CENTER for BIOLOGICAL DIVERSITY
Because life is good.

May 9, 2016

VIA ELECTRONIC DELIVERY

Secretary Sally Jewell
Department of the Interior
1849 C Street, N.W.
Washington D.C. 20240
exsec_exsec@ios.doi.gov

Director Neil Kornze
Bureau of Land Management
1849 C Street, N.W., Rm. 5665
Washington DC 20240
director@blm.gov

Lieutenant General Thomas P. Bostick
Commanding General and Chief of Engineers
U.S. Army Corps of Engineers
441 G Street, NW
Washington, D.C. 20314-1000
hq-realestate@usace.army.mil

Re: Man-made earthquake risks connected to April 20, 2016 Oil and Gas Lease Auction

Dear Secretary Jewell, Director Kornze, and Lieutenant General Bostick:

We write to urge you to protect communities from man-made earthquakes by not issuing 11 leases for oil and gas development on over 2,300 acres in Oklahoma and Kansas that were auctioned by the Bureau of Land Management's New Mexico State Office on April 20, 2016.[1]

We are deeply concerned that increased hydraulic fracturing and underground injection of oil wastewater within or around the leased areas will increase earthquake risks resulting from underground wastewater disposal and threaten the physical safety and homes of tens of thousands of residents.

[1] BLM has stated it will not issue the leases until all protests have been resolved. The parcels at issue are: NM-201604-001, NM-201604-002, NM-201604-003, NM-201604-004, NM-201604-005, NM-201604-006, NM-201604-007, NM-201604-008, NM-201604-009, NM-201604-010, NM-201604-011.

Alaska . Arizona . California . Florida . Minnesota . Nevada . New Mexico . New York . Oregon . Vermont . Washington, DC
Wendy S. Park, Staff Attorney, Public Lands Program . 1212 Broadway, Suite 800 . Oakland, CA 94612
Phone: 510-844-7100 x 338 . Fax: 510-844-7150 . wpark@biologicaldiversity.org

Concerns about oil industry-induced earthquakes are backed by solid science. Two recent studies by the U.S. Geological Survey (USGS) and U.S. Army Corps of Engineers (Army Corps), discussed below, highlight and confirm these risks. But despite skyrocketing injection-induced earthquakes in Oklahoma in recent years, BLM failed to even mention the problem of induced seismicity in its Environmental Assessment for the lease auction, in violation of the National Environmental Policy Act (NEPA). BLM's total disregard for this issue is irresponsible and wrong, and adds insult to injury for the communities at risk.

Earthquake activity in Oklahoma has increased dramatically in recent years as a direct result of underground oil and gas wastewater disposal,[2] which jeopardizes the safety of Oklahoma's communities. Oklahoma's earthquake activity is 600 times greater than it was prior to 2008 according to the Oklahoma Geological Survey, and earthquakes swarms are occurring over a large portion of Oklahoma covering about 15% of the state's area.[3] The largest earthquake attributed to oil and gas wastewater injection in the U.S. was a magnitude 5.6 earthquake in 2011 near Prague, Oklahoma, outside of Oklahoma City, the biggest in the state's history.[4] It injured two people, destroyed 14 homes, and caused millions of dollars' worth of damage to homes and buildings near the epicenter.

On March 30, 2016, we submitted to BLM the USGS's newly released 2016 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes.[5] The USGS study contains important analyses that BLM should have considered before the lease auction. First, it evaluated the risk of damage from both natural and induced earthquakes in Oklahoma and other states and displayed the areas at risk on a map. A map we have prepared overlaying the April 2016 lease parcels on this map (Exhibit A) shows that at least four parcels lie in areas that already have a significant risk of damage from induced earthquakes caused by existing oil and gas industry activities:

- Parcel 8, which is within a few miles of Fairview in central Major County, is within an area that has an extremely high 5%-10% risk of damaging shaking in 2016, principally from induced earthquakes, which is similar to the chance of damage at high-hazard sites in California.[6] A seismic activity map that we previously submitted shows that this area has experienced numerous earthquakes since 2005.[7]

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[2] Keranen, K.M. et al. 2013. Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence. Geology 41: 699-702; Keranen, K.M. et al. 2014. Sharp increase in Central Oklahoma seismicity since 2008 induced by massive wastewater injection, Science 345: 448-451 (Exhibit F).

[3] Oklahoma Geological Survey. 2015. Statement on Oklahoma Seismicity, April 21, 2015, available at http://wichita.ogs.ou.edu/documents/OGS_Statement-Earthquakes-4-21-15.pdf (Exhibit G).

[4] Keranen, K.M. et al. 2014. Sharp increase in Central Oklahoma seismicity since 2008 induced by massive wastewater injection, Science 345: 448-451 ("Keranen 2014") (Exhibit H).

[5] USGS. 2016. One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes, Open-File Report 2016–1035 (2016) ("USGS 2016)"), available at http://pubs.usgs.gov/of/2016/1035/ofr20161035.pdf.

[6] USGS 2016 at 40.

[7] Exhibit B.

- Parcel 10 near Salpupa, Dewey County and Parcel 11 near Longdale and Canton in northern Creek County are within areas that have a 2%-5% risk of damage from earthquakes. Parcel 10 appears to be less than 25 miles away from the giant oil tank farm in Cushing, Oklahoma, which stores approximately 54 million barrels of oil in tanks that are not designed for severe shaking.[8]

- Parcel 9 in the northeastern edge of Roger Mills County near Leedey is within an area that has a 1%-2% risk of damage from earthquakes.

These risk evaluations are based on past patterns of earthquake activity.[9] With increased injection in and around the lease areas, the risk of induced seismicity and related damage could significantly increase. In addition, as noted in a recent *New York Times* article on the USGS study, the cumulative impact of many small, human-caused earthquakes may "set the stage for a larger, more destructive one."[10]

In addition, the USGS study mapped areas with wastewater injection wells that have been associated with induced seismicity, i.e., injection wells within a 15 km radius and active at the time of an earthquake.[11] We have prepared a map overlaying the lease parcels on this map (Exhibit D). It shows that parcel 7 near Perryton in southern Beaver County and parcel 8 in Major County overlie or are very near wastewater injection wells associated with earthquake activity.

In March 2016, the Army Corps also released a study analyzing the risks of fracking and wastewater injection near the Joe Pool Dam in Grand Prairie, Texas.[12] As a result of the study, the Corps increased the drilling setback from 3,000 feet to 4,000 feet away from the dam due to the risk of subsidence caused by gas production. It further stated it would "work to limit injection wells within five miles of the Joe Pool project," given the risk of damage to the dam from induced seismicity, and that these measures "are considered necessary to ensure that public safety is not reduced as a result of minerals related activities at Joe Pool."[13]

As we have explained before, this new information bears directly on the safety of drilling and especially wastewater injection that could occur on and around two Oklahoma parcels for lease

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[8] Exhibit C.
[9] USGS 2016 at 12 ("Our assessment of induced earthquake hazard was dependent on the assumption that past earthquake rates will remain constant over the next year of the forecast. While this assumption will not hold for areas of injection over long periods, recent studies…indicate that assessing earthquake rates observed over short time windows of a year or less are currently the best method available for forecasting the next year's rate of induced earthquakes. This model, however, does not account for increased, reduced, or new induced activity in 2016.").
[10] Wines, Michael, Drilling Is Making Oklahoma as Quake Prone as California, New York Times (March 28, 2016), available at http://www.nytimes.com/2016/03/29/us/earthquake-risk-in-oklahoma-and-kansas-comparable-to-california.html?smid=pl-share&_r=0.
[11] USGS 2016 at 6.
[12] See Army Corps, Dam Safety Implications of Drilling, Hydrofracturing and Extraction, Joe Pool Dam, Grand Prairie, Texas, 72-73 (February 2015), available at http://www.swf.usace.army.mil/Portals/47/docs/pao/JoePoolDrillingStudy_14Mar16_PublicRelease_Secured.pdf.
[13] *Id*. at 1.

that are only within a few miles of Heyburn Lake and Lake Canton (parcels 10 and 11), which are both drinking water supplies for residents in Creek County and Oklahoma City, respectively.[14] Importantly, a study of induced seismicity in central Oklahoma found that induced earthquakes can occur up to 21 miles (35 km) from the wastewater injection site,[15] indicating that dams could be susceptible to induced seismicity from drilling and injection on the nearby parcels. Earthquakes in the range of magnitudes 2.6 to 3.0 have occurred in the vicinity of parcel 11 near Lake Canton.[16] And as noted above both parcels are within areas that are at 2%-5% risk of damage from an earthquake, which new drilling and increased wastewater injections could make worse.

It is also critical to note that hydraulic fracturing and wastewater injection on parcels 10 and 11, which overlap Tiger Creek and the North Canadian River, could endanger downstream drinking water supplies stored in Heyburn Lake and Lake Canton. Before the April 20 auction, BLM withdrew all of the Texas parcels underlying or near dams, presumably out of concern for the dangers of oil and gas activities near dams and municipal water supplies. BLM must do the same here.

We urge the Secretary and BLM to halt issuance of all of the April 20 auctioned leases and request the Army Corps to withdraw parcels 10 and 11. BLM's failure to address induced seismicity risks violates NEPA, and issuing these leases for oil and gas production could put many communities in harm's way by increasing the risk of dangerous man-made earthquakes.

Please let us know if you have any questions, and thank you for considering our concerns.

Sincerely,

Wendy Park
Staff Attorney
Center for Biological Diversty

David Brown
Chair
Oklahoma Chapter Sierra Club

cc: Amy Lueders, Director, New Mexico State Office, BLM
Rebecca Hunt, Natural Resource Specialist – Minerals, New Mexico State Office, BLM
Colonel Richard A. Pratt, Commander and District Engineer, Tulsa District, Army Corps

[14] Exhibit C (maps of parcels 10 and 11); Exhibit E (April 20 email from Center for Biological Diversity to Director Amy Lueders discussing Army Corps study).
[15] Keranen 2014.
[16] Exhibit B.

EXHIBIT A

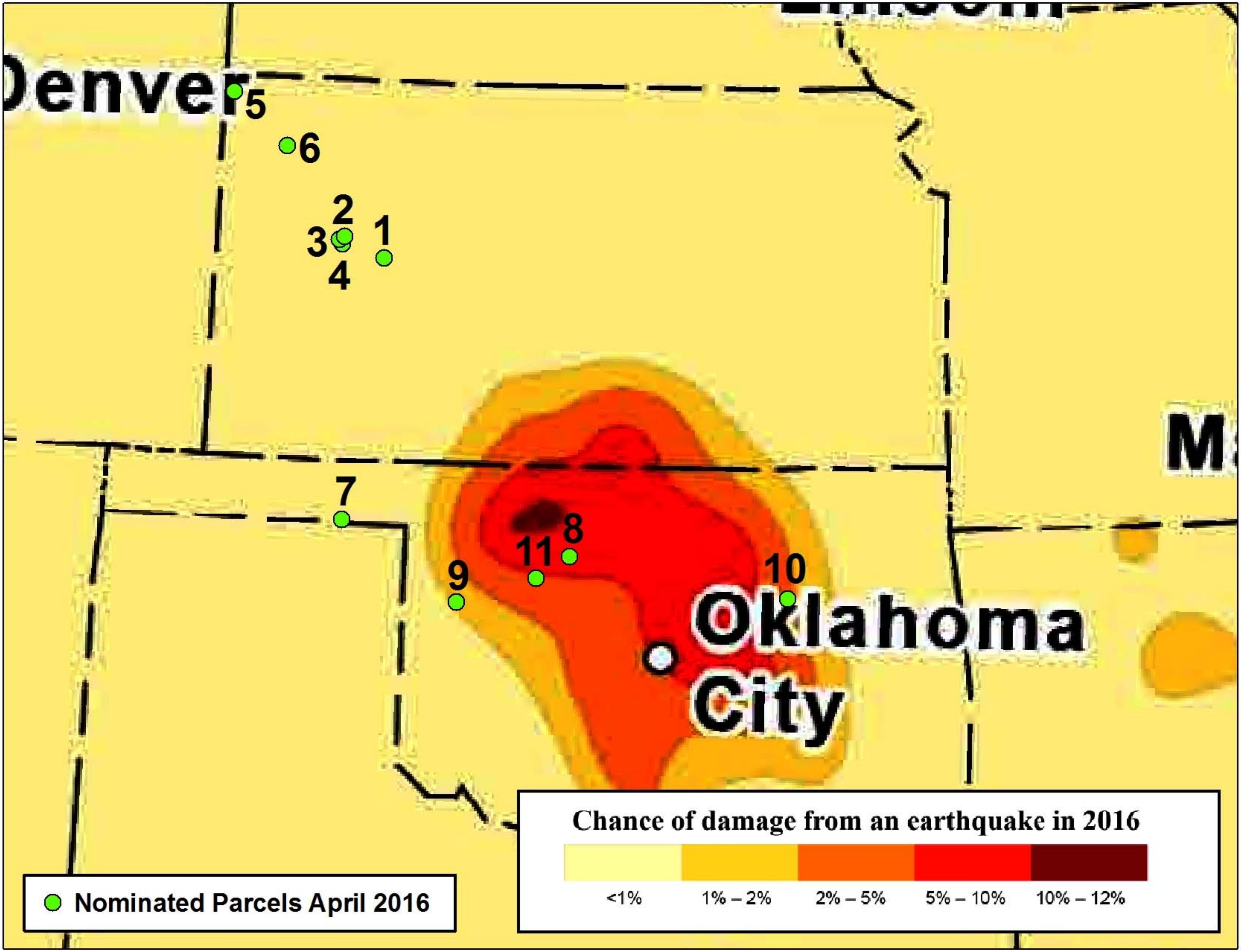

Denver
5
6
2
1
3
4
7
8
11
9
10
Oklahoma City
Nominated Parcels April 2016
Chance of damage from an earthquake in 2016
<1%
1% – 2%
2% – 5%
5% – 10%
10% – 12%

EXHIBIT B

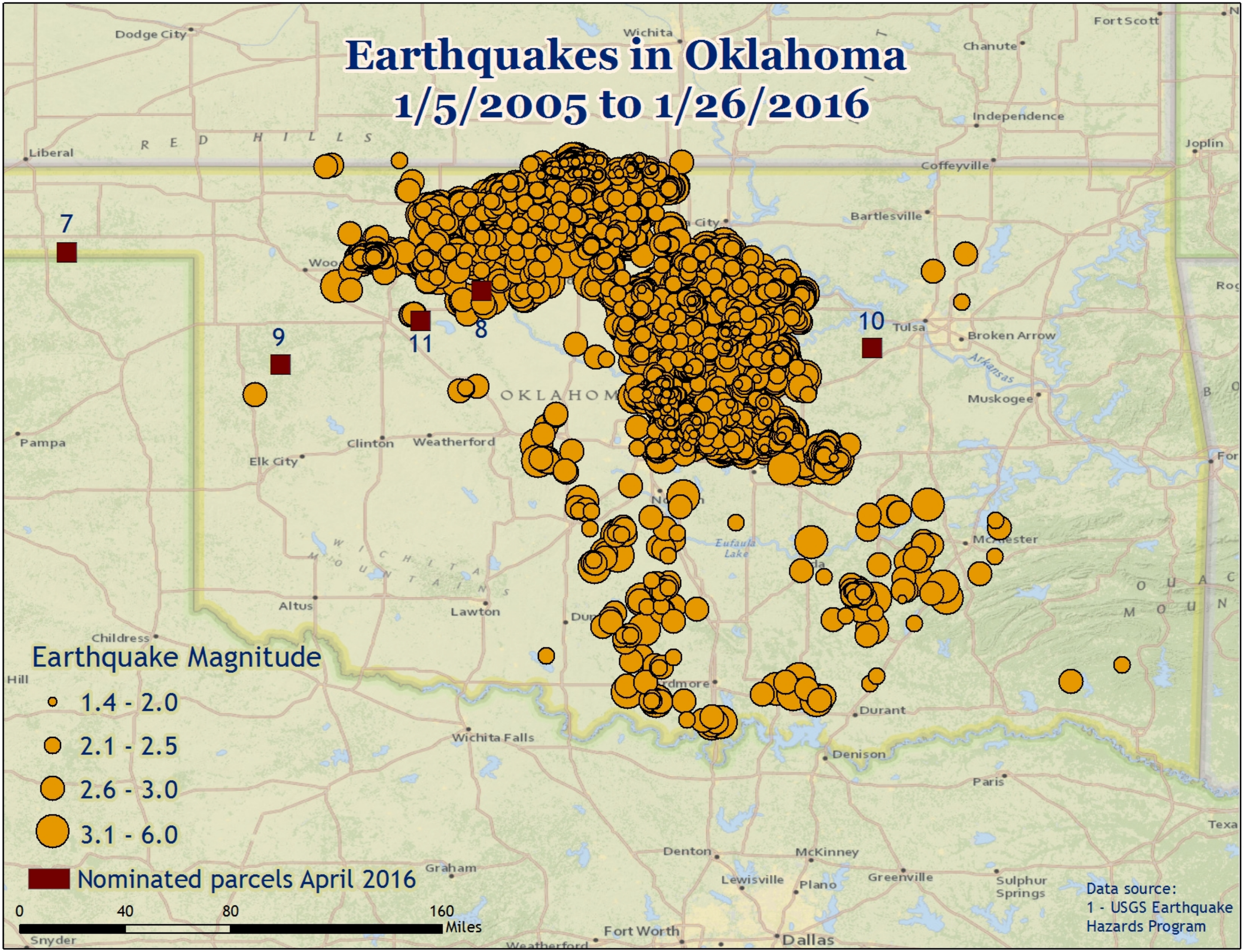
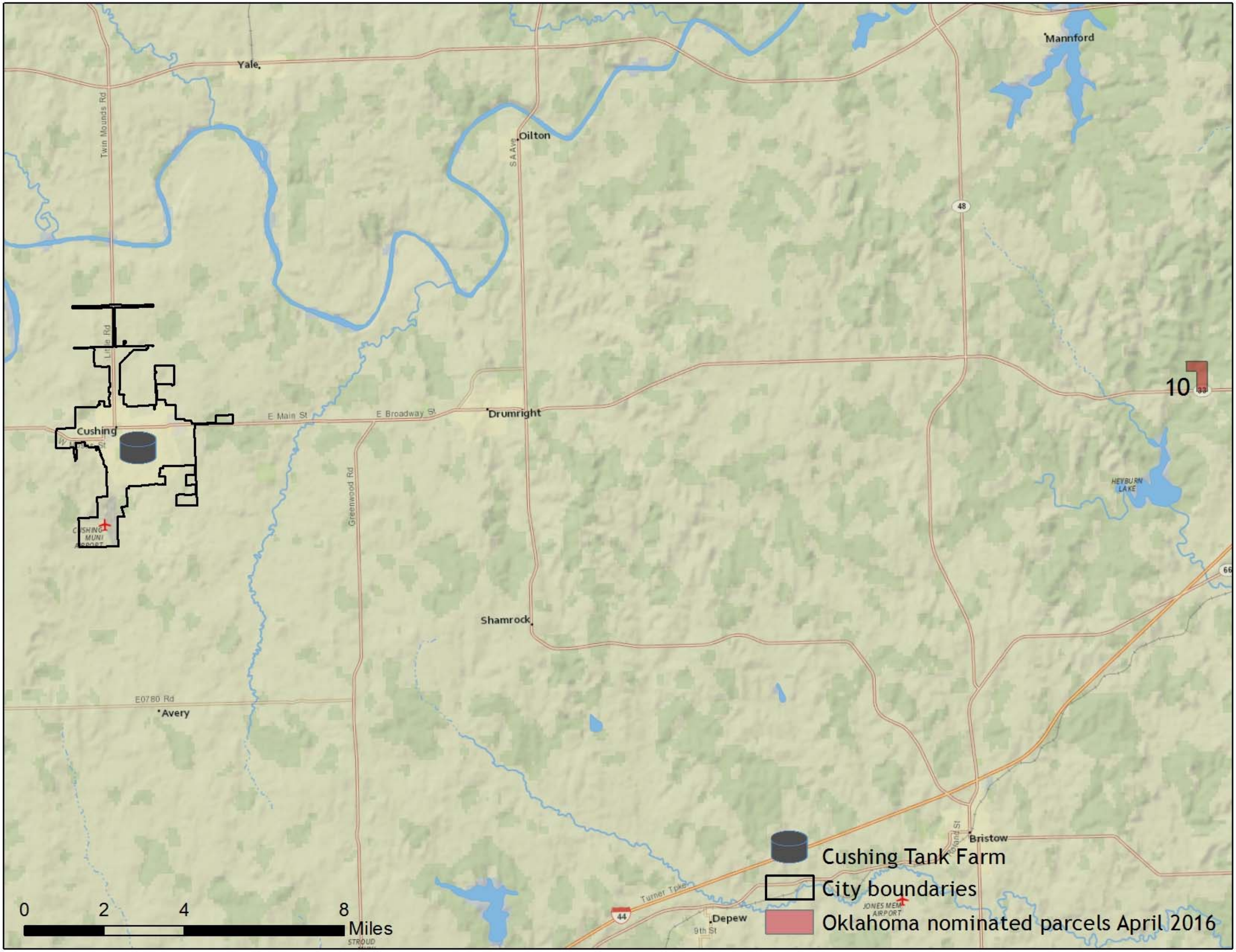
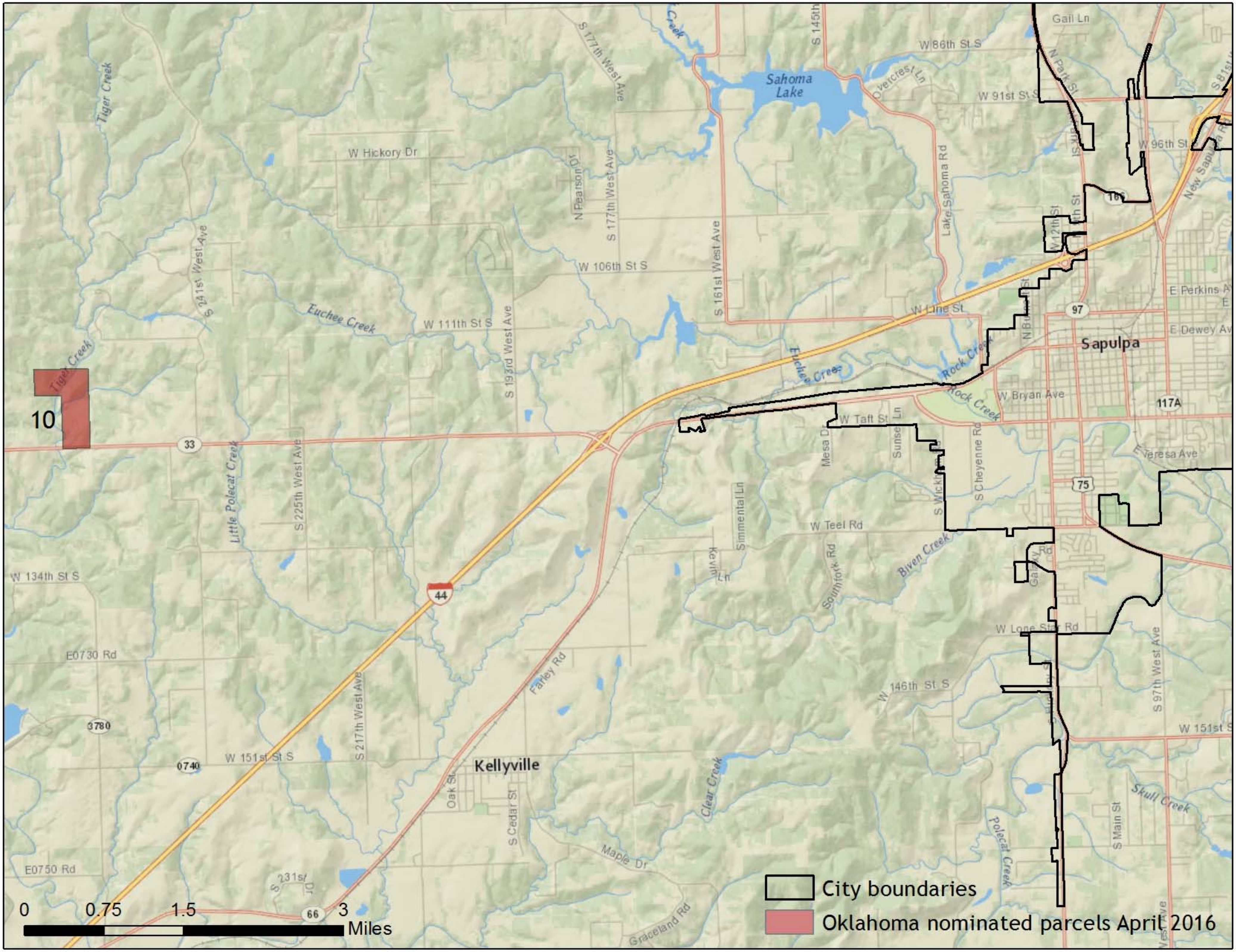

Earthquakes in Oklahoma
1/5/2005 to 1/26/2016
Earthquake Magnitude
1.4 - 2.0
2.1 - 2.5
2.6 - 3.0
3.1 - 6.0
Nominated parcels April 2016
7
8
9
10
11
0
40
80
160
Miles
Data source:
1 - USGS Earthquake
Hazards Program
Dodge City
Wichita
Chanute
Fort Scott
Independence
Joplin
Coffeyville
Liberal
R E D H I L L S
Bartlesville
Tulsa
Broken Arrow
Arkansas
Muskogee
OKLAHOM
Pampa
Elk City
Clinton
Weatherford
McAlester
Eufaula Lake
W I C H I T A
M O U N T A I N S
Altus
Lawton
Childress
Hill
Durant
Wichita Falls
Denison
Paris
Denton
McKinney
Graham
Lewisville
Plano
Greenville
Sulphur Springs
Fort Worth
Dallas
Snyder
Weatherford

EXHIBIT C

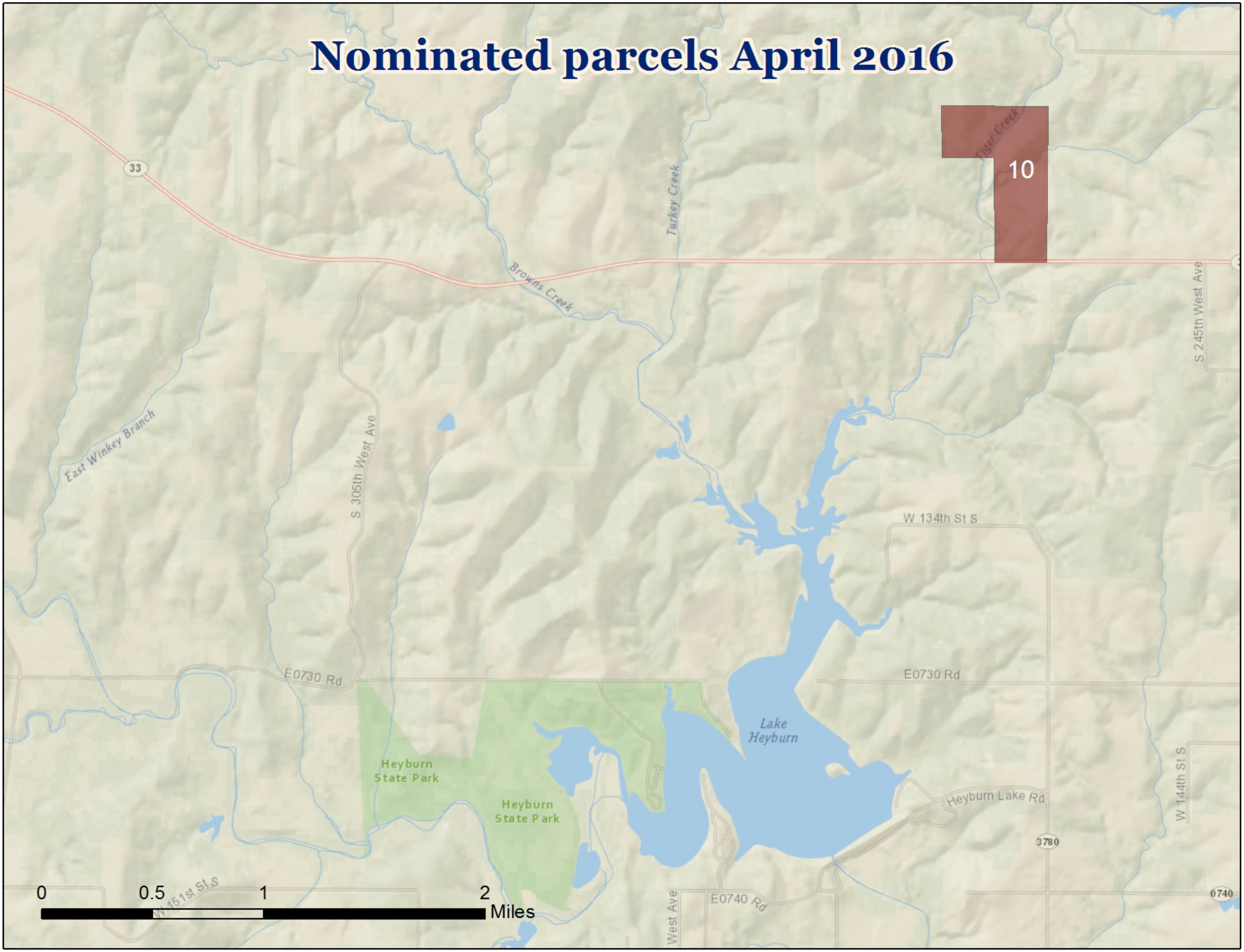


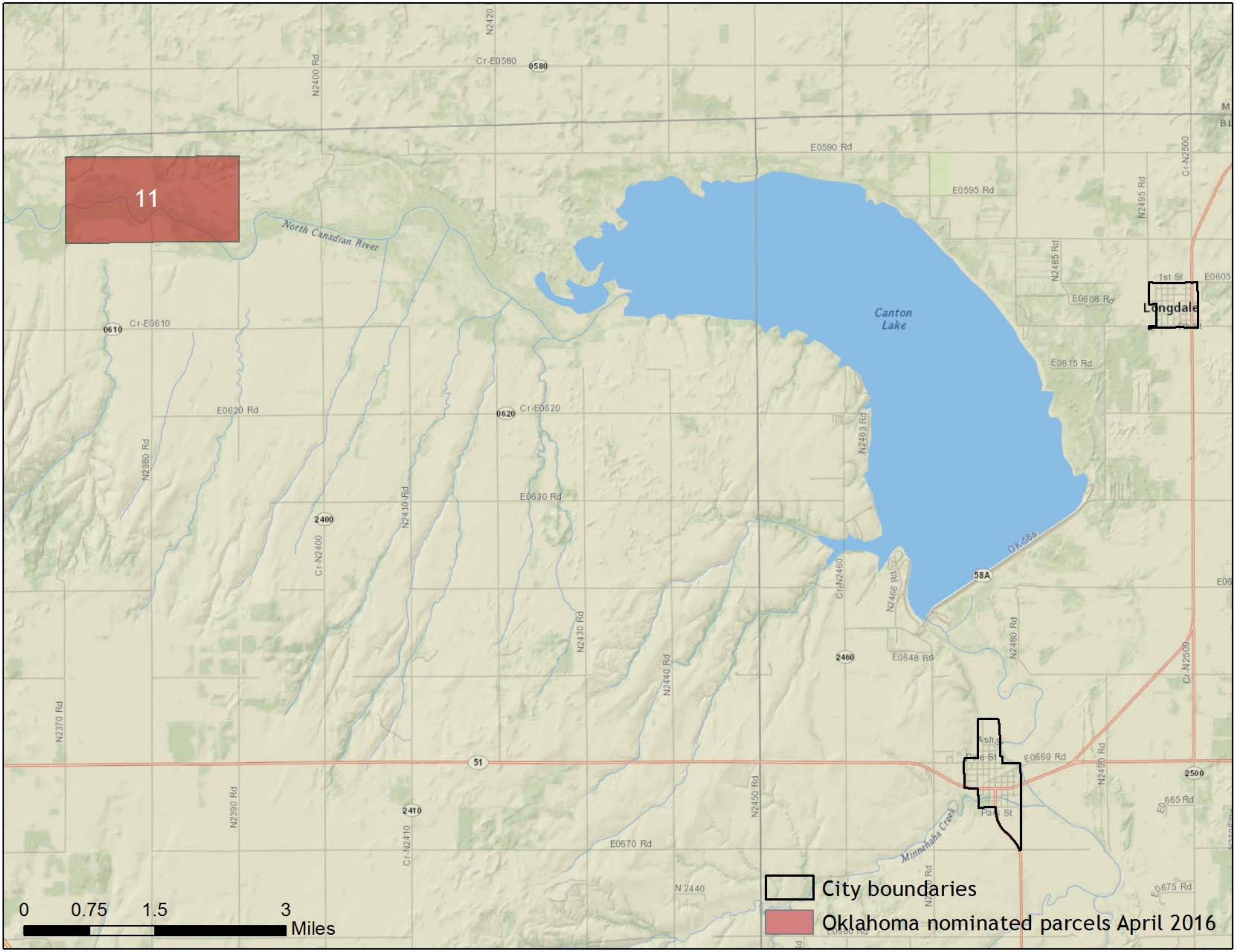
Yale
Mannford
Oilton
Twin Mounds Rd
S A Ave
48
Little Rd
10
33
E Main St
E Broadway St
Drumright
Cushing
HEYBURN LAKE
CUSHING MUNI AIRPORT
Greenwood Rd
66
Shamrock
E0780 Rd
Avery
Bristow
Turner Tpke
44
JONES MEM AIRPORT
Depew
9th St
0
2
4
8
Miles
Cushing Tank Farm
City boundaries
Oklahoma nominated parcels April 2016

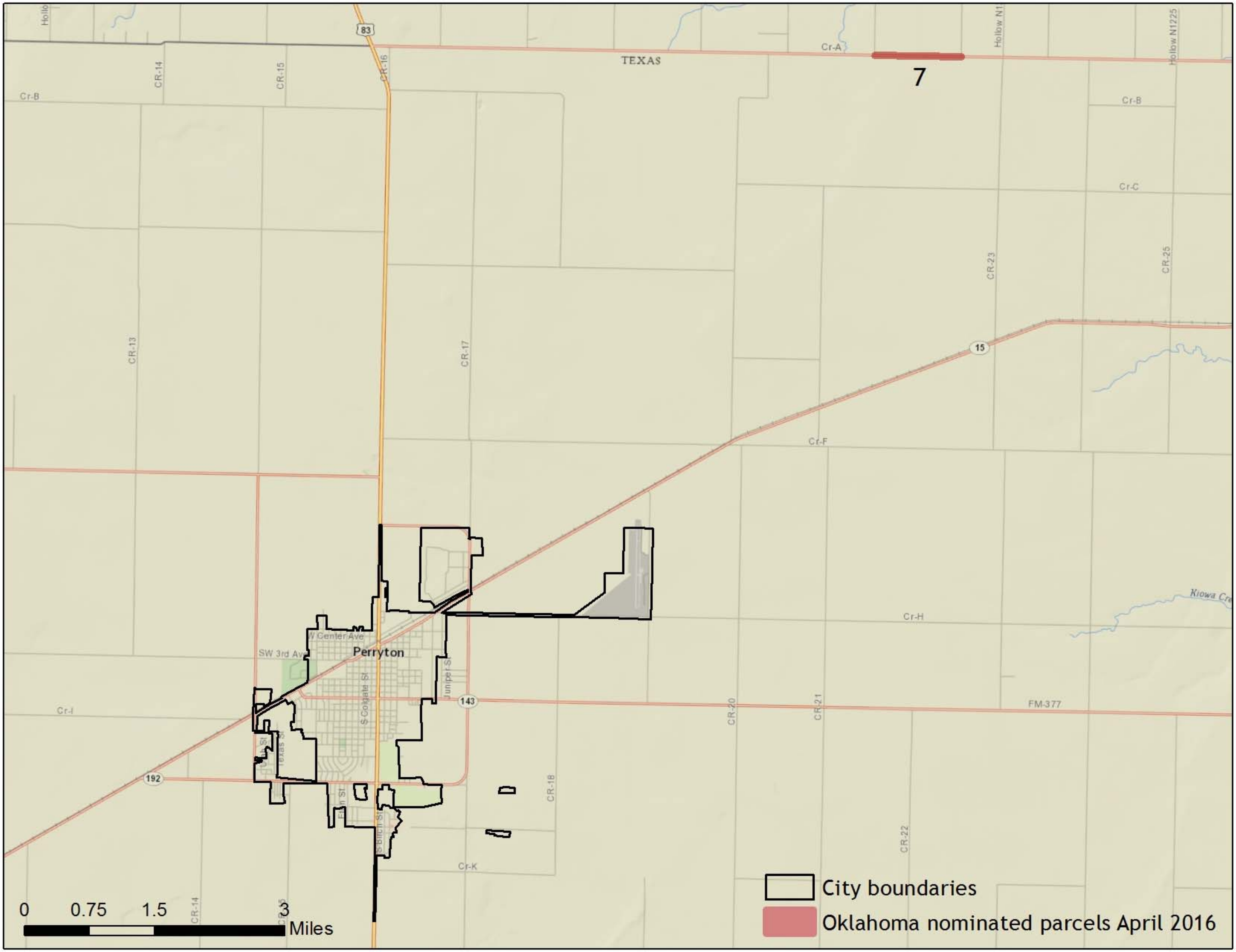


10
City boundaries
Oklahoma nominated parcels April 2016
0
0.75
1.5
3
Miles
Sapulpa
Kellyville
Sahoma Lake
Tiger Creek
Euchee Creek
Little Polecat Creek
Rock Creek
Biven Creek
Clear Creek
Polecat Creek
Skull Creek
W Hickory Dr
W 86th St S
W 91st St S
W 96th St S
W 106th St S
W 111th St S
W 134th St S
W 146th St S
W 151st St S
W Line St
W Taft St
W Bryan Ave
W Teel Rd
W Lone Star Rd
E0730 Rd
E0750 Rd
S 241st West Ave
S 225th West Ave
S 217th West Ave
S 193rd West Ave
S 177th West Ave
S 161st West Ave
S 145th
S 97th West Ave
N Pearson Dr
Lake Sahoma Rd
Overcrest Ln
Farley Rd
Maple Dr
Graceland Rd
Oak St
S Cedar St
S Main St
S Cheyenne Rd
Simmental Ln
Southfork Rd
Mesa Dr
Kevin Ln
E Perkins Ave
E Dewey Ave
Teresa Ave
Gail Ln
N Park St
33
44
66
75
97
117A
166
3780
0740

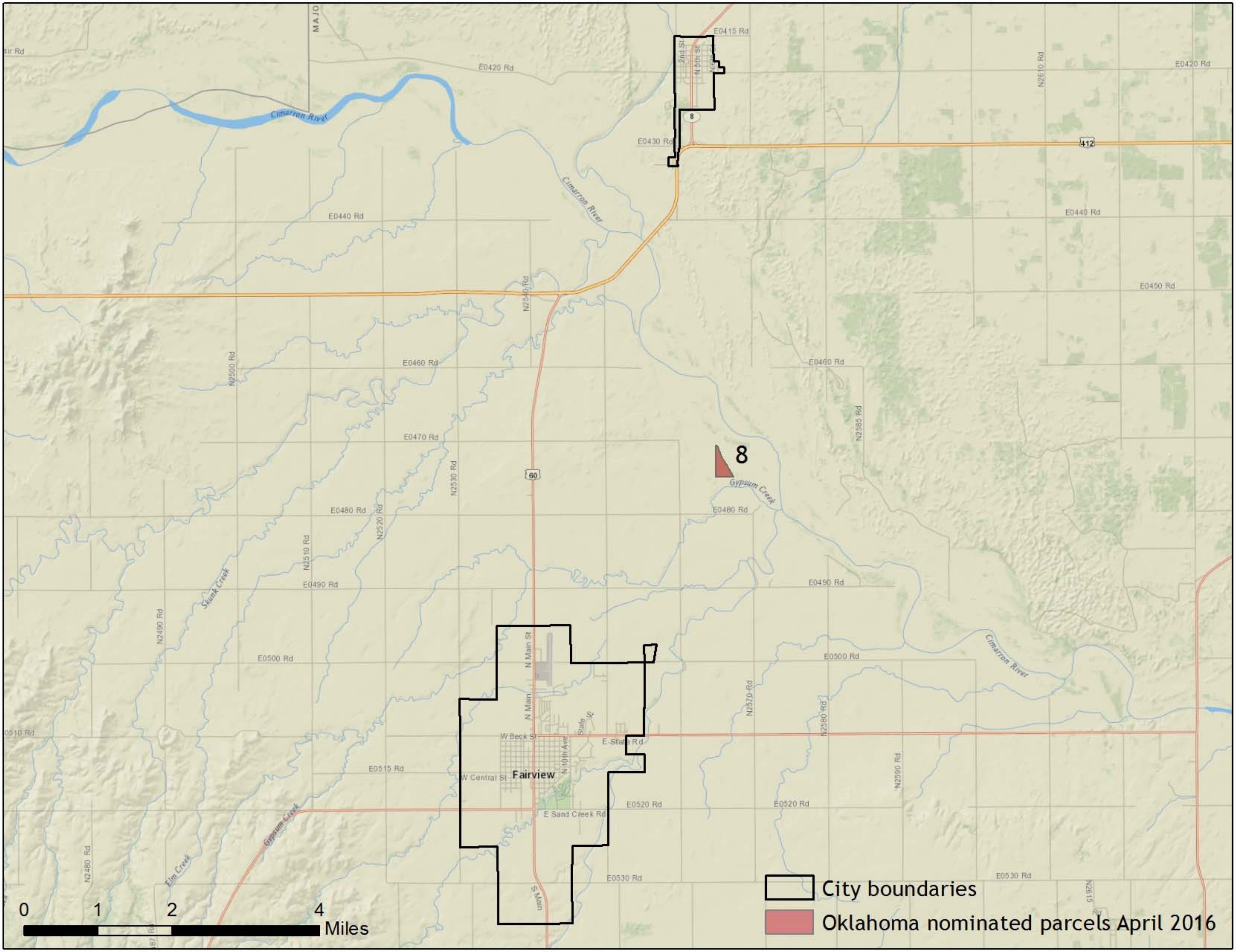
Nominated parcels April 2016




11
North Canadian River
Canton Lake
Longdale
Minnehaha Creek
Cr-E0580
E0590 Rd
E0595 Rd
Cr-E0610
E0620 Rd
Cr-E0620
E0630 Rd
E0615 Rd
E0608 Rd
1st St
E0605
E0648 Rd
E0660 Rd
E0670 Rd
665 Rd
675 Rd
N2400 Rd
N2420
N2380 Rd
N2370 Rd
N2390 Rd
N2410 Rd
Cr-N2400
Cr-N2410
N2430 Rd
N2440 Rd
N 2440
N2450 Rd
N2463 Rd
Cr-N2460
N2466 Rd
N2480 Rd
N2485 Rd
N2490 Rd
N2495 Rd
Cr-N2500
OK-58a
58A
51
0580
0610
0620
2400
2410
2460
2500
Ash
Park St
0 0.75 1.5 3 Miles
City boundaries
Oklahoma nominated parcels April 2016



TEXAS
7
Perryton
Cr-A
Cr-B
Cr-C
Cr-F
Cr-H
Cr-I
Cr-K
CR-13
CR-14
CR-15
CR-16
CR-17
CR-18
CR-20
CR-21
CR-22
CR-23
CR-25
FM-377
83
15
143
192
W Center Ave
SW 3rd Ave
S Colgate St
Juniper St
Kiowa Cre
Hollow N1225
0 0.75 1.5 3 Miles
City boundaries
Oklahoma nominated parcels April 2016


Cimarron River
E0415 Rd
E0420 Rd
E0430 Rd
E0440 Rd
E0450 Rd
E0460 Rd
E0470 Rd
E0480 Rd
E0490 Rd
E0500 Rd
E0510 Rd
E0515 Rd
E0520 Rd
E0530 Rd
N2490 Rd
N2500 Rd
N2510 Rd
N2520 Rd
N2530 Rd
N2540 Rd
N2570 Rd
N2580 Rd
N2585 Rd
N2590 Rd
N2610 Rd
2nd St
N 5th St
8
412
60
Gypsum Creek
Skunk Creek
Elm Creek
N Main St
N Main
W Beck St
E State Rd
N 10th Ave
W Central St
Fairview
E Sand Creek Rd
S Main
0
1
2
4
Miles
City boundaries
Oklahoma nominated parcels April 2016

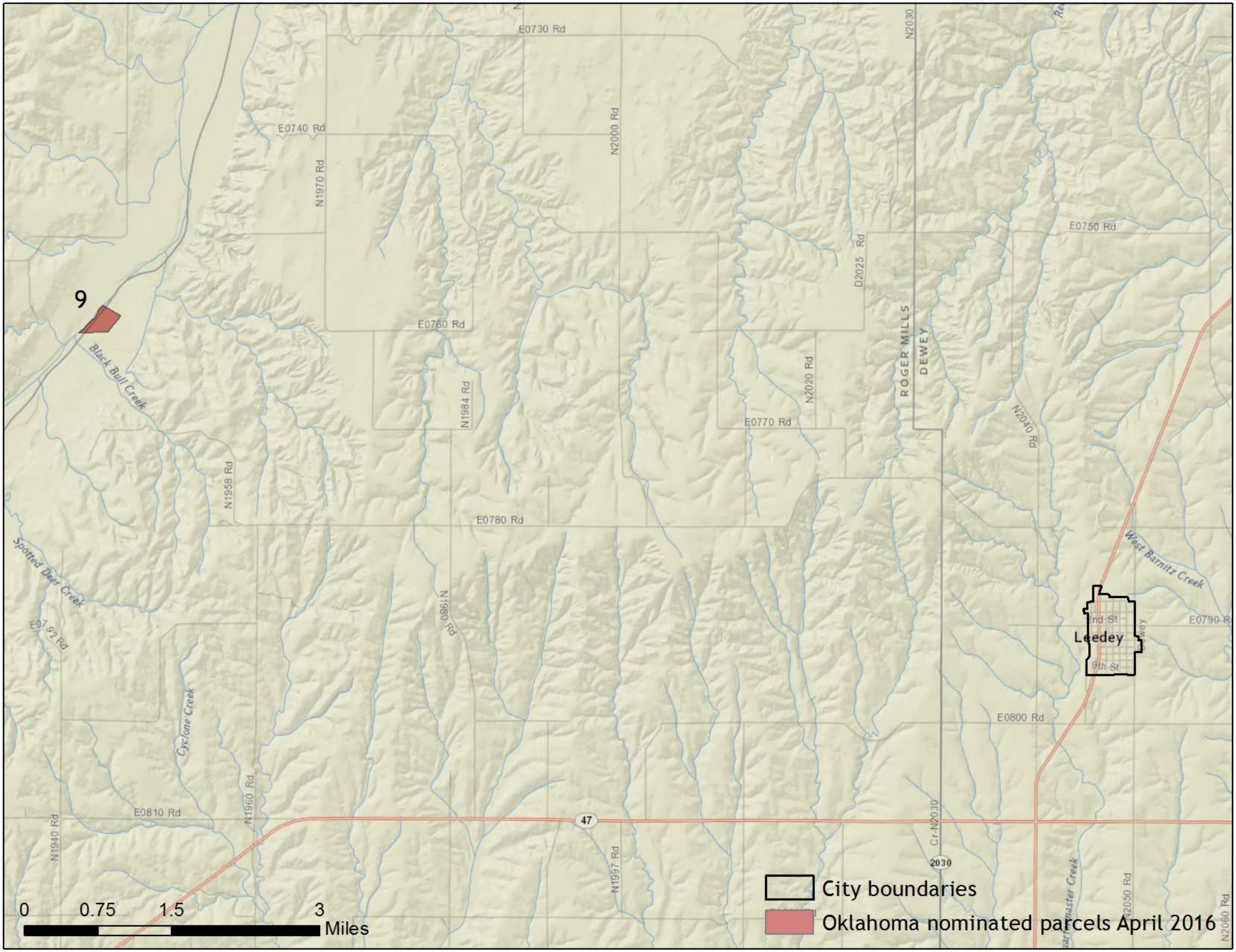

9
E0730 Rd
E0740 Rd
N1970 Rd
N2000 Rd
N2030
E0750 Rd
D2025 Rd
E0760 Rd
Black Bull Creek
N1984 Rd
N2020 Rd
ROGER MILLS
DEWEY
E0770 Rd
N2040 Rd
N1958 Rd
E0780 Rd
West Barnitz Creek
Spotted Deer Creek
N1980 Rd
E0790 Rd
E07.92 Rd
2nd St
Leedey
9th St
Cyclone Creek
E0800 Rd
E0810 Rd
N1960 Rd
N1940 Rd
47
Cr-N2030
2030
N1997 Rd
N2050 Rd
N2060 Rd
0
0.75
1.5
3
Miles
City boundaries
Oklahoma nominated parcels April 2016

EXHIBIT D

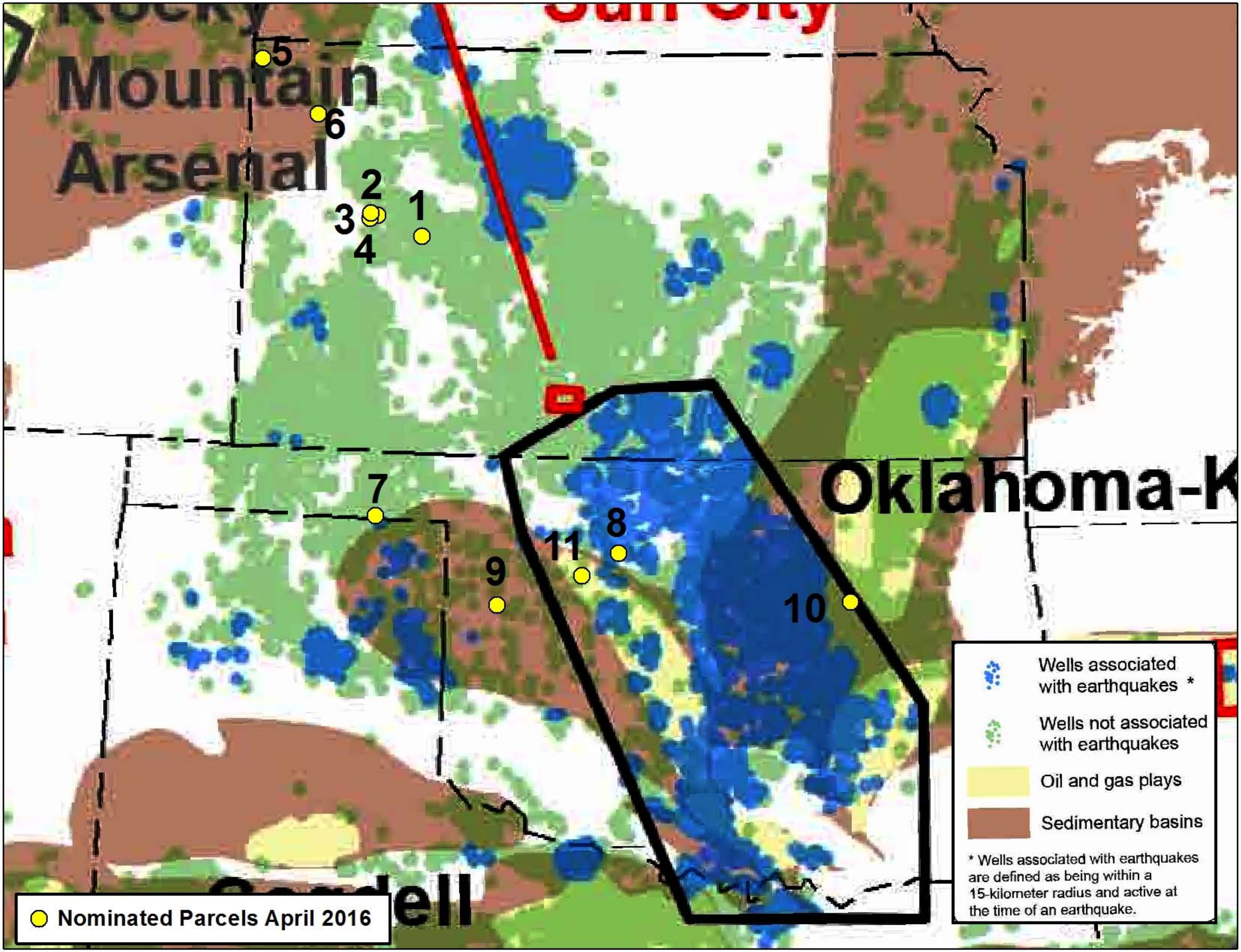

Mountain
Arsenal
Oklahoma-K
1
2
3
4
5
6
7
8
9
10
11
Wells associated with earthquakes *
Wells not associated with earthquakes
Oil and gas plays
Sedimentary basins
* Wells associated with earthquakes are defined as being within a 15-kilometer radius and active at the time of an earthquake.
Nominated Parcels April 2016

EXHIBIT E

Wendy Park

From: Wendy Park [wpark@biologicaldiversity.org]
Sent: Wednesday, April 20, 2016 12:44 AM
To: 'ceswt-pa@usace.army.mil'; 'Alueders@blm.gov'; 'Hunt, Rebecca'
Cc: My-Linh Le; Michael Saul
Subject: April 2016 Oklahoma-Kansas lease sale
Attachments: OK_water_resources.pdf; Harkins 2016 Oklahoma rattled by state's third-largest earthquake.pdf; Army Corps 2016 Corps of Engineers Expands Exclusion Zone.pdf

Dear Colonel Pratt, Director Lueders, and Ms. Hunt:

I write to you regarding new information concerning two Oklahoma parcels for sale in the April 20, 2016 lease auction. We recently learned that last month the Army Corps' Fort Worth District announced new restrictions on drilling and wastewater injection near the Joe Pool Dam in Grand Prairie, Texas. Specifically, the Corps increased the drilling setback from 3,000 feet to 4,000 feet away from the dam due to the risk of subsidence caused by gas production. It further recommended a five-mile setback for wastewater injection wells, given the risk that injection-induced seismicity could damage the dam. This new information bears directly on the safety of drilling and especially wastewater injection that could occur on and around two Oklahoma parcels for lease that are only within a few miles of Heyburn and Canton Lakes (parcels 10 and 11). See attached map. Yet this issue has never been addressed in the environmental review for the auction, despite the potential for a catastrophic dam breach.

With respect to the problem of induced seismicity, a 2015 study commissioned by the Army Corps evaluated (1) the maximum possible earthquake that an injection could induce in the region and (2) the distance within which such an earthquake could cause structural damage to the dam:

> To assess seismic risk to Joe Pool Dam, earthquake magnitude and proximity are needed. Frohlich (2012) suggests that induced earthquakes should have magnitudes that are less than or equal to the largest natural earthquake in a region. The largest recorded earthquake anywhere in Texas was a M5.8 on the Richter scale, which occurred in 1931 in Valentine, Texas (Stover and Coffman, 1993) and is considered of natural occurrence. The largest induced earthquake in Texas was a M4.6 near Snyder, Texas in 1978 (Appendix B), attributed to waterflood operations in an oilfield. Given the sparse seismic record for North Texas and the historical precedent of the M4.6 quake in Snyder, it seems reasonably conservative to choose M4.5 to M5.0 as the range for the maximum possible earthquake induced by a Barnett injection well. Structural damage to the dam requires sufficient ground acceleration, which is proportional to earthquake magnitude and dies off with distance from the earthquake source.
>
> ...
>
> Using M4.5 to M5.0 as the induced earthquake size, and assuming a maximum allowable acceleration of 0.2g (personal communication, USACE), Fig. 37 shows that the earthquake source would need to be 2 to 4 km (6560 – 13,120 ft) distant from the dam to keep induced ground motions within acceptable limits. Given that an injection well can raise the pore pressure over a broad area (a reasonable radius of influence would be 1 km), the epicenter of an induced quake wouldn't necessarily be centered at the well surface location. ***Combining all these factors and their uncertainty, a conservative exclusion zone for injection wells around Joe Pool Dam should be at least a 16,400 ft (5 km) radius. Extending the stand-off to 32,810 ft (10 km) would reduce likely ground acceleration to the 0.2g threshold for even a M5.8 (the magnitude of the Valentine quake).***

See Army Corps Study ("2015 study") at 72-73, available at http://www.swf.usace.army.mil/Portals/47/docs/pao/JoePoolDrillingStudy_14Mar16_PublicRelease_Secured.pdf. (Incidentally, we requested a copy of this study from the Army Corps' Fort Worth District before the Feb. 19 protest deadline but received no response from the Corps.)

On February 17, 2016, the Army Corps issued a memo with the following recommendation based on the 2015 study:

> From this process, it was concluded that the 3,000-foot exclusion zone at the project does not meet agency tolerable risk guidelines and, as a result, puts the project and public at risk. As a result, USACE has adopted a 4,000-foot exclusion zone at Joe Pool Dam within which no drilling will be allowed, regardless of depth. ***Additionally, in order to protect the project from induced seismicity, USACE will work to limit injection wells within five miles of the Joe Pool project. These recommendations are more conservative than the subject study recommends; however, they are considered necessary to ensure that public safety is not reduced as a result of minerals related activities at Joe Pool.***

See 2015 study cover sheet (PDF p. 1). On March 15, 2016, the Army Corps published a news release announcing the results of the 2015 study and the above recommendations. *See* http://www.swf.usace.army.mil/Media/NewsReleases/tabid/6565/Article/694607/corps-of-engineers-expands-exclusion-zone-after-completing-study-on-dam-safety.aspx.

Earthquakes of magnitude 5.1 and 5.6 have recently been recorded in Oklahoma. *See* http://www.tulsaworld.com/earthquakes/oklahoma-rattled-by-state-s-third-largest-earthquake-recorded-near/article_64a0daf2-16fc-5478-a3ca-12f2220d9736.html. But no comparable restrictions appear to apply to the Oklahoma parcels for lease near Heyburn and Canton Lakes. Further, the Environmental Assessment for the lease auction does not even mention the problem of induced seismicity, let alone the effects of induced earthquakes on the structural integrity of Heyburn and Canton Lakes. Given the high risk of induced seismicity in and around the lease parcels in Oklahoma (as outlined in our Feb. 19 lease sale protest and our supplemental email of March 30--see below) and the potential for a major disaster in the event of a dam breach, BLM and the Corps must not offer these parcels for sale without considering the effects of fracking- and injection-induced earthquakes on the Heyburn and Canton Lake dams.

We urge the Corps and BLM to withdraw the Lake Canton and Lake Heyburn lease parcels.

Please let me know if you have any questions, and thank you for considering our concerns.

Best,

Wendy Park
Staff Attorney
Center for Biological Diversity
1212 Broadway #800
Oakland, CA 94612
510-844-7138

-----Original Message-----
From: My-Linh Le [mailto:MLLe@biologicaldiversity.org]
Sent: Wednesday, March 30, 2016 6:08 PM
To: rhunt@blm.gov
Cc: Wendy Park; Michael Saul
Subject: April 2016 Oil and Gas Lease Sale

Dear Ms. Hunt,

Yesterday the U.S. Geological Survey released the following report:
http://pubs.usgs.gov/of/2016/1035/ofr20161035.pdf

which contains new and highly relevant data that may substantially affect BLM's analysis of the parcels in the lease sale. The report describes a seismic hazard assessment showing that the risks of a destructive earthquake in the next year is as great in north-central Oklahoma and southern Kansas as it is in parts of California with the highest chances of damage.

According to the USGS Oklahoma, Kansas, Texas, and New Mexico are among the six states that face the most significant hazards from induced seismicity.

The report also notes that Oklahoma has experienced a rising number of earthquakes after the boom from oil and gas exploration (historically, from
1950 to 2005, it had fewer than two quakes of magnitude 3 or greater each year; however, last year it recorded several hundred quakes at a magnitude 3 and above). The New York Times published this article yesterday http://nyti.ms/1RLePUL summarizing the assessment and notes that the pace slowed after the Oklahoma Corporation Commission effectively imposed steep reductions in underground waste disposal in February and March.

We hope you will consider this new information as you review our protest comments. Thank you.

Best,

My-Linh Le

Center for Biological Diversity

1212 Broadway, Suite 800

Oakland, CA 94612

Phone (510) 844-7100

Fax (510) 844-7150

<mailto:aweber@biologicaldiversity.org> mylle@biologicaldiversity.org

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EXHIBIT F

Geology

Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 M_w 5.7 earthquake sequence

Katie M. Keranen, Heather M. Savage, Geoffrey A. Abers and Elizabeth S. Cochran

Geology published online 26 March 2013;
doi: 10.1130/G34045.1

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Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 M_w 5.7 earthquake sequence

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ABSTRACT

Significant earthquakes are increasingly occurring within the continental interior of the United States, including five of moment magnitude (M_w) ≥ 5.0 in 2011 alone. Concurrently, the volume of fluid injected into the subsurface related to the production of unconventional resources continues to rise. Here we identify the largest earthquake potentially related to injection, an M_w 5.7 earthquake in November 2011 in Oklahoma. The earthquake was felt in at least 17 states and caused damage in the epicentral region. It occurred in a sequence, with 2 earthquakes of M_w 5.0 and a prolific sequence of aftershocks. We use the aftershocks to illuminate the faults that ruptured in the sequence, and show that the tip of the initial rupture plane is within ~200 m of active injection wells and within ~1 km of the surface; 30% of early aftershocks occur within the sedimentary section. Subsurface data indicate that fluid was injected into effectively sealed compartments, and we interpret that a net fluid volume increase after 18 yr of injection lowered effective stress on reservoir-bounding faults. Significantly, this case indicates that decades-long lags between the commencement of fluid injection and the onset of induced earthquakes are possible, and modifies our common criteria for fluid-induced events. The progressive rupture of three fault planes in this sequence suggests that stress changes from the initial rupture triggered the successive earthquakes, including one larger than the first.

INTRODUCTION

Three earthquakes with M_w of 5.0, 5.7, and 5.0 (moment magnitudes from Global Centroid Moment Tensor Catalog, GCMT; http://www.globalcmt.org) occurred within the North American midcontinent near Prague, Oklahoma, United States (Fig. 1) on 5, 6, and 8 November 2011 ~180 km from the nearest known Quaternary-active fault. Earthquakes with M_w ≥ 5.0 are rare in the United States east of the Rocky Mountains; however, the number per year recorded in the midcontinent increased 11-fold between 2008 and 2011, compared to 1976–2007. Of the total seismic moment released in the region, ~66% occurred in 2011 (from the GCMT). The M_w 5.7 earthquake was the largest instrumentally recorded in Oklahoma. It created shaking up to intensity VIII in the epicentral region, destroyed 14 homes, damaged many other buildings, injured 2 people, and buckled pavement (U.S. Geological Survey, 2011). In this study we refer to the M_w ≥ 5.0 earthquakes of 5, 6, and 8 November 2011 as events A, B, and C, respectively. Moment tensor solutions (from the GCMT;

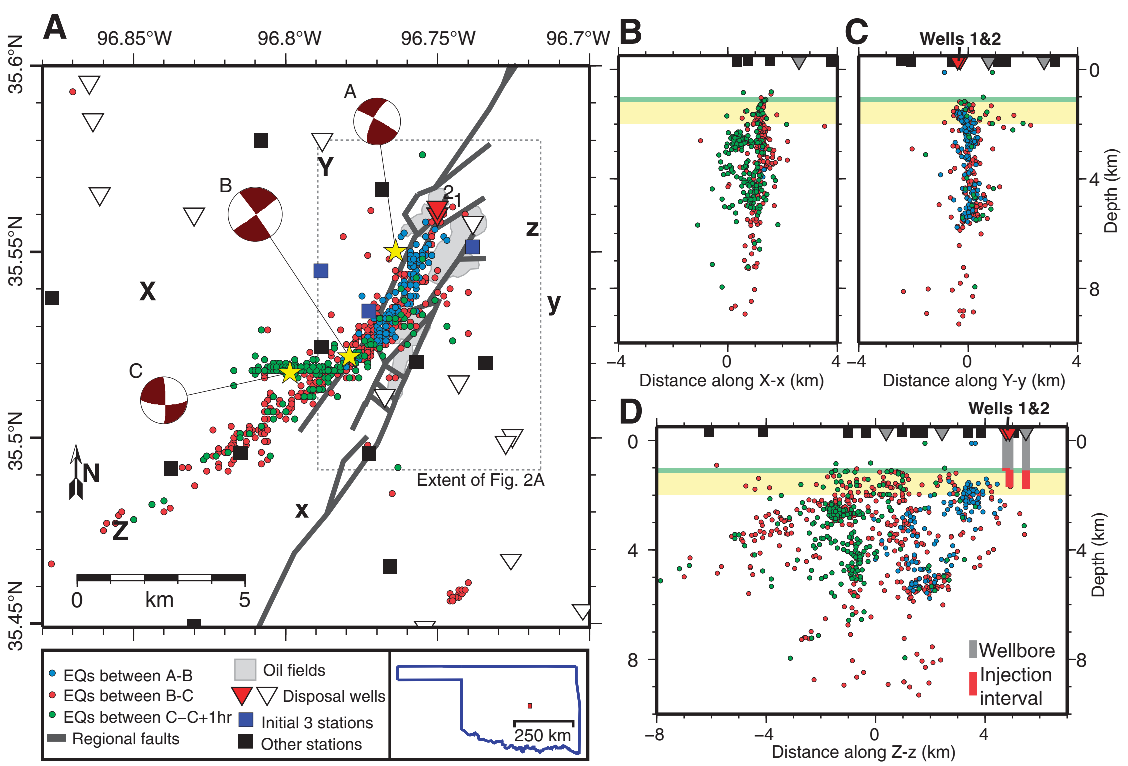

Figure 1. A: Seismicity, centroid moment tensor mechanisms, seismic stations, active disposal wells, and oil fields in central Oklahoma, United States. Epicenters of major earthquakes (EQs) are plotted at Oklahoma Geological Survey location for event A and at our relocations for events B and C, where we had sufficient control (Table DR1 [see footnote 1]). Event A likely nucleated on fault defined by aftershock locations (permitted within location error). Faults are merged from regional compilation (Joseph, 1987) and detailed local study (Way, 1983), mapped using seismic lines, well logs, and formation tops. Wells 1 and 2 inject near aftershocks of event A. B–D: Cross sections of seismicity projected from within 4 km of plane of each section. Vertical lines beneath wells indicate well path, red where perforated or open hole. Green bands denote Hunton and Simpson Groups, and yellow bands denote Arbuckle Group. Arbuckle Group overlies basement; base depth of Arbuckle Group locally is uncertain (between 1.8 and 2.2 km depth). Depths are relative to sea level, land elevation is ~300 m. Inset shows state of Oklahoma and location of map area.

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Fig. 1; Table DR1 in the GSA Data Repository[1]) indicate strike-slip rupture on steeply dipping fault planes with different fault-plane orientations. Local earthquake activity began in February 2010 with an M_w 4.1 earthquake within a few kilometers of event A.

The 2010 and 2011 Prague earthquakes occurred in the structurally controlled Wilzetta oil field, within the complex, ~200-km-long, Pennsylvanian-age Wilzetta fault system (Way, 1983). Structural traps in the Wilzetta field are formed by the offset of porous limestone along high-angle faults (Fig. 2). Production of oil from the Wilzetta North field, where the earthquake sequence initiated, occurred primarily in the 1950s and 1960s from the Hunton Limestone; limited production continues. There are three active fluid injection wells located within 1.5 km of aftershocks of event A, and two within the Wilzetta North field (Fig. 1). Fluid injection in these wells began after 1993 and occurs into units from the Hunton Limestone to the deeper Arbuckle Group, predominantly dolomitic limestone, between ~1.3 and 2.1 km depth (Oklahoma Corporation Commission Well Data System: http://www.occpermit.com/WellBrowse; Fig. 2).

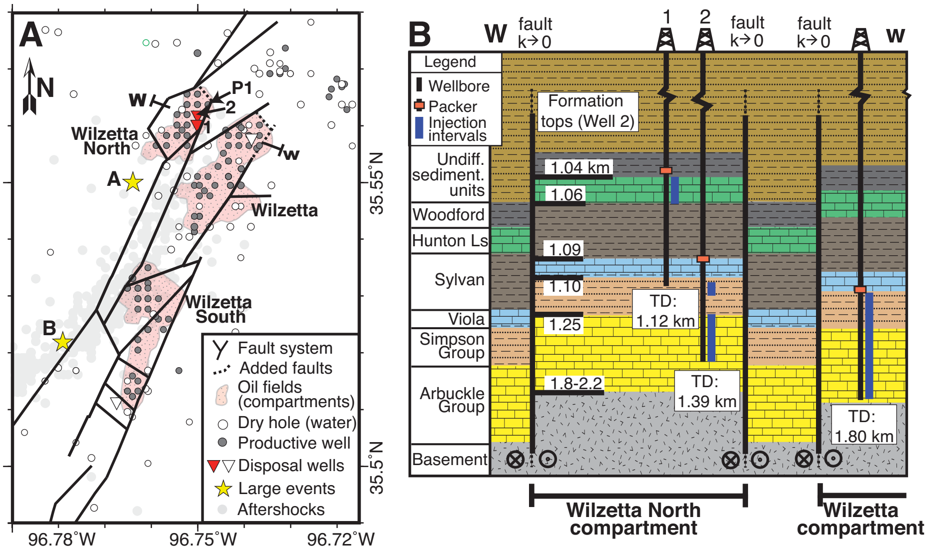

Figure 2. Subsurface geology and compartmentalization in Wilzetta oilfields, Oklahoma, United States. A: Wilzetta fault system (area shown in Fig. 1) including fault-bounded compartments, disposal wells, earthquakes, and exploration wells into Hunton Limestone or deeper units. Boundaries between producing and dry wells closely correlate to mapped faults. Wells 1, 2, and P1 are discussed in text. B: Schematic cross-section W-w across Wilzetta North and Wilzetta compartments. High-permeability reservoirs are interbedded with low-permeability shale units vertically, and faults are low-permeability barriers to fluid flow. Well paths and injection intervals are from Oklahoma Corporation Commission Well Data System (http://www.occpermit.com/WellBrowse) database. Relative offset of fault blocks is based on formation tops at closely spaced production wells (not shown). Depths to formation tops and total depth (TD) of each injection well are noted (in km below sea level).

Earthquakes are commonly considered induced by wastewater disposal if they adhere to criteria established by Davis and Frohlich (1993) that include proximity to injection wells, a change from background seismicity, and a correlation with wastewater injection parameters. In this study we demonstrate a relationship between the 2011 Oklahoma seismicity and fluid injection, and suggest modifications to the criteria for induced earthquakes. We use the term “induced” without implying a relationship between anthropogenic stresses and earthquake magnitude, following the Committee on Induced Seismicity Potential (National Research Council of the National Academies, 2012).

METHODOLOGY

Seismic Data and Network

We deployed seismometers within 24 h of event A, and recorded the later 2 large earthquakes and thousands of aftershocks. The first 3 seismometers deployed, within 2 km of events A and B, recorded 7 h of locatable seismicity prior to event B. Additional seismometers (3) were deployed in the 24 h after event B, and 12 in the following 5 days, using digital three-component seismometers from the University of Oklahoma and the PASSCAL RAMP (Program for Array Seismic Studies of the Continental Lithosphere, Rapid Array Mobilization Program) pool. The locally recorded data were supplemented by EarthScope Transportable Array stations (Meltzer et al., 1999) at 25–150 km distance. Many stations were within 1 focal depth of the nearest earthquakes, providing accurate depth estimates; nonlinear inversions on sample hypocenters give 95% confidence bounds of <500 m in epicenter and <800 m in depth for earthquakes recorded by 3 stations before event B, and <50–100 m in epicenter and depth for those recorded by the full 18 station local array. Most ray paths were <10 km from source to station, with <2 s between S and P wave arrivals. Several hundred aftershocks per hour occurred within the first few hours of each large earthquake.

We report results based on P and S wave arrivals for (1) all identifiable events after the array installation before event B (the M_w 5.7), (2) 1–2 h time windows immediately following events B and C, and (3) larger aftershocks within 2 mo of the mainshocks and recorded on >15 stations. In most cases, both P and S wave arrival times could be picked to a precision of 10 ms or better from the local stations. Arrivals were picked manually; the high event rate caused standard automatic detection schemes to fail.

The one-dimensional velocity model (Fig. DR1 in the Data Repository) was determined by inversion methods that solve jointly for P and S wave velocities and hypocenters (Abers and Roecker, 1991) for aftershocks recorded on >15 stations. The global root mean square residual in the velocity model is 0.029 s, and influences of possible lateral variations appear to be minimal. (For details of the network, the velocity model, and location selection, see the Data Repository.)

RESULTS

Aftershock Locations and Fault Rupture Areas

For this study we located 1183 aftershocks recorded by the dense network, and show the best located 798 (see the Data Repository). We use the extent of the aftershocks measured within a few hours to days after the mainshocks to estimate the area of the faults that ruptured, as is common if an event does not rupture to the surface (e.g., Kanamori and Anderson, 1975). The aftershocks we use in this study represent <10% of the total number of earthquakes, as only a few hours of data from time periods following each $M_w \geq 5.0$ event have been examined thoroughly. Hypocenters for events A, B, and C are less well constrained than the aftershocks (see the Data Repository). However, the fault rupture sequence is clear from the focal mechanisms of the large events combined with the aftershock pattern.

The earthquakes located delineate the major seismic zones as narrow, steeply dipping planes in the sedimentary section and basement (Fig. 1), well correlated to previously identified fault structures (Way, 1983; Joseph, 1987). The strikes (from the GCMT) of events A (27°) and B

[1]GSA Data Repository item 2013191, network and event details, velocity model, and 2010–2011 injection data, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

(54°) parallel the two predominant orientations within the Wilzetta fault zone, and the strike of event C (91°) defines a clear secondary orientation. Therefore, three separate segments within the Wilzetta fault network ruptured successively during the sequence. The slip on the apparent fault planes of the three largest earthquakes are consistent with an east-northeast direction of maximum horizontal stress. Significantly, the northern tip of the aftershock zone for event A is in sedimentary units near an active disposal well (Fig. 1); the closest earthquakes are 200 ± 250 m distant from the wells. The depths of 83% of the aftershocks are <5 km; 30% of early aftershocks (and 20% of all earthquakes) were located within the sedimentary units into which fluids are injected (Fig. 1).

Fluid Triggering and Correlation of Seismicity to Fluid Injection Data

Earthquake triggering by fluid injection occurs if pore pressure at the fault increases beyond a critical pressure threshold (Hubbert and Rubey, 1959; Healy et al., 1968; Raleigh et al., 1976), lowering effective normal stress on a fault close to failure. In the induced seismicity experiment at Rangely, Colorado, downhole reservoir pressure measurements were available and the seismicity rate rose and fell within months of changes in reservoir pressure (Raleigh et al., 1976). Pressure data available for the Wilzetta North field are limited to monthly reported wellhead pressure (pressure at the surface while pumping), and no direct measurements of pressure within the reservoir are accessible. We thus follow standard methods and investigate possible temporal correlations between seismicity rate and surface injection parameters (e.g., Healy et al., 1968; Frohlich et al., 2011; Horton, 2012).

No short-term monthly correlation is evident in the Wilzetta field (Fig. DR2). Such a temporal correlation to surface injection parameters is rare, though evident at the Rocky Mountain Arsenal in Colorado (Healy et al., 1968). A more common observation in cases of induced seismicity is the onset of earthquakes soon after the initiation of fluid injection. Seismicity began within months of the start date of injection at the Rocky Mountain Arsenal (Healy et al., 1968), in Arkansas (Horton, 2012), and at the Dallas–Fort Worth (Texas) airport (Frohlich et al., 2011). However, within oilfields near Prague, Oklahoma, the first noted earthquake (M_w 4.1, 2010) did not occur until 17 yr after injection commenced (Fig. 3A). It is difficult to know if small earthquakes were occurring prior to 2010 near Prague, given the lack of nearby seismic stations; none were recorded or reported. A similarly long delay was observed at the Cogdell oil field in Texas (Davis and Pennington, 1989), where induced earthquakes began 20 yr after injection initiated.

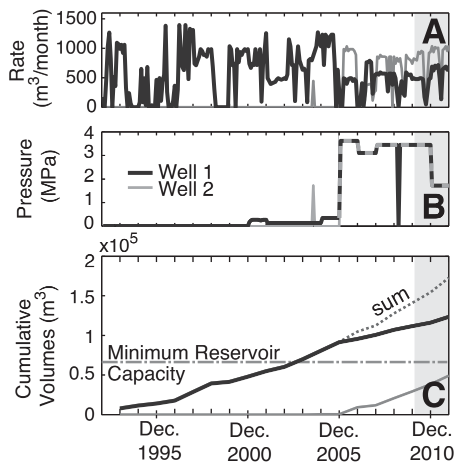

Figure 3. Available injection data. A: Monthly volumes of wastewater disposed at injection wells 1 and 2 (Fig. 2) near nucleation of event A. Monthly volumes were reported for 2002–2011; daily average volumes are multiplied by number of days per month for 1993–2002. B: Wellhead pressure for periods when pump is active, for same wells. C: Cumulative volume injected at wells 1 and 2 (from yearly totals). Minimum capacity of reservoir is denoted as horizontal dashed line and equals volume of oil extracted from Wilzetta North field, estimated by dividing total volume extracted from three Wilzetta fields by fractional area of Wilzetta North. This is absolute minimum estimate of reservoir fluid capacity; no data are available for water extracted or reinjected during production. Gray shading notes earthquakes in 2010–2011.

Increasing Injection (and Reservoir?) Pressure

Wellhead pressure in the Wilzetta North field appears fixed at a constant value during pumping, as it was at Rangely, Colorado (Gibbs et al., 1972), with multiyear intervals of constant surface pressure punctuated by step increases (Well 1; Fig. 3). Initially, fluid was injected into the Hunton Limestone in Well 1 at zero reported wellhead pressure (Oklahoma Corporation Commission Well Data System) (Fig. 3B), signifying an underpressured reservoir (below hydrostatic pressure) depleted by earlier hydrocarbon production. Wellhead pressure increased in steps, starting in 2001 at ~0.2 MPa (25–40 psi) and reaching a maximum of 3.6 MPa (525 psi) in 2006 (Fig. 3). The final tenfold increase in wellhead pressure, and the concurrent addition of a second disposal well into deeper units, came after the volume of water injected into the Hunton Limestone at Well 1 exceeded the volume of oil extracted from the Hunton strata at wells throughout the compartment (Way, 1983) (Fig. 3C). The volume of oil extracted is only an approximate estimate of reservoir capacity, and likely an underestimate; no data are available for water volume extracted or reinjected during production.

In the Wilzetta field, hydrocarbon accumulations were isolated to fault blocks of <1 km^2 areal extent, surrounded by water-saturated zones, indicating that the compartment-bounding faults were likely seals against fluid migration over geologic time. Such low-permeability barriers are common in sedimentary basins (Bradley and Powley, 1994) and can inhibit the diffusion of fluid pressure. In an idealized sealed reservoir, reservoir pressure gradually rises as injection volume increases (Fig. 4A), and the pressure difference between wellhead pressure (corrected for the water column) and reservoir pressure decreases (Fig. 4B), along with flow rate. When wellhead pressure is increased, as in the Wilzetta North field (Fig. 3), pressure gradient and flow rate increase. With sufficient time, volume injected, and wellhead pressure, pressure at the fault may exceed the critical pressure (Fig. 4B) and trigger slip. The time required for pressure at the fault to rise to the critical threshold in a closed compartment depends upon injection rate and reservoir volume and permeability, explaining delays before the onset of induced seismicity such as observed in this study and at the Cogdell oil field (Davis and Pennington, 1989).

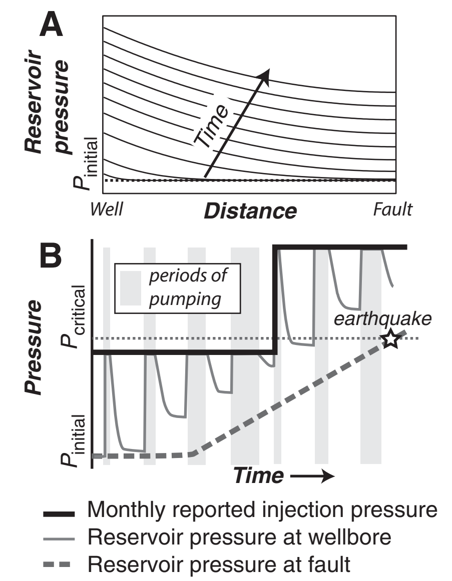

Figure 4. A: Reservoir pressure in simplistic sealed reservoir. Fluid pressure in reservoir, including at fault, rises through time as reservoir fills. Left edge of model is injection wellbore; right edge represents sealed fault. B: Predicted reservoir pressure compared to reported monthly wellhead pressure (plus weight of water column), apparently constant because pressure is reported only during pumping. Reservoir pressure near wellbore equals reported injection pressure while pumping, but drops when pump stops. Over multiple pumping cycles, time-averaged formation pressure near well rises slowly (A), and pressure gradient decreases, lowering flow rate and requiring longer periods of pumping (shaded in gray) to maintain constant monthly disposal volume. When wellhead pressure is increased, pressure gradient increases and pumping becomes more efficient.

Neither reservoir pressure data nor detailed flow rates, required to fully test this hypothesis, are available for the Prague, Oklahoma, wells. Injection rate in Oklahoma is reported as a monthly volume and the averaging of flow rate per month smooths out higher frequency variations. Alternative hypotheses to raise fluid pressure at the fault unrelated to the identified compartments, including the concurrent increase in wellhead pressure and the addition of a second injection well in 2006, cannot be rejected without reservoir pressure data. However, the agreement between original oil volume extracted and cumulative water injected prior to seismicity (Fig. 3) supports the notion that a critical volume was reached through injection in the Wilzetta North compartment.

Minor production is reported from the Hunton Limestone 500 m to the north, near the edge of the compartment (Fig. 2; well P1) (Oklahoma Corporation Commission Well Data System). It is unknown if the well is in pressure communication with the injection wells, because we have no measurements of reservoir pressure to determine connectivity. However, fluid pressure can rise throughout portions of a semirestricted reservoir following injection, and high fluid pressure can be maintained for years even if one side is infinitely open, as observed at the Rocky Mountain Arsenal (Hsieh and Bredehoeft, 1981).

DISCUSSION

Continuing injection over 18 yr into subsurface compartments in the Wilzetta field may have refilled a compartment, eventually reducing the effective stress along reservoir-bounding faults and triggering the 2010–2011 earthquakes. Injection has continued and earthquakes with magnitudes ≥3.0 continue to occur. We interpret event A (M_w 5.0) to have been induced by increased fluid pressure, exceeding the largest earthquake known to be induced by injected fluid (M_w 4.8; National Research Council of the National Academies, 2012). Aftershocks of event A appear to deepen away from the well, and may imply downward pressure propagation into basement. Event B, of much larger magnitude (M_w 5.7), and event C may also be considered consequences of injection; however, Coulomb stress calculations show that the fault geometries are consistent with triggering by stress transfer (Cochran et al., 2012). The triggering implies that the faults were close to failure, supporting the view that favorably oriented faults are critically stressed throughout the continents (Zoback et al., 2002). In this manner, small- to moderate-sized injection-induced events may result in release of additional tectonic stress. The scalar moment released in the Oklahoma sequence exceeds predictions based on the volume of injected fluid (McGarr, 1976) by several orders of magnitude, requiring the release of substantial tectonic stress.

The 2011 Prague, Oklahoma, earthquakes necessitate reconsideration of the maximum possible size of injection-induced earthquakes, and of the time scale considered diagnostic of induced seismicity. Typically, a response of seismicity to injection within months has been sought to diagnose earthquake triggering (Raleigh et al., 1976; Davis and Frohlich, 1993). Here we present a potential case of fluid injection into isolated pockets resulting in seismicity delayed by nearly 20 yr from the initiation of injection, and by 5 yr following the most substantial increase in wellhead pressure.

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EXHIBIT G

Oklahoma Geological Survey
Richard D. Andrews
Interim Director and State Geologist
Dr. Austin Holland, State Seismologist

Statement on Oklahoma Seismicity
April 21, 2015

Based on observed seismicity rates and geographical trends following major oil and gas plays with large amounts of produced water, the rates and trends in seismicity are very unlikely to represent a naturally occurring process. Historically, the Oklahoma Geological Survey (OGS) recorded on average about 1 ½, magnitude three or greater (M3+) earthquakes each year, within Oklahoma. During 2013, the OGS observed on average about 2, M3+ earthquakes each week on average, and this rate continued to increase during 2014. Currently, the OGS is reporting on average about 2 ½, M3+ earthquakes each day. The OGS considers it very likely that the majority of recent earthquakes, particularly those in central and north-central Oklahoma, are triggered by the injection of produced water in disposal wells.

The primary suspected source of triggered seismicity is not from hydraulic fracturing, but from the injection/disposal of water associated with oil and gas production. Produced water is naturally occurring water within the Earth that is often high in salinity and co-exists with oil and gas in the subsurface. As the oil and gas is extracted/produced, so is the water. This water is then separated from the oil and gas and re-injected into disposal wells, often at greater depth from which it was produced. However, it is often stated that disposed water is wastewater from hydraulic fracturing. While there are large amounts of wastewater generated from hydraulic fracturing, this volume represents a small percentage of the total volume of wastewater injected in disposal wells in Oklahoma.

The observed seismicity of greatest concentration, namely in central and north-central Oklahoma, can be observed to follow the oil and gas plays characterized by large amounts of produced water. Seismicity rates are observed to increase after a time-delay as injection volumes increase within these plays. In central and north-central Oklahoma, this time-delay can be weeks to a year or more.

The OGS can document the following geological and geophysical characteristics related to the recent earthquake activity within Oklahoma.

- The seismicity rate in 2013 was 70 times greater than the background seismicity rate observed in Oklahoma prior to 2008. While unlikely, this rate could have been potentially explained by natural variations in earthquake rates from naturally occurring swarms. The seismicity rate is now about 600 times greater than the background seismicity rate, and is very unlikely the result of a natural process.
- The majority of earthquakes in central and north-central Oklahoma occur as earthquake swarms and not in the typical foreshock-mainshock-aftershock sequences that are characteristic of naturally occurring earthquake sequences throughout the world in a variety of tectonic settings. However, it is recognized that naturally occurring earthquake swarms do occur and have occurred within the region.

- These earthquakes swarms are occurring over a large area, about 15% of the area of Oklahoma, that has experienced significant increase in wastewater disposal volumes over the last several years.
- The earthquakes are primarily occurring on faults that are optimally and sub-optimally oriented within Oklahoma's tectonic stress regime.
- Both triggered and naturally occurring earthquakes release accumulated tectonic stress on these faults.
- Most of the earthquakes in Oklahoma are occurring within crystalline basement, deeper than most oil and gas operations. However, reactivation of deeper basement faults from water injection/disposal at shallower depths is often observed in cases of triggered seismicity.
- The majority of wastewater disposal is targeted for injection in the Arbuckle formations, which closely overlie the crystalline basement.
- As a result of high bulk permeability within sections of the Arbuckle, pressure from water injection/disposal may be transmitted several miles from an injection site.
- The high density of injection wells in central and north-central Oklahoma combined with the high permeabilites within the Arbuckle makes identifying relationships between specific wells and seismic activity difficult.

The OGS endeavors to accurately document seismicity within Oklahoma, and is increasing its capability to improve earthquake monitoring and data products. This includes the addition of staff, as well as updating and adding seismic equipment to improve seismic monitoring coverage throughout the state. In addition, the OGS is compiling a database of known fault locations within Oklahoma from published scientific literature and voluntarily fault data contributions from the Oklahoma Independent Petroleum Association (OIPA). The OGS also participates in projects with the United States Geological Survey (USGS) and other researchers worldwide in the ongoing investigation of Oklahoma seismicity.

The OGS also works closely with the Oklahoma Corporation Commission (OCC) to provide information on Oklahoma seismicity and research publications on triggered and induced seismicity. The OGS collaborates with the Interstate Oil and Gas Compact Commission and Ground Water Protection Council States First Initiative Workgroup on Induced Seismicity in multi-state efforts to better understand the problem and develop a regulatory framework.

The OGS continues to make its data and data products publicly available in a timely manner, and to contribute to research and the public discussion of earthquakes in Oklahoma. As communicated in the joint USGS/OGS statement dated May 2, 2014, the earthquake hazard in Oklahoma has increased due to the increased rate of seismicity. It is important for Oklahomans to learn what to do during a significant earthquake, and be prepared. The OGS and the Oklahoma Office Emergency Management provide such information on their respective websites.

EXHIBIT H

and North Atlantic and indicate the potential for amplification of decadal-scale variability through interbasin resonance (*42*, *43*). Before the 1970s, variability in poleward heat fluxes and storm tracks in the North Pacific and North Atlantic regions were uncorrelated; more recently, highly correlated behavior has emerged (*44*). Our study documents that the development of such teleconnected variability between these regions is a fundamentally important phenomenon associated with rapid warming, suggesting that such properties may be high-priority targets for detailed monitoring in the future.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/345/6195/444/suppl/DC1
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INDUCED EARTHQUAKES

Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection

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Unconventional oil and gas production provides a rapidly growing energy source; however, high-production states in the United States, such as Oklahoma, face sharply rising numbers of earthquakes. Subsurface pressure data required to unequivocally link earthquakes to wastewater injection are rarely accessible. Here we use seismicity and hydrogeological models to show that fluid migration from high-rate disposal wells in Oklahoma is potentially responsible for the largest swarm. Earthquake hypocenters occur within disposal formations and upper basement, between 2- and 5-kilometer depth. The modeled fluid pressure perturbation propagates throughout the same depth range and tracks earthquakes to distances of 35 kilometers, with a triggering threshold of ~0.07 megapascals. Although thousands of disposal wells operate aseismically, four of the highest-rate wells are capable of inducing 20% of 2008 to 2013 central U.S. seismicity.

Seismicity in the United States midcontinent surged beginning in 2008 (*1*), predominantly within regions of active unconventional hydrocarbon production (*2*–*6*). In Arkansas, Texas, Ohio, and near Prague, Oklahoma, recent earthquakes have been linked to wastewater injection (*2*–*7*), although alternative interpretations have been proposed (*1*, *8*). Conclusively distinguishing human-induced earthquakes solely on the basis of seismological data remains challenging.

Seismic swarms within Oklahoma dominate the recent seismicity in the central and eastern United States (*9*), contributing 45% of magnitude (M) 3 and larger earthquakes between 2008 and 2013 (*10*). No other state contributed more than 11%. A single swarm, beginning in 2008 near Jones, Oklahoma, accounts for 20% of seismicity in this region (*10*). East of Jones, the damaging 2011 moment magnitude (M_w) 5.7 earthquake near Prague, Oklahoma, was likely induced by wastewater injection (*2*, *8*, *11*, *12*), the highest magnitude to date. These earthquakes are part of a 40-fold increase in seismicity within Oklahoma during 2008 to 2013 as compared to 1976 to 2007 (Fig. 1, inset A) (*10*). Wastewater disposal volumes have also increased rapidly, nearly doubling in central Oklahoma between 2004 and 2008. Many studies of seismicity near disposal wells rely upon statistical relationships between the relative timing of seismicity, disposal well location, and injected water volume to evaluate a possible causal relationship (*3*–*7*, *13*).

Here we focused on the Jones swarm and compared modeled pore pressure from hydrogeological models to the best-constrained earthquake hypocenters (*14*). Using data from local U.S. Geological Survey NetQuake accelerometers, the Earthscope Transportable Array, and a small local seismic network (fig. S1), we generated a catalog of well-located earthquakes between 2010 and 2013. Event-station distances were predominantly less than 10 km (fig. S2D), and all earthquakes were recorded on at least one seismometer within 20 km of the initial hypocenter. To study pore pressure changes at earthquake hypocenters and the apparent migration in seismicity, we developed a three-dimensional hydrogeological model of pore pressure diffusion from injection wells.

The Jones swarm began within 20 km of high-rate wastewater disposal wells, among the highest rate in Oklahoma, between two regions of fluid injection (Fig. 2). The four high-rate wells are southwest of Jones in southeast Oklahoma City (SE OKC) and dispose of ~4 million barrels per month (*15*) (Fig. 3). The target injection depth is 2.2 to 3.5 km into the Cambrian-Ordovician

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Arbuckle Group (fig. S3), a dolomitized carbonate; one disposal well ends near Precambrian basement. The large disposal wells are within dewatering plays (fig. S4). Dewatering production wells produce substantial wastewater volumes with initially up to 200 times as much water per barrel of oil as conventional production wells (*16*, *17*). The rate of wastewater disposal in central Oklahoma has gradually increased since the mid-1990s (fig. S5), but disposal rates jumped after 2004 as high-rate injection wells began operating, including the first of the SE OKC wells in 2005 (Fig. 3) (*15*). Seismic moment release escalated in the Jones swarm in 2009, concurrent with the initial reported application

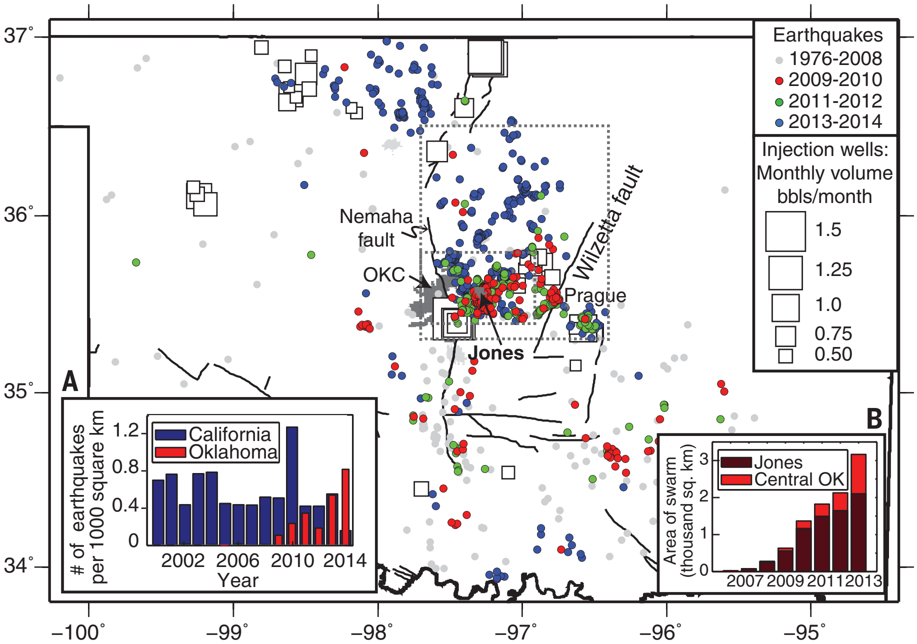

Fig. 1. Earthquakes in Oklahoma between 1976 and 2014. Earthquakes are $M > 1$ from the NEIC catalog (*10*). Black lines are faults (*26*–*28*). Small and large dashed gray boxes outline the areas used for analysis of the Jones swarm and of central Oklahoma, respectively, in inset B. OKC: Oklahoma City. **Inset A:** Comparison of $M3+$ earthquake rate in Oklahoma and California, normalized by area. California is ~2.3 times larger than Oklahoma. 2014 earthquakes are through the first 4 months. **Inset B:** Expanding area of the Jones and the broader central Oklahoma swarms. Regions were divided into 5 km by 5 km grid cells, and any cell with an earthquake was considered part of the swarm. Swarm area per year is inclusive of all prior years.

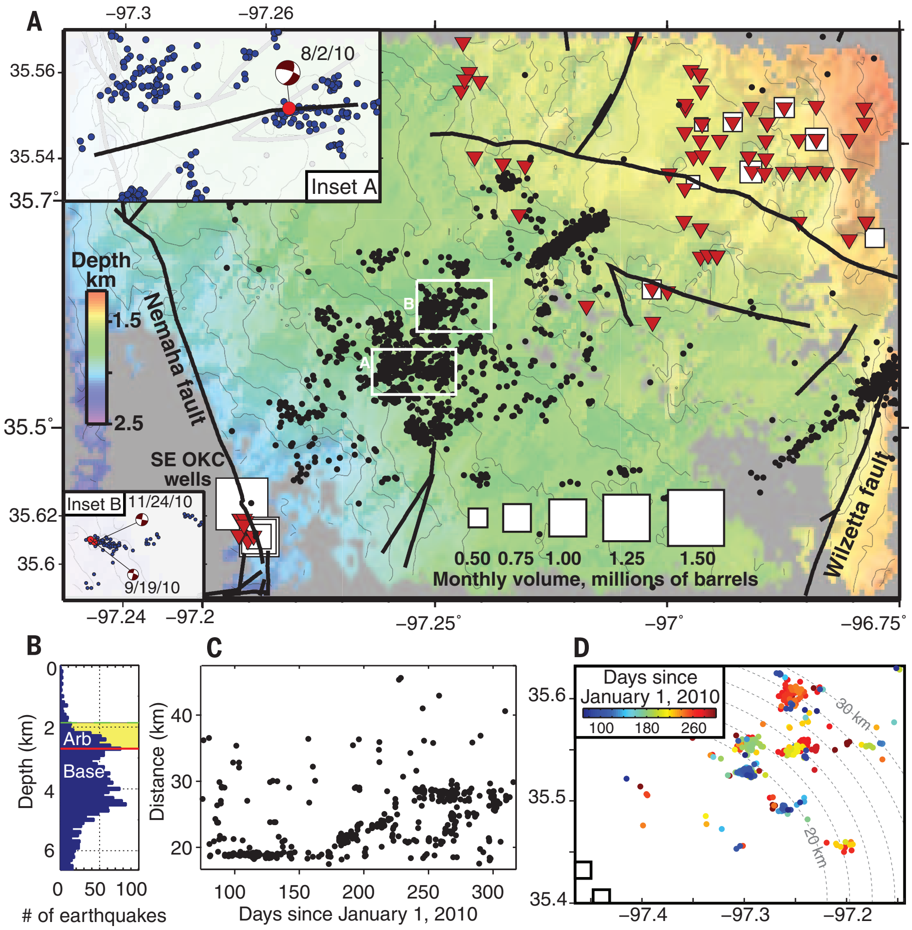

Fig. 2. Earthquake catalog and swarm migration. (**A**) Jones earthquake catalog March 2010 to March 2013 using local stations. Squares are injection wells operating at an average rate ≥ 400,000 barrels per month (*15*, *29*); triangles are high–water production wells. Background color and contours represent depth to the top of the Hunton Group (*15*). The Hunton Group is higher in section than the Arbuckle Group but has more data on formation depth. (**B**) Earthquake depth histogram; earthquakes are dominantly in sediment and upper basement. (**C**) Distance of each March to October 2010 Jones earthquake to the SE OKC disposal wells. The dense region of the swarm increases in distance between days 150 and 250 in 2010. (**D**) Map view of Jones earthquakes during March to October 2010, colored by time. Semicircles are equidistant lines from SE OKC disposal wells. Faults at greater distance from the wells become active at later times. Details of two of these fault planes are shown in insets of Fig. 2A and are discussed in the text.

of positive wellhead pressure at the SE OKC wells (Fig. 3B).

Earthquakes in our catalog primarily nucleated either within the Arbuckle Group or within the upper 2 km of basement, with 22 to 33% above basement (Fig. 2B and fig. S6). Well-constrained earthquake hypocenters from March to October 2010 migrated northeast from the initial swarm centroid near Jones at 0.1 to 0.15 km/day (Fig. 2, C and D), followed by a broad spread in seismicity. Earthquake hypocenters are not diffusely distributed; instead, relocated aftershock sequences of individual earthquakes (*18*) illuminate narrow faults parallel to one plane of calculated focal mechanisms (*19*) (Fig. 2A, insets). An earthquake on 2 August 2010 ruptured a portion of a 7-km-long mapped fault; if the entire fault had ruptured, earthquake scaling laws suggest a maximum magnitude of ~*M*6.0 (*20*). Earthquakes later in 2010 ruptured an unmapped east-southeast– to west-northwest–trending fault, at an oblique angle to the overall northeast-southwest migration direction of the swarm. Although the swarm of seismicity migrates to the northeast parallel to structural dip, the individual faults, as evidenced by earthquake lineations, are not preferentially oriented in this direction.

Our hydrogeological model simulated injection into the Arbuckle Group using reported injection rates at 89 wells within 50 km of the Jones swarm between 1995 and 2012 (*14*). The wells include the four high-rate wells in SE OKC and 85 wells to the northeast of Jones. The model predicts a region of high fluid pressure perturbation spreading radially eastward from the SE OKC wells and a lesser perturbation around the lower-rate wells to the northeast (Fig. 4). The high pore pressure increase occurs within the Arbuckle Group and in the upper 1 to 2 km of the basement in our model; nearly all earthquakes occur within this same depth range (Fig. 2B). The migrating front of the Jones earthquake swarm corresponds closely to the expanding modeled pressure perturbation away from the SE OKC wells, which reaches 25 km from the wells by December 2009 and ~35 km by December 2012. The pore pressure change modeled at each hypocenter indicates a critical threshold of ~0.07 MPa, above which earthquakes are triggered. This threshold is compatible with prior observations that static stress changes of as little as ~0.01 to 0.1 MPa are sufficient to trigger earthquakes when faults are near failure in the ambient stress field (*21*–*23*).

Our results indicate that for modeled diffusivities, ~85% of the pore pressure perturbation is contributed by the four high-rate SE OKC wells. The 85 wells to the northeast contribute ~15% additional pore pressure change at the center of the Jones swarm by the end of 2012 and may contribute to the triggering of earthquakes particularly outside the region affected by the SE OKC wells (fig. S7). The modeled dominance of the SE OKC wells is attributable to their high rate; these wells include one of the largest wells in the state and three closely spaced wells 3.5 km away with a combined monthly volume of ~3 million barrels per month. The only other Oklahoma wells of similar size, in northern Oklahoma (fig. S8), are on the boundary of a second rapidly growing seismic swarm (Fig. 1). The summed rate of this well cluster near SE OKC is higher than previous cases of reported induced seismicity (Fig. 3A), including several times higher than the high-rate disposal wells linked to earthquakes near Dallas–Fort Worth, Texas, and Cleburne, Texas (*5*–*7*). Comprehensive compilations of injection well rates for other high-injection states, including Texas and California, are not yet accessible.

We view the expanding Jones earthquake swarm as a response to regionally increased pore pressure from fluids primarily injected at the SE OKC wells. As the pressure perturbation expanded and encountered faults at various orientations, critically stressed, optimally oriented faults are expected to rupture first (*24*). Additional faults at near-optimal orientations may rupture after further pressure increase (Fig. 4). As fluid pressure continues to

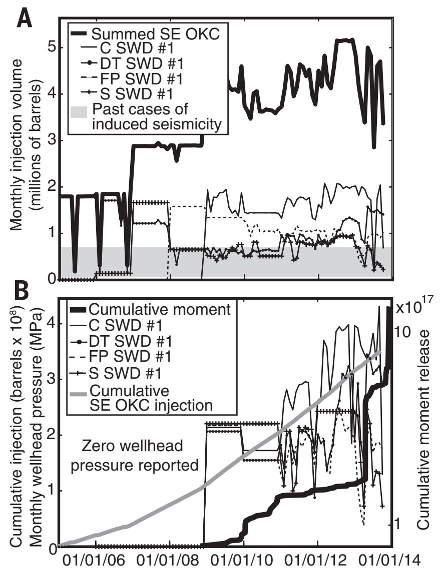

Fig. 3. Fluid injection reported in the four high-rate SE OKC wells. (**A**) Sum and individual monthly injection volumes and (**B**) wellhead pressure and cumulative, summed injected volume (*15*). The DT SWD #1, FP SWD #1, and S SWD #1 wells are in close proximity; the C SWD #1 well is ~3.5 km away. Gray shading denotes injection rates for notable past cases of induced seismicity for reference (table S1). Cumulative seismic moment in (B) is calculated from *M*3+ earthquakes from 2005 to January 2014 (*10*) for earthquakes within the box outlining the Jones swarm in Fig. 1.

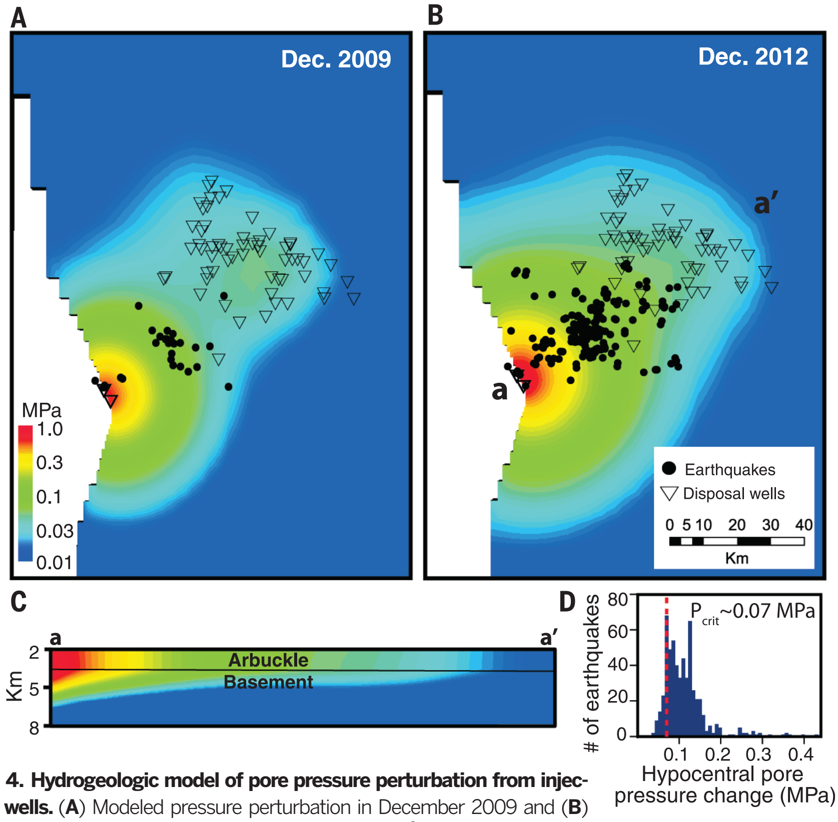

Fig. 4. Hydrogeologic model of pore pressure perturbation from injection wells. (**A**) Modeled pressure perturbation in December 2009 and (**B**) in December 2012 with a hydraulic diffusivity of 2 m^2/s (*14*). The model includes the four high-rate SE OKC wells and 85 wells northeast of the Jones swarm near the West Carney field. The modeled pressure perturbation is dominated by fluid injected at the high-rate SE OKC wells. Earthquakes are plotted from 2008 to 2009 (A) and 2008 to 2012 (B) (*10*). (**C**) Vertical cross section through model results. Pore pressure rises in the Arbuckle Group and uppermost basement. (**D**) Pore pressure increase at the hypocenter of each earthquake in our local catalog. A pore pressure increase of ~0.07 MPa is the modeled triggering threshold. Modeled pore pressure rises throughout much of the swarm area for hydraulic diffusivity between 1 and 4 m^2/s (fig. S7).

propagate away from the wells and disturbs a larger and larger volume, the probability increases that fluid pressure will encounter a larger fault and induce a larger-magnitude earthquake. The absence of earthquakes in regions above the critical pressure threshold may result from either a lack of faults or lack of well-oriented, critically stressed faults. Alternatively, fluid flow may preferentially migrate along bedding structure (Fig. 2A).

Though seven earthquakes were recorded in 2006 to 2009 near the base of the SE OKC wellbores (*10*), the main swarm began ~15 km to the northeast (fig. S9), despite the high modeled pressure perturbation near the wells. Earthquakes in 2009 primarily occurred, within location uncertainty, near injection wells or on the nearest known faults to the northeast of the wells (fig. S9). Focal mechanisms near the swarm onset indicate fault planes at orientations favorable to failure (*19*) (Fig. 2, inset B). Faults subparallel to the north-northwest–south-southeast–trending Nemaha fault would not be well oriented for failure in the regional ~N70E stress regime (*25*) and would require substantially larger pressure increase to fail. Recent earthquakes near the fault may be evidence for continued pressure increase. This 50-km-long segment of the Nemaha fault is capable of hosting a *M*7 earthquake based on earthquake scaling laws (*20*), and the fault zone continues for hundreds of kilometers. The increasing proximity of the earthquake swarm to the Nemaha fault presents a potential hazard for the Oklahoma City metropolitan area.

Our earthquake relocations and pore pressure models indicate that four high-rate disposal wells are capable of increasing pore pressure above the reported triggering threshold (*21*–*23*) throughout the Jones swarm and thus are capable of triggering ~20% of 2008 to 2013 central and eastern U.S. seismicity. Nearly 45% of this region's seismicity, and currently nearly 15 $M > 3$ earthquakes per week, may be linked to disposal of fluids generated during Oklahoma dewatering and after hydraulic fracturing, as recent Oklahoma seismicity dominantly occurs within seismic swarms in the Arbuckle Group, Hunton Group, and Mississippi Lime dewatering plays. The injection-linked seismicity near Jones occurs up to 35 km away from the disposal wells, much further than previously considered in existing criteria for induced seismicity (*13*). Modern, very high-rate injection wells can therefore affect regional seismicity and increase seismic hazard. Regular measurements of reservoir pressure at a range of distances and azimuths from high-rate disposal wells could verify our model and potentially provide early indication of seismic vulnerability.

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SUPPLEMENTARY MATERIALS

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DINOSAUR EVOLUTION

A Jurassic ornithischian dinosaur from Siberia with both feathers and scales

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Middle Jurassic to Early Cretaceous deposits from northeastern China have yielded varied theropod dinosaurs bearing feathers. Filamentous integumentary structures have also been described in ornithischian dinosaurs, but whether these filaments can be regarded as part of the evolutionary lineage toward feathers remains controversial. Here we describe a new basal neornithischian dinosaur from the Jurassic of Siberia with small scales around the distal hindlimb, larger imbricated scales around the tail, monofilaments around the head and the thorax, and more complex featherlike structures around the humerus, the femur, and the tibia. The discovery of these branched integumentary structures outside theropods suggests that featherlike structures coexisted with scales and were potentially widespread among the entire dinosaur clade; feathers may thus have been present in the earliest dinosaurs.

The origin of birds is one of the most-studied diversification events in the history of life. Principal debates relate to the origin of key avian features such as wings, feathers, and flight (*1*–*9*). Numerous finds from China have revealed that diverse theropods possessed feathers and various degrees of flight capability (*4*–*9*). The identification of melanosomes in non-avian theropods (*10*, *11*) confirms that fully birdlike feathers originated within Theropoda at least 50 million years before *Archaeopteryx*.

But were feathers more widespread among dinosaurs? Quill-like structures have been reported in the ornithischians *Psittacosaurus* (*12*) and *Tianyulong* (*13*), but whether these were true feathers, or some other epidermal appendage, is unclear. Bristlelike epidermal appendages occur in pterosaurs, some early theropods (*14*), and extant mammals ("hairs"), and so the *Psittacosaurus*

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Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection

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