Class II Saltwater Disposal for 2009–2014 at the Annual-, State-, and County- Scales by Geologic Zones of Completion, Oklahoma

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Preface:

This Open-File Report presents a summary of data compiled from Oklahoma Corporation Commission (OCC) records. This report supersedes papers, reports, or conference slides previously presented by the author. Subsequent updates, though not expected to be substantial, may be required as other records and data are made available by operators or the OCC.

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Abstract

This report is an update for an ongoing research effort to compile Oklahoma's Class II underground injection control (UIC) well data by geologic zone of completion on annual-, state-, and county- scales. Because most previous studies indicate that saltwater disposal (SWD) wells are of greater concern than enhanced oil recovery injection (EORI) wells, only SWD data were compiled, updated, and reported. Thousands of annual fluid injection, well completion, mechanical integrity test, and permit reports, filed by operators with the Oklahoma Corporation Commission (OCC), were the primary sources of data. SWD well data were compiled into a relational database, checked against scanned and electronic OCC records, and then summarized at annual-, state-, and county- scales.

Based on data compiled for this report, estimated statewide (excluding Osage County) SWD volumes were 849, 861, 976, 1051, 1326, and 1538 million barrels (MMbbl) for the respective years 2009–2014. Annual SWD volumes increased substantially (i.e., more than 50 MMbbl) in Alfalfa (+282 MMbbl), Grant (+70 MMbbl), Woods (+67 MMbbl), Payne (+63 MMbbl), and Garfield (+50 MMbbl) Counties from 2009–2014, while SWD volumes decreased substantially in only Lincoln County (-56 MMbbl) over that same time period. Increases in SWD volumes likely coincided with the onset of dewatering operations in the Hunton Lime and Mississippian plays, which produce large volumes of water per unit of oil or gas. The Arbuckle basal sedimentary strata were the target for the majority of Class II UIC SWD volumes in Oklahoma. Statewide Arbuckle zone SWD volumes comprised more than 50% of the statewide total with about 434 (51%), 449 (52%), 525 (54%), 566 (54%), 843 (64%), and 1047 (68%) MMbbl for the respective years 2009–2014. Arbuckle zone SWD wells are predominantly located in the Cherokee Platform or Anadarko Shelf geologic provinces where Hunton and Mississippian operations were active. Mean disposal rates for SWD wells completed in the Arbuckle zone substantially increased in 2013 to more than 1 MMbbl/yr and increased again in 2014 to more than 1.2 MMbbl/yr.

In future research, the UIC database will be continuously appended and updated with historic (≤ 2008) and new (2015 to present) data at a monthly timescale. Studies will continue to investigate geologic variability and properties of various zones, especially the Arbuckle because it is the primary disposal zone in Oklahoma. SWD data will be integrated with other geologic data to better understand complex relationships between hydrogeology, geomechanics, seismology, market forces, operational changes, and regulatory controls.

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1. Introduction

Petroleum was produced in Oklahoma before 1900 and has been continuously produced and reported for more than 100 years (Figure 1). Oil production peaked at about 278 million barrels of oil (MMBO) in 1927 (Murray and Holland 2014) and gas production peaked at about 376 million barrels of oil equivalent (MMBOE) in 1990 (EIA 2015). Less than 100 MMBO per year were produced in Oklahoma after 1992 with an annual low of about 61 MMBO in 2005, but a resurgence in production occurred in recent years because of technological innovation and economic drivers (Murray and Holland 2014). In 2014, about 128 MMBO were produced in Oklahoma, largely from sandstone and carbonate dominated zones (Murray 2016-*in preparation*). Annual gas production in Oklahoma, after 1990, fluctuated to a lesser degree than oil production with an annual low of about 260 MMBOE in 2003. Oklahoma's new peak annual gas production occurred in 2014 with about 385 MMBOE (EIA 2015), and the unconventional Woodford Shale being the most prominent gas-producing zone (Murray 2016-*in preparation*).

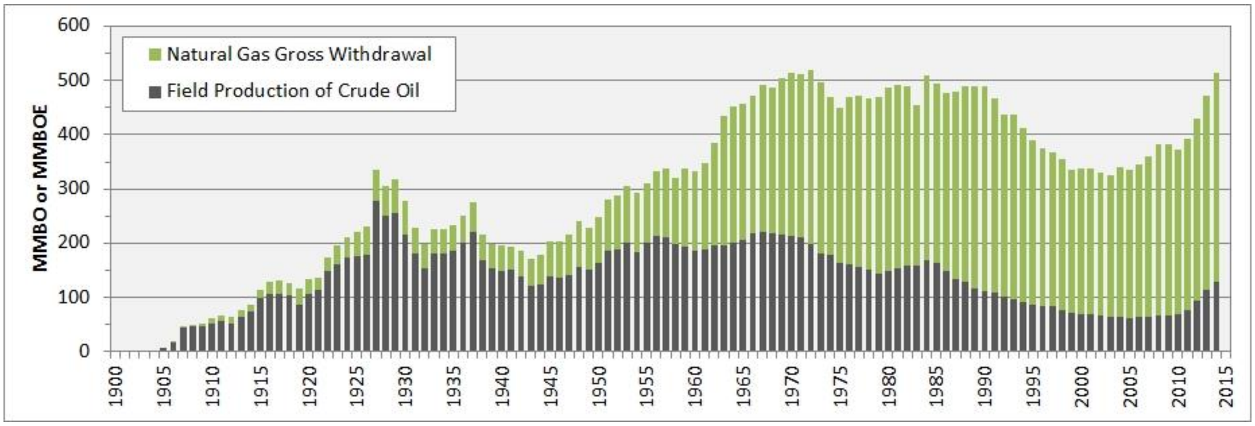

Figure 1 Annual natural gas gross withdrawal and annual field production of crude oil from petroleum producing wells in Oklahoma

1.1. *Co-Produced Water and SWD*

Concurrent with increased petroleum production by unconventional methods (e.g., horizontal wells, production from shale zones, and dewatering) has been an increased rate of co-production of saltwater from the producing zones. Oklahoma's statewide co-produced water volumes were estimated, by multiplying H_2O:oil ratio by oil production and H_2O:gas ratio by oil-equivalent gas production, to range from 811–925 million barrels (MMbbl) from 2000–2011 (Murray 2013). 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, which may not have been accounted for by Murray (2013) when he used median H_2O:oil and H_2O:gas ratios. Therefore, the estimates of statewide produced water volumes by Murray (2013) were likely underestimating actual produced water volumes. Refined estimates of produced water volumes indicate a rate of about 3000 MMbbl per year in Oklahoma from 2009–2014 (Murray 2016-*in preparation*).

SWD volumes in Oklahoma steadily increased from about 877 million barrels (MMbbl) in 2010 to >1066 MMbbl in 2013 (Murray 2014); however, annual fluid injection reports were incomplete at the time of publication. The Arbuckle Group (Arbuckle) has been documented as the predominant target disposal zone regardless of the version of the database (Murray 2014, Murray and Holland 2014). Therefore, the update presented in this report will further refine the SWD volumes reported by Murray (2014) and expand the database to include 2009 and 2014 data with an emphasis on validating data for wells completed in the Arbuckle.

1.2. *Objectives*

The objectives of this ongoing research effort include continuing to append and update 2009–2014 SWD volume and well completion data previously compiled by Murray (2014), validating data against online annual fluid injection, well completion, permits, other reports, and summarizing SWD data at an annual-, state-, and county- scale by disposal zones.

2. Methods

A relational database developed by Murray (2014) was appended and updated throughout the 2015 calendar year. Data for Osage County were not included because a considerable investment of time and resources would have been required to append and validate with the Osage SWD well data. American Petroleum Institute (API) unique identifiers for wells (i.e., API number) were used to manage individual well records in the database, and relate to data reported to OCC.

2.1. *Compile SWD Well Data*

Operator number, well name, ten-digit API number, type of well (e.g., SWD, 2D, 2DNC, or 2DCm), type of fluid injected/disposed (e.g., Brackish Water, Fresh Water, or Salt Water), ‘total annual injected or disposed volume of fluids’ in bbls/yr, and ‘average daily wellhead pressure’ in pounds per square inch (psi) were obtained from Annual Fluid Injection Reports (i.e., Form 1012A) that were published online (OCC 2015). When injection depth and completion/production zone were not previously attributed, these data were obtained from digitally accessible OCC records and updated in the database. Disposal intervals were represented using twelve “zones” including Multiple-Undifferentiated, Other or Unspecified, Permian, Virgilian, Missourian, Desmoinesian, Atokan-Morrowan, Mississippian, Woodford, Devonian to Middle Ordovician (Dev to Mid Ord), Arbuckle, and Basement (Figure 2). ‘Producing’ or ‘injection’ formation(s) were correlated to the appropriate zone based on the Stratigraphic Guide to Oklahoma Oil and Gas Reservoirs (Boyd 2008) and General Geologic Sections of Oklahoma and Northern Arkansas (Cipriani 1963). 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) not within one of the ten designated zones was used for injection or the target formation was not discernible, then the well was attributed as ‘Other or Unspecified’. SWD well records in the database were also attributed with maximum injection depth based on deepest perforated or open-hole interval reported on the well completion report (i.e., Form 1002A), mechanical integrity test (i.e., Form 1075), or permit (i.e., Form PER).

Zone	Group	Formation
Multiple-Undiff		
Other or Unspec.		
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 - Deese	Oswego
	Cabaniss - Deese	Skinner
	Krebs - Deese	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
	Hunton	Frisco
		Bois d'Arc
		Henryhouse
		Chimneyhill
	Cincinnatian	Sylvan
		Viola
	Simpson	Bromide
		Wilcox
		McLish
		Oil Creek
Arbuckle	Arbuckle Group	West Spring Creek
		Kindblade
		Cool Creek
		McKenzie Hill
		Butterly dolomite
		Signal mountain
		Royer dolomite
		Fort sill limestone
Basement & Crystalline Rock	Cambrian	Reagan
	Pre-Cambrian	Granite

Key to Symbols
Sandstone
Carbonate
Shale
Coal
Granite

Figure 2 Simplified stratigraphic guide to geologic zones targeted in Oklahoma for completion of petroleum producing or saltwater disposal wells, modified from Murray and Holland (2014) and based on Boyd (2008) and Cipriani (1963)

2.2. *Quality Assurance Quality Control (QAQC) check of SWD Data*

Total annual injected or disposed volume of fluids recorded in various OCC underground injection control (UIC) databases (OCC 2014a, OCC 2014b) included carbon dioxide (CO_2) in units of million cubic feet (MCF) or liquefied petroleum gas (LPG) in units of barrels (bbls) in addition to brackish-, fresh-, or salt- water in units of bbls. Therefore, total annual injected or disposed volume of fluids required a quality assurance quality control (QAQC) check by comparing and manually validating against scanned 'Form 1012A: Annual Fluid Injection Reports' from UIC operators. Annual volumes were modified in the Oklahoma UIC database to ensure that only water volumes were recorded in the QAQC checked database. Total annual injected or disposed volumes of fluids were also corrected, for example, when calculated annual volumes were miscalculated as a result of operators reporting barrels per day (BPD) instead of barrels per month (BPM) for monthly volumes on scanned hand-written 1012As from 2009 or 2010.

Because Form 1012As continue to be submitted to and/or published by the OCC, it is highly likely that continuing updates of the UIC database will result in additional wells being added to the inventory for each year. An estimated 50–150 SWD wells may be appended to the 2009 and 2014 datasets, and included in future updates to this report.

2.3. *Summarize Annualized SWD Volumes by Zone and by County*

Class II UIC wells that were reported as SWD, 2D, 2DNC, or 2DCm were selected (i.e., queried) from the Oklahoma UIC database. Annual disposed volumes of water were summed for each year from 2009–2014 after grouping the selected wells by injection zone (e.g., Permian), injection type (i.e., 2D), and county.

3. Results

SWD volumes can be summarized at a variety of scales from the UIC database; however, annual-, state-, and county- scales are presented in this report to be consistent with previous reports (Murray 2014, Murray and Holland 2014).

3.1. *SWD Volumes per Zone*

Despite the limitations and dynamic nature of the UIC database, several observations can be made about SWD volumes in Oklahoma. Annual SWD volume into all zones increased from about 849 MMbbl in 2009 to more than 1538 MMbbl in 2014 (Table 1, Figures 3 and 4). Annual SWD volume into the Arbuckle increased from about 434 MMbbl in 2009 to more than 1046 MMbbl in 2014 (Table 1, Figures 3 and 4). From 2009–2014 there was little change in volumes disposed into other zones, but disposal volumes into the Arbuckle zone increased by about two-and-one-half times (Figure 4). A substantial increase of fluid injection into the Arbuckle, unless balanced by fluid production, would theoretically lead to an increase in the Arbuckle "reservoir" pressure. Increase in Arbuckle zone disposal volumes has motivated more intensive studies of Arbuckle rock properties (Morgan and Murray 2015) and modeling of pressure change along fault zones (Carrell and Murray 2016-*in preparation*).

Table 1 Annual, 2009–2014, saltwater disposal (SWD) volumes in thousands of barrels (Mbbl) per zone

Zone	Mbbl of SWD in 2009	Mbbl of SWD in 2010	Mbbl of SWD in 2011	Mbbl of SWD in 2012	Mbbl of SWD in 2013	Mbbl of SWD in 2014
Multiple-Undiff	114837	119355	141226	135938	131955	131646
Other or Unspec.	13921	11213	12270	11752	11713	10745
Permian	48996	51156	69411	82715	87947	89770
Virgilian	27261	27360	29359	38863	38687	42222
Missourian	21706	25912	24601	29348	31656	34438
Desmoinesian	32894	33267	33504	34825	33565	32450
Atokan-Morrowan	40812	33886	34963	40140	35831	33581
Mississippian	9102	9354	9259	9140	8531	8315
Woodford	838	415	434	244	265	258
Dev to Mid Ord	102868	98721	94838	100482	102070	105858
Arbuckle	434230	449406	525027	566047	842631	1046913
Basement	1368	771	621	1379	820	2162
Statewide Total	848832	860817	975513	1050873	1325670	1538358

3.2. *Number of SWD Wells and Disposal Rates per Well*

Based on data compiled for this report, an estimated 2777, 2729, 2855, and 2808 active SWD wells were disposing water into other zones (i.e., not Arbuckle) for the respective years 2010–2013 (Figure 5) versus Murray's (2014) previously reported numbers of 2820, 2684, 2840, and 2530 active SWD wells disposing into other zones for the respective years 2010–2013. Figure 5 illustrates the number of active (i.e., ≥1 bbl water disposed) SWD wells disposing into the

Arbuckle zone versus the number of active SWD wells disposing into other zones. Discrepancies between the number of active SWD wells reported by Murray (2014) and the current UIC database is the result of combination of (A) additional Form 1012As were submitted to and/or published by the OCC after December 30, 2014, the date of the Murray (2014) report; or (B) types of wells were reclassified from 2R to 2D or 2D to 2R because the addition of 2009 and 2014 data indicated that the type of well was previously misrepresented. There were about 2764 active SWD wells disposing into other zones during 2014 versus about 2773 active SWD wells disposing into other zones in 2009 (Figure 5).

There were 475, 540, 675, and 767 active Arbuckle SWD wells for the respective years 2010–2013 (Figure 5) versus Murray's (2014) previously reported numbers of 477, 537, 667, and 667 active wells disposing into the Arbuckle Group for the respective years 2010–2013. The substantial difference between the number of active SWD wells reported by Murray (2014) for 2013 and the current UIC database is largely the result of additional Form 1012As being submitted to and/or published by the OCC after December 30, 2014, the date of the Murray (2014) report. There were about 839 active SWD wells disposing into the Arbuckle during 2014 versus about 456 active SWD wells disposing into the Arbuckle in 2009 (Figure 5).

Mean disposal rates for SWD wells (Figure 6) completed in other disposal zones (i.e., not Arbuckle) increased steadily but subtly from 2009 (150,000 bbl/yr) to 2014 (178,000 bbl/yr). Mean disposal rates for SWD wells completed in the Arbuckle zone substantially increased in 2013 to more than 1 MMbbl/yr and increased again in 2014 to more than 1.2 MMbbl/yr (Figure 6).

3.3. *SWD Volumes by County*

Petroleum production, co-production of water, and SWD vary substantially in space and time (Murray 2016-*in preparation*); therefore, it is best to view trends on a smaller spatial scale (i.e., county-scale). Locations and average SWD rates (bbl/yr) are illustrated in map view (Figure 7) for all active wells in Oklahoma, while only active SWD wells disposing into the Arbuckle zone are illustrated in Figure 8. The large majority of Arbuckle zone SWD wells are located in the Cherokee Platform or Anadarko Shelf geologic provinces (Figure 8), which are separated by the Nemaha Fault zone and Nemaha Uplift in central and north-central Oklahoma (Holland 2015, Northcutt and Campbell 1995).

Sixty-six counties in Oklahoma had ≥1 bbl water disposed into Class II SWD wells from 2009–2014, with statewide total SWD volumes increasing by about 690 MMbbl from 2009 to 2014 (Table 2). SWD volumes increased from 2009–2014 in 43 out of the 66 counties, with the greatest county-scale increases of 282, 70, 67, and 63 MMbbls occurring in Alfalfa, Grant, Woods, and Payne Counties, respectively (Table 2). Arbuckle zone disposal in these counties accounts for a large proportion of the statewide increase from 2009–2014, and is closely related to increases in co-produced water volumes generated by a few major operators in the Mississippian (Murray 2016-*in preparation*).

Table 2 Annual, 2009–2014, saltwater disposal (SWD) volumes in thousands of barrels (Mbbl) by County

County	Mbbl of SWD in 2009	Mbbl of SWD in 2010	Mbbl of SWD in 2011	Mbbl of SWD in 2012	Mbbl of SWD in 2013	Mbbl of SWD in 2014	∆SWD 2014 - 2009
Alfalfa	16566	18905	62053	38564	249884	298582	282016
Beaver	3664	4346	6927	11875	16355	13474	9810
Beckham	8038	8218	12336	11808	10796	10478	2441
Blaine	4188	5170	9187	10013	6546	5836	1649
Bryan	40	0	0	136	43	56	16
Caddo	6764	6193	6632	7605	7091	4856	-1908
Canadian	6387	6823	7922	10557	15160	18364	11977
Carter	11475	15097	15490	18456	21262	25878	14403
Cimarron	204	407	150	150	213	305	100
Cleveland	2409	2356	2314	2096	2214	2192	-217
Coal	9098	12098	8030	5497	6245	5877	-3221
Comanche	169	152	154	152	156	174	5
Cotton	1814	1407	1070	1607	2344	2291	478
Craig	169	449	29	257	168	125	-44
Creek	55223	57806	48357	55472	43279	56069	846
Custer	509	504	1366	4399	3562	3763	3254
Dewey	9418	5488	11093	20119	21564	20682	11264
Ellis	2233	3070	5853	7705	11621	12041	9807
Garfield	14506	14609	16231	19690	31533	69877	55372
Garvin	14656	14543	17594	21751	18606	17831	3175
Grady	4746	4549	4961	5498	5592	7456	2710
Grant	11706	10947	27922	18320	74416	81530	69825
Greer	11	11	5	18	21	21	10
Harmon	18	18	24	23	32	31	13
Harper	5961	5111	3875	3447	2968	3229	-2732
Haskell	25	21	17	9	8	5	-20
Hughes	16185	13812	17157	16474	16166	15725	-461
Jackson	438	405	337	486	510	590	152
Jefferson	1675	1697	1776	1841	1774	1362	-313
Kay	31240	77199	99377	103812	59486	61336	30096
Kingfisher	6584	6740	7136	6369	9464	15150	8567
Kiowa	241	135	67	127	169	168	-73
Latimer	1163	1116	1049	939	914	801	-362
Le Flore	409	343	340	272	286	247	-162
Lincoln	113519	77878	72284	64986	57735	58019	-55500
Logan	8424	7345	9019	11464	18227	38152	29729
Love	1225	1162	1134	1317	1449	777	-449
Major	10011	9423	10232	9677	8385	10589	579
Marshall	86	87	84	163	171	143	58
Mayes	0	0	15	0	0	0	0
McClain	5129	3271	3958	4839	5329	5454	325

County	Mbbl of SWD in 2009	Mbbl of SWD in 2010	Mbbl of SWD in 2011	Mbbl of SWD in 2012	Mbbl of SWD in 2013	Mbbl of SWD in 2014	ΔSWD 2014 - 2009
McIntosh	3451	3394	3658	2684	1770	1560	-1891
Murray	8733	5871	10232	10555	8806	10341	1609
Muskogee	2174	1182	1125	701	665	467	-1707
Noble	40605	37640	32529	43377	59392	71767	31161
Nowata	5141	5631	5120	5793	6756	5632	491
Okfuskee	15265	19129	22063	23865	17953	16500	1235
Oklahoma	63483	64548	67459	77430	70231	72904	9421
Okmulgee	5399	6730	6933	6784	6198	6140	741
Pawnee	9509	13365	13728	18392	27788	26123	16614
Payne	19039	16843	18450	24808	35373	81904	62866
Pittsburg	2531	2890	2646	4423	4818	4097	1566
Pontotoc	15954	18413	18049	20567	18656	16545	592
Pottawatomie	56825	57380	55223	56756	58084	54320	-2504
Roger Mills	7918	6516	13085	14710	10662	11102	3184
Rogers	1101	1076	1220	1081	1036	798	-303
Seminole	104051	102993	98771	113802	111109	119085	15034
Stephens	17194	16367	16315	17054	17672	22877	5683
Texas	5486	4641	4239	6569	7043	4300	-1187
Tillman	892	1025	1058	1487	1759	2205	1312
Tulsa	5194	4943	5211	4817	5250	5163	-31
Wagoner	1562	1440	1355	1569	1456	1472	-89
Washington	8717	8290	7309	7678	7344	7871	-846
Washita	4230	5234	5369	4652	4208	4267	37
Woods	50196	46921	61431	75555	105329	116739	66542
Woodward	7859	9442	9376	7770	4563	4642	-3217
Statewide Total	848832	860817	975513	1050873	1325670	1538358	689526

3.4. *Arbuckle Zone SWD Well Injection Depths*

Injection intervals of Arbuckle SWD wells were appended and updated in the UIC database. Median Arbuckle SWD well injection depth varied from about 4000 ft in the Ardmore Basin or Arbuckle Uplift to more than 10,000 ft in the Anadarko Basin (Figure 9). The majority of Arbuckle SWD wells (Figure 8) are completed in the Cherokee Platform (555 wells) or Anadarko Shelf (256 wells) with respective median depths of 5134 ft and 7572 ft (Figure 9).

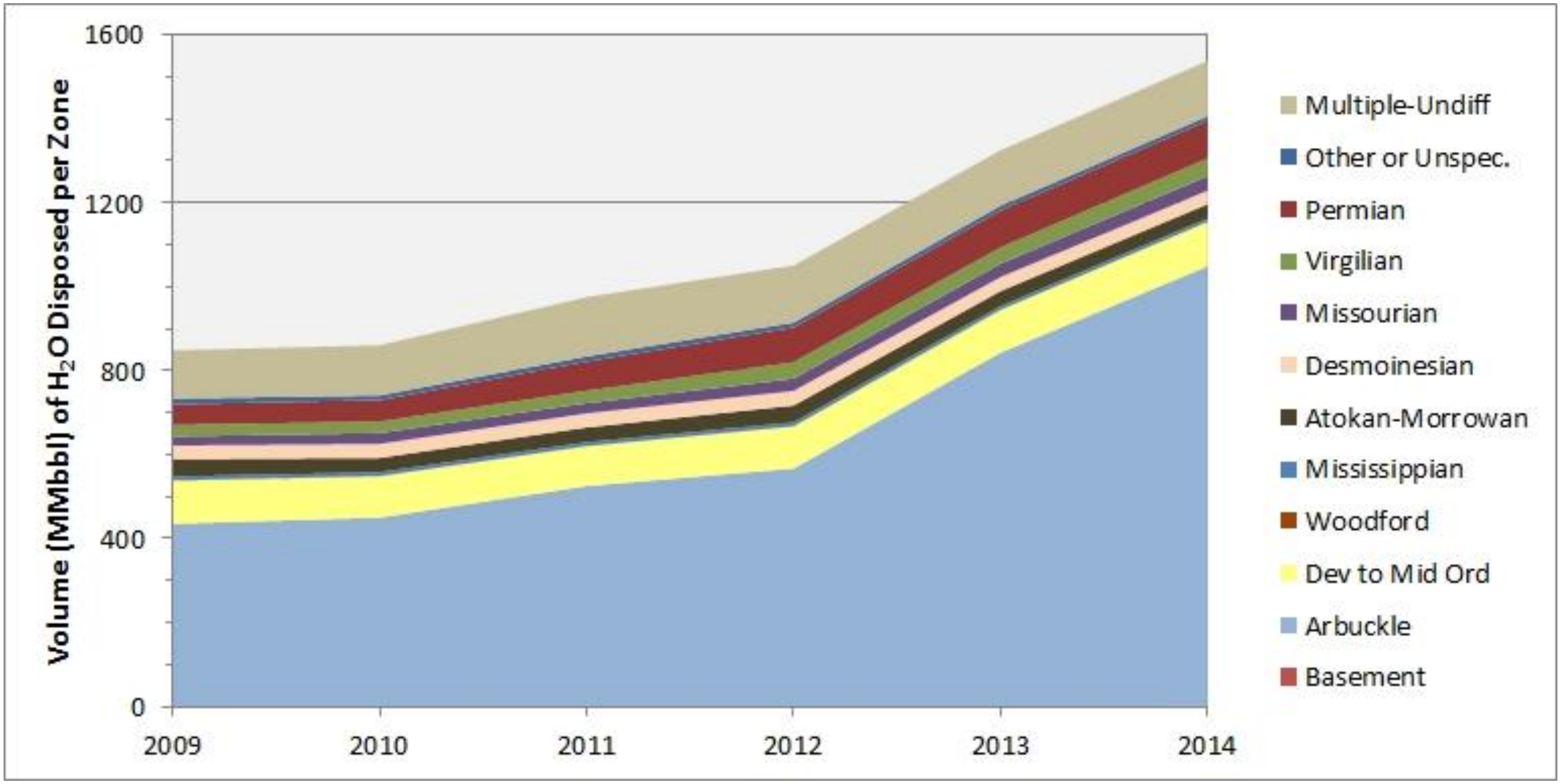

Figure 3 Annual volumes of saltwater or brackish water reportedly disposed into Oklahoma SWD wells, by zone, from 2009–2014

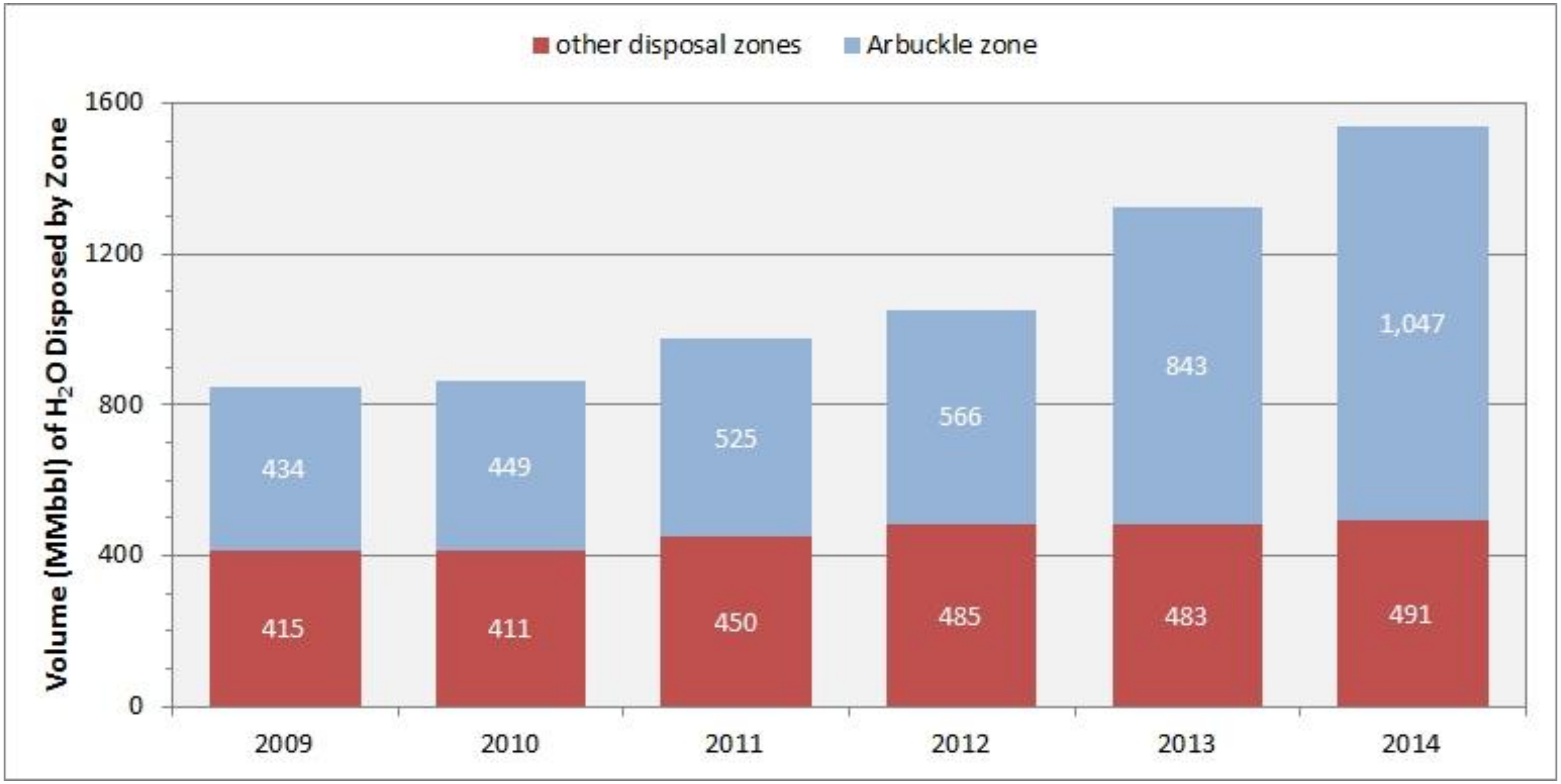

Figure 4 Annual volumes of saltwater and brackish water reportedly disposed into Oklahoma's Arbuckle or other disposal zones from 2009–2014

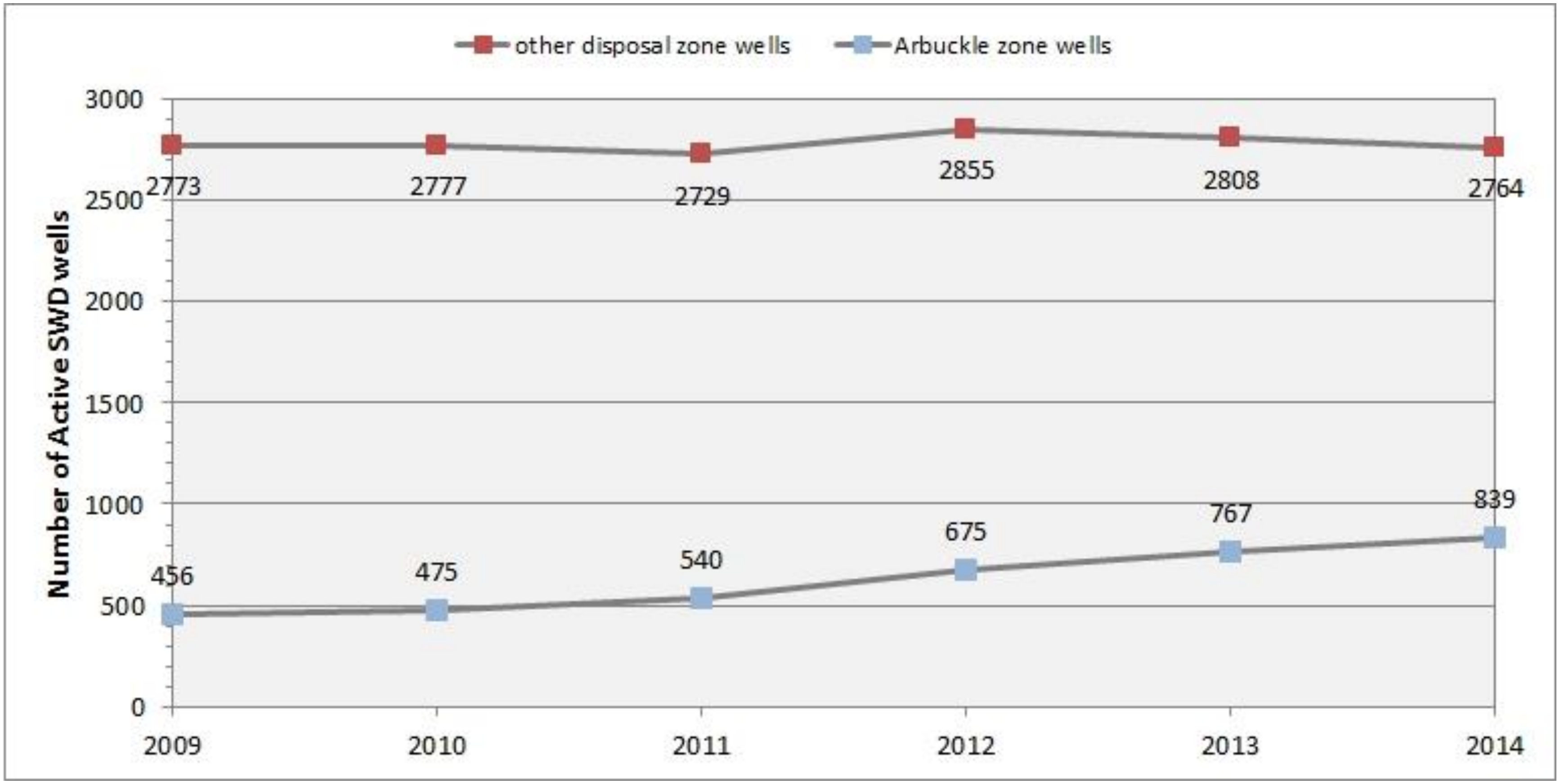

Figure 5 Number of active saltwater disposal (SWD) wells in Oklahoma from 2009–2014

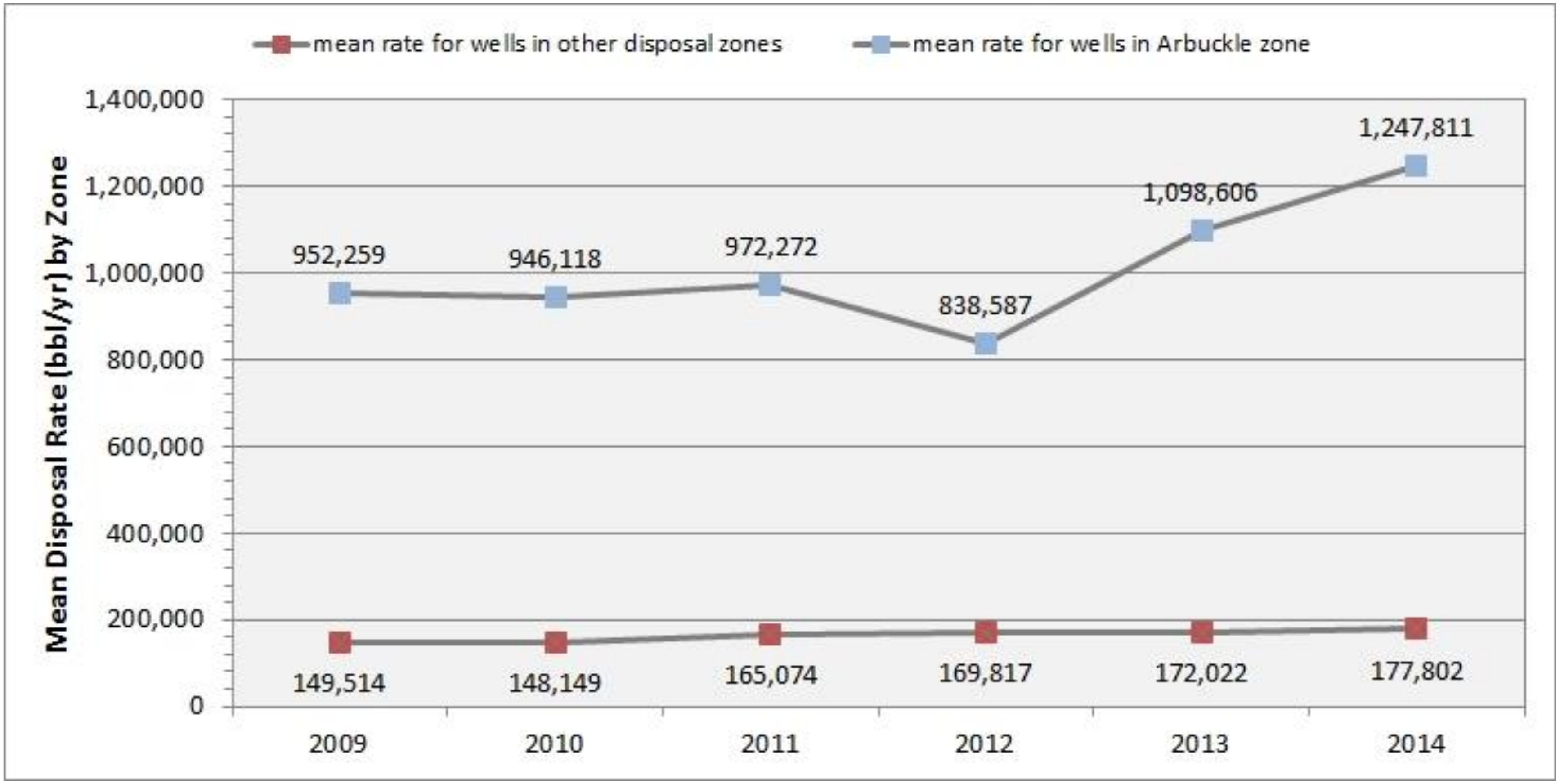

Figure 6 Mean annual disposal rate (bbl/yr) for wells completed in the Arbuckle zone versus wells completed in other disposal zones

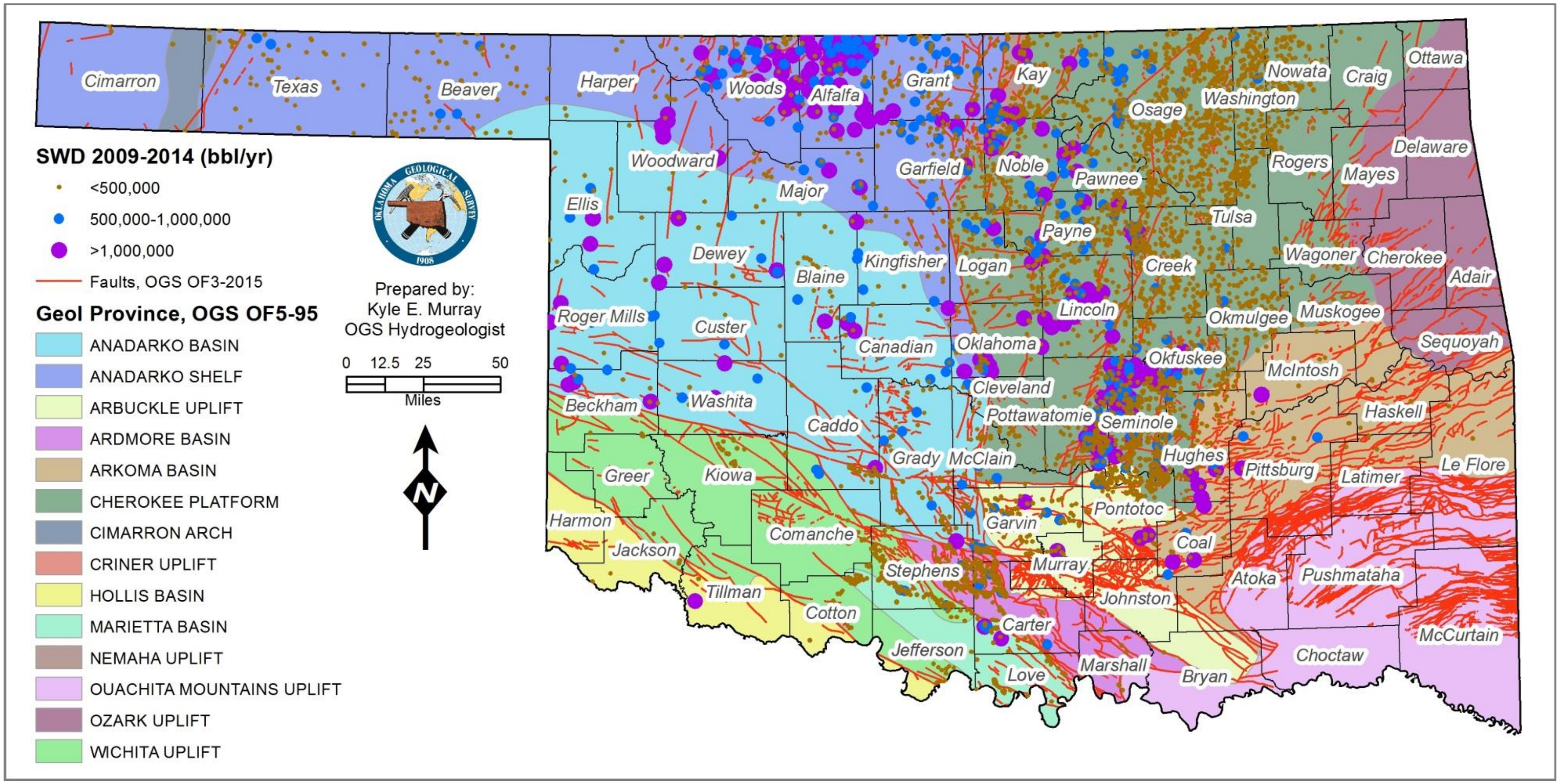

Figure 7 Map of saltwater disposal (SWD) wells for all disposal zones symbolized with relative disposal rate (bbl/yr), also showing regional-scale fault locations (Holland 2015), and geologic provinces (Northcutt and Campbell 1995)

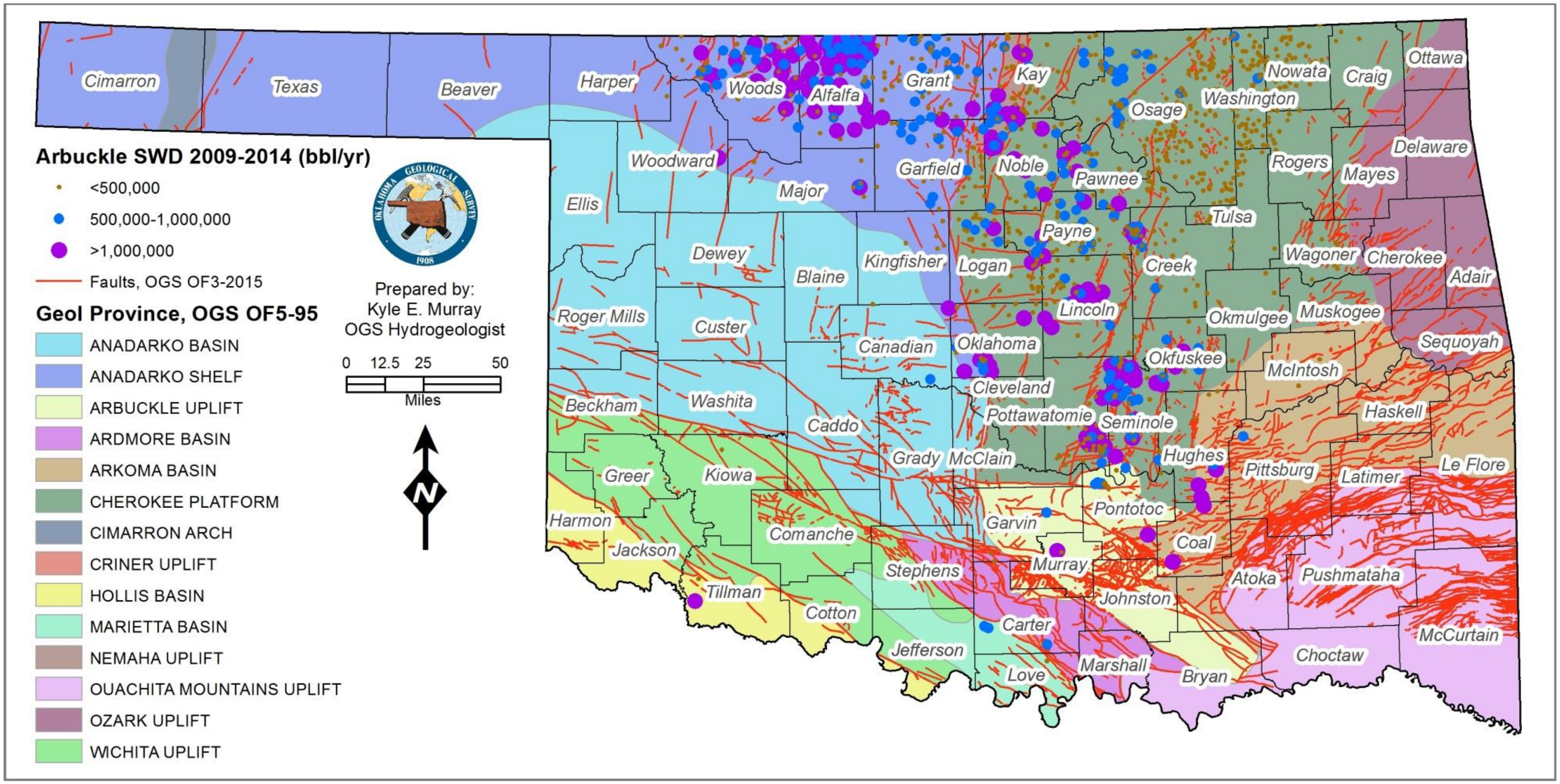

Figure 8 Map of saltwater disposal (SWD) wells for Arbuckle disposal zone symbolized with relative disposal rate (bbl/yr), also showing regional-scale fault locations (Holland 2015), and geologic provinces (Northcutt and Campbell 1995)

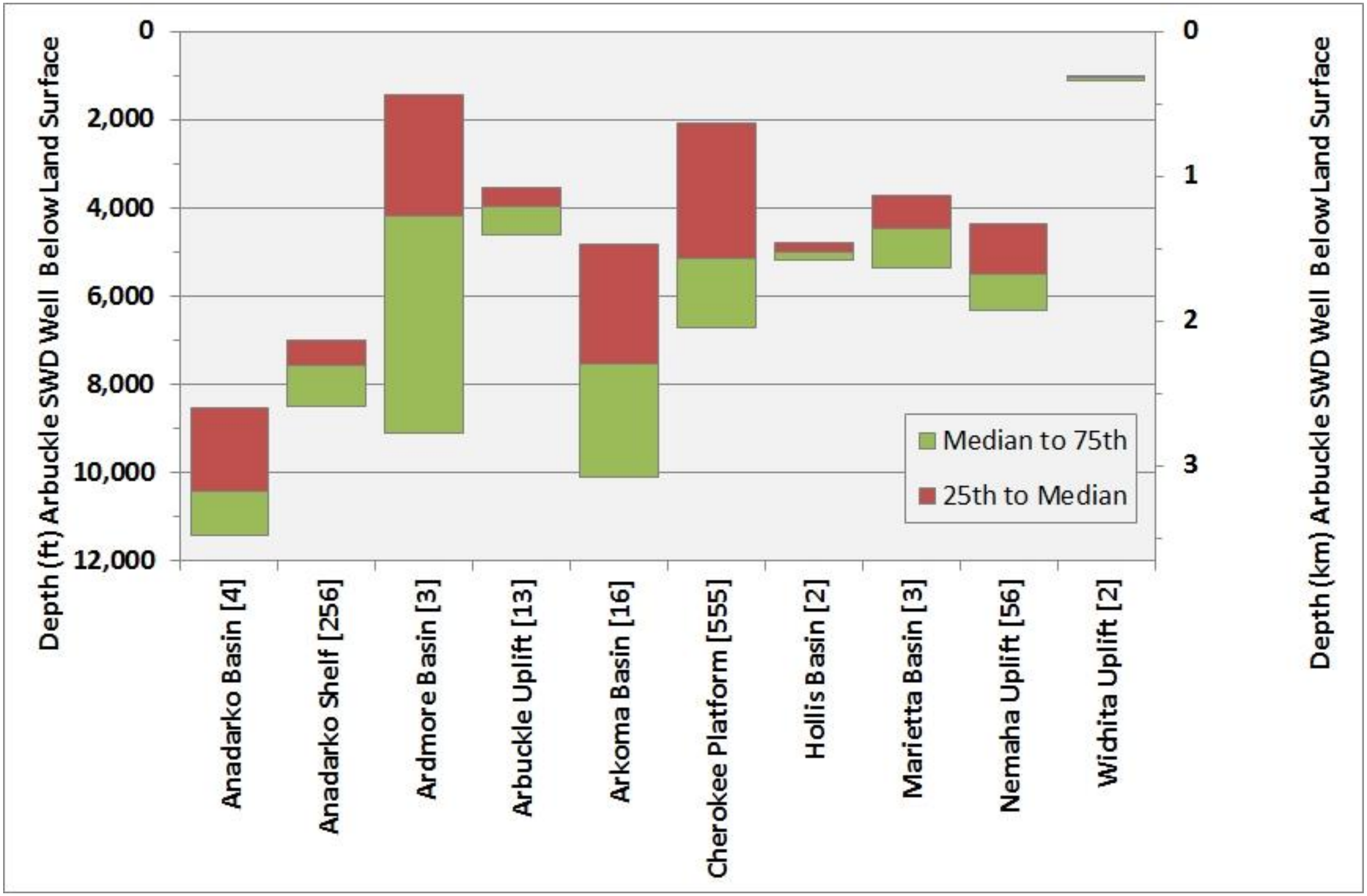

Figure 9 Interquartile range of depths below land surface for Arbuckle SWD wells, by geologic province

4. Future Directions

The UIC database described in this report must be continuously appended and updated with historic (≤ 2008) and new (2015 to present) data including SWD volumes, EORI volumes, and average wellhead pressures, preferably with monthly or shorter timescales. These data must be QAQC checked to ensure accuracy and to fill data gaps that may still exist in the UIC database.

Research must continue to focus on understanding geologic variability and properties of various zones, especially the Arbuckle Group because it is the primary disposal zone in Oklahoma. This would include compilation and analysis of well bottomhole pressures from drill-stem-test (DST) data, and acquisition of reservoir pressure data from repeat formation tester (RFT), Modular Formation Dynamics Tester (MFDT), Wireline Formation Tester (WFT), or Multiprobe Formation Tester (MFT) sources. Hydraulic conductivity (K) and specific storage (Ss) data for various zones by depth and formation must also be compiled, and then used to compute and possibly map hydraulic diffusivity in three-dimensions. Fluid production and injection volumes must be calculated at a small- (i.e., county) scale to understand the relative pressure change from 2009–2014 in various zones so that spatial trends can be examined. These data must then be integrated with other geologic data to better understand complex relationships between hydrogeology, geomechanics, seismology, market forces, operational changes, and regulatory controls.

5. Acknowledgements

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