field. Oklahoma is known to have had nonnegligible seismicity before the significant increase that started in 2009 (*33*). Clearly, there are naturally occurring, potentially active faults throughout Oklahoma, as there are everywhere in intraplate areas. Earthquakes occurred in each of the six study areas before 2009. Occasional earthquakes are observed in intraplate areas around the world (*34*), a phenomenon sometimes referred to as the critically stressed crust.

In the context of a critically stressed crust, small perturbations of fluid pressure have the potential to initiate slip on preexisting faults that are already close to frictional failure (*9*). The stresses on the faults are the result of natural geologic processes—the same process that results in naturally occurring seismicity in other intraplate areas. It is important to recognize that relatively small pressure perturbations have the potential to trigger sizeable events, as is the case with reservoir triggered seismicity (*24*).

The second point to note is that potentially active faults in crystalline basement have a much higher permeability than the basement rocks themselves or preexisting faults that are not active in the current stress field. In other words, faults that are geologically active today are hydrologically active today (*35*). Because of this, pore pressure increases resulting from injection into sedimentary formations adjacent to the basement (such as the Arbuckle Group) are expected not only to spread out from the injection wells with time but also to penetrate potentially active faults in basement. Because some of these faults will be close to failure in the context of a critically stressed crust, triggered seismicity can result from even small pressure increases.

Finally, widely used earthquake scaling laws demonstrate that earthquakes as large as *M*4.7 and *M*5.7, the largest earthquakes in the Guy, Arkansas (*6*), and Prague sequences (*25*), require slip on faults that are several kilometers to tens of kilometers in extent (*14*). Because the sedimentary rocks in this area are generally 2 to 3 km thick, it is clear that

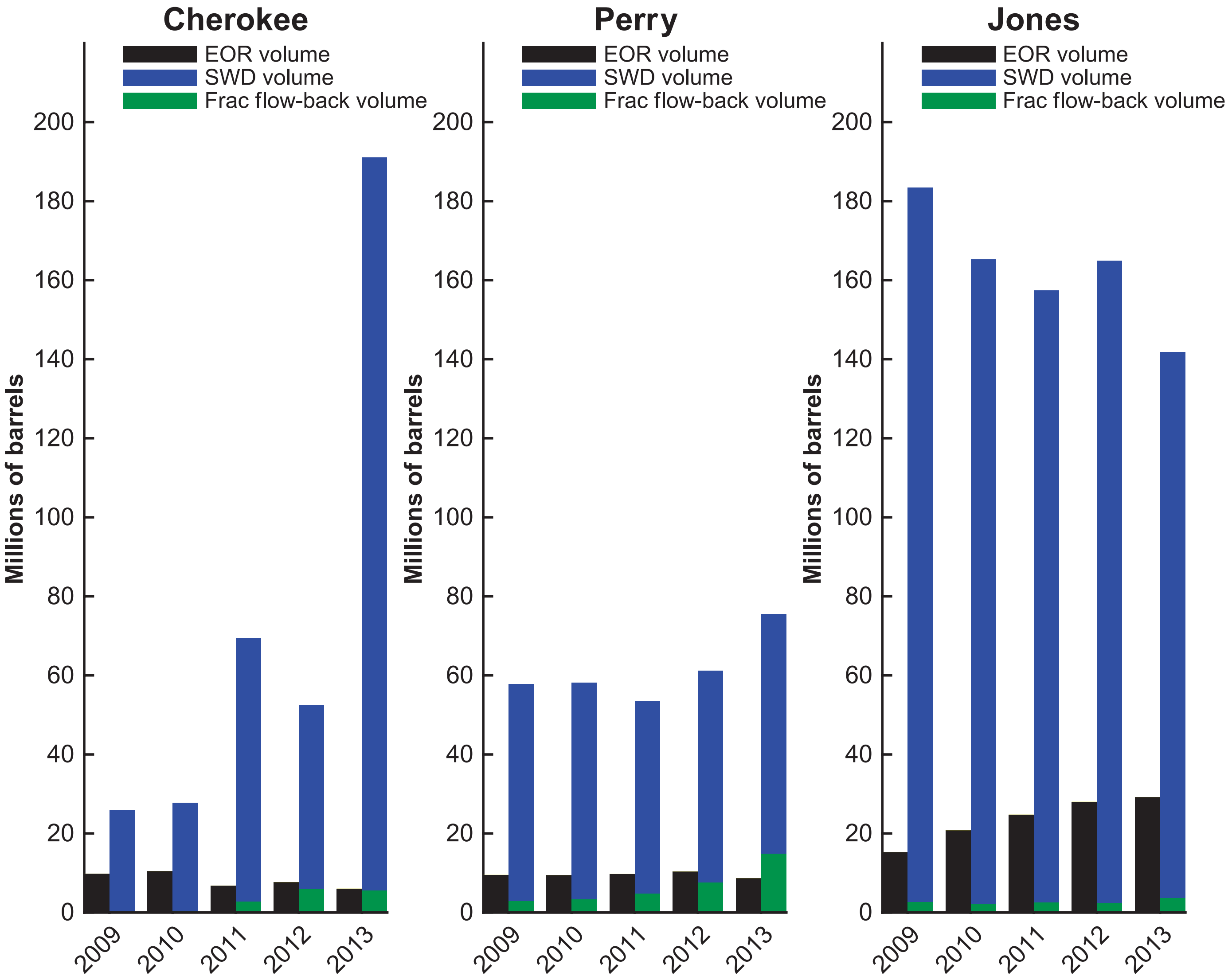

Fig. 6. SWD in the three seismically active areas shown in Fig. 3. Volumes injected into EOR wells and SWD wells in the Cherokee, Perry, and Jones study areas are shown between 2009 and 2013. Also shown is an upper bound estimate of the volume of hydraulic fracturing flow-back water that was disposed of in each area in any given year. It is clear that most of the saltwater disposed of in SWD is produced water and not flow-back water from hydraulic fracturing.

hazardous faults must extend into the basement simply based on the size of a fault required to cause a large earthquake. Aftershock studies of both of these earthquake sequences demonstrate that appreciable faulting in basement was involved (*6*, *25*), and as noted above, the recent seismicity in Oklahoma is clearly occurring on basement faults [(*22*); fig. S1].

It should be noted that oil, gas, or water production can also potentially trigger earthquakes (*9*, *36*). However, in the three areas of recent seismicity, the earthquakes occur at least 3 to 4 km from the producing zones where the stress perturbations due to production would be quite small (*36*). Moreover, strike-slip earthquakes, the predominant style of faulting in the areas of recent seismicity (*17*), are not likely to be triggered by production-related stress changes (*36*).

To identify the sources of the increased saltwater disposal in Oklahoma, Fig. 6 shows the annual injection volume of the three seismically active study areas (Cherokee, Perry, and Jones) over the past 5 years. As noted above, there are two principal sources of saltwater being injected into the SWD wells—produced water and hydraulic fracturing flow-back water. Hence, we separately indicate in Fig. 6 the annual injection into EOR wells in each area (black), the annual injection into all SWD wells (blue), and an upper bound estimate of the amount of injection into saltwater disposal wells that could be flow-back from hydraulic fracturing operations (green). The volume of water injected during hydraulic fracturing operations is known in each area (*37*). Because flow-back water typically comprises 10 to 30% of fracturing fluid pumped in unconventional horizontal wells, we used 30% to estimate the maximum volume of hydraulic fracturing flow-back water that would need to be disposed of in SWD wells. As the figure clearly shows, hydraulic fracturing flow-back water comprises an extremely small fraction of the injection into the SWD wells. In only one area and year (Perry in 2013) could the maximum amount of SWD from hydraulic fracturing flowback water have approached 20%, and in most years and areas it was under 5% of the total SWD volume. In other words, nearly all the water being injected into SWD wells in these areas is produced water.

MANAGING INJECTION-RELATED SEISMIC RISKS

Injection of large volumes of saltwater into the Arbuckle group appears to be triggering the release of already stored strain energy in crystalline basement. It would seem logical that reducing the volume of injected saltwater into the Arbuckle should reduce the amount of triggered seismicity. In addition, as shown by the areas with many EOR wells recycling produced water in producing horizons, reinjection of the saltwater into the horizons that produced the water and oil would not be expected to trigger seismicity. Thus, the feasibility of injecting the large volumes of produced water back into depleted portions of the producing reservoirs needs to be investigated.

In a recent study of the Jones earthquakes (*30*), it was argued that four large-scale injectors (two of which were injecting more than 1 million barrels/month) located just southeast of Oklahoma City are the principal cause of the Jones seismicity, much of which is located over 10 km from the injectors. In the three study areas where SWD injection and seismicity have increased, the few SWD wells injecting unusually large volumes (for example, more than 400,000 barrels/month) contribute a relatively small fraction of the total SWD volume in those areas (21% in Cherokee, 19% in Perry, and 45% in Jones; see fig. S2). Thus, whereas reducing the cumulative volume of SWD should be beneficial, establishing an arbitrary upper limit to injection rates of any single well may not reduce the probability of triggering seismicity if the same volume was to be injected in a number of lower-rate wells nearby.

Without detailed modeling, it is difficult to predict how restricting or more broadly distributing the injection volumes in the study areas would affect seismicity. It is likely that even if injection from many wells were to stop immediately, seismicity would continue as pressure continues to spread out from past injection. Over time, of course, one would expect seismicity to diminish if the aggregate rate of injection in the seismically active areas were to significantly decrease. As the seismicity rate in Oklahoma a decade ago was similar to the historical rate, there may be some rate of injection that can be accommodated by the regional hydrologic system without generating the pressure increases responsible for seismicity.

To date, there have been two published modeling studies relevant to Oklahoma seismicity (*24*, *30*). In both, it was argued that small pressure perturbations could propagate laterally within the disposal zone for 10 km or more, before triggering slip on critically stressed faults in the basement. However, with little constraint of subsurface hydrologic properties such as porosity, permeability, and pore pressure (and its variations with time), it is difficult to use models to make reliable predictions. A concerted effort of systematic data collection is needed to better constrain hydrologic models to devise strategies for modifying injection practices to reduce the probability of triggered seismicity.

It would be helpful to evaluate if there is stratigraphic control on the tendency for SWD into particular wells or zones to trigger seismicity. The importance of a bottom-sealing layer to prevent pressurization of basement faults has been pointed out in a generic modeling study (*24*). Injection into aquifers that are physically separated from crystalline basement by relatively impermeable formations would be beneficial as would avoiding pressurization near potentially active faults (*2*). Combining subsurface fault data with information about the stress field permits identification of which faults are critically stressed and to be avoided.

It has been suggested that the largest earthquake in an area correlates with the total injected volume in the area (*27*). However, in the context of triggered seismicity, the largest earthquake that might be triggered is determined by preexisting geologic conditions, not the magnitude of the perturbation of pore pressure. It is also clear that greatly improved earthquake monitoring and real-time analysis would be helpful to assess changes in seismic hazard with time. Determination of accurate earthquake locations (especially earthquake depth) requires relatively dense seismic networks. Real-time analysis of earthquake locations and the style of faulting can be used to identify potentially hazardous situations, such as earthquakes aligning along basement faults that could be large enough to cause a potentially damaging earthquake.

MATERIALS AND METHODS

Class II UIC injection data were provided by the Oklahoma Corporation Commission. Because well type (EOR or SWD) was not provided for pre-2011 data, well types were identified on the basis of the 2011–2013 API well identification number or the exact well location. Wells that were not operational in 2011–2013 were plotted as wells of unknown type. The U.S. Geological Survey NEIC earthquake database provided the earthquake locations and magnitudes presented in this study.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/1/5/e1500195/DC1

Fig. S1. Relocations of certain events in parts of the Jones box (*22*).

Fig. S2. Cumulative injection in the seismically active study areas as a function of the average injection rate of individual wells.

REFERENCES AND NOTES

1. W. F. Ellsworth, Injection-induced earthquakes. *Science* **341**, 1225942 (2013).
2. M. D. Zoback, Managing the seismic risk posed by wastewater disposal. *Earth Mag.* **57**, 38–43 (2012).
3. C. Frohlich, C. Hayward, B. Stump, E. Potter, The Dallas–Fort Worth earthquake sequence: October 2008 through May 2009. *Bull. Seismol. Soc. Am.* **101**, 327–340 (2011).
4. W.-Y. Kim, Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio. *J. Geophys. Res.* **118**, 3506–3518 (2013).
5. C. Frohlich, W. Ellsworth, W. A. Brown, M. Brunt, J. Luetgert, T. MacDonald, S. Walter, The 17 May 2012 *M*4.8 earthquake near Timpson, East Texas: An event possibly triggered by fluid injection. *J. Geophys. Res.* **119**, 581–593 (2014).
6. S. Horton, Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in central Arkansas with potential for damaging earthquake. *Seismol. Res. Lett.* **83**, 250–260 (2012).
7. A McGarr, B. Bekins, N. Burkardt, J. Dewey, P. Earle, W. Ellsworth, S. Ge, S. Hickman, A. Holland, E. Majer, J. Rubinstein, A. Sheehan, Coping with earthquakes induced by fluid injection. *Science* **347**, 830–831 (2015).
8. G. E. King, Hydraulic Fracturing 101: What every representative, environmentalist, regulator, reporter, investor, university researcher, neighbor and engineer should know about estimating frac risk and improving frac performance in unconventional gas and oil wells. *Soc. Petrol. Eng.* 152596 (2012).
9. NRC (National Research Council), *Induced Seismicity Potential in Energy Technologies* (The National Academies Press, Washington, DC, 2012).

10. J. H. Healy, W. W. Rubey, D. T. Griggs, C. B. Raleigh, The Denver earthquakes. *Science* **161**, 1301–1310 (1968).
11. C. B. Raleigh, J. H. Healy, J. D. Bredehoeft, An experiment in earthquake control at Rangely, Colorado. *Science* **191**, 1230–1237 (1976).
12. J. Suckale, Induced seismicity in hydrocarbon fields. *Adv. Geophys.* **51**, 55–106 (2009).
13. A. McGarr, D. Simpson, L. Seeber, Case histories of induced and triggered seismicity. *Int. Handb. Earthq. Eng. Seismol.* **81A**, 647–661 (2002).
14. M. D. Zoback, S. M. Gorelick, Earthquake triggering and large-scale geologic storage of carbon dioxide. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 10164–10168 (2012).
15. J. L. Rubinstein, W. L. Ellsworth, A. McGarr, H. M. Benz, The 2001–present induced earthquake sequence in the Raton Basin of northern New Mexico and southern Colorado. *Bull. Seismol. Soc. Am.* **104**, No. 5 (2014).
16. U.S. Geological Survey, National Earthquake Information Center earthquake catalog; http://earthquake.usgs.gov/earthquakes/search/.
17. A. Holland, G. R. Keller, A. Darold, K. Murray, S. Holloway, Multidisciplinary approach to identify and mitigate the hazard from induced seismicity in Oklahoma, in *American Geophysical Union Fall Meeting, San Francisco, CA, 2014*; http://wichita.ogs.ou.edu/documents/Holland_etal_2014_AGUpres.pdf
18. Technical report: Central and eastern United States seismic source characterization for nuclear facilities (Electric Power Research Institute, Palo Alto, CA; U.S. Department of Energy and U.S. Nuclear Regulatory Commission, Washington, DC, 2012), chap. 3, appendix B.
19. Oklahoma Corporation Commission (2014).
20. K. Murray, A. Holland, Inventory of class II underground injection control volumes in the midcontinent. *Shale Shaker* **65**, 97–106 (2014).
21. K. Murray, State-scale perspective on water use and production associated with oil and gas operations, Oklahoma, U.S. *Environ. Sci. Technol.* **47**, 4918–4925 (2013).
22. D. E. McNamara, H. M. Benz, R. B. Herrmann, E. A. Bergman, P. Earle, A. Holland, R. Baldwin, A. Gassner, Earthquake hypocenters and focal mechanisms in central Oklahoma reveal a complex system of reactivated subsurface strike-slip faulting. *Geophys. Res. Lett.* (2015).
23. D. W. Simpson, Seismicity changes associated with reservoir loading. *Eng. Geol.* **10**, 123–150 (1976).
24. Y. Zhang, M. Person, J. Rupp, K. Ellett, M. A. Celia, C. W. Gable, B. Bowen, J. Evans, K. Bandilla, P. Mozley, T. Dewers, T. Elliot, Hydrogeologic controls on induced seismicity in crystalline basement rocks due to fluid injection into basal reservoirs. *Ground Water* **51**, 525–538 (2013).
25. K. M. Keranen, H. M. Savage, G. A. Abers, E. S. Cochran, Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 M_w 5.7 earthquake sequence. *Geology* **41**, 699–702 (2013).
26. X. Sun, S. Hartzell, Finite-fault slip model of the 2011 Mw 5.6 Prague, Oklahoma earthquake from regional waveforms. *Geophys. Res. Lett.* **41**, 4207–4213 (2014).
27. A. McGarr, Maximum magnitude earthquakes induced by fluid injection. *J. Geophys. Res.* **119**, 1008–1019 (2014).
28. S. E. Hough, Shaking from Injection-induced earthquakes in the central and eastern United States. *Bull. Seismol. Soc. Am.* **104**, 2619–2626 (2014).
29. K. V. Luza, R. F. Madole, A. J. Crone, Investigation of the Meers Fault, Southwestern Oklahoma. *Oklahoma Geological Survey Special Publication 87-1* (1987); www.ogs.ou.edu/pubsscanned/SPs/SP87_1.pdf.
30. K. M. Keranen, M. Weingarten, G. A. Abers, B. A. Bekins, S. Ge, Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection. *Science* **345**, 448–451 (2014).
31. K. E. Murray, Class II underground injection control well data for 2010–2013 by geologic zones of completion, Oklahoma. *Oklahoma Geological Survey Open File Report OF1* (2014), p. 32.
32. E. K. Franseen, A. P. Byrnes, J. R. Cansler, D. M. Steinhauff, T. R. Carr, The geology of Kansas Arbuckle Group, in *Current Research in Earth Sciences* (Bulletin 250, part 2, 2004), p. 43; www.kgs.ku.edu/Current/2004/franseen/franseen1.html.
33. M. D. Petersen, A. D. Frankel, S. C. Harmsen, C. S. Mueller, K. M. Haller, R. L. Wheeler, R. L. Wesson, Y. Zeng, O. S. Boyd, D. M. Perkins, N. Luco, E. H. Field, C. J. Wills, K. S. Rukstales, Documentation for the 2008 update of the United States national seismic hazard maps. *U.S. Geological Survey Open File Report 2008–1128* (2008), p. 61.
34. M. D. Zoback, J. Townend, B. Grollimund, Steady state failure equilibrium and deformation of intraplate lithosphere. *Int. Geol. Rev.* **44**, 383–401 (2002).
35. J. Townend, M. D. Zoback, How faulting keeps the crust strong. *Geology* **28**, 399–402 (2008).
36. P. Segall, Earthquakes triggered by fluid extraction. *Geology* **17**, 942–946 (1989).
37. Estimates of fracturing fluid load recovery are based on proprietary data licensed from IHS Energy. Copyright 2015, all rights reserved.

Acknowledgments: We thank G. R. Keller, A. Holland, and K. Murray of the Oklahoma Geological Survey for continuous helpful conversations, and many of our colleagues who made helpful suggestions. We thank R. LaFollette of Baker Hughes for providing the estimates of hydraulic fracturing flow-back water in Fig. 6. We also thank D. McNamara and H. Benz for helpful conversations and use of their earthquake relocations in fig. S1. This study would not have been possible without the UIC injection data provided by the Oklahoma Corporation Commission and the U.S. Geological Survey National Earthquake Information Center earthquake catalog. **Funding:** The Stanford Center for Induced and Triggered Seismicity provided the financial support for this study. **Competing interests:** The authors declare that they have no competing interests.

Submitted 11 February 2015
Accepted 25 April 2015
Published 18 June 2015
10.1126/sciadv.1500195

Citation: F. R. Walsh, M. D. Zoback, Oklahoma's recent earthquakes and saltwater disposal. *Sci. Adv.* **1**, e1500195 (2015).