Class II Underground Injection Control Well Data for 2010–2013 by Geologic Zones of Completion, Oklahoma

Open-File Report (OF1-2014)

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Abstract

Water and energy resources are fundamentally connected and have created what some refer to as the energy-water or water-energy nexus. A common goal of water and energy management is to maximize the supply of one while minimizing the use of the other. Water management in Oklahoma has become an important issue not only because of recurring droughts and increased water demand, but because large volumes of saltwater are being co-produced with oil and gas and must be properly managed. Oklahoma's statewide co-produced water volumes were estimated to range from 811–925 million barrels (MMbbl) from 2000–2011. In the last few years, an estimated 40–60% of Oklahoma's co-produced water originated from oil and gas wells in the Mississippian play where median fluid production ratios of H_2O:oil and H_2O:gas were 7.4 and 9.8, respectively. Other practices, such as dewatering in the Hunton play of central Oklahoma, have resulted in high volumes of co-produced water and subsequently high volumes for saltwater disposal (SWD). Seismic activity from 2009–2014 far exceeds historic seismicity and, in a few cases, has been correlated to subsurface fluid injection in the midcontinent. Therefore, there is an urgent need to quantify volumes and pressures of injections by geologic zone of completion, and use this information to develop best management practices for water that is co-produced with oil and gas.

This report is part of an ongoing effort to compile Oklahoma's Class II underground injection control (UIC) well data on county- and annual- scales by geologic zone of completion. Thousands of annual fluid injection reports and well completion reports, filed by operators with the Oklahoma Corporation Commission (OCC), were the primary sources of data for this report. Data were compiled into a relational database, checked against scanned and electronic OCC records, and then summarized at county-, state-, and annual- scales.

Because most previous studies indicate that SWD, especially into basal sedimentary strata, are in closer proximity to basement faults, the volumes and pressures of SWD wells were more carefully examined than enhanced oil recovery injection (EORI) wells. Statewide (excluding Osage County) SWD volumes were 878, 991, 1067, and 1193 MMbbl from 2010–2013, respectively, and are increasing at a rate that mimics statewide petroleum production. SWD volumes into the Arbuckle basal sedimentary strata increased most in Alfalfa, Grant, and Woods Counties of northern Oklahoma from 2010–2013, while SWD volumes in Kay, Lincoln, and Creek Counties decreased substantially in that same time period. Seismic activity increased most in Lincoln, Grant, and Seminole Counties from 2010 & 2011 to 2012 & 2013. A comparison of temporal trends in SWD volumes for wells completed in the Arbuckle or Basement zones versus county-scale seismicity exhibit a variety of direct and inverse correlations.

1. Introduction

Petroleum production began in Oklahoma before 1900 and has been continuously produced for more than 100 years, with oil peaking at ~278 million barrels of oil (MMBO) in 1927 and gas production peaking at ~399 million barrels of oil equivalent (MMBOE) in 1990 (Murray and Holland 2014). Modest volumes of oil were produced in Oklahoma for several decades, but a resurgence in production has occurred because of technological innovation and economic drivers. More than 26% of Oklahoma's petroleum wells completed in 2009 were horizontally drilled and hydraulically fractured, but the proportion appears to have increased annually with more than 43% being horizontal in 2011 (Murray 2013). Higher production has also occurred from unconventional shale plays and from conventional sandstone and carbonate reservoirs (Murray and Holland 2014). Crude-oil production averaged 76.7 MMBO in Oklahoma from 2010–2012, ranking as the 5th highest producing U.S. state (EIA 2014a). Gross natural-gas production averaged 89.3 MMBOE in Oklahoma from 2010–2012, ranking as the 5th highest producing U.S. state (EIA 2014b).

Concurrent with higher annual statewide petroleum production is a higher annual statewide co-production of water. By multiplying H_2O:oil ratio by oil production and H_2O:gas ratio by oil-equivalent gas production, Murray (2013) estimated Oklahoma's statewide co-produced water volumes to range from 811–925 million barrels (MMbbl) from 2000–2011. Dewatering from the Hunton Lime and other plays, such as the Mississippian of southern Kansas and northern Oklahoma, produce large volumes of water per unit of oil or gas. Petroleum production from the Mississippian has been highest in Woods, Alfalfa, Grant, Kay, and Osage counties in northern Oklahoma, so co-production of water may be potentially higher in this region.

1.1. 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. The Oklahoma Corporation Commission (OCC) is delegated authority over Class II UIC wells, except in Osage County (i.e., Osage Nation) where EPA maintains authority. Current regulatory controls over Class II UIC wells were designed to protect potable-water sources from contamination.

Class II UIC wells are used for two basic purposes in the oil and gas sector, enhanced oil-recovery injection (i.e., EORI or 2R) and salt-water disposal (i.e., SWD or 2D). UIC wells of the 2R type are designed to inject fluids (water and/or CO_2) into the subsurface to mobilize oil and/or gas into production wells. During 2R injection, pressure across the field is monitored so as not to exceed virgin pressure conditions. UIC wells of the 2D type are designed to dispose of brine water that was co-produced with oil and gas. These 2D wells ideally function on a vacuum or require low wellhead-injection pressures. The term 'injection' is used throughout this report because the wells are part of the UIC program; however, use of the term injection does not imply high-pressure such as would be used for hydraulic fracturing during well completion.

1.2. *Potential for Induced Seismicity from Fluid Injection*

Fluid injections, including 2R (Davis and Pennington 1989) and 2D (Horton 2012, Keranen et al. 2013, Nicholson and Wesson 1990) have been correlated to seismicity and are assumed to reduce 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 correlated with 2D injections were centered in the midcontinent states of Arkansas, Oklahoma, and Texas (Frohlich 2012, Horton 2012, Keranen et al. 2013). Regardless of potential correlations, research on the topic of induced seismicity recognizes the uncertainty and the difficulty in distinguishing between natural or induced seismic events. Major limitations of previous studies relate 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-injection induced seismicity are related to stresses and strength of faults, hydraulic properties of injection zones, and pressure diffusion (Ellsworth 2013, Holland 2013).

1.3. *Objectives*

Absent from the fluid-injection induced seismicity literature are broad-scale perspectives on fluid-injection volumes and pressures or accurate reporting of geologic intervals that receive those fluids. The objectives of this research were to compile and summarize water (e.g., brackish or saltwater) injection volumes and wellhead injection pressures for Class II UIC wells in Oklahoma by geologic completion zone, examine spatial and temporal trends for subsurface injection from 2010–2013, and map annual seismic activity from 2010–2013.

2. Methods

Because disparate data for Class II UIC program wells in Oklahoma were reported to OCC and EPA for the 2010–2013 timeframe, multiple databases were designed and maintained during the course of this research. American Petroleum Institute (API) unique identifiers for wells (i.e., API number) were used to manage data reported to OCC, while EPA assigned inventory number was used for UIC wells in Osage County, Oklahoma.

2.1. *Compile UIC Well Locations and Injection Data*

Monthly fluid-injection volumes and pressures for Class II UIC wells were obtained from the OCC (Lord 2014, Lord 2012, OCC 2014a, OCC 2014b) and used to create a relational database for wells in Oklahoma (i.e., Oklahoma UIC database), excluding Osage County, from 2010–2013. Records were managed using API number when appending data to the Oklahoma UIC database.

Fluid injection data for Class II UIC wells in Osage County were obtained from the EPA District 6 office and used to create a relational Osage UIC database. Maximum monthly injection volumes per well were provided by EPA, so annual injection volumes were ‘overestimated’ by multiplying maximum monthly injection volume by 12 (months per year). UIC well records in the Osage UIC database were managed using an inventory number assigned by the EPA.

2.2. *Quality Assurance Quality Control (QAQC) of UIC Data*

Annual injection volumes and injection pressures in the Oklahoma UIC database were compared to scanned ‘Form 1012A: Annual Fluid Injection Reports’ that were submitted to the OCC by UIC operators. Annual volume recorded in the Oklahoma

UIC database, before the quality assurance quality control (QAQC) check, included carbon dioxide (CO_2) in units of MCF or Liquefied Petroleum Gas (LPG) in units of barrels in addition to water volumes. Thus, annual volumes were modified in the Oklahoma UIC database to represent only water volumes. In other cases, the operators reported a barrels per day (BPD) injection rate instead of barrels per month (BPM) which, when annualized, was underrepresenting injection volume.

The Osage UIC database did not go through a QAQC check because more detailed records were only accessible in hard-copy at the Bureau of Indian Affairs (BIA) office in Pawhuska, Oklahoma and would require an even greater time commitment.

2.3. *Attribute Injection Zones for Wells*

Well-completion data for Oklahoma UIC database wells were obtained from the OCC well database and interactive web-site (OCC 2014c). Injection zones were represented using twelve categories after Murray and Holland (2014): 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 zone based on the Stratigraphic Guide to Oklahoma Oil and Gas Reservoirs (Boyd 2008). When producing or injection formation was not specified in the Oklahoma UIC databases, the completion reports (e.g., OCC’s Form 1002A) or other digitally accessible records were examined for each API number in Oklahoma. The injection formation(s) for the most recent completion of each API number was determined, when possible, and added as an attribute to the Oklahoma UIC database. When records indicated that the injection interval consisted 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 indicated that a formation (e.g., Cretaceous Niobrara) other than the ten designated zones was used for injection or the target formation was not discernible, then the well was attributed as ‘Other or Unspecified’. UIC well records in the Oklahoma UIC database were also attributed with maximum injection depth based on deepest perforated or open-hole interval.

2.4. *Summarize Volumes by Zone and County*

Class II UIC wells were selected (i.e., queried) from the Oklahoma UIC database. Annual injection volumes were summed for each year from 2010–2013, after grouping the selected wells by injection zone (e.g., Permian, Virgilian), injection type (i.e., 2R or 2D), and county. From these queries, total water-injection volumes were estimated for each zone by county from 2010–2013.

2.5. *Obtain Earthquake Data for 2010–2013*

Earthquake data including date, xy location, depth, and magnitude were downloaded from the Oklahoma Geological Survey (OGS) Geophysical Observatory earthquake catalog (http://www.okgeosurvey1.gov/pages/earthquakes/catalogs.php). Data were sorted and counted by year of origin, magnitude, or depth and plotted versus time in Microsoft Excel, or spatial location was plotted in ArcGIS. UIC well and earthquake locations were mapped in relation to Oklahoma regional fault systems that were previously published as part of a study of the geologic provinces of Oklahoma (Northcutt and Campbell 1995), and for the Cherokee Platform geologic province by the Kansas Geological Survey (Nodine-Zeller and Thompson 1977).

3. Results and Discussion

Limited access to Osage County UIC well completion forms and annual fluid injection reports did not allow for confirmation of zones of injection and resulted in extreme overestimation of annual injection volumes. Because Osage County UIC well data have a greater degree of uncertainty, they were not critically analyzed or represented in all data tables or figures in this report.

In the Oklahoma UIC database, a well is referred to as ‘active’ if, for any given year, at least 1 bbl of water was reportedly injected. A query of the QAQC checked Oklahoma UIC database indicates that 8390, 8265, 8738, and 8239 UIC wells were ‘active’ from 2010–2013, respectively. Form 1012As for the year 2011 were unavailable for at least 280 UIC wells or 3.3% and 3.2% of those that were active in 2010 and 2012, respectively. This data gap is believed to be due to Form 1012A submittals changing from hard-copy in 2010 to electronic in 2011. Additional uncertainties and data gaps undoubtedly exist in the Oklahoma UIC database, for example, estimated 2D+2R water injection volumes for 2010 in Oklahoma (excluding Osage County) were reported as 1921 MMbbl in a 2013 paper (Murray 2013) but the estimated 2D+2R water injection volume for 2010 in Oklahoma (excluding Osage County) is 1837 MMbbl in this report. Presumably additional QAQC will lead to more accurate future reports of injection volumes, pressures, and depths.

3.1. *Highest Volume Class II UIC Wells*

An injection rate exceeding 150,000 BPM (i.e., 1.8 MMbbl per year) was selected to represent a ‘high volume UIC well’ because it was notable in the Barnett Shale region of Johnson County, Texas where 33.3% of the UIC wells exceeded this injection rate and potential induced seismicity was reported (Frohlich 2012). Oklahoma, excluding Osage County, had 3297, 3221, 3507, and 3197 active 2D wells from 2010–2013, respectively, which are symbolized by relative annual injection volume in Figures 1–4. A small fraction, 174 out of 3197 (5.44%) of the 2D wells shown in Figure 4 were high volume UIC wells during 2013. Oklahoma, excluding Osage County, had 5093, 5044, 5231, and 5042 active 2R wells from 2010–2013, respectively, which are symbolized by relative annual injection volume in Figures 5–8. Only 11 out of the 5042 (0.22%) active 2R wells shown in Figure 8 were high volume UIC wells during 2013.

3.2. *SWD Wells and Volumes by Geologic Zone of Completion*

Oklahoma, excluding Osage County, had more than 3200 active SWD (i.e., 2D) wells from 2010–2013 (Table 1). The low number of active SWD wells during 2013 relative to 2012 is because an estimated 296 annual fluid injection reports were not yet available from OCC.

Table 1 Number of active SWD (i.e., 2D) wells in Oklahoma, by zone of completion

Zone	Active Wells in 2010	Active Wells in 2011	Active Wells in 2012	Active Wells in 2013
Permian	353	344	377	340
Virgilian	225	216	226	204
Missourian	286	268	280	259
Desmoinesian	618	567	602	537
Atokan-Morrowan	281	265	264	230
Mississippian	126	126	124	109
Woodford	4	4	3	3
Dev to Mid Ord	462	448	469	425
Arbuckle	477	537	667	667
Basement	7	8	11	10
Multiple-Undiff	175	169	197	163
Other Or Unspec	283	269	287	250
Total	**3297**	**3221**	**3507**	**3197**

Records of Class II UIC well volumes are believed to be unreliable and incomplete before the year 2009, so it is uncertain whether present Class II UIC volumes exceed historic Class II UIC volumes. For example, much larger volumes of oil and gas were produced in the 1980s and 1990s; therefore, comparable volumes of water may have been co-produced at that time.

Table 2 Volume of water injected into SWD (i.e., 2D) wells in Oklahoma, by zone of completion

Zone	MMbbl H_2O Injected in 2010	MMbbl H_2O Injected in 2011	MMbbl H_2O Injected in 2012	MMbbl H_2O Injected in 2013
Permian	51.1	68.2	82.3	77.7
Virgilian	30.5	32.0	40.0	34.0
Missourian	26.5	24.7	27.0	29.1
Desmoinesian	34.1	33.3	34.7	30.7
Atokan-Morrowan	46.8	46.7	52.3	46.4
Mississippian	9.3	9.5	9.4	7.9
Woodford	0.4	0.4	0.2	0.3
Dev to Mid Ord	101.8	99.7	105.7	102.9
Arbuckle	449.2	523.1	568.2	739.1
Basement	0.8	0.6	1.4	0.7
Multiple-Undiff	114.4	136.6	131.0	111.7
Other Or Unspec	13.5	15.8	14.6	12.8
Total	**878.3**	**990.8**	**1066.8**	**1193.3**

Annual statewide 2D water injection volumes were 878.3, 990.8, 1066.8, and 1193.3 MMbbl from 2010–2013, respectively (Table 2 and Figures 9–12). SWD (i.e., 2D) wells completed in the Arbuckle, predominantly carbonate, received the highest annual volumes of saltwater with 449.2, 523.1, 568.2, and 739.1 MMbbl from 2010–2013, respectively, (Table 2 and Figures 9–12) which corresponds to a 289.9 MMbbl or 64.5% increase from 2010 to 2013.

3.3. *EORI Wells and Volumes by Geologic Zones of Completion*

Oklahoma, excluding Osage County, had more than 5000 active EORI (i.e., 2R) wells from 2010–2013 (Table 3). The relatively low number of active wells for 2013 is because an estimated 165 EORI (i.e., 2R) well annual fluid injection reports were not yet available at OCC, assuming that those reported in 2012 are still active.

Table 3 Number of active EORI (i.e., 2R) wells in Oklahoma, by zone of completion

Zone	Active Wells in 2010	Active Wells in 2011	Active Wells in 2012	Active Wells in 2013
Permian	344	348	358	351
Virgilian	91	87	99	82
Missourian	1016	1004	1045	1021
Desmoinesian	1894	1854	1930	1883
Atokan-Morrowan	692	713	725	692
Mississippian	130	131	129	125
Woodford	4	3	3	4
Dev to Mid Ord	402	419	423	389
Arbuckle	20	23	22	21
Basement	0	0	1	1
Multiple-Undiff	211	195	213	214
Other Or Unspec	289	267	283	259
Total	**5093**	**5044**	**5231**	**5042**

Table 4 Volume of water injected into EORI (i.e., 2R) wells in Oklahoma, by zone of completion

Zone	MMbbl H_2O Injected in 2010	MMbbl H_2O Injected in 2011	MMbbl H_2O Injected in 2012	MMbbl H_2O Injected in 2013
Permian	33.8	40.9	43.9	43.8
Virgilian	12.9	11.2	11.9	9.6
Missourian	226.1	234.5	269.1	253.0
Desmoinesian	283.0	290.4	296.9	295.0
Atokan-Morrowan	155.4	168.6	181.5	172.9
Mississippian	37.5	38.4	36.4	34.9
Woodford	0.1	0.2	0.2	0.2
Dev to Mid Ord	116.0	153.2	204.7	163.4

Arbuckle	10.4	14.9	14.7	14.2
Basement	0.0	0.0	0.0	0.0
Multiple-Undiff	49.3	48.2	51.6	56.9
Other Or Unspec	34.3	32.5	37.4	36.1
Total	**958.8**	**1033.0**	**1148.5**	**1080.0**

Oklahoma annual statewide, excluding Osage County, volume of EORI (i.e., 2R) water injection was 958.8, 1033.0, 1148.5, and 1080.0 MMbbl from 2010–2013, respectively (Table 4 and Figures 9–12). EORI (i.e., 2R) wells completed in the Desmoinesian, comprised mostly of sandstones, received the highest annual volumes of water with 283.0, 290.4, 296.9, and 295.0 MMbbl from 2010–2013, respectively (Table 4 and Figures 9–12).

3.4. *Temporal Trends in SWD by County*

Petroleum production, co-production of water, and SWD vary substantially in space and time; therefore, it is best to view trends on a smaller spatial scale (i.e., county-scale).

Table 5 SWD (i.e., 2D) volumes by county

County	MMbbl of SWD in 2010	MMbbl of SWD in 2011	MMbbl of SWD in 2012	MMbbl of SWD in 2013
Alfalfa	18.7	61.8	36.8	225.5
Beaver	3.0	5.5	8.3	13.0
Beckham	7.0	11.0	10.8	8.9
Blaine	4.3	8.6	6.6	3.5
Caddo	5.2	6.0	6.9	6.4
Canadian	6.3	7.7	10.1	9.6
Carter	9.1	9.6	11.3	12.4
Cleveland	1.3	1.2	1.1	0.6
Coal	11.3	7.9	6.7	3.8
Creek	46.4	37.7	44.2	28.9
Custer	0.5	1.4	4.3	3.3
Dewey	16.3	21.9	29.4	29.4
Ellis	3.0	5.8	7.3	10.4
Garfield	11.9	12.9	14.2	21.0
Garvin	9.8	12.7	16.3	14.9
Grady	2.2	3.3	3.9	3.7
Grant	8.2	24.2	19.6	54.2
Harper	4.4	3.4	3.1	2.7
Hughes	9.1	13.4	11.9	11.3
Kay	72.1	93.9	97.5	43.0
Kingfisher	5.7	6.4	5.4	7.7
Latimer	0.8	0.8	0.7	0.7
Le Flore	0.3	0.3	0.2	0.2
Lincoln	73.1	67.7	58.9	52.0
Logan	5.2	7.2	8.7	10.2
Love	0.3	0.3	0.3	0.3
McClain	1.6	2.3	3.5	4.0
McIntosh	3.2	3.5	2.6	1.6
Major	7.9	8.9	8.3	7.2
Murray	5.4	9.7	10.4	8.5
Muskogee	0.7	0.6	0.2	0.2
Noble	33.0	28.6	39.0	46.8
Nowata	0.8	0.5	0.8	2.0
Okfuskee	15.0	19.1	20.4	14.2
Oklahoma	61.8	65.8	74.8	67.2
Okmulgee	3.2	3.4	3.1	2.6
Pawnee	8.5	9.1	12.3	20.4
Payne	12.2	13.1	16.7	16.9
Pittsburg	1.4	2.2	4.3	3.1
Pontotoc	14.8	16.8	20.9	19.2
Pottawatomie	49.9	49.0	48.8	46.0
Roger Mills	6.5	13.1	14.3	6.3
Seminole	88.9	87.9	103.6	88.1
Stephens	5.1	5.1	5.7	3.9
Texas	2.1	2.2	3.9	4.4
Tillman	1.0	1.0	1.2	1.5
Tulsa	1.4	1.4	1.4	1.3
Wagoner	0.7	0.6	0.8	0.6
Washington	1.7	1.6	1.6	1.5
Washita	5.0	5.4	4.7	3.1
Woods	45.5	60.3	67.9	72.1
Woodward	7.2	7.2	5.8	3.2

Table 5 lists the 52 counties in Oklahoma that had a cumulative volume of ≥1 MMbbl water injected into Class II SWD wells from 2010–2013. Reported annual volumes of SWD (i.e., 2D) increased for 28 out of the 52 counties from 2010 to 2013. Annual and county-scale SWD volumes are also illustrated as charts on Figures 1–4. Alfalfa, Grant, and Woods Counties had the greatest increases of 206.8, 46.0, and 26.6 MMbbls, respectively.

3.5. *Injection Depths and Pressures of SWD*

SWD wells are designed to be cased, with steel and cement seals, below underground sources of drinking water (USDW). The injection interval is completed as open hole or the liner may be perforated within the target injection zone. Depths of injection intervals varied from 356–18,886 ft below the land surface for active SWD (i.e., 2D) wells. The shallowest active SWD (i.e., 2D) well (named Jamison) injects into the Permian zone in Stephens

County, Oklahoma to a depth of 356 ft. The deepest active SWD (i.e., 2D) well (named Tipton) injects into the Atokan-Morrowan zone in Roger Mills County, Oklahoma to a depth of 18,886 ft. SWD (i.e., 2D) wells completed in the 'Other or Unspecified' zone had the lowest median depth of 1785.5 ft, while SWD (i.e., 2D) wells completed in the Arbuckle zone had the deepest median depth of 6852 ft (shown in Figure 13).

Wellhead injection pressure for active SWD (i.e., 2D) wells in the Basement had the highest median value of 245 psi in 2010, while the Atokan-Morrowan, Dev to Mid Ord, and Arbuckle zone wells had a median injection pressure of <0 psi (Table 6 and Figures 14–17). Wellhead injection pressure data are of unknown quality because a large percentage of SWD (i.e., 2D) wells were reportedly operating on a vacuum, but were reported as injecting at 0 psi rather than <0 psi.

Table 6 Median wellhead pressures reported for active SWD (i.e., 2D) wells, by completion zone

Zone	Median psi in 2010	Median psi in 2011	Median psi in 2012	Median psi in 2013
Permian	188	200	171	167
Virgilian	200	200	200	216
Missourian	125	120	117	105
Desmoinesian	100	100	91	82
Atokan-Morrowan	10	0	0	0
Mississippian	50	50	50	50
Woodford	11	20	40	40
Dev to Mid Ord	0	0	0	10
Arbuckle	0	0	0	5
Basement	245	186	100	231
Multiple-Undiff	150	150	125	135
Other Or Unspec	50	50	50	50

3.6. *Temporal Trends in EORI by County*

Secondary oil production can be realized using enhanced oil recovery (EOR), whereby fluids (e.g., H_2O or CO_2) are injected into an EORI well. 'Water flooding' is a common practice in several Oklahoma counties. Table 7 lists the 38 counties in Oklahoma that had a cumulative volume of ≥1 MMbbl water injected into EORI wells from 2010–2013. Reported annual water (e.g., brackish or saltwater) volumes of EORI (i.e., 2R) increased for 23 out of the 38 counties from 2010 to 2013. Pontotoc, Carter, and Garvin Counties had the greatest increases of 37.9, 14.8, and 9.8 MMbbls, respectively.

Table 7 EORI (i.e., 2R) volumes by county

County	MMbbl of EORI in 2010	MMbbl of EORI in 2011	MMbbl of EORI in 2012	MMbbl of EORI in 2013
Alfalfa	0.6	0.9	0.9	1.0
Beaver	6.0	6.6	6.1	6.8
Bryan	0.2	0.2	0.3	0.3
Caddo	7.4	7.9	8.0	9.4
Carter	241.2	247.5	274.5	256.0
Cimarron	0.2	0.3	0.3	0.3
Cleveland	0.4	0.4	0.4	0.1
Cotton	0.5	0.5	0.6	0.5
Creek	69.8	73.0	76.5	71.7
Dewey	15.0	14.6	15.0	14.1
Garfield	0.3	0.3	0.4	0.4
Garvin	26.0	32.8	34.3	35.8
Grady	10.2	11.3	12.2	9.9
Grant	3.7	3.1	4.0	2.7
Jefferson	1.0	1.0	1.8	1.1
Kay	6.6	7.1	7.2	6.0
Lincoln	7.2	7.9	6.2	5.7
Logan	0.2	0.2	0.3	0.3
Love	0.3	0.3	0.3	0.3
McClain	0.7	2.2	0.2	0.0
Murray	4.1	10.4	12.0	11.4
Muskogee	0.4	0.3	0.4	0.1
Noble	1.2	1.2	1.3	1.5
Nowata	13.6	13.7	13.2	13.5
Okfuskee	3.0	4.5	5.5	5.1
Oklahoma	4.0	4.0	5.2	5.7
Okmulgee	0.9	0.9	0.4	1.4
Pawnee	3.9	3.7	4.1	4.6
Payne	0.9	0.9	0.9	0.8
Pittsburg	0.5	0.7	0.7	0.5
Pontotoc	79.4	108.3	156.6	117.2
Pottawatomie	3.2	4.3	3.7	3.6
Seminole	26.7	27.5	28.7	26.5
Stephens	42.3	47.2	51.1	45.7
Texas	34.3	34.6	36.3	40.0
Wagoner	0.2	0.2	0.3	0.4
Woods	4.9	5.1	5.7	3.8
Woodward	7.1	7.7	7.2	7.0

3.7. *Seismic Activity in Oklahoma*

Seismic activity has increased significantly in recent years, with about 109 magnitude 3.0 or greater earthquakes occurring in 2013 and more than 500 magnitude 3.0 or greater earthquakes occurring in 2014 (OGS 2014). From 2010-2012, the majority of earthquakes were located in central Oklahoma (Figures 18–20), but numerous earthquakes occurred in Grant, Alfalfa, and Woods Counties of north-central Oklahoma during 2013 (Figure 21). Median depth for earthquakes (i.e., focal depth or origin) in Oklahoma was about 12,303 ft (~3.75 km), and more than 75% of focal points were at depths of more than 9842 ft (~2.5 km), as shown in Figure 22.

Because SWD (i.e., 2D) wells injecting into the Arbuckle zone are in direct contact with or close proximity to basement rock, they may be the most relevant for comparison to seismic activity, which is typically focused on basement fault networks (Zhang et al. 2013). Changes in seismicity were observed in numerous counties of Oklahoma having active Class II SWD wells completed in the Arbuckle or Basement zones. A spatiotemporal comparison was made between change in SWD volumes into the Arbuckle or Basement zones (2013 & 2012 versus 2011 & 2010) and change in seismicity (2013 & 2012 versus 2011 & 2010) at a county-scale. These data were organized into four quadrants on Figure 23, whereby Quad A includes counties (e.g., Oklahoma) with an increase in SWD (+SWD) and a decrease in number of earthquakes (-EQ), Quad B includes counties (e.g., Grant and Alfalfa) with an increase in SWD (+SWD) and an increase in number of earthquakes (+EQ), Quad C includes counties (e.g., Lincoln) with a decrase in SWD (-SWD) and an increase in number of earthquakes (+EQ), and Quad D includes counties (e.g., Garvin) with a decrease in SWD (-SWD) and a decrease in number of earthquakes (-EQ) from 2010–2013. Those counties (e.g., Alfalfa, Coal, Garvin, Grant, Kay, Lincoln, Oklahoma, Payne, Seminole, and Woods) that deviate substantially from the origin in Figure 23 would be interesting for more detailed studies of geologic factors that may affect seismicity.

4. Future Directions

Measurement of pre-injection hydraulic conditions and formation pressure, along with increased temporal resolution of injection rates and pressures are critical for 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 production versus injection versus seismicity can be put into the proper perspective. Integrated hydrogeologic, structural geologic, and seismologic datasets may then be evaluated to establish mechanisms by which fluid injection affects pore pressure along a fault plane.

These integrated scientific studies could be useful for the development of adaptable regulatory requirements and best-management practices for Class II wells managed in the underground injection control program.

5. References

Boyd DT (2008) Stratigraphic Guide to Oklahoma Oil and Gas Reservoirs. Oklahoma Geological Survey, SP2008-1. Norman, OK. pp. 2.

Davis SD, Pennington WD (1989) Induced seismic deformation in the Cogdell oil field of west Texas. Bulletin of the Seismological Society of America 79:1477-1495

EIA (2014a) Field Production of Crude Oil in the United States. http://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm. Cited Jul 22

EIA (2014b) Natural Gas Gross Withdrawals and Production. http://www.eia.gov/dnav/ng/ng_prod_sum_dcu_nus_m.htm. Cited Jul 1

Ellsworth WL (2013) Injection-Induced Earthquakes. Science 341:142-149 DOI 10.1126/science.1225942

Frohlich C (2012) Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas. Proceedings of the National Academy of Sciences 109:13934-13938 DOI 10.1073/pnas.1207728109

Healy JH, Rubey WW, Griggs DT, Raleigh CB (1968) The Denver Earthquakes. Science 161:1301-1310 DOI 10.2307/1725684

Holland AA (2013) Earthquakes Triggered by Hydraulic Fracturing in South-Central Oklahoma. Bulletin of the Seismological Society of America 103:1784-1792 DOI 10.1785/0120120109

Horton S (2012) Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake. Seismological Research Letters 83:250-260 DOI 10.1785/gssrl.83.2.250

Keranen KM, Savage HM, Abers GA, Cochran ES (2013) Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence. Geology 41:699-702 DOI 10.1130/g34045.1

Lord C (2012) Monthly injection volumes for Class II Underground Injection Control (UIC) wells in Oklahoma, 2011. In: Oil and Gas Division, Oklahoma Corporation Commission, Oklahoma City, OK.

Lord C (2014) Monthly injection volumes for Class II Underground Injection Control (UIC) wells in Oklahoma. In: Oil and Gas Division, Oklahoma Corporation Commission, Oklahoma City, OK.

Murray KE (2013) State-Scale Perspective on Water Use and Production Associated with Oil and Gas Operations, Oklahoma, U.S. Environ Sci Technol 47:4918-4925 DOI 10.1021/es4000593

Murray KE, Holland AA (2014) Inventory of Class II Underground Injection Control Volumes in the Midcontinent. Shale Shaker 65:98-106

Nicholson C, Wesson RL (1990) Earthquake hazard associated with deep well injection-A report to the U.S. Environmental Protection Agency. US Geological Survey Bulletin 1951. pp. 74.

Nodine-Zeller DE, Thompson TL (1977) Age and structure of subsurface beds in Cherokee County, Kansas: Implications from endthyrid foraminifera and conodonts. Kansas Geological Survey, Lawrence, KS

Northcutt RA, Campbell JA (1995) Geologic provinces of Oklahoma. Oklahoma Geological Survey Open-File Report (OF5-95)

NRC (2012) Induced Seismicity Potential in Energy Technologies. National Academy of Sciences, Washington, DC

OCC (2014a) UIC Injection Volumes 2012. http://www.occeweb.com/og/ogdatafiles2.htm. Cited Nov 25

OCC (2014b) UIC Injection Volumes 2013. http://www.occeweb.com/og/ogdatafiles2.htm. Cited Nov 25

OCC (2014c) Well Data System. http://www.occpermit.com/WellBrowse/Home.aspx. Cited various dates

OGS (2014) Leonard Geophysical Observatory Catalog. http://www.okgeosurvey1.gov/pages/earthquakes/catalogs.php. Cited 1 Sep 2014

Raleigh CB, Healy JH, Bredehoeft JD (1976) An experiment in earthquake control at Rangely, Colorado. Science 191:1230-1237

Zhang Y, Person M, Rupp J, Ellett K, Celia MA, Gable CW, Bowen B, Evans J, Bandilla K, Mozley P, Dewers T, Elliot T (2013) Hydrogeologic Controls on Induced Seismicity in Crystalline Basement Rocks Due to Fluid Injection into Basal Reservoirs. Ground Water 51:525-538 DOI 10.1111/gwat.12071

Abbreviations, Units, and Definitions

2D: Class II Disposal (aka SWD)
2R: Class II Recovery (aka EORI)
API: American Petroleum Institute
bbl: barrels
BIA: Bureau of Indian Affairs
BPD: Barrels Per Day
BPM: Barrels Per Month
BWPM: Barrels of Water Per Month
CO_2: carbon dioxide
EOR: Enhanced Oil Recovery
EORI: Enhanced Oil Recovery Injection (aka 2R)
EPA: Environmental Protection Agency
high volume UIC well: exceeding 150,000 BWPM or 1.8 MMbbl per year
LPG: Liquefied Petroleum Gas
MCF: thousand cubic feet
MMbbl: Millions of barrels
OCC: Oklahoma Corporation Commission
OGS: Oklahoma Geological Survey
psi: pounds per square inch
SWD: SaltWater Disposal (aka 2D)
QAQC: Quality Assurance Quality Control
UIC: Underground Injection Control
USDW: Underground Sources of Drinking Water

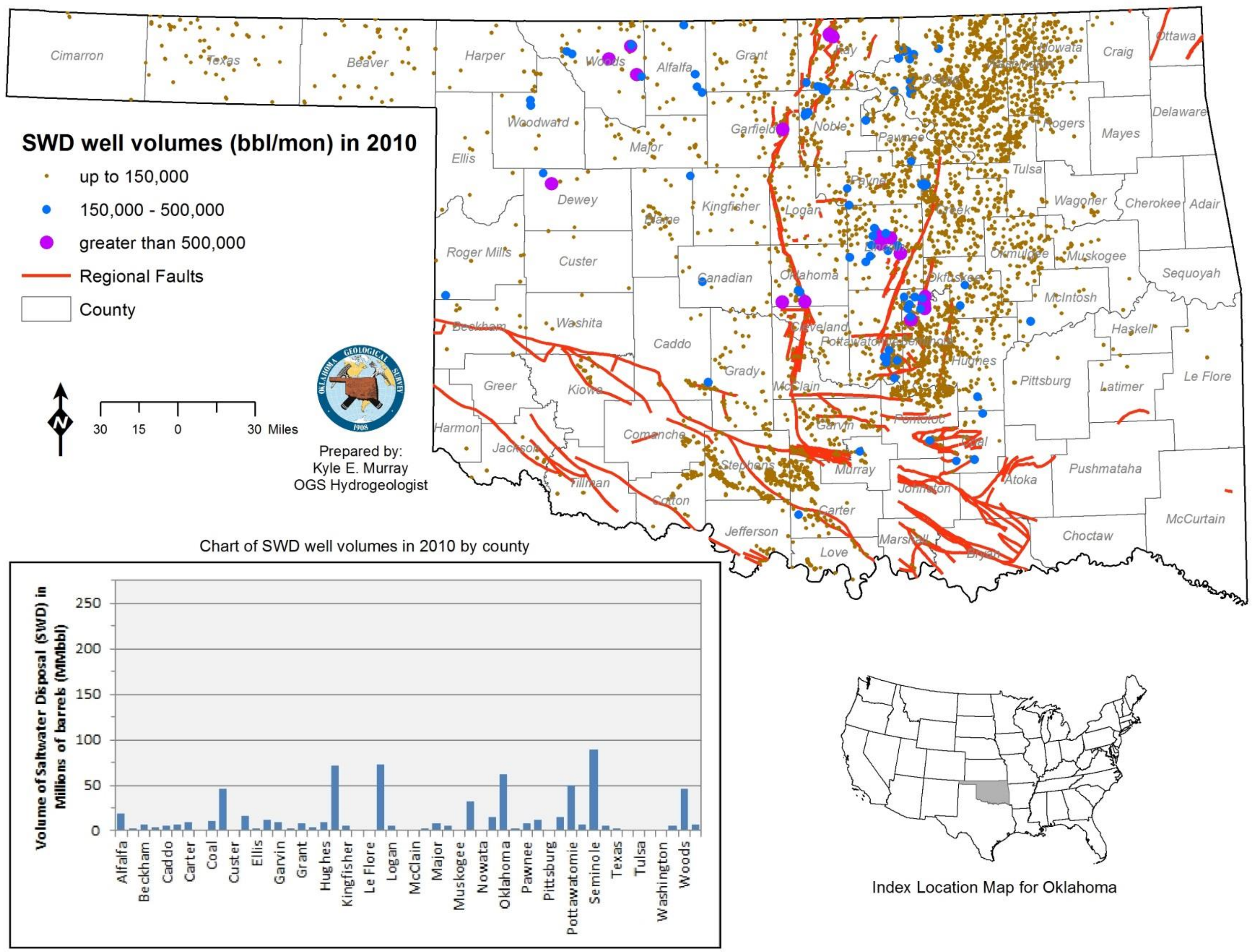

Figure 1 Map of SWD wells and relative volumes of water injected into SWD Class II UIC wells (i.e., 2D) during 2010. Chart of SWD well volumes in 2010 by county.

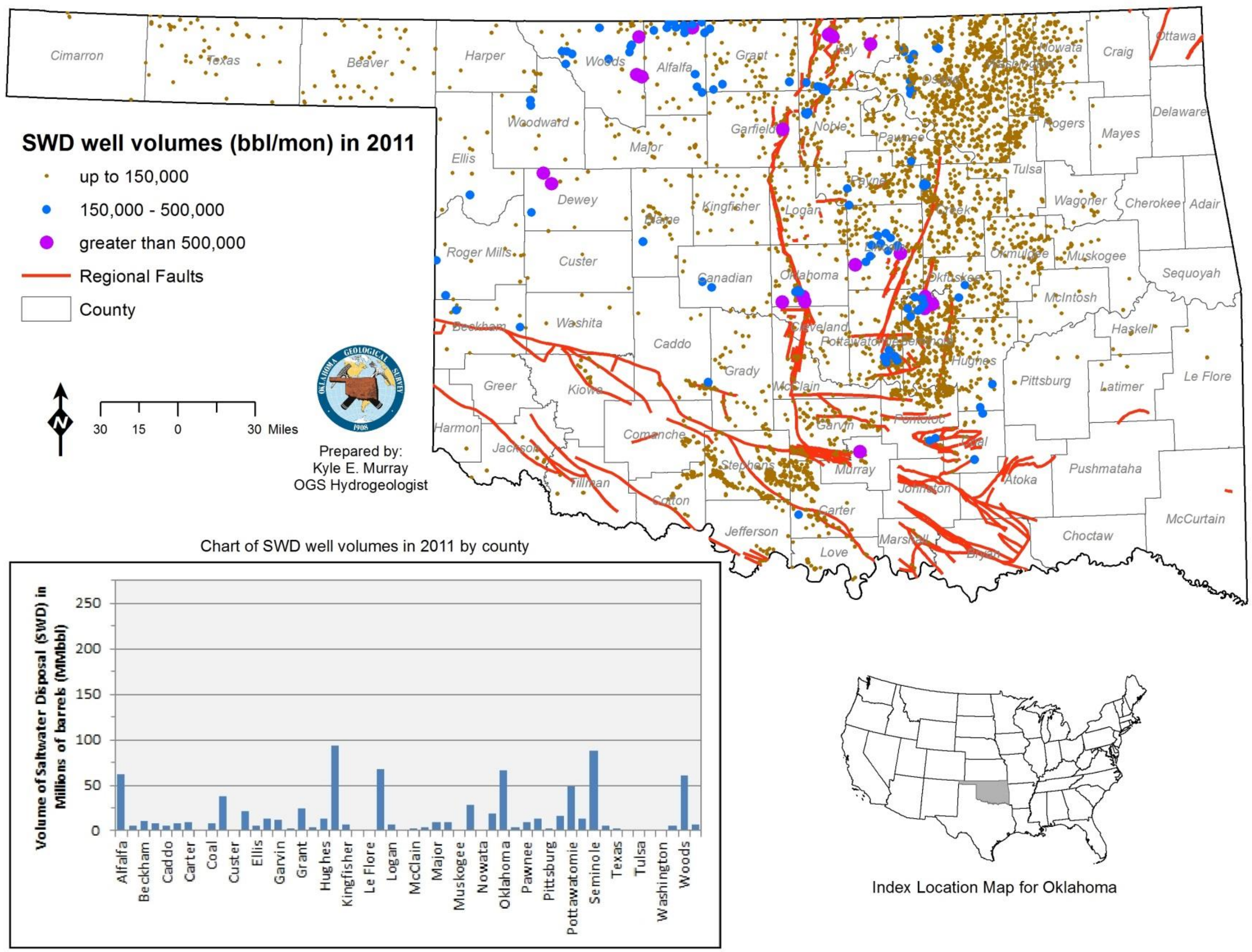

Figure 2 Map of SWD wells and relative volumes of water injected into SWD Class II UIC wells (i.e., 2D) during 2011. Chart of SWD well volumes in 2011 by county.

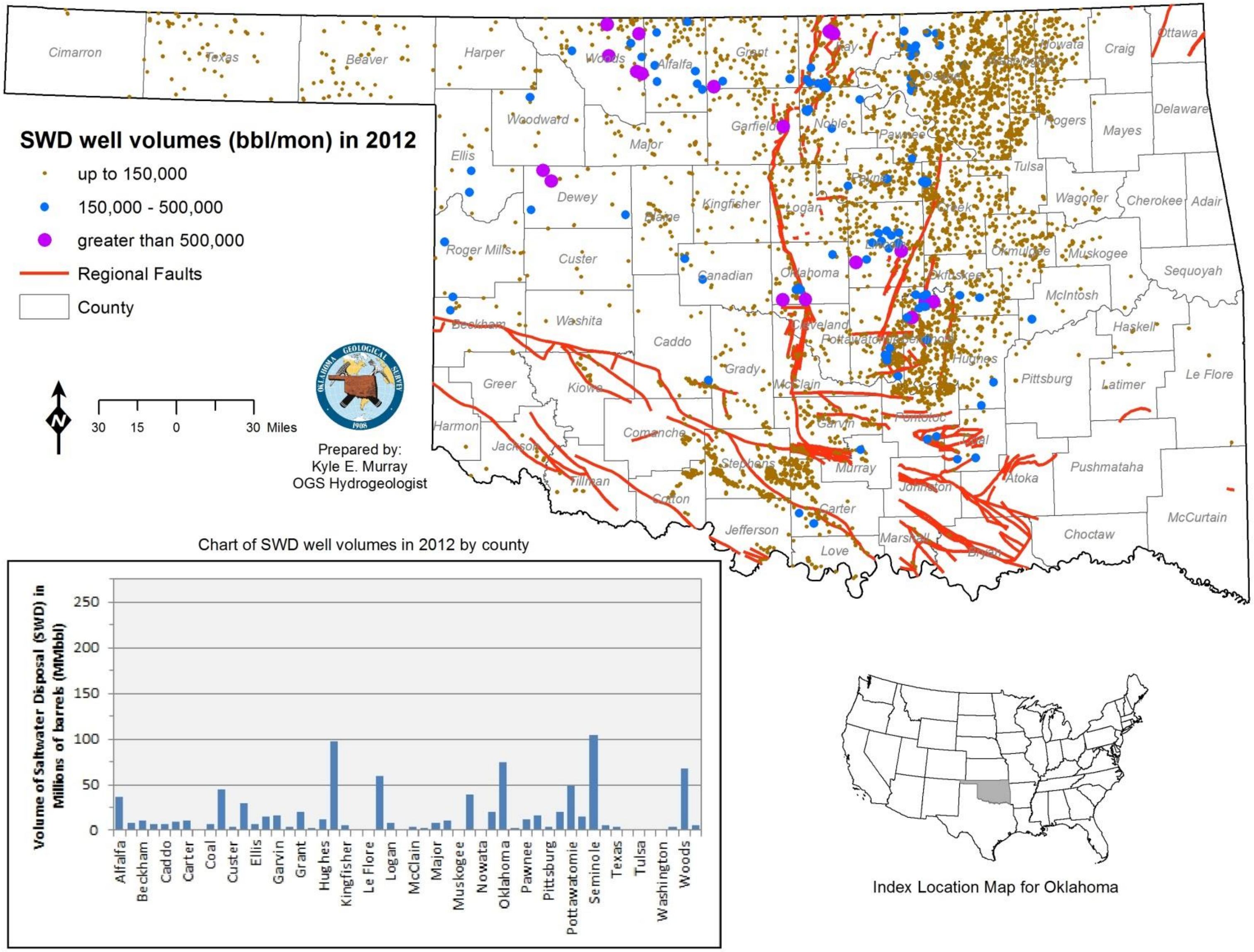

Figure 3 Map of SWD wells and relative volumes of water injected into SWD Class II UIC wells (i.e., 2D) during 2012. Chart of SWD well volumes in 2012 by county.

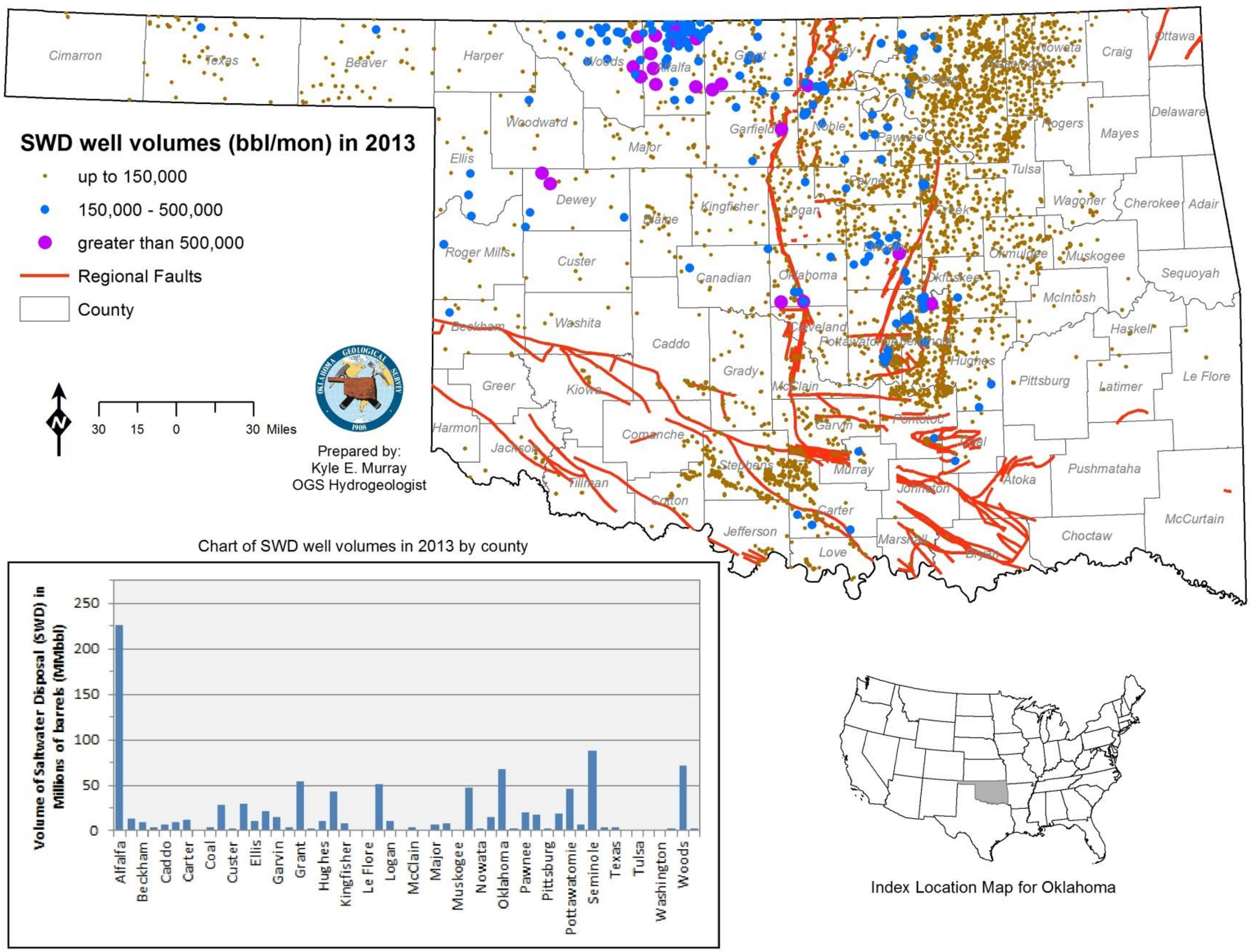

Figure 4 Map of SWD wells and relative volumes of water injected into SWD Class II UIC wells (i.e., 2D) during 2013. Chart of SWD well volumes in 2013 by county.

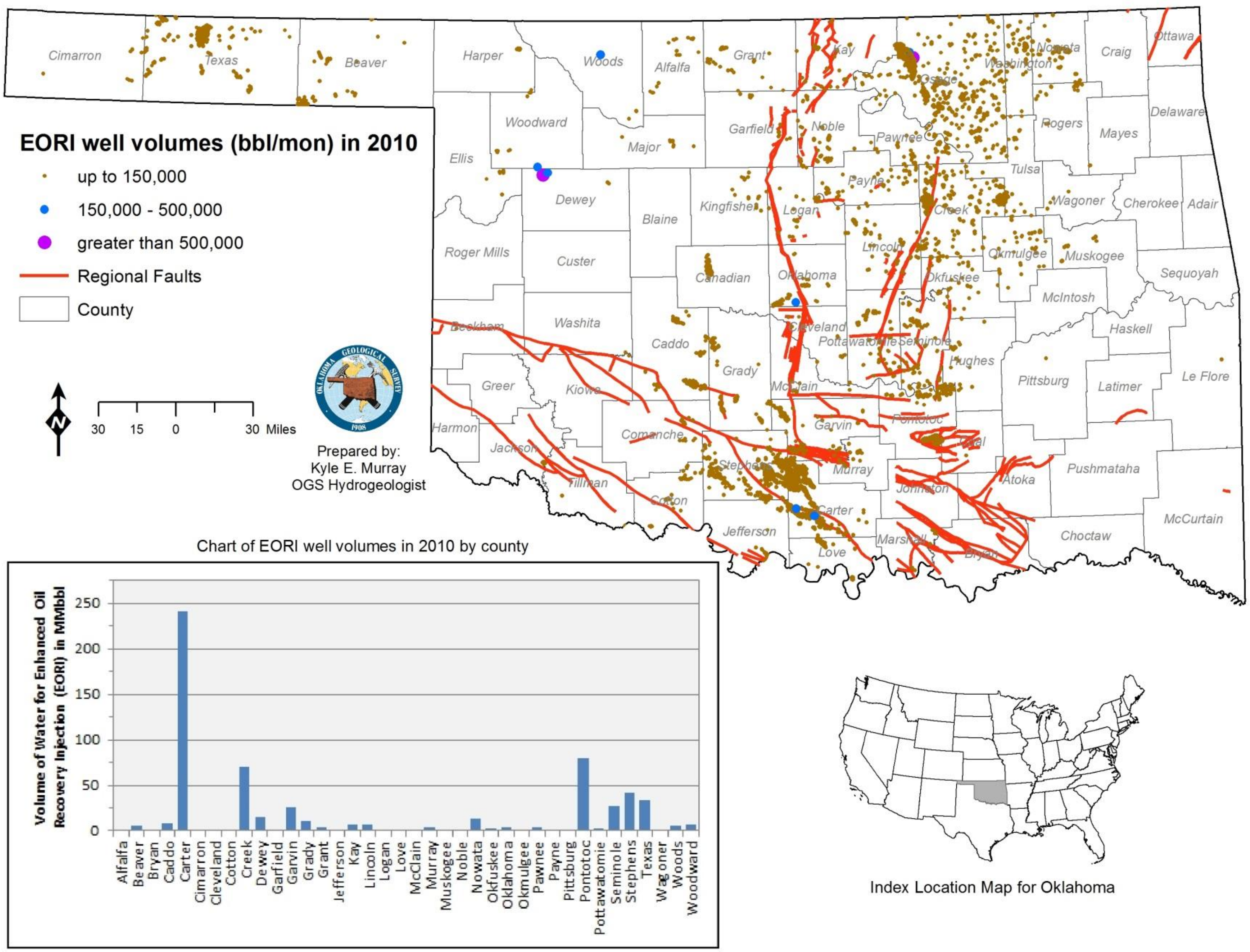

Figure 5 Map of EORI wells and relative volumes of water injected into EORI Class II UIC wells (i.e., 2R) during 2010. Chart of EORI well volumes in 2010 by county.

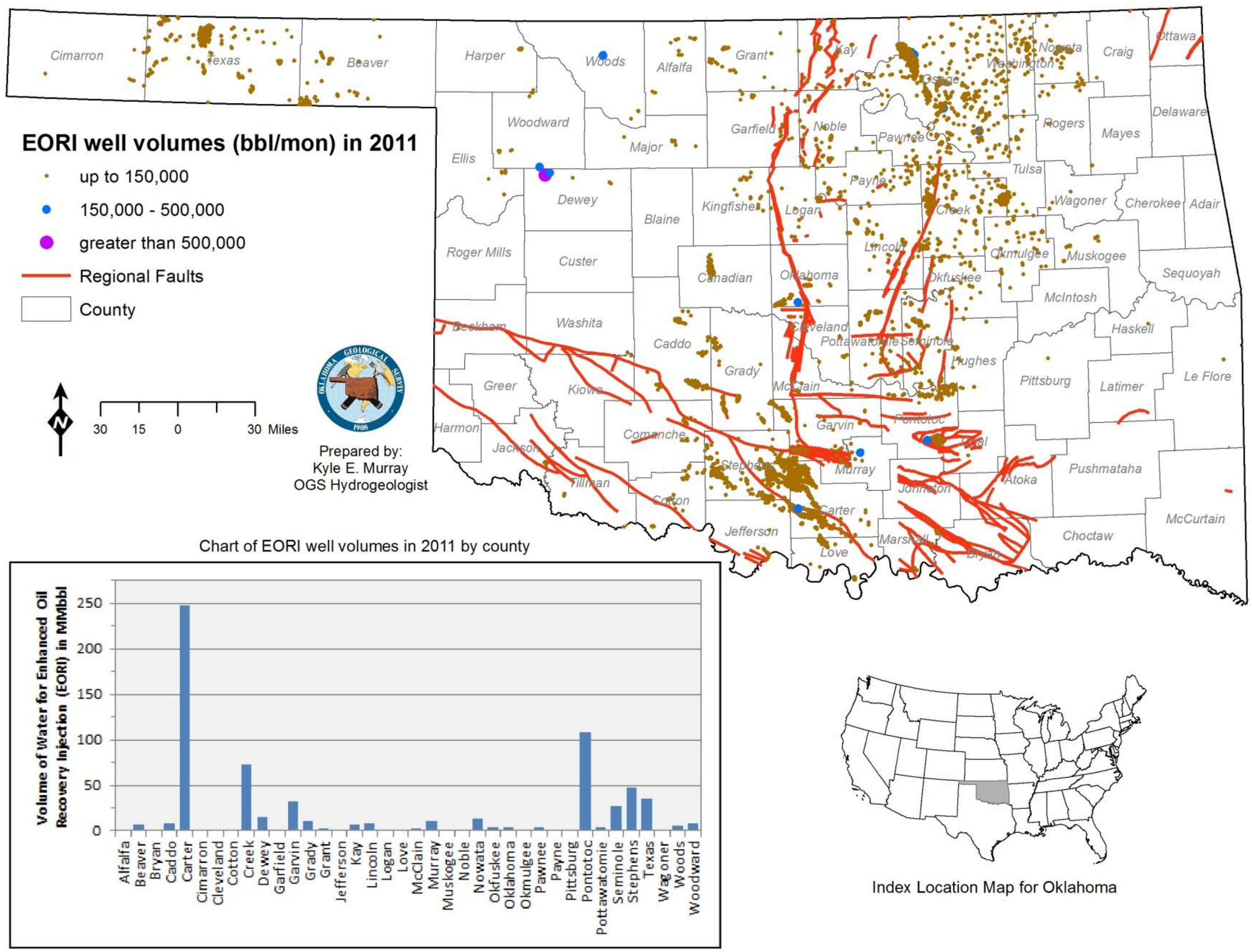

Figure 6 Map of EORI wells and relative volumes of water injected into EORI Class II UIC wells (i.e., 2R) during 2011. Chart of EORI well volumes in 2011 by county.

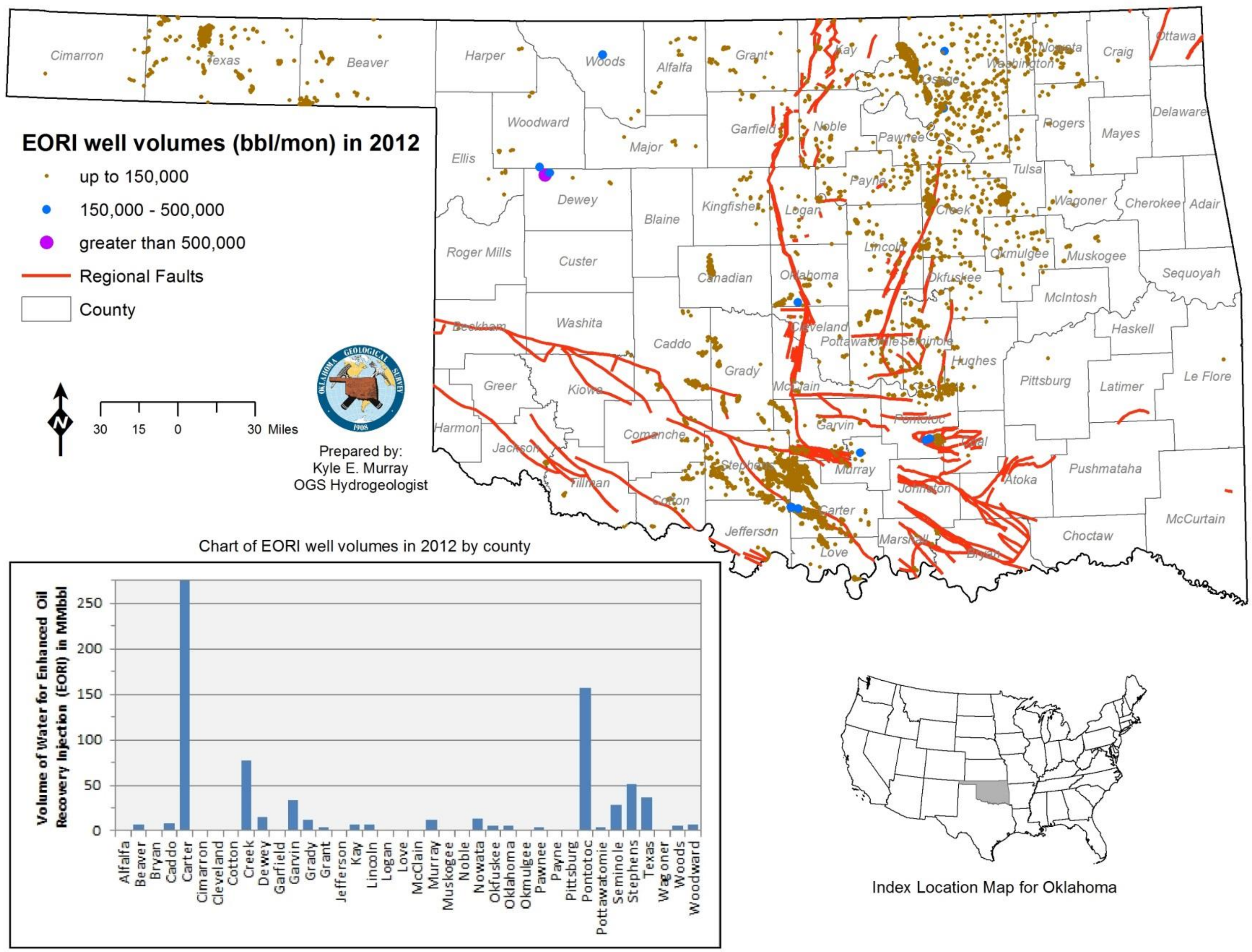

Figure 7 Map of EORI wells and relative volumes of water injected into EORI Class II UIC wells (i.e., 2R) during 2012. Chart of EORI well volumes in 2012 by county.

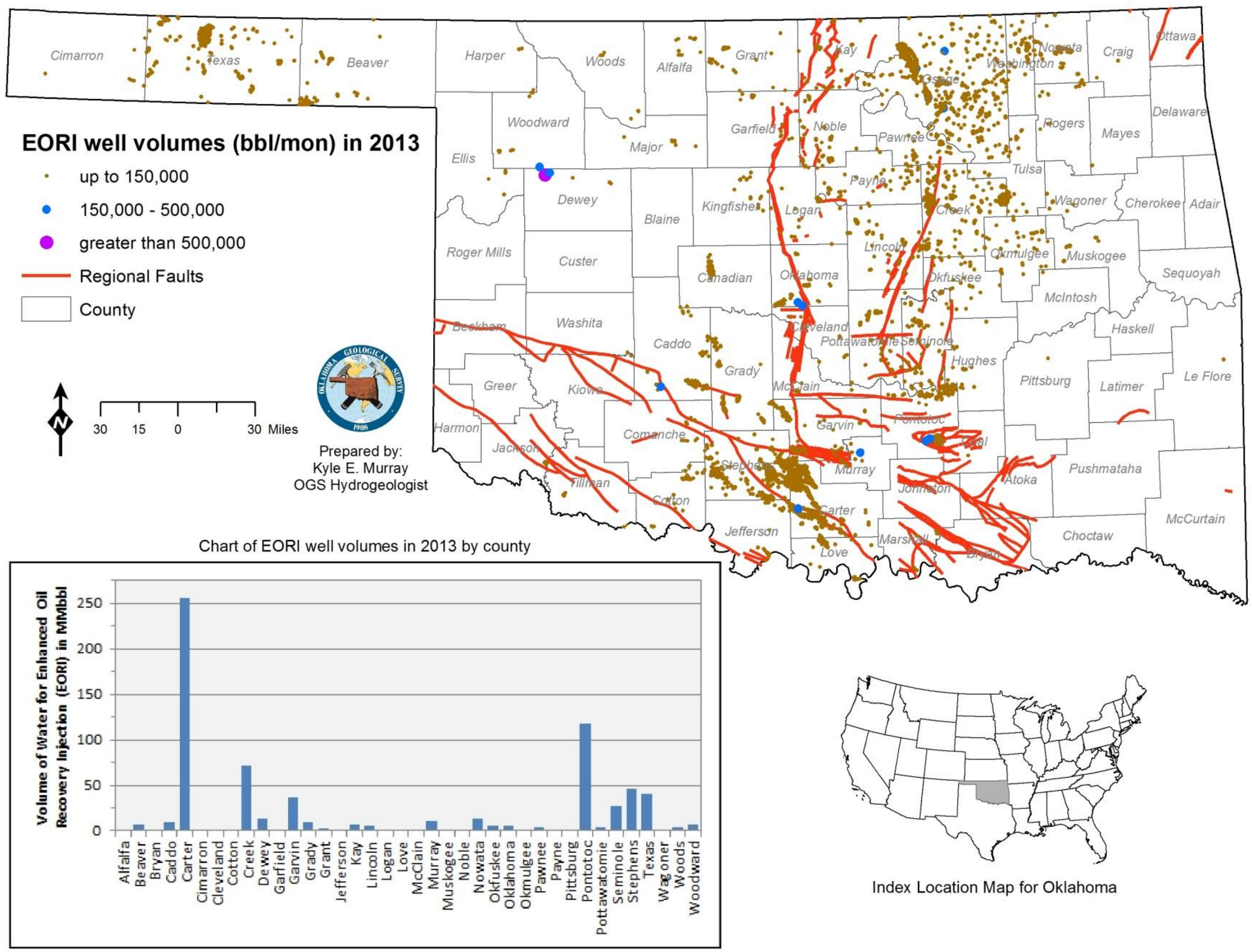

Figure 8 Map of EORI wells and relative volumes of water injected into EORI Class II UIC wells (i.e., 2R) during 2013. Chart of EORI well volumes in 2013 by county.

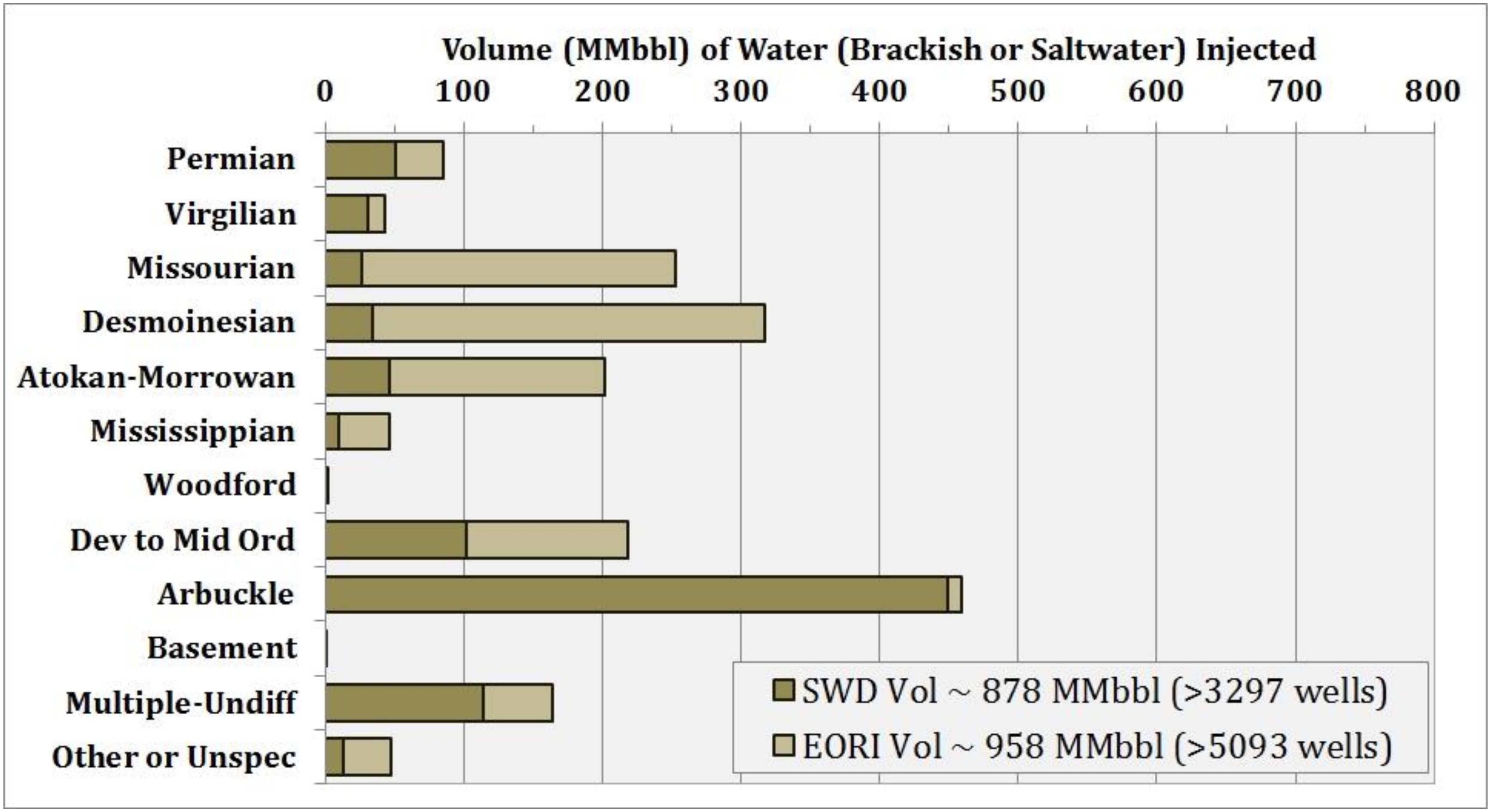

Figure 9 Chart of UIC well volumes in 2010 by geologic zone of completion.

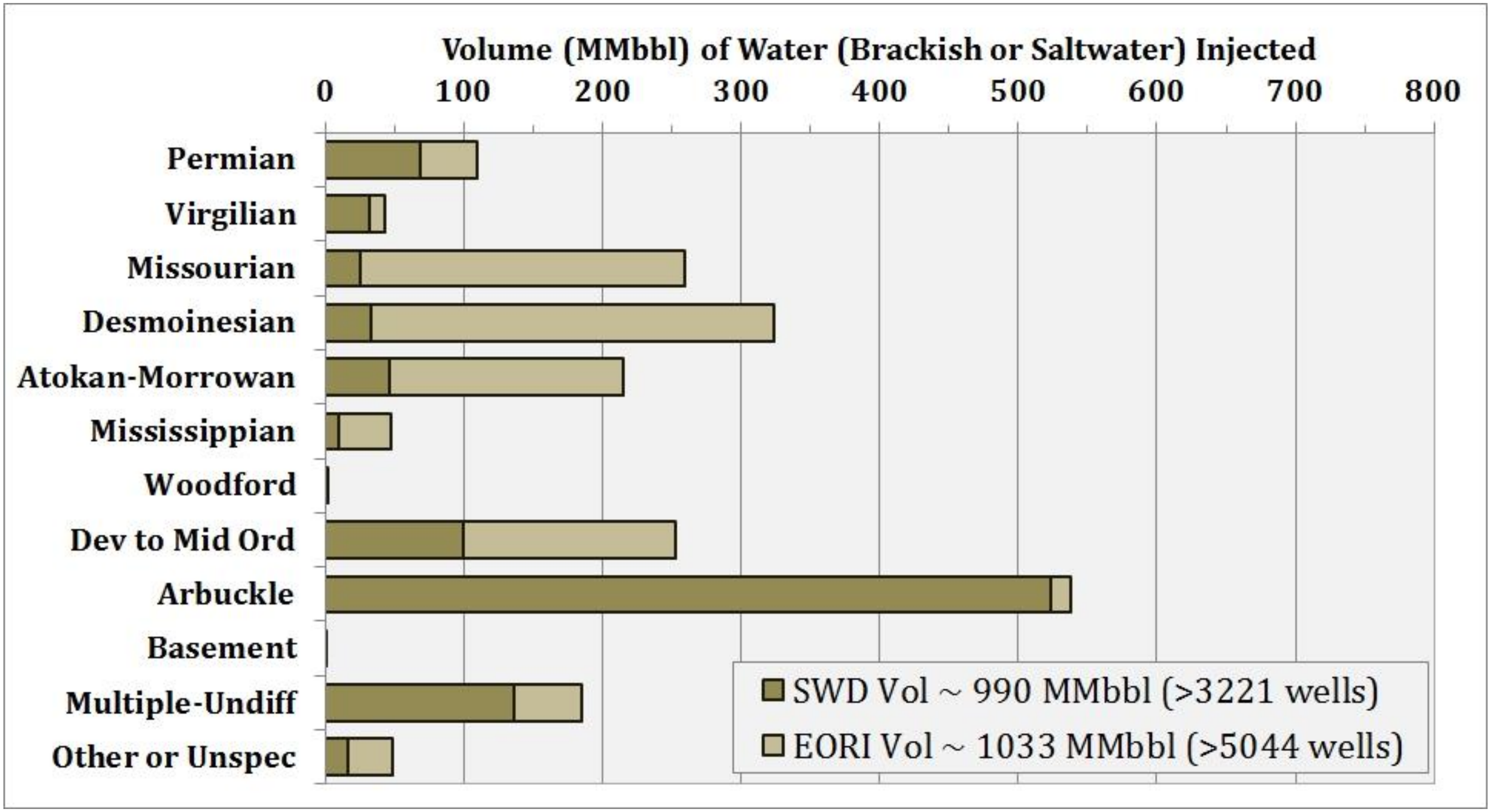

Figure 10 Chart of UIC well volumes in 2011 by geologic zone of completion.

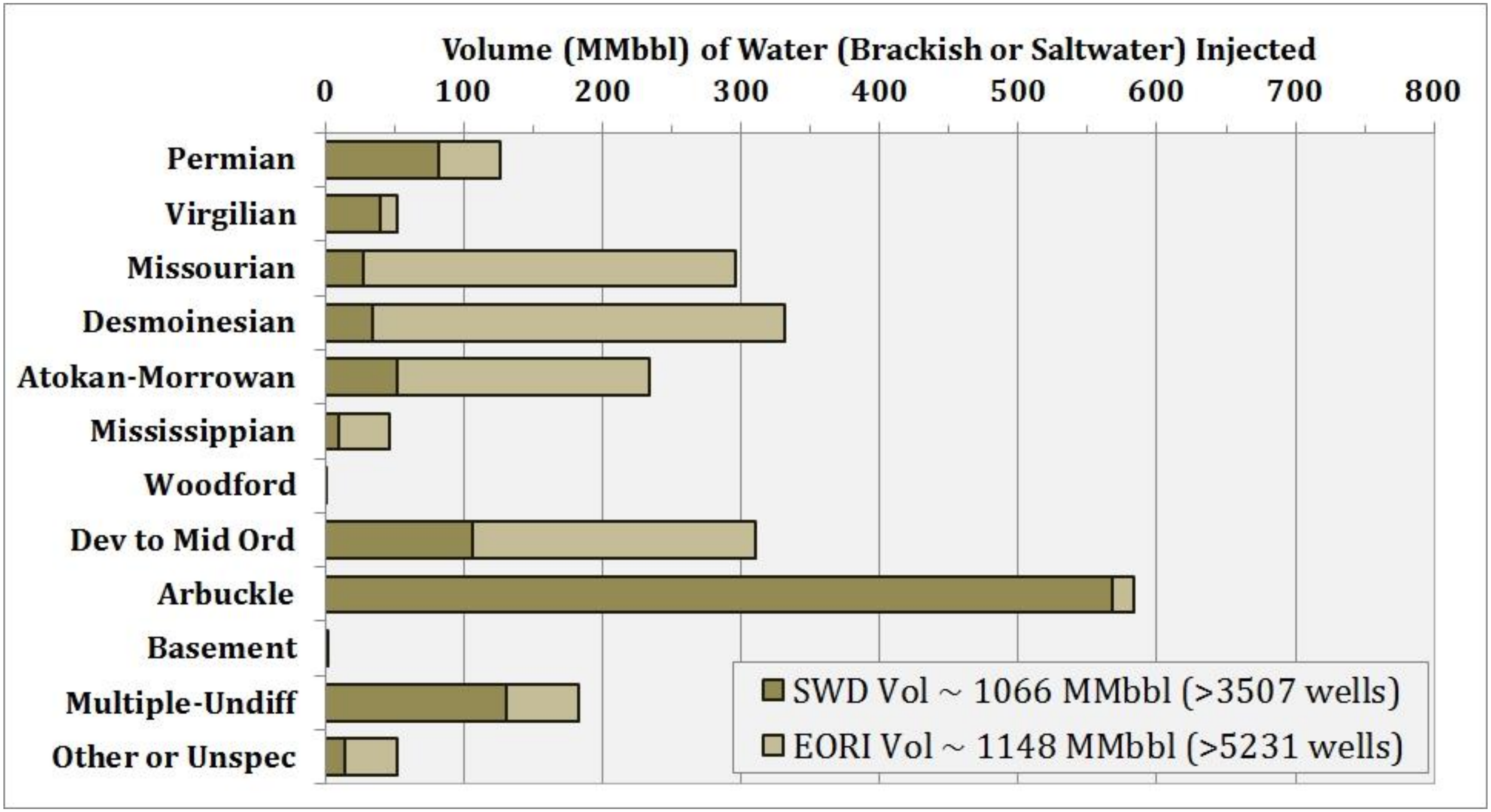

Figure 11 Chart of UIC well volumes in 2012 by geologic zone of completion.

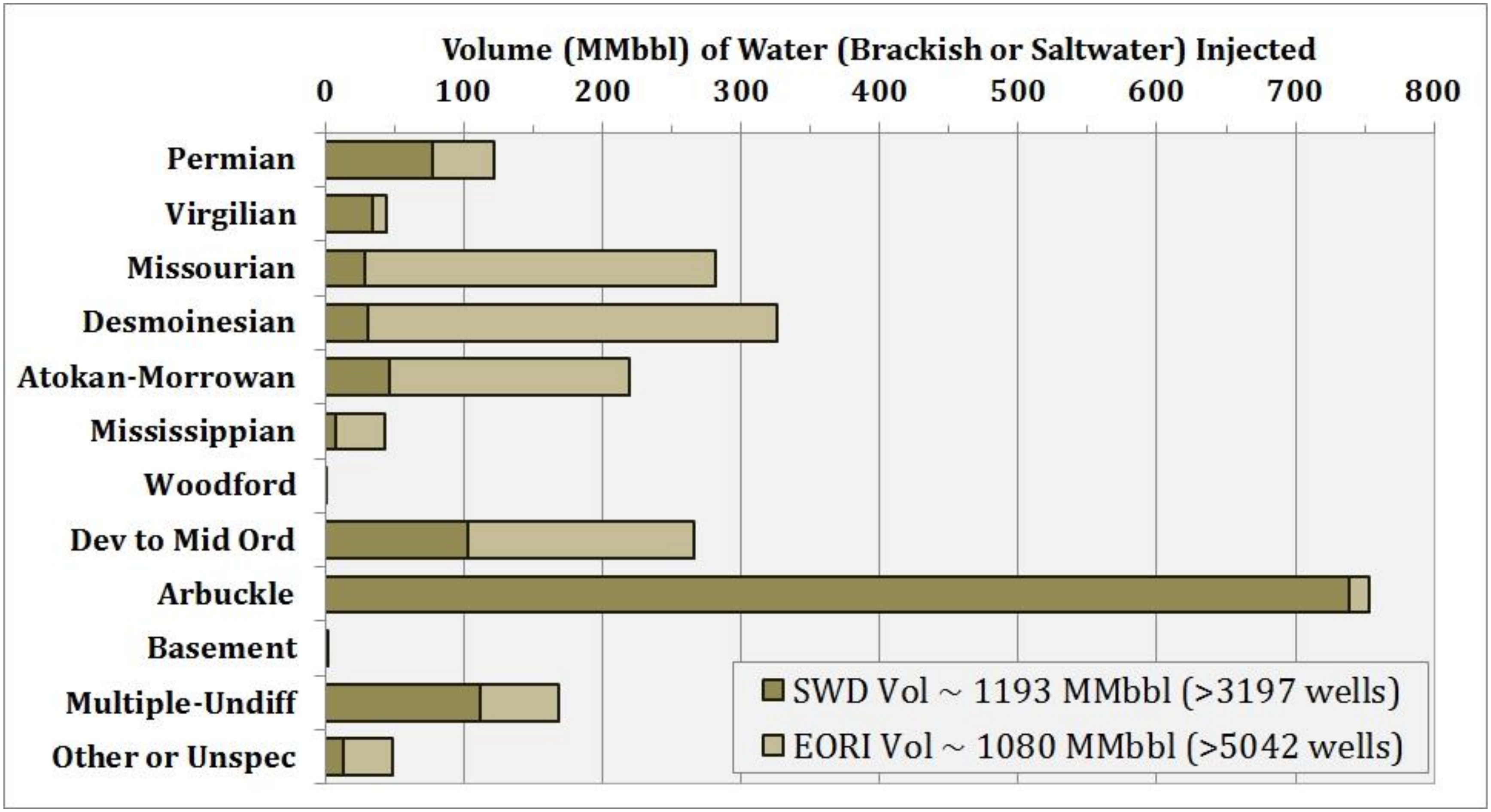

Figure 12 Chart of UIC well volumes in 2013 by geologic zone of completion.

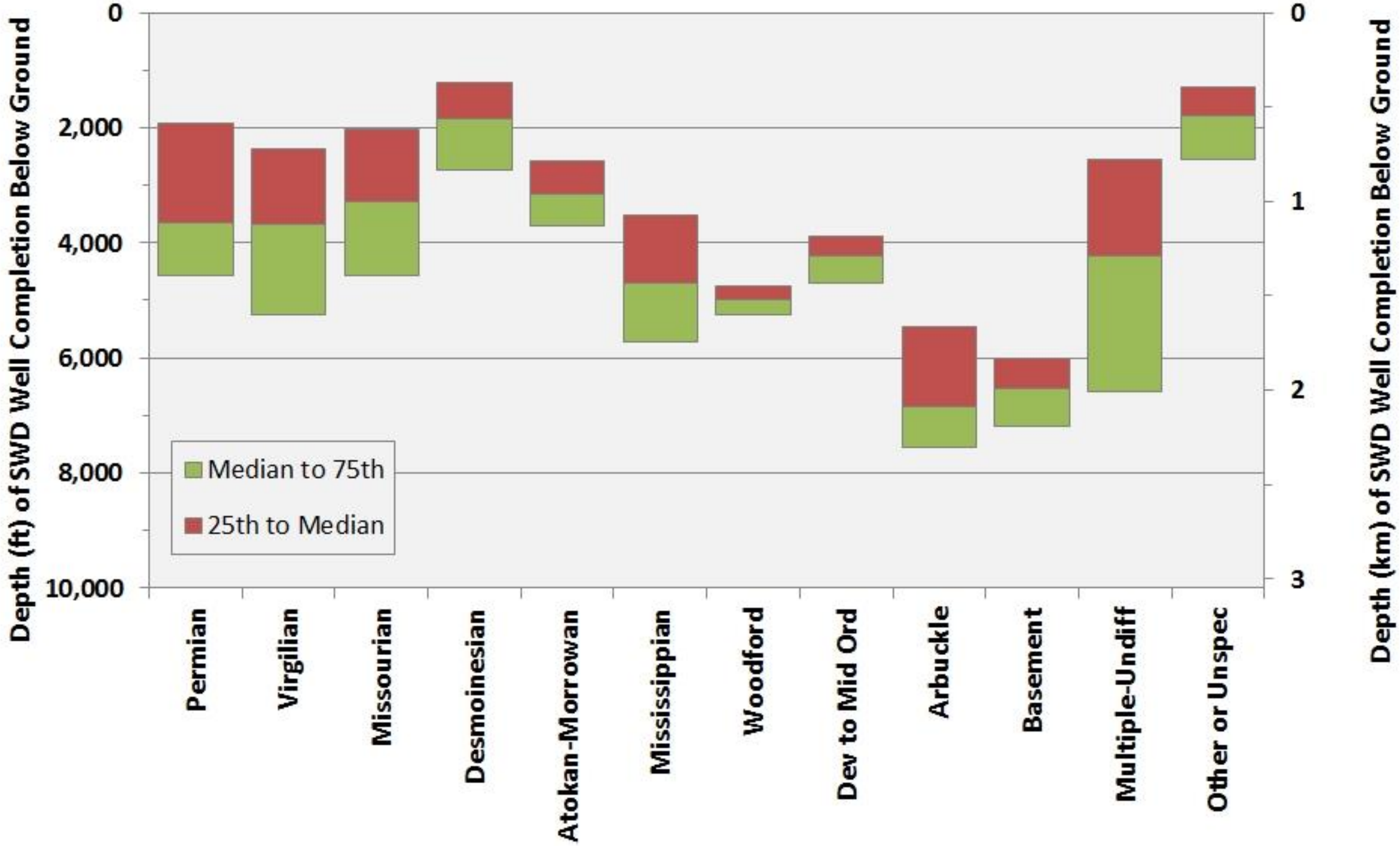

Figure 13 Depths, below land surface, for completion intervals of 2010–2013 active SWD (i.e., 2D) wells in Oklahoma

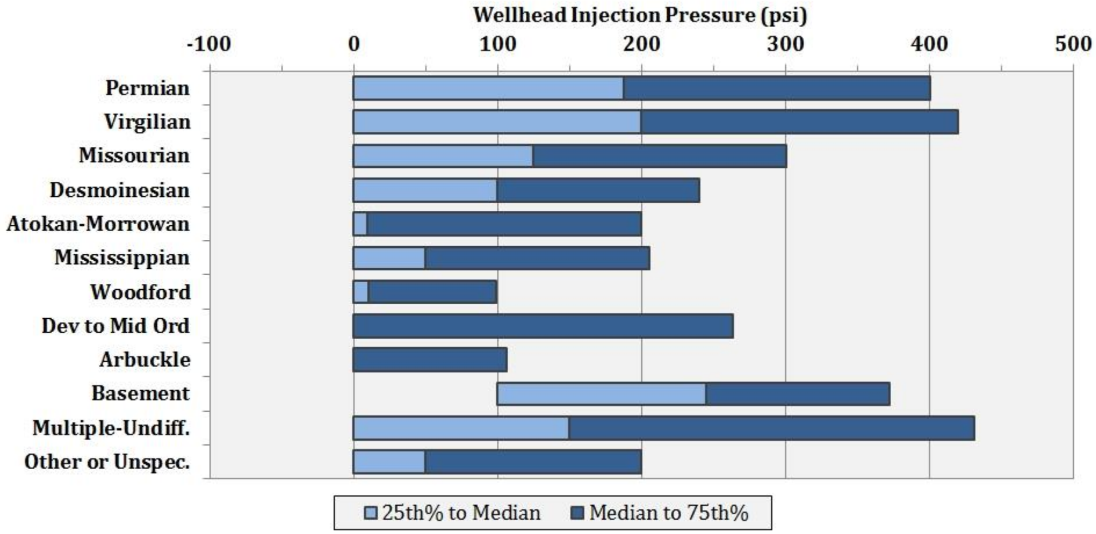

Figure 14 Wellhead injection pressure (psi) for active SWD (i.e., 2D) wells in 2010

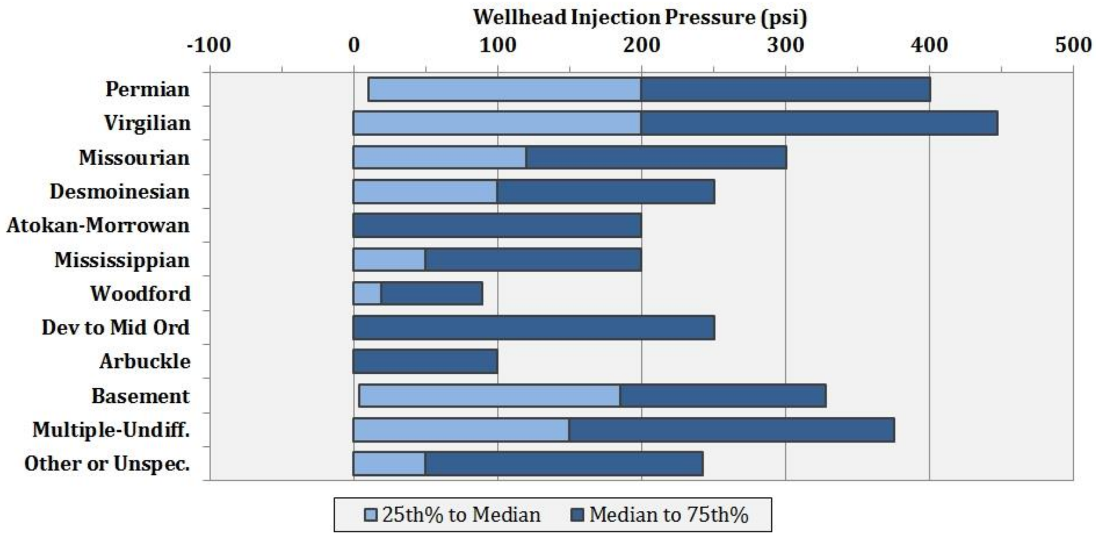

Figure 15 Wellhead injection pressure (psi) for active SWD (i.e., 2D) wells in 2011

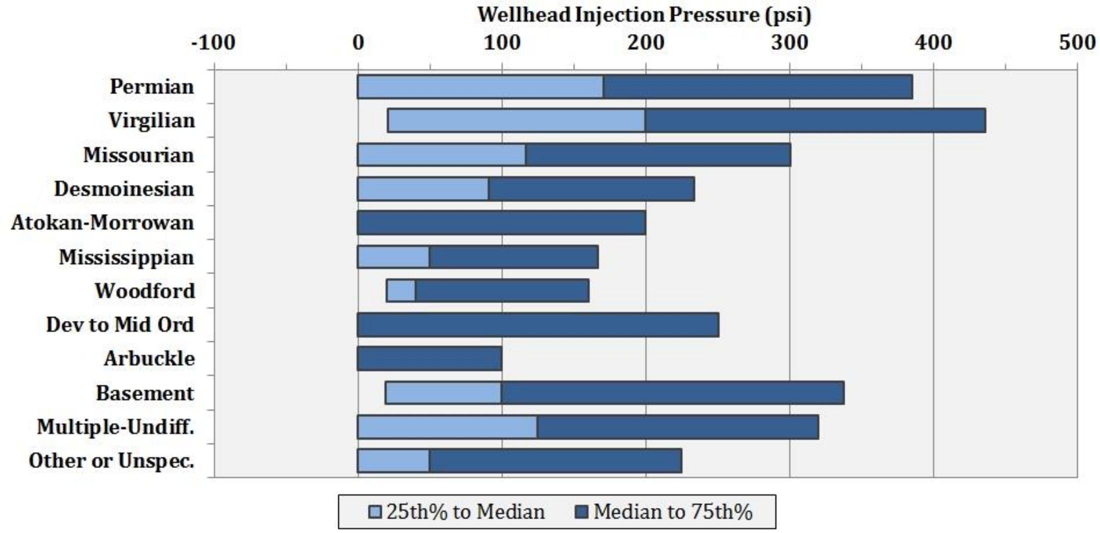

Figure 16 Wellhead injection pressure (psi) for active SWD (i.e., 2D) wells in 2012

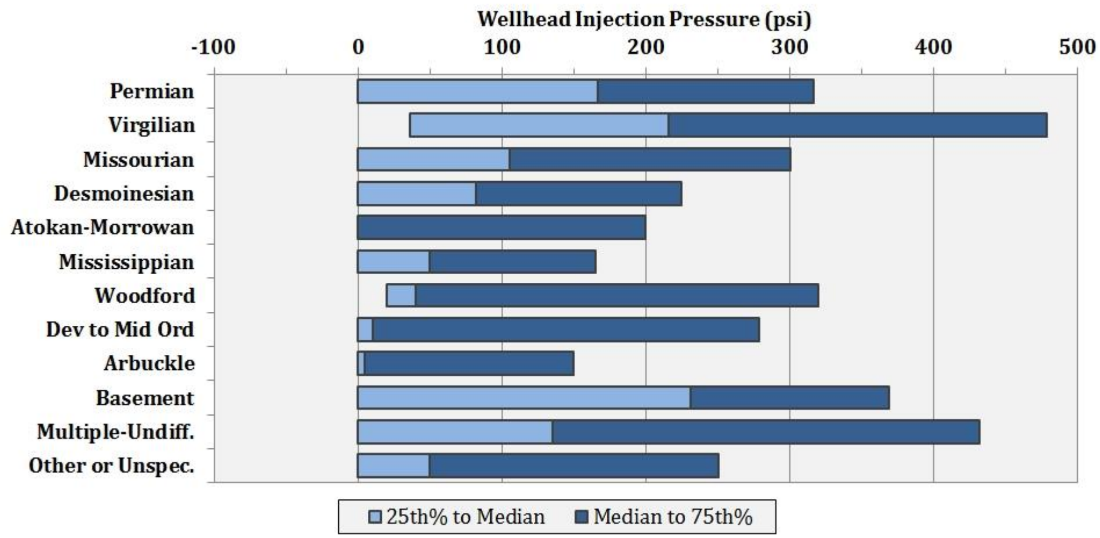

Figure 17 Wellhead injection pressure (psi) for active SWD (i.e., 2D) wells in 2013

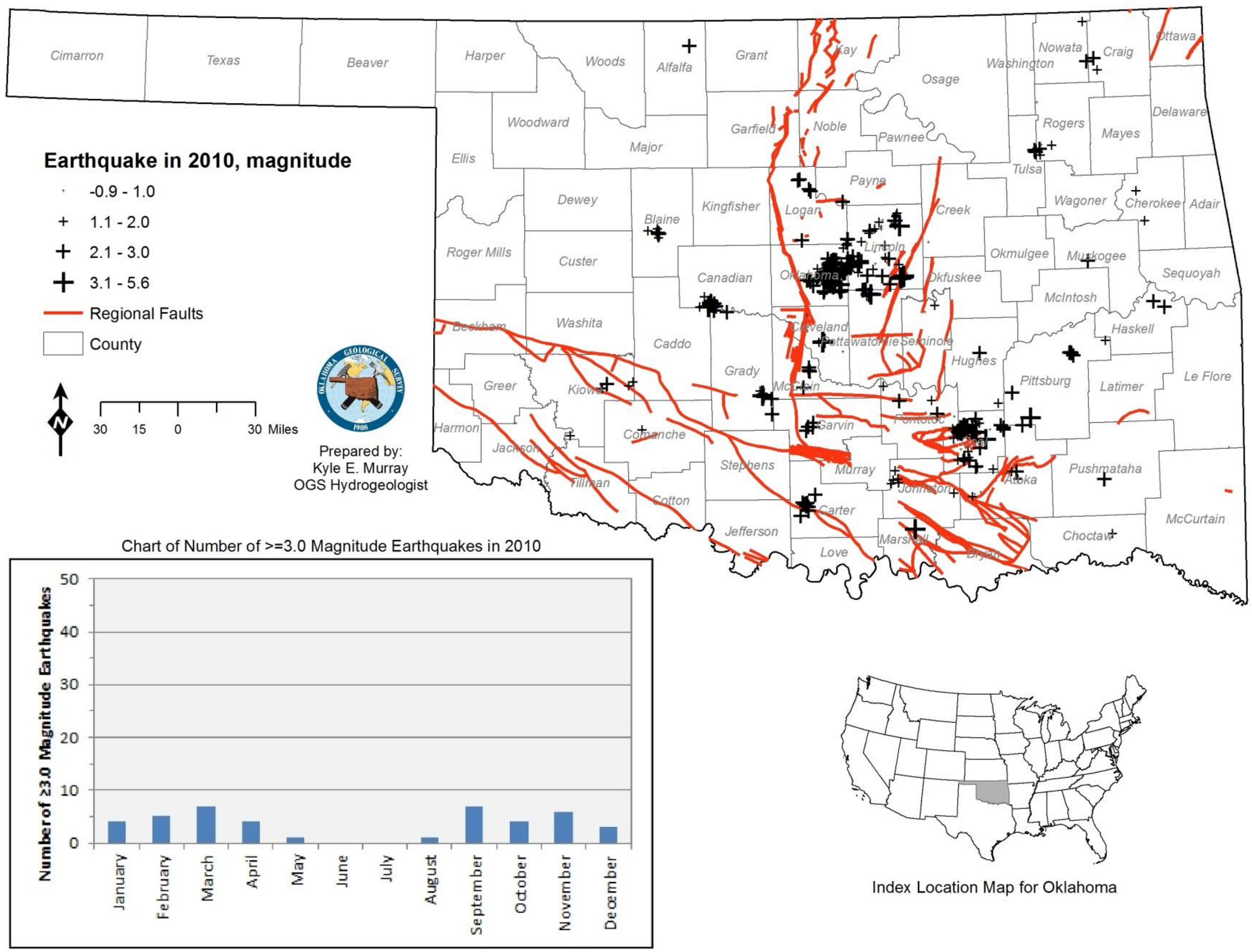

Figure 18 Map of earthquakes and relative magnitudes during 2010, data from OGS earthquake catalog. Chart of >=3.0 magnitude earthquakes in 2010 by month.

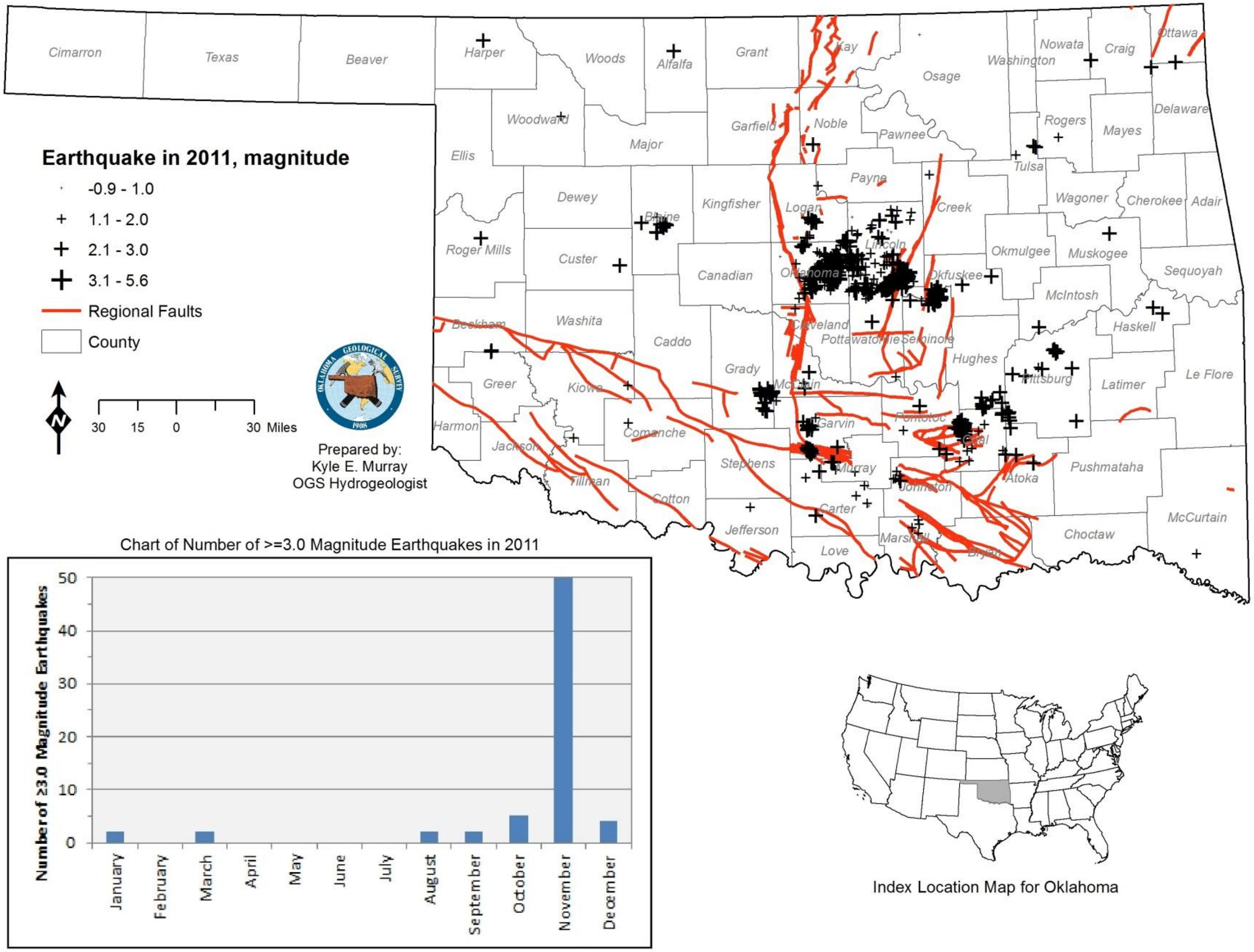

Figure 19 Map of earthquakes and relative magnitudes during 2011, data from OGS earthquake catalog. Chart of >=3.0 magnitude earthquakes in 2011 by month.

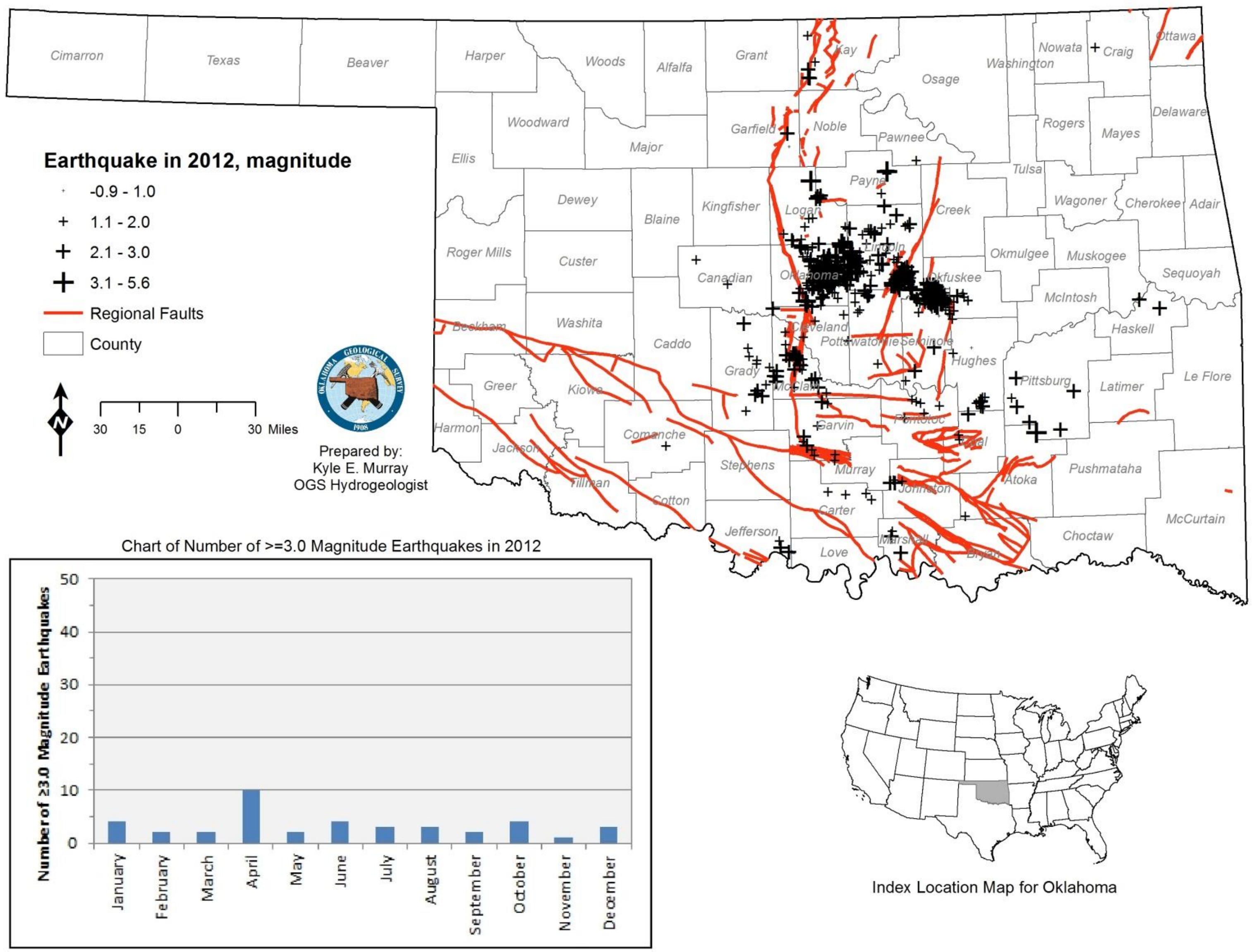

Figure 20 Map of earthquakes and relative magnitudes during 2012, data from OGS earthquake catalog. Chart of >=3.0 magnitude earthquakes in 2012 by month.

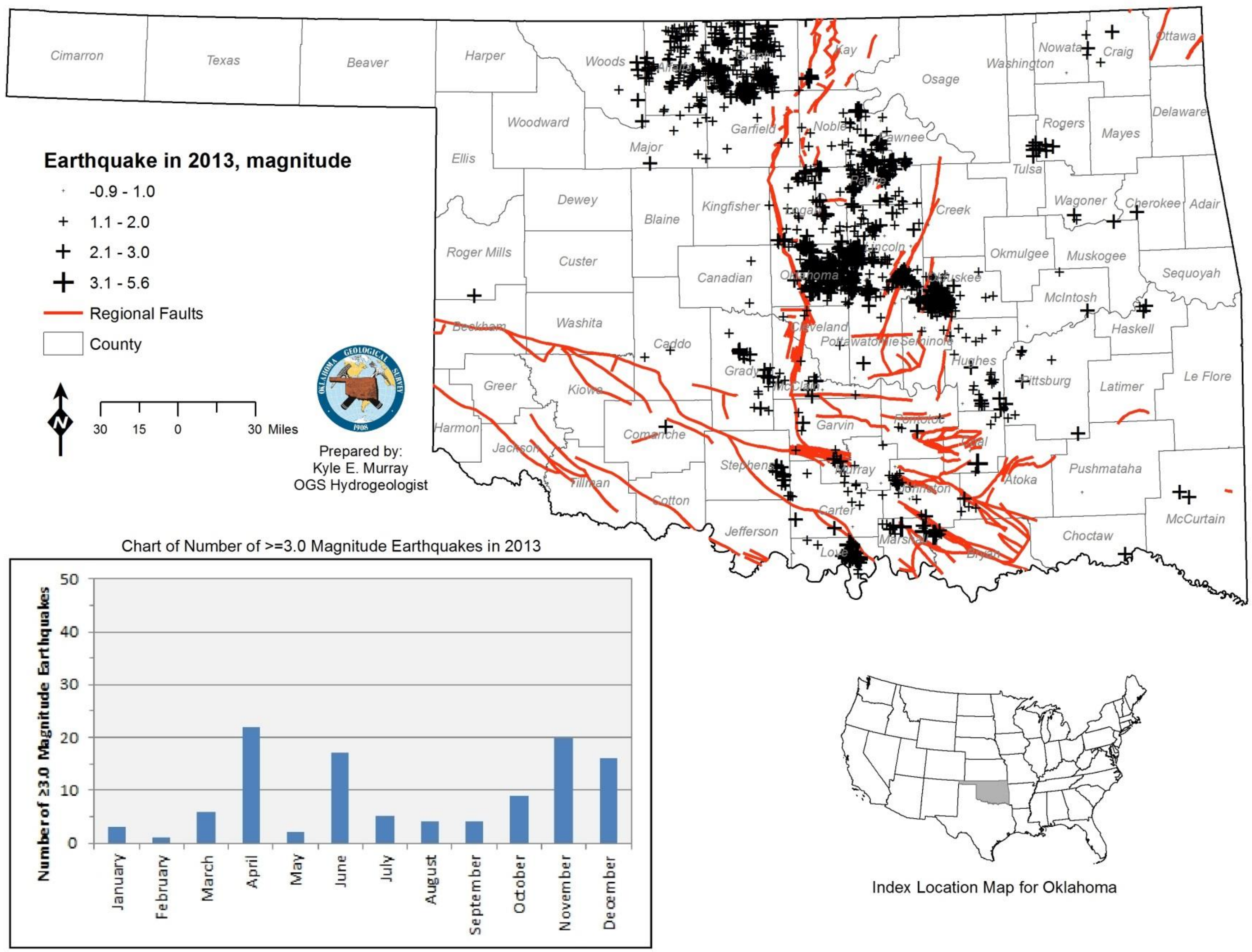

Figure 21 Map of earthquakes and relative magnitudes during 2013, data from OGS earthquake catalog. Chart of >=3.0 magnitude earthquakes in 2013 by month.

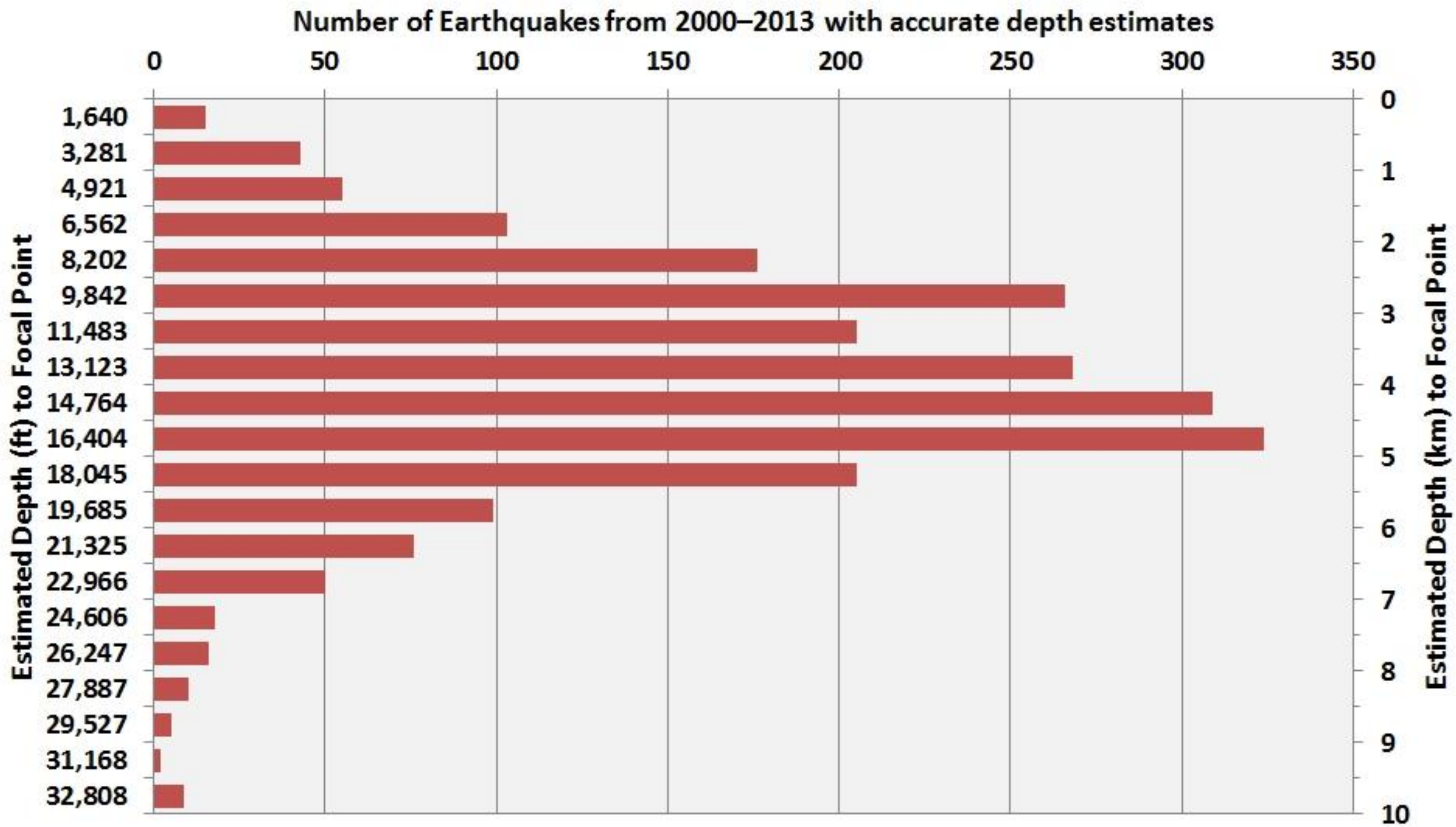

Figure 22 Number of earthquakes versus depth of focal point for 2000–2013

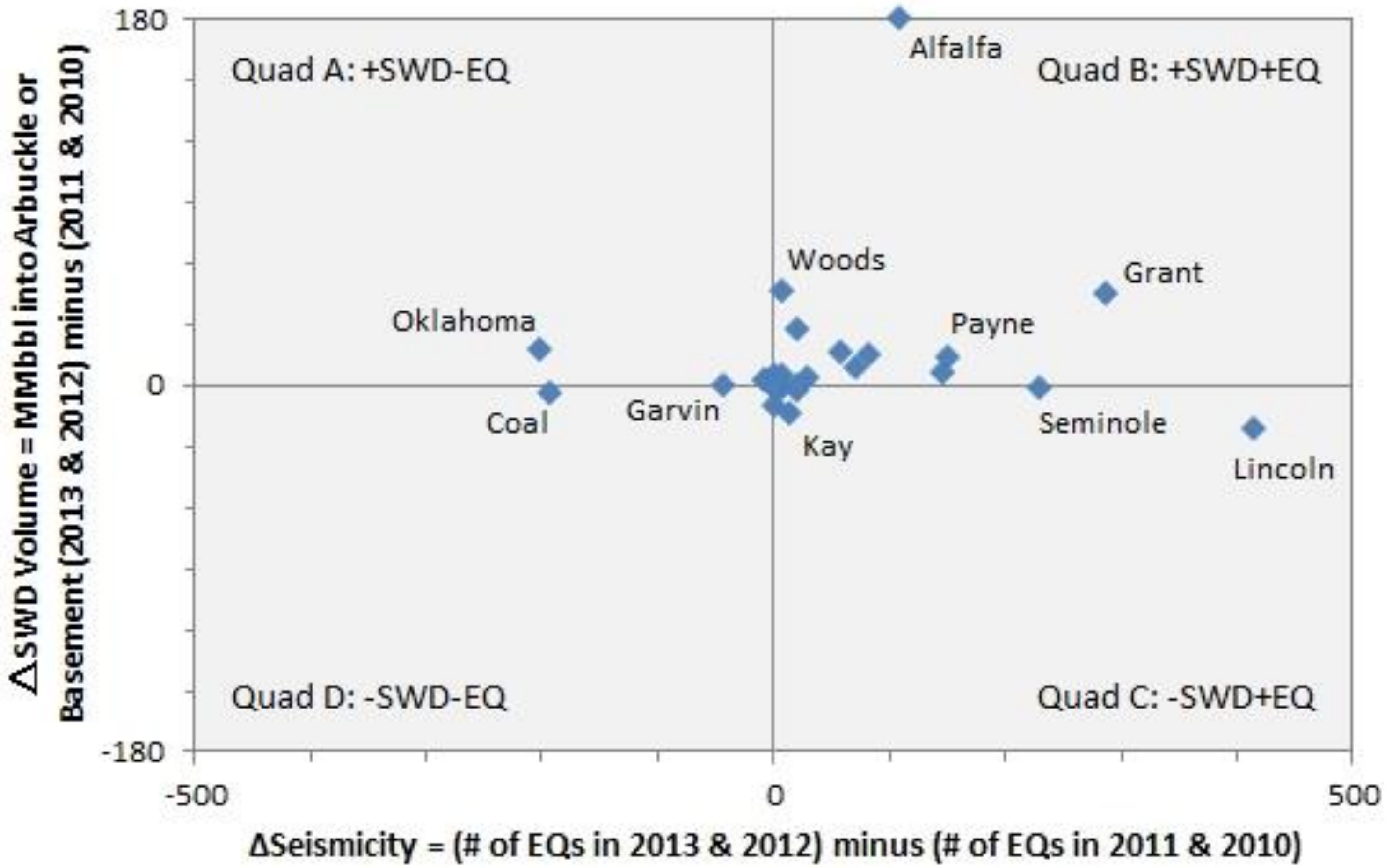

Figure 23 Spatiotemporal comparison of change in SWD versus change in seismicity at a county-scale