# Subsurface Fluid Injection in Oil and Gas Reservoirs and Wastewater Disposal Zones of the Midcontinent*

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## Abstract

Water and other fluids have been injected into the subsurface for decades in enhanced oil recovery (EOR) operations and for saltwater disposal (SWD). In recent years, hydraulic fracturing and horizontal wells have allowed development of unconventional oil and gas reservoirs or redevelopment of conventional resources. Intense leasing, drilling, and production from the Mississippian zone of southern Kansas and northern Oklahoma are prime examples of this. Because it is economic to produce at low oil-cuts, such as in the Mississippian, there is a disproportionate increase in the co-production of water. After separating water from oil and gas at the wellhead, producers are left with co-produced water having ~150,000 ppm median concentrations of total dissolved solids (TDS), which is typically disposed of via SWD wells.

Research has cited an increasing number of seismic events in the Midcontinent, some of which are potentially induced by fluid injection. Unfortunately, limited data are published for volumes and pressures of fluids injected or distribution of those fluids into subsurface zones. The objectives of this research were to compile Class II underground injection control (UIC) data for the year 2011 and inventory injection data by geologic zone in Kansas and Oklahoma. EOR volumes totaled 265.5 million barrels (Mbbl) in Kansas and 1093 Mbbl in Oklahoma with the Desmoinesian and Atokan-Morrowan zones receiving the highest EOR volumes. SWD volumes totaled 754.0 Mbbl in Kansas and 891.9 Mbbl in Oklahoma with the Arbuckle and Devonian to Middle Ordovician zones receiving the highest SWD volumes. The Arbuckle Group is underpressured throughout most of the Midcontinent and has an unwavering capacity to accept fluids without any observed increases in pressure. Future studies of relationships between fluid injection and seismicity must carefully compare extraction/injection histories, characterize

hydrogeologic parameters, identify critically stressed faults, and explain mechanisms by which pore pressure diffuses or increases stress along a fault plane.

## Introduction

### Fluid Production in the U.S. Midcontinent (Kansas and Oklahoma)

Petroleum production began in the U.S. Midcontinent before 1900. Oil and gas have both been consistently produced in the states of Kansas (KS) and Oklahoma (OK) since 1906. Oil production in KS during 1906 was approximately 3.63 million barrels of oil (MBO) and peaked at ~124 MBO in 1956 (Adkins-Heljeson, 2013), as shown in Figure 1. Oil production in OK during 1906 was approximately 18.1 MBO and peaked at ~278 MBO in 1927 (OCC, 2012), as shown in Figure 2. Gas production in KS during 1906 was approximately 12.2 million barrels of oil equivalent (MBOE) and peaked at ~160 MBOE in 1970 (Adkins-Heljeson, 2013; EIA, 2013b). Gas production in OK during 1906 was approximately 0.62 MBOE and peaked at ~399 MBOE in 1990 (EIA, 2013b; OCC, 2012).

Since the year 2000 there has been an increase in the proportion of horizontal wells and hydraulic fracturing (HF) to stimulate producing formations in OK (Murray, 2013). Horizontal wells and HF have increased production from unconventional shale plays and contributed to a resurgence of production from conventional sandstone and carbonate reservoirs in the Midcontinent. Crude oil production was approximately 41.5 MBO in KS and ~76.7 MBO in OK during 2011, ranking as the 9$^{th}$ and 5$^{th}$ highest producing U.S. states, respectively (EIA, 2013a). Gross natural gas production was approximately 43.7 MBOE in KS and ~89.3 MBOE in OK during 2011, ranking as the 13$^{th}$ and 5$^{th}$ highest producing U.S. states, respectively (EIA, 2013b).

Dewatering projects, such as in the Hunton Group (Devonian to Silurian), are prevalent throughout the Midcontinent. While other plays, such as the Mississippian “Line” of southern KS and northern OK, produce large volumes of water per unit of oil or gas. By multiplying water:oil ratio (3.7) by oil production and water:gas ratio (2.1) by oil equivalent gas production, Murray (2013) estimated Oklahoma’s statewide produced water volumes to range from 811 to 925 Mbbl between 2000 and 2011. Historic (i.e., prior to 2000) produced water volumes are difficult to estimate, but they may have been similar to present-day volumes, assuming that lower water:oil and water:gas ratios from conventional production were offset by higher petroleum production rates that peaked between ~1960 and ~1980 (Figure 1) and between ~1965 and ~1995 (Figure 2) in KS and OK, respectively.

## Underground Injection Control (UIC) Well Designations

The underground injection control (UIC) program was implemented by the U.S. Environmental Protection Agency (EPA) in the 1980s to manage and regulate fluid injections into the subsurface. Six UIC well designations (Class I, II, III, IV, V, and VI) are used to manage injections from various industries. The EPA maintains regulatory authority over subsurface fluid injection but may delegate authority of Class II wells to state agencies. Current regulatory controls over Class II UIC wells were designed to protect potable water sources from contamination. Class II UIC wells fulfill two basic purposes in the oil and gas sector: enhanced oil recovery (EOR) and salt water disposal (SWD). EOR wells are designed to inject fluids (water and/or $CO_2$) into the subsurface to mobilize oil and/or gas into production wells. During EOR, pressure across the field is monitored so as not to exceed virgin pressure conditions. SWD wells are designed to dispose of brine water that is co-produced with oil and gas. SWD wells ideally function on a vacuum or require low wellhead injection pressures.

## Potential for Induced Seismicity from Fluid Injection

Fluid injections, including EOR (Davis and Pennington, 1989), and SWD (Horton, 2012; Keranen et al., 2013; Nicholson and Wesson, 1990) have been shown to contribute to seismicity mainly by reducing normal stress so that movement occurs along a pre-existing fault (Healy et al., 1968; NRC, 2012; Raleigh et al., 1976). Some of the largest magnitude earthquakes associated with SWD injections were centered in the states of Arkansas, Oklahoma, and Texas (Frohlich, 2012; Horton, 2012; Keranen et al., 2013). Regardless of potential connections, research on the topic of induced seismicity recognizes the uncertainty and the difficulty in distinguishing between natural or induced seismic events. One major limitation of this line of research relates to the unknown quality of UIC data including x-y location, z elevation, zone of completion, volume, and pressure. Integrated hydrogeologic, structural geologic, and seismologic studies are required because mechanisms for fluid induced seismicity are related to stresses and strength of faults, hydraulic properties of injection zones, and pressure diffusion (Ellsworth, 2013; Holland, 2013).

## Objectives

Absent from the fluid-injection-induced seismicity literature are broad-scale perspectives on fluid-injection volumes and pressures, and accurate reporting of geologic intervals that receive those fluids. The objectives of this research were to compile and summarize volumes of water used for EOR and SWD in the Midcontinent and summarize volumes by geologic injection zone.

## Methodology

Because data related to UIC programs in KS and OK were reported to multiple organizations and uniquely formatted, multiple databases were designed and maintained during the course of this research. American Petroleum Institute (API) identifiers for wells (i.e., API number) were used to manage data associated with unique well locations.

### Compile UIC Well Locations and Injection Volumes

Fluid injection volumes into Class II UIC wells in 2011 were obtained from the Kansas Corporation Commission (KCC) and the Oklahoma Corporation Commission (OCC) (Lord, 2012; Snider, 2013) and used to create a relational database for each state (i.e., KS UIC and OK UIC). Records were managed using API number when appending data to the respective KS UIC and OK UIC databases. Well completion data were obtained from the Kansas Geological Survey (KGS) aandr OCC well databases and interactive web-sites (KGS, 2013; OCC, 2013). Fluid injections into Osage County, OK Class II UIC wells, regulated by EPA, have different reporting procedures; therefore, were not included in this study.

### Attribute Injection Zones for Wells

Injection zones were represented using twelve categories: Permian, Virgilian, Missourian, Desmoinesian, Atokan-Morrowan, Mississippian, Woodford, Devonian to Middle Ordovician (Dev to Mid Ord), Arbuckle, Basement, Multiple-Undifferentiated, and Other or Unspecified. 'Producing' or 'injection' formation(s) were correlated to the appropriate injection zone (Figure 3) based on the Stratigraphic Guide to Oklahoma Oil and Gas Reservoirs (Boyd, 2008). When producing or injection formation was not specified in the KS UIC, or OK UIC databases, then completion reports (e.g., OK's Form 1002A) or other digitally accessible records were examined for each API number in KS (http://www.kgs.ku.edu/Magellan/Qualified/index.html) or in OK (http://www.occpermit.com/WellBrowse/Home.aspx). The injection formation(s) for the most recent completion of each API number was determined, when possible, and added as an attribute. When records indicate that the injection interval consist of multiple groups or formations (e.g., Bartlesville and Dutcher) from more than one zone, then the well was attributed as 'Multiple-Undifferentiated.' When records indicate that a formation (e.g., Cretaceous Niobrara) other than the ten designated zones (Figure 3) was used for injection or the target formation was not discernible, then the well was attributed as 'Other or Unspecified.'

### Summarize Volumes by Injection Zones

Injections in the KS UIC and OK UIC databases were selected and summed using queries that were grouped by injection zone and injection type (e.g., EOR or SWD). From these queries, total injection volumes were estimated for each zone in KS and OK during 2011.

## Results and Discussion

The KS UIC database contained 9559 UIC wells of which 6118 wells had reported EOR volumes and 3441 wells had SWD volumes in 2011. The OK UIC database contained 9630 UIC wells of which 5506 had reported EOR and 4124 wells had SWD volumes in 2011.

### Class II UIC Statewide Volumes by Geologic Injection Zone

Total volume of EOR fluid injection in KS was ~265.5 Mbbl in 2011. A substantial number of KS UIC wells were not attributed with a known injection zone, so the largest EOR volumes are illustrated in Figure 4 as going to ‘Other or Unspecified’ zones. Injection zones in KS receiving the largest proportions of EOR fluid were the Atokan-Morrowan and Missourian. Total volume of EOR fluid injection in OK was 1093 Mbbl in 2011. The Desmoinesian (278.3 Mbbl) and Atokan-Morrowan (259.2 Mbbl) zones received the largest proportions of EOR fluid in OK (illustrated in Figure 5). EOR injection volumes into the Arbuckle and underlying Precambrian Basement zones were minimal, which suggests that EOR injection has a low probability of inducing seismic activity.

Total volume of SWD in KS was ~754.0 Mbbl in 2011. Because the completion zones were unknown for a high percentage of KS UIC wells, the largest SWD volumes are illustrated in Figure 4 as going to ‘Multiple-Undifferentiated’ and ‘Other or Unspecified’ zones. Receiving the largest proportions of SWD fluid in KS were the Arbuckle and Mississippian zones. Total volume of SWD in OK was ~891.9 Mbbl in 2011, as illustrated in Figure 5. The Arbuckle (440.1 Mbbl) and Permian (68.5 Mbbl) zones received the largest proportions of SWD fluid in OK, with substantial proportions also being injected into Multiple-Undifferentiated (125.5 Mbbl) zones. Because the Arbuckle, in some cases, directly overlies the Precambrian basement, SWD wells have higher probability than EOR wells for inducing seismicity. Those wells that are completed in the Basement or attributed as ‘Multiple-Undifferentiated’ with completion intervals in the Basement should be further examined to determine the risk of induced seismicity.

## Highest Volume Class II UIC Wells

Active EOR wells in KS (6118) and OK (5506) were numerous during 2011; however, only a small fraction (0.27%) of the EOR wells, shown in Figure 6, injected substantial volumes (>150,000 bbl/month). This injection rate was notable in the Barnett Shale region of Johnson County, Texas where 33.3% of the UIC wells exceeded 150,000 bbl/month, and seismicity was potentially induced (Frohlich, 2012).

Active SWD wells in KS (3441) and OK (4124) were numerous during 2011. A small fraction (2.64%) of the SWD wells in KS and OK exceeded 150,000 bbl/month (Figure 7).

## Research Priorities for Understanding Fluid-Injection Induced Seismicity

Measurement of pre-injection hydrologic conditions and formation pressure, along with increased temporal resolution for injection rates and pressures, are critical to understanding the dynamic relationships between fluid injection and seismicity (Ellsworth, 2013). Thorough evaluation of the presence or absence of faulting near fluid injection wells (Frohlich, 2012) is also a priority for understanding potential for induced seismicity. Reasonable estimates of field-scale historic and future fluid injection and withdrawal volumes must be made for all production or injection zones, so that critical pore pressures can be understood. Integrated hydrogeologic, structural geologic, and seismologic datasets may then be evaluated to establish mechanisms by which fluid injection increases pore pressure along a fault plane. These integrated scientific studies would be useful for the development of adaptable regulatory requirements and best management practices for fluid injection.

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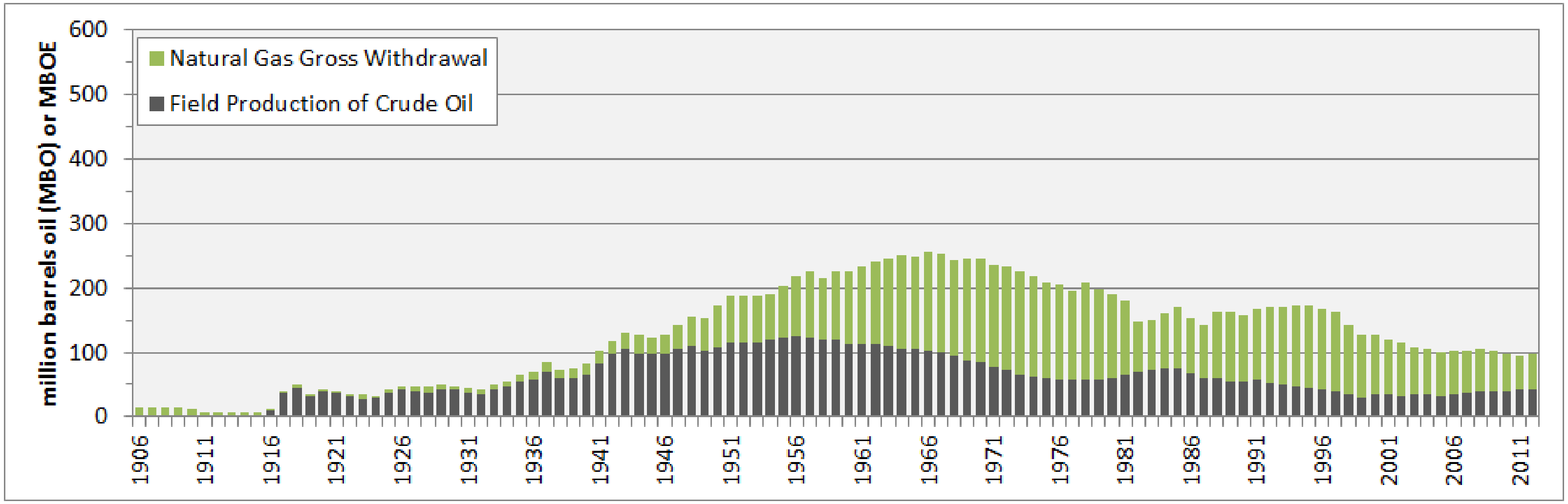


Figure 1. Annual field production of crude oil and annual natural gas gross withdrawal in Kansas from 1906 to 2012.

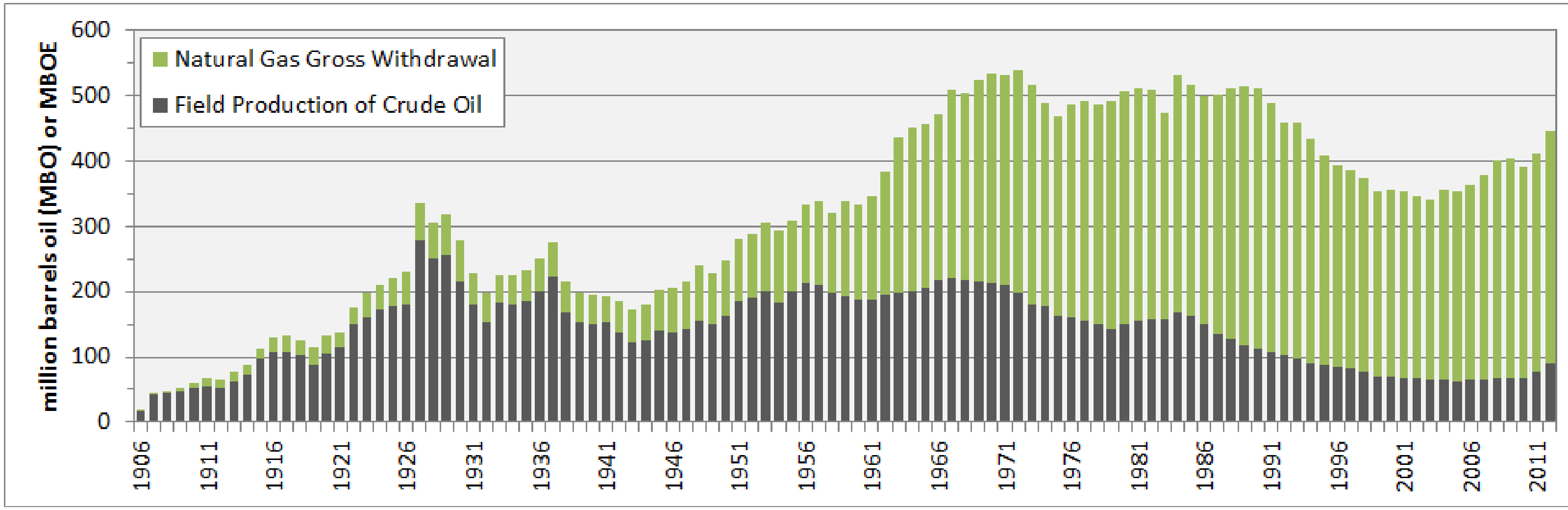


Figure 2. Annual field production of crude oil and annual natural gas gross withdrawal in Oklahoma from 1906 to 2012.

| Zone | Group | Formation |
|---|---|---|
| Permian | | Garber |
| | Chase | Brown Dolomite |
| | Council Grove | Pontotoc |
| | Admire | Belveal |
| Virgilian | Wabaunsee | Cisco Lime |
| | Shawnee | Pawhuska |
| | | Endicott |
| | Douglas | Tonkawa |
| Missourian | Hoxbar | Lansing |
| | | Cottage Grove |
| | | Kansas City |
| | | Hogshooter |
| | | Layton |
| | | Cleveland |
| Desmoinesian | Marmaton | Oswego |
| | Cabaniss | Skinner |
| | Krebs | Red Fork |
| | | Burbank |
| | | Bartlesville |
| | | Hartshorne |
| Atokan-Morrowan | Atoka | Gilcrease |
| | | Dutcher |
| | Morrow | Cromwell |
| | Springer | Wamsley |
| Mississippian | Chester | Manning |
| | | Caney |
| | Meramec | Miss Lime |
| | | Miss Chat |
| | | St. Louis |
| | | Mayes |
| | Osage | Sycamore |
| | Kinderhook | Kinderhook |
| Woodford | Upper Devonian | Woodford |
| Dev to Mid Ord | Middle Devonian | Misener |
| | Lower Dev - Silurian | Hunton |
| | Cincinnatian | Sylvan |
| | | Viola |
| | Simpson | Bromide |
| | | Wilcox |
| | | McLish |
| | | Oil Creek |
| Arbuckle | Arbuckle Group | Turkey Mountain |
| | | West Spring Creek |
| | | Kindblade |
| Basement & Crystalline Rock | Cambrian | Reagan |
| | Precambrian | Granite |

| Key to Symbols |
|---|
| Sandstone |
| Carbonate |
| Shale |
| Coal |
| Granite |

Figure 3. Correlation chart of Precambrian and Paleozoic groups and formations that in some part, or parts, of the study area include injection zones.

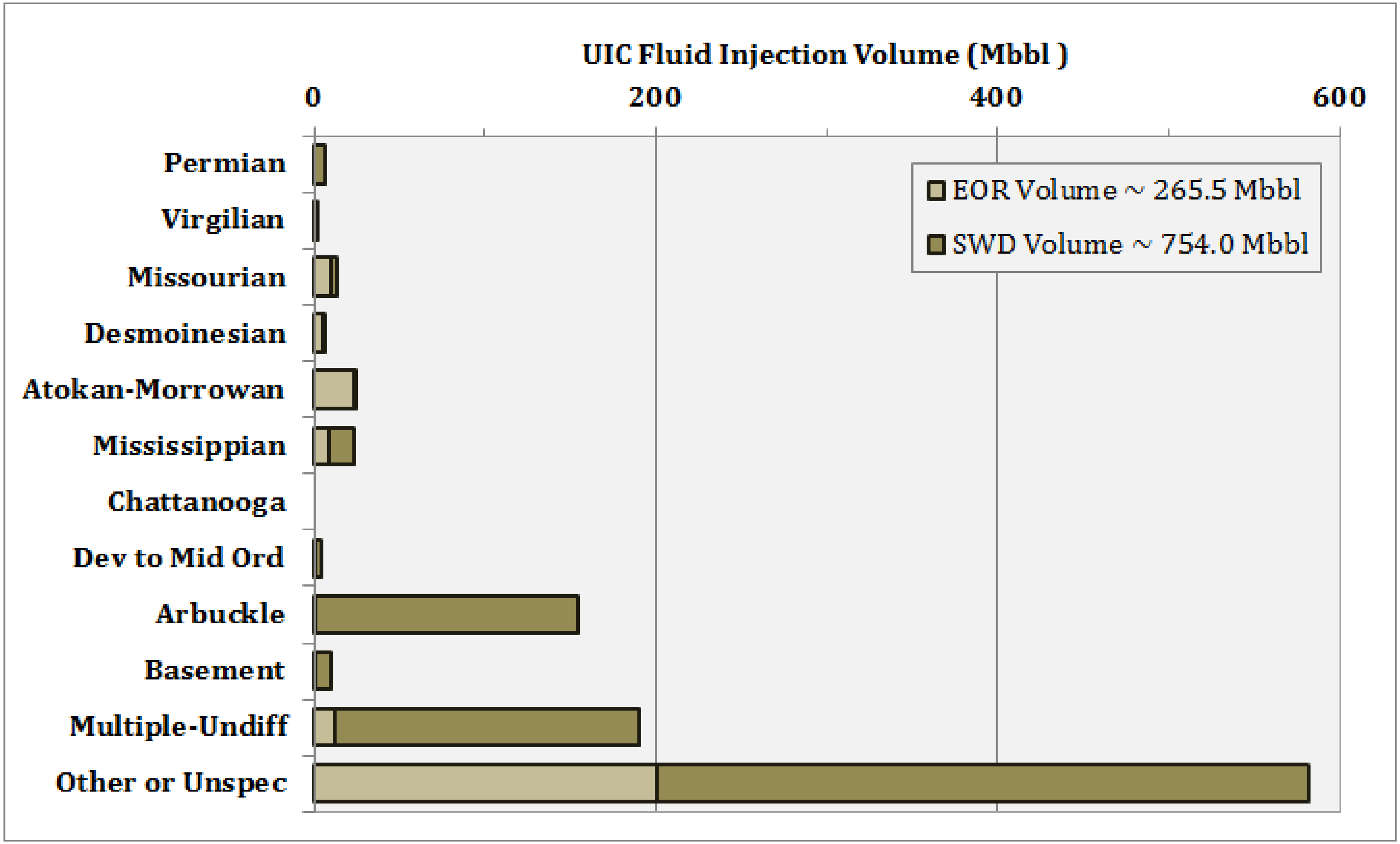


Figure 4. Fluid volumes injected, by zone, into UIC wells in KS during 2011.

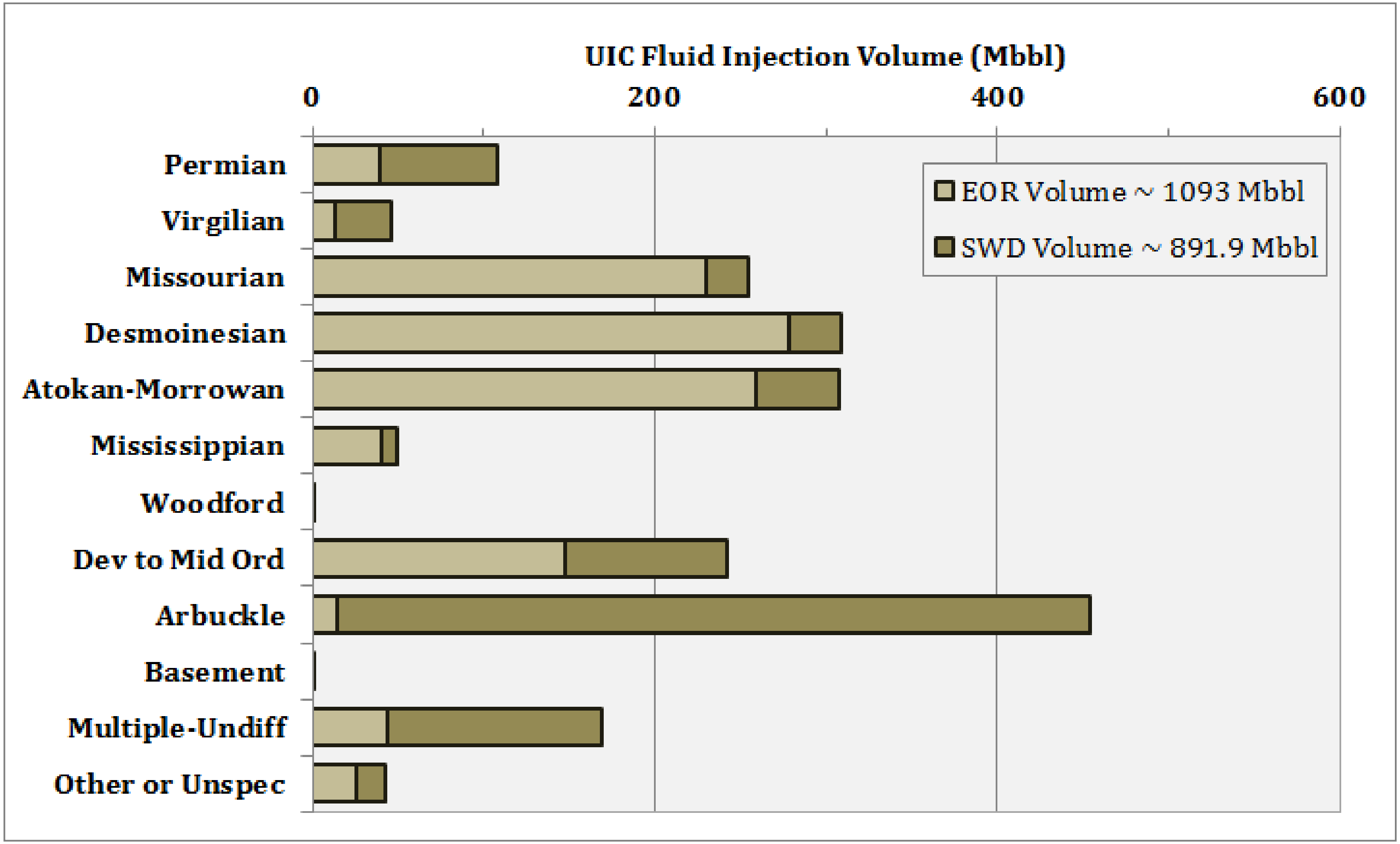


Figure 5. Fluid volumes injected, by zone, into UIC wells in OK during 2011.

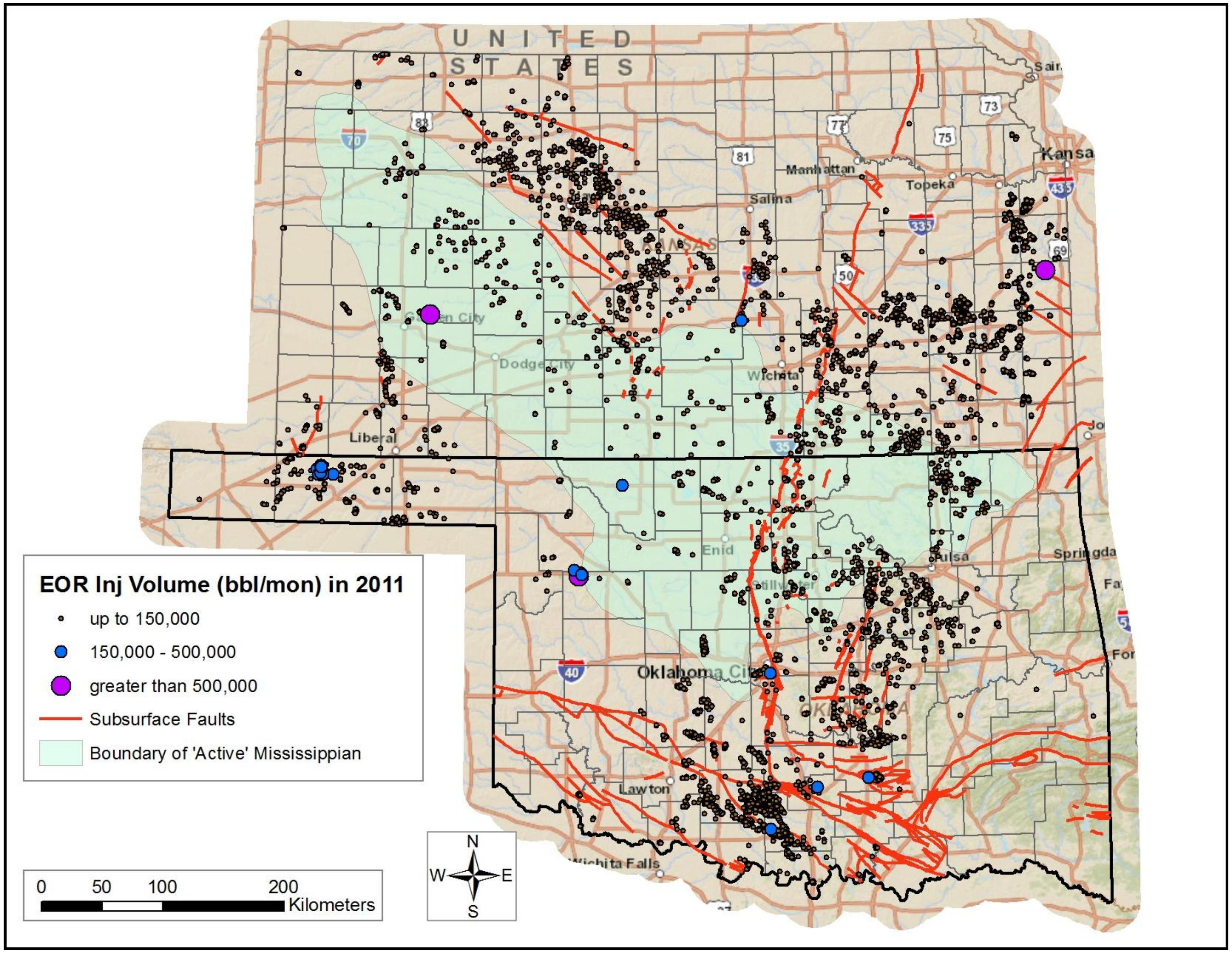


Figure 6. Locations of EOR wells in the Midcontinent (KS and OK). Symbol size is relatively proportional to injection rate.

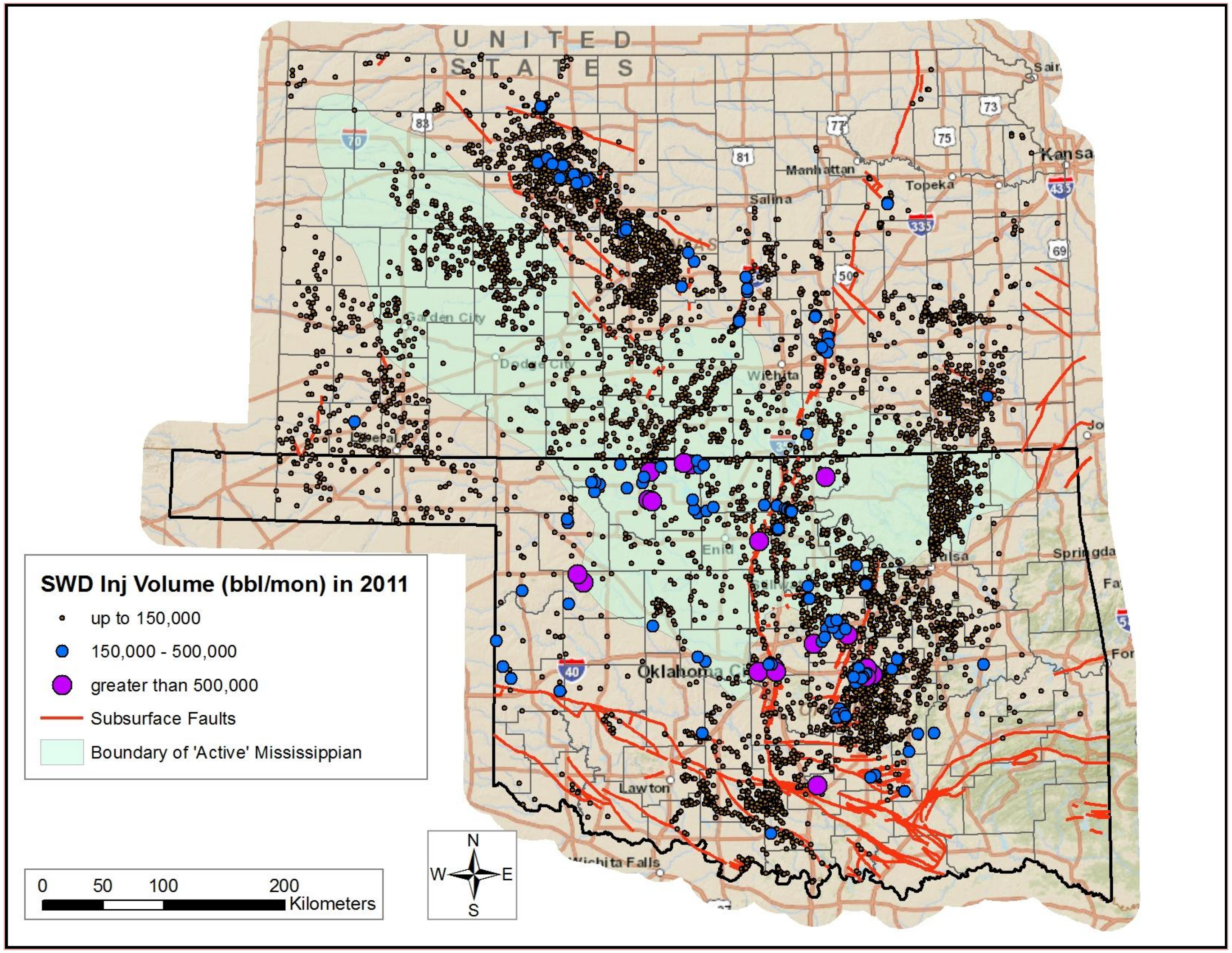


Figure 7. Locations of SWD wells in the Midcontinent (KS and OK). Symbol size is relatively proportional to injection rate.