



RESEARCH LETTER

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Key Points:

- Oklahoma seismicity is occurring on faults capable of larger earthquakes
- A high degree of potential earthquake hazard exists in Oklahoma
- Reactivated structures in Oklahoma are optimally oriented for failure

Supporting Information:

- Text S1, Figures S1–S8, and Tables S1–S2

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Earthquake hypocenters and focal mechanisms in central Oklahoma reveal a complex system of reactivated subsurface strike-slip faulting

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Abstract The sharp increase in seismicity over a broad region of central Oklahoma has raised concern regarding the source of the activity and its potential hazard to local communities and energy industry infrastructure. Since early 2010, numerous organizations have deployed temporary portable seismic stations in central Oklahoma in order to record the evolving seismicity. In this study, we apply a multiple-event relocation method to produce a catalog of 3639 central Oklahoma earthquakes from late 2009 through 2014. Regional moment tensor (RMT) source parameters were determined for 195 of the largest and best recorded earthquakes. Combining RMT results with relocated seismicity enabled us to determine the length, depth, and style of faulting occurring on reactivated subsurface fault systems. Results show that the majority of earthquakes occur on near-vertical, optimally oriented (NE-SW and NW-SE), strike-slip faults in the shallow crystalline basement. These are necessary first-order observations required to assess the potential hazards of individual faults in Oklahoma.

1. Introduction

Since late 2009, the rate of magnitude 3 or larger earthquakes in north central Oklahoma is nearly 300 times higher than in previous decades (Figure 1). Several of these earthquakes caused damage and many were felt with over 153,000 individual felt reports for 474 separate earthquakes entered at the Did you feel it? (DYFI) website of the U. S. Geological Survey's (USGS) Did You Feel It? website. The earthquakes are located within the upper crust on subsurface reactivated structures in the Nemaha and Wilzetta fault zones (Figure 2). These fault systems bound a broad region of uplift in central Oklahoma that was originally formed as a result of the Ancestral Rocky Mountains orogeny during the Pennsylvanian period [Joseph, 1987; Luza and Lawson, 1982]. The uplifted region is a complex belt of ancient, buried, high-angle faults [Northcutt and Campbell, 1995] that have been exploited for the past 100 years for their reservoirs of oil and gas [Dolton and Finn, 1989]. The recent increased seismicity poses an elevated earthquake hazard to the infrastructure, communities, and regional population.

Beginning in early 2010, the USGS cooperated with the Oklahoma Geological Survey (OGS) to deploy temporary portable seismic stations in order to improve monitoring of the increasing earthquake rate in central Oklahoma and potentially capture ground shaking from a large event (see supporting information for additional details). The largest seismic sequence was a series of three moderate, but damaging earthquakes (M_w 4.8, 5.6, and 4.8) that occurred in early November 2011 near the town of Prague (Figures 1 and 2). The sustained increase in earthquake rates has raised both interest and concern among numerous research groups as well as state and federal agencies [Petersen et al., 2014]. Llenos and Michael [2013] have noted that the recent activity does not follow the statistical distribution of naturally occurring tectonic earthquakes, indicating a fundamental change in the earthquake triggering process may have occurred. Of particular concern is whether wastewater injection by the oil and gas industry is influencing seismic activity and what the potential hazards are to the communities and structures in the seismic zone [Keranen et al., 2013, 2014; Ellsworth, 2013]. Earthquake source characterization is essential to address these questions. Understanding the orientation and style of the faults along with their location relative to larger, established faults in the region is critical in determining both the cause of the activity and the potential hazards. Drawing from the analysis presented in

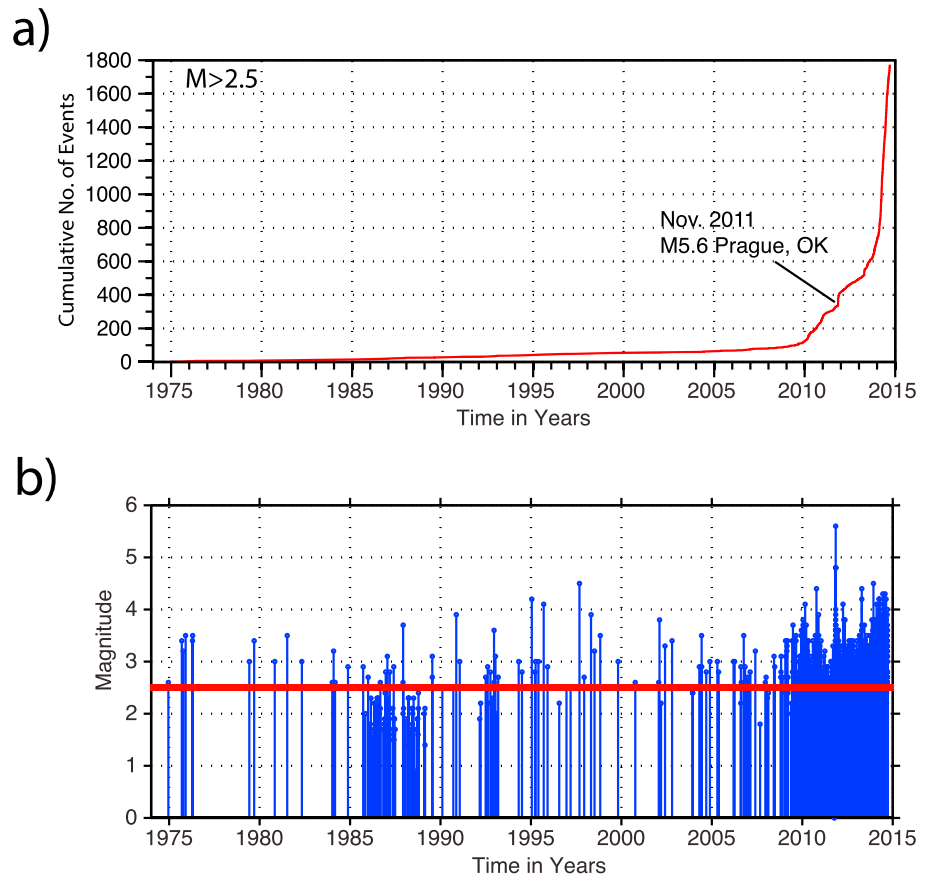


Figure 1. Earthquakes from the NEIC COMCAT system. (a) Plot showing Oklahoma cumulative seismicity ($M > 2.5$) from 1975 through December 2014. (b) Timeline showing earthquake magnitude from 1975 through December 2014.

this study, we identified several factors that signify the potential for larger and more damaging earthquakes to occur in the future. Key findings include the following: (1) the majority of the faults in the region are favorably oriented relative to the regional compressive stress field (N85E) and thus susceptible to rupture; (2) earthquakes are shallow and primarily constrained to the upper portion of the crystalline basement (less than 6 km depth); (3) a substantial number of faults are relatively long (up to 10 km), and (4) in a few cases, earthquakes are occurring on well-known, subsurface faults that have the potential to produce larger earthquakes. Together these findings indicate an increased level of potential earthquake hazard in central Oklahoma.

2. Data and Methods

Immediately following the M_w 4.8 earthquake of 05 November 2011 in the Prague region, the University of Oklahoma, the USGS and the Incorporated Research Institutions in Seismology (IRIS) installed additional broadband seismograph stations near the epicenter of the earthquake; fortunately, three stations were deployed in time to record the M_w 5.6 Prague earthquake on the following day [Keranen *et al.*, 2013]. Since the November 2011 Prague sequence, additional seismic stations have been deployed to improve monitoring of earthquake sequences near Oklahoma City (Guthrie, Langston, Jones, and Cushing) and in north central Oklahoma near the towns of Medford and Stillwater (Figure 2). Complementing the portable deployments were temporary regionally distributed stations in the Earthscope Transportable Array and permanent stations operated by the OGS and USGS. Waveforms and phase picks from over 100 seismic stations were analyzed in this study to determine detailed earthquake source parameters that can be used to characterize regions of reactivated faulting in central Oklahoma (see supporting information for additional details).

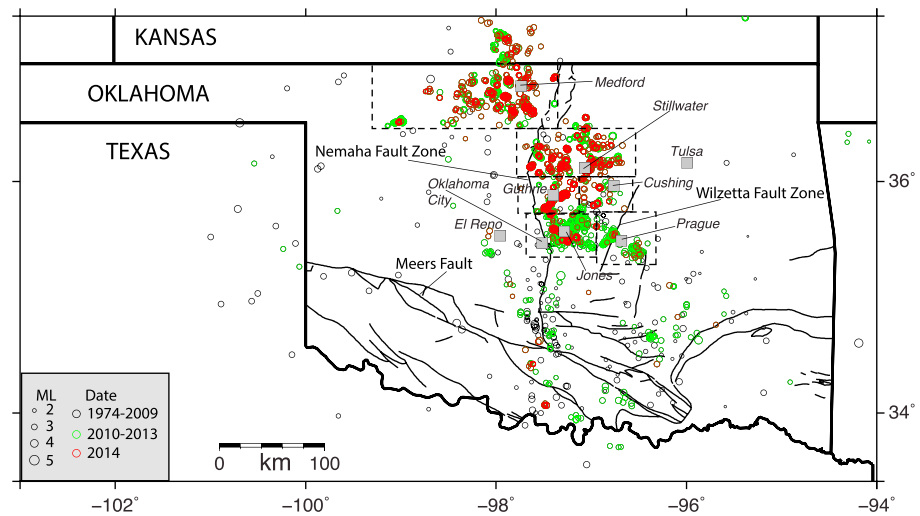


Figure 2. Map showing the USGS NEIC single-event epicenters (1974 to December 2014). Grey lines are subsurface and surface faults from *Northcutt and Campbell [1995]*. Dashed black lines outline the regions discussed in the section 3 and shown in Figures 4 and S7. The Meers fault is also shown and is the only known active fault in Oklahoma prior to the recent increase in seismicity.

2.1. Multiple-Event Location

An initial catalog of USGS National Earthquake Information Center (NEIC) hypocenter locations and phase data was used as input to determine calibrated multiple-event relocations using the Hypocentroidal Decomposition (HD) method first developed by *Jordan and Sverdrup [1981]*. HD is a multiple-event procedure in the same class of methods that include Joint Hypocentral Determination [*Dewey, 1972*] and Double Difference [*Waldhauser and Ellsworth, 2000*]. The HD relocation method provides improved hypocenter locations with minimized location bias and realistic estimates of location uncertainty for each earthquake. When local seismic stations are available, location uncertainty is reduced to <1 km. In other cases uncertainty is reduced to <2 km. In addition, relocating earthquakes using HD can reduce, by a factor of 2, the scatter in hypocenter locations determined using single-event methods. Another advantage of this method is the ability to accurately relocate a main shock using regional stations that also recorded aftershocks on the more dense local network. Recent examples of HD applications can be found in *McNamara et al. [2014]*, *Hayes et al. [2013]*, [2014], and *Rubinstein et al. [2014]* (see supporting information for additional details).

2.2. Regional Moment Tensors

We took advantage of the fact that the regional moment tensor (RMT) method provides good estimates of the earthquake depth, magnitude, and style of faulting. RMT solutions were computed using the broadband waveform modeling method described in *Herrmann et al. [2011]* and the multiple-event HD hypocenter locations determined in this study. The waveforms were typically filtered between 16 and 50 s periods but were filtered to shorter periods of 12–30 s for smaller earthquakes (typically $< M_w 3.5$). Green's functions were computed using the western U.S. model of *Herrmann et al. [2011]*, a model that best fit the observed local and regional *P* wave travel times and surface wave amplitude and dispersion in the period band 10–100 s for Oklahoma earthquakes. RMT source parameters were determined for 195 of the largest and best recorded earthquakes modeled in this study (Figures 3 and 4) (see supporting information for additional details).

3. Results

The complete catalog of 3639 central Oklahoma earthquakes produced in this study is magnitude complete to 2.5 (Table S1). Additional processing was done to the Prague sequences to lower the magnitude of completeness to 0.5. The Prague sequence was a special study because of a deployment of temporary stations in the area prior to and following the $M_w 5.6$ main shock. Of the 3639 relocated earthquakes in this study, 1434 are associated with the Prague sequence.

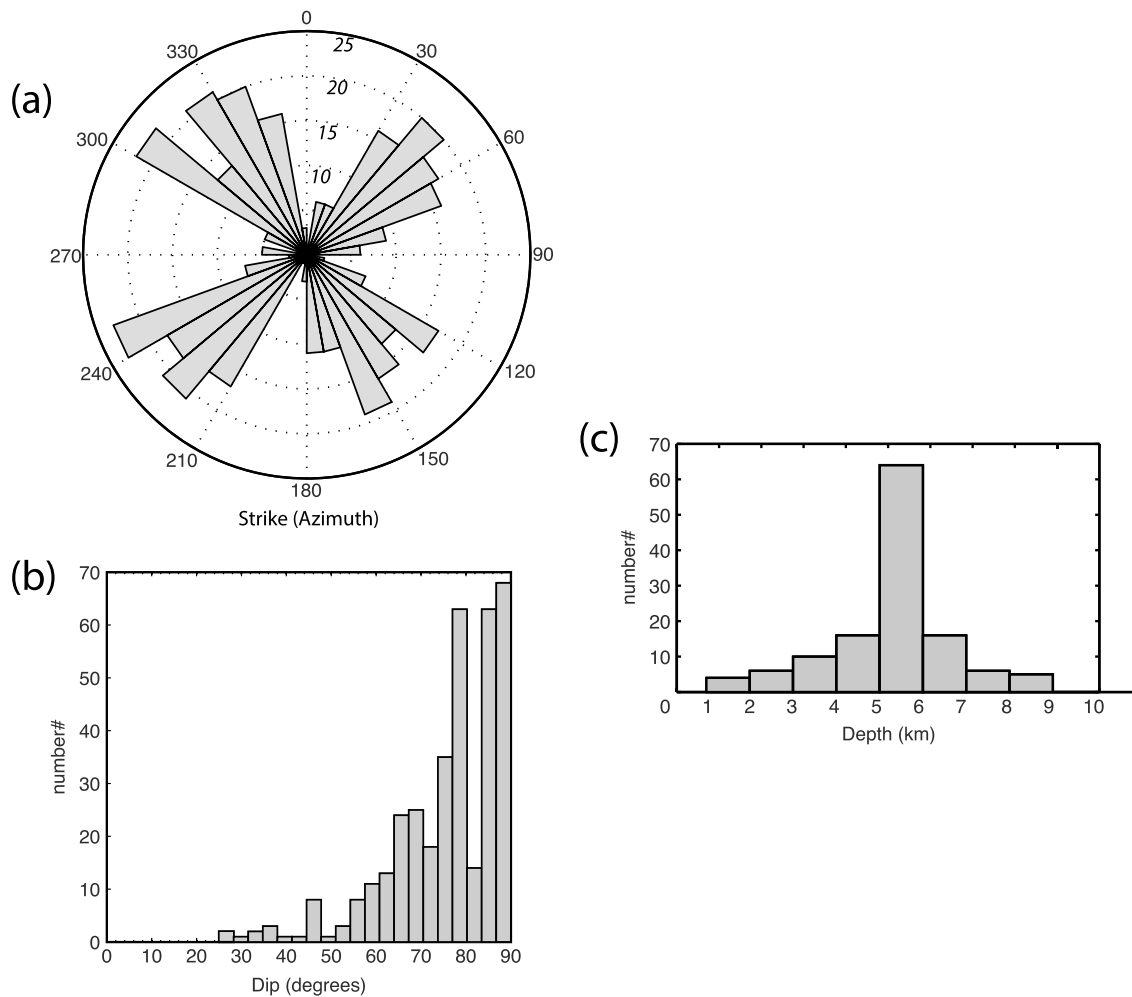


Figure 3. Histograms of RMT source parameters. (a) Rose histogram showing strikes of all nodal planes. (b) Histogram showing dips of all nodal planes. (c) Histogram showing RMT depths.

From late 2009 through 2013, the most intense seismic activity was primarily observed in central Oklahoma, east and northeast of Oklahoma City (Figure 2). Starting in late 2013, activity began to occur in a broader region of north central Oklahoma extending from Oklahoma City into south central Kansas (Figure 2). The increase in seismicity is best illustrated in a plot of cumulative seismicity versus time (Figure 1), which shows a steady increase until late 2009, followed by another increase in 2011 due to the November 2011 Prague sequence. The latter includes a damaging M_w 5.6 and several $M_w \geq 4$ earthquakes. Following the Prague sequence, cumulative seismicity rose moderately into 2014 (Figure 1), when it began to climb significantly due to an expanded area over which earthquakes were occurring and a significant increase in the number of $M_w > 4$ earthquakes in the larger area of active seismicity (Figures 1 and 2).

The majority of the recent earthquakes in central Oklahoma define reactivated ancient faults at shallow depths in the crust (< 6 km) (Figure 3c); these faults cut through the Cambro-Ordovician Arbuckle Group and extend down into the crystalline basement. The RMT focal mechanisms determined in this study are predominantly strike slip with one nodal plane oriented on average $45^\circ \pm 5^\circ$ and the other oriented $135^\circ \pm 5^\circ$ (Figure 3) (Table S2). These nodal planes are optimally oriented relative to the maximum horizontal compression direction (N85E) for reactivating earthquake activity on ancient faults [Alt and Zoback [2014]; Zoback and Zoback, 1991; Holland, 2013]. The following sections describe results in each region shown in Figure 2.

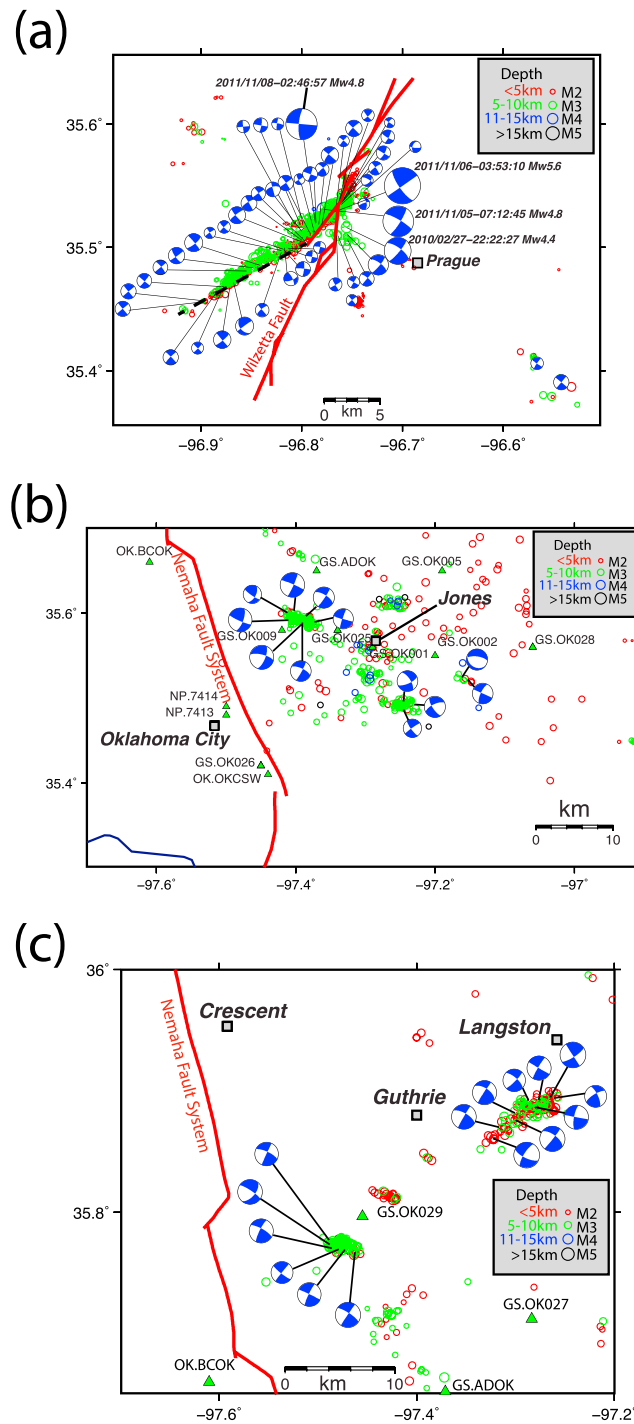


Figure 4. Oklahoma HD relocated epicenters and RMTs shown in three regions corresponding to boxes in Figure 1. Grey squares show Oklahoma cities within each region. Circles show the HD relocated hypocenters sized by magnitude and colored by depth. Green triangles show the locations of seismic stations used in this study. Red lines are subsurface and surface faults from *Northcutt and Campbell* [1995] and *Joseph* [1987]. (a) Prague Region. (b) Jones Region. (c) Guthrie-Langston Region.

3.1. Seismicity in the Vicinity of Prague, Oklahoma

The Prague earthquake sequence has been well studied by numerous groups [Holland, 2013; Keranen et al., 2013; Sumy et al., 2014] with an emphasis on understanding the connection between the M_w 4.8 foreshock, the M_w 5.6 main shock and the injection of hydraulic fracturing wastewater into deep disposal wells. Our HD relocation moved the November 2011 Prague main shock (M_w 5.6) approximately 1 km to the southwest, placing it well within the main aftershock zone and directly along a southwest trending splay of the Wilzetta Fault (Figure 4a). The earthquake was one of the largest in Oklahoma history and caused major damage to residences in the epicentral region (MMI VIII USGS PAGER). Relocated seismicity of the Prague earthquake sequence (Figure 4a) defines a complex intersection of reactivated fault segments within the Wilzetta fault system that includes a relatively long (approximately 20 km) main branch, along with several shorter (2–4 km) antithetic structures (Figures S5 and S6) (see supporting for additional details).

The Wilzetta fault (also known as the Seminole uplift) is one of a series of small faults formed in the Pennsylvanian Epoch (approximately 300 Ma ago) during the formation of the Nemaha fault system [Northcutt and Campbell, 1995]. The northern portion of the northeast southwest trending belt of seismicity closely aligns with the spatial location of a splay of the Wilzetta fault (red line Figure 4a). The southern half, however, deviates westward away from the previously mapped main trace of the Wilzetta Fault (dashed red line Figure 4a). The extension of the aftershocks well past the mapped splay of the Wilzetta Fault follows a topographic low in the pre-Pennsylvanian unconformity [Joseph, 1987], suggesting a possible continuation of the fault (Figure S5). At depth, the aftershocks

define the active fault as a near-vertical structure. Aftershocks within this band of seismicity died off very rapidly (p value = 1.3, Figure S7) and occur primarily in the depth range of about 1 to 10 km, placing the

shallow aftershocks (<3 km depth) within the Arbuckle Group, the primary wastewater disposal formation, and deeper earthquakes in the underlying basement rocks.

The RMT analysis for the M_w 4.8 foreshock and M_w 5.6 main shock defines a near-vertical northeast striking nodal plane with, right-lateral strike-slip motion that aligns with the relocated seismicity (Figure 4a). The 08 November 2011 M_w 4.8 aftershock also has a near-vertical, strike-slip mechanism, but with an E-W nodal plane that aligns with a ~5 km splay of aftershock seismicity. The seismicity and mechanism combined indicate activity on an antithetical left-lateral strike-slip fault, likely activated in response to the stress changes from the M_w 5.6 main shock (see supporting information for additional details).

3.2. Seismicity in the Vicinity of Jones, Oklahoma

Beginning in 2010, earthquake rates increased in the Jones region. The over 420 earthquakes shown in this region are more diffuse and occur within several different clusters with the largest area of activity occurring northwest of the town of Jones (Figure 4b). This cluster of over 100 earthquakes lies on an approximately 6 km long northwest southeast trending fault consistent with one of the RMT nodal planes. The cluster of earthquakes has been previously linked to fluid migration from high-rate disposal wells (averaging about 1,000,000 barrels/month) located about 20 km SSW in southeast Oklahoma City [Keranen *et al.*, 2014]. Relocated earthquake depths (1–10 km) are within large disposal formations and deeper basement structures [Gay, 1999].

3.3. Seismicity in the Vicinity of Guthrie and Langston, Oklahoma

In mid-2013, earthquake activity significantly increased in the Guthrie-Langston region as shown by the nearly 400 earthquakes in Figure 4c. Relocated seismicity identifies two large and several small earthquake clusters in the area. The largest earthquake in the area is an M_w 4.4 about 12 km SSW of Guthrie. The trend of the seismicity and RMT focal mechanisms suggests the active structure is a left-lateral strike-slip basement fault that strikes to the NW. The largest earthquake cluster in this region is SW of Langston where the trend of seismicity and RMT focal mechanisms indicates faulting on a right-lateral strike-slip basement fault. This sequence is unusual in being relative long (approximately 12 km) as compared to clusters that are typically less than 5–6 km in length. In total 15 RMT solutions have been computed in the region, and all RMT solutions are characteristically near-vertical strike-slip mechanisms that only fit well using a shallow source (<4 km depth).

3.4. Seismicity in the Vicinity of Cushing, Oklahoma

In late 2014, a new area of seismicity was observed in a region between Chandler and Cushing, Oklahoma (Figure S8a). The two largest earthquakes (M_w 4.0 and M_w 4.3 on 7 and 10 October, respectively) occurred approximately 5 km south of Cushing with reported minor damage at the regional airport and community youth center. Earthquakes within this cluster died off rapidly after the largest M_w 4.3, are relatively shallow (<5 km) and align along an approximately 5 km long E-W trending basement fault that is consistent with a RMT nodal plane and runs directly beneath the Cushing airport and eastward under the southern end of the Cushing oil storage and transportation facility (Figure S8a). The relocated seismicity occurs at a complex intersection of conjugate strike-slip faults within the Wilzetta-Whitetail fault zone and represents a significant hazard to energy industry infrastructure [Bennison, 1964; Joseph, 1987; McBee, 2003].

3.5. Seismicity in North Central Oklahoma Region (Medford, Stillwater)

This area of Oklahoma has only experienced significant increases in seismicity since late 2013. Station coverage in the region is relatively limited as compared to farther south near Oklahoma City. However, the recent addition of stations in southern Kansas [Rubinstein *et al.*, 2013] enables us to identify several small clusters of earthquakes and relocate 1320 shown in Figures S8b and S8c. Twelve earthquakes were large enough to compute RMTs, the two largest (M_w 4.1 and M_w 4.2 on 30 March 2014 at 14:09:59 UTC and 06:51:56 UTC, respectively) occurred on a northeast to southwest striking splay of the Nemaha fault zone north of Crescent, Oklahoma (Figure S8b). The trend of this relocated sequence is consistent with the right-lateral nodal plane of six the RMTs.

In the Medford region (Figure S8c), seventeen earthquakes were large enough to compute RMTs; the two largest were a M_w 4.0 on 19 September 2014 at 01:31:53 UTC and a M_w 4.3 on 29 July 2014 at 02:46:36 UTC. According to the USGS Did You Feel It system, the M_w 4.3 event was felt widely up to 250 km away in central

and eastern Kansas and south to Oklahoma City and Norman, Oklahoma. Locally, the maximum earthquake shaking was estimated to be Mercalli Intensity VI. We can identify several small clusters within the generally dispersed seismicity with a mix of northwest to southeast and northeast to southwest striking fault planes. Several small 1–2 km long earthquake clusters are of significance to future earthquake hazards due to their proximity to longer faults associated with the Nemaha fault zone. Both the seismicity and RMT solutions constrain source depths to be less than about 5 km.

4. Discussion

Developing spatial correlations between earthquakes and specific faults in the Central United States (CUS) has traditionally been difficult. This has primarily been due to low seismicity rates and few well-constrained earthquake locations and moment tensor solutions. The combination of the recent increased earthquake rate, good station coverage over a broad region of the CUS and strategically located temporary stations enabled us to build a catalog of calibrated earthquake locations and RMT solutions to relatively small magnitudes (typically $M_{3.5}$ or larger). Combining RMT results with relocated seismicity enabled us to determine the length, depth, and style of faulting occurring on ancient reactivated fault systems. These are necessary first-order observations required to assess the potential hazards of individual faults in Oklahoma.

Based on our catalog of earthquake source parameters, we can delineate numerous reactivated subsurface faults throughout central Oklahoma and provide guidance on which faults are of most concern. The majority of the reactivated faults in the region are favorably oriented for earthquake rupture relative to the regional compressive stress field (Figure 3) [Alt and Zoback, 2014]. Earthquakes are shallow and primarily constrained to the upper portion of the crystalline basement (less than 6 km depth) with some seismicity reaching into the overlying sedimentary bedrock. The shallow earthquake depths can increase ground shaking from smaller earthquakes. A substantial number of previously unmapped subsurface faults are relatively long (up to 10 km). For example, the largest observed active earthquake sequence (Prague) ruptured a previously unmapped portion of the Wilzetta Fault (Figure 4a). In other regions relocated seismicity can be associated with structures and splays along the Nemaha fault zone. In a few cases, earthquakes are occurring on well-known, larger faults that have the potential to produce larger earthquakes. Of particular concern are active earthquake clusters that are associated with long fault structures that may be capable of supporting significantly larger earthquakes (M_{5-6}). Examples include the approximately 10 km long sequence south of Langston (Figure 4c), the sequence south of Cushing along the Wilzetta fault zone (Figure 4d) [Bennison, 1964], and several smaller clusters in the Medford and Stillwater regions that are located along very long and optimally oriented splays of the Nemaha fault zone (Figures 4e and 4f).

In several cases, aftershocks are distributed over a much larger area than predicted for the associated main shock and died off rapidly (Prague, Jones, Langston, and Cushing) [Wells and Coppersmith, 1994]. In the specific case of the Prague sequence, aftershocks are distributed for a length of approximately 20 km and depth range of approximately 10 km, which is 12–15 km longer than expected for a M_w 5.6 main shock subsurface rupture. The very large modeled rupture area requires very low stress drop (<1 MPa, 10 bars) [Eshelby, 1957], which is consistent with a growing body of evidence that injection-induced earthquakes are characterized by low stress drop [Hough, 2014; Sun and Hartzell, 2014 and Block et al., 2014].

Currently, the USGS National Seismic Hazard Map Project (NSHMP) does not include human-induced seismicity, and therefore, likely underestimates earthquake hazard in the region [Petersen et al., 2014]. A significant issue for government earthquake hazard scientists is to consider how to incorporate injection-induced earthquakes into the calculation of the NSHMP. Engineers, architects, and regulatory bodies in the region should be aware of the current increased earthquake hazard in central Oklahoma whether the seismicity increase is natural or is induced by wastewater injection.

5. Conclusions

To better understand the spatiotemporal distribution and source mechanisms of earthquakes in central Oklahoma, we computed well-constrained earthquake locations and magnitudes for 3639 earthquakes and 195 regional moment tensor (RMT) solutions. Improved earthquake source parameter estimates were derived using all available seismic data in the central and eastern United States. Results show that the majority of earthquakes occur on near-vertical, strike-slip faults in the shallow crystalline basement (<6 km depth). These

reactivated structures trend either northeast or northwest, which is consistent with a favorable orientation for failure from a regional compression stress that is orientated N85E [Alt and Zoback, 2014; Zoback and Zoback, 1991]. Many of the earthquakes relocated in this study coalesce from diffuse and scattered locations into discontinuous small clusters with fault lengths of 1–3 km. Some of these discontinuous clusters are aligned along trends suggestive of faults several tens of kilometers long, but we are very uncertain about whether there are longer fault structures tying together these independent clusters. Based on this study, we suggest that the increased rate and occurrence of earthquakes near optimally oriented and long fault structures has raised the earthquake hazard in central Oklahoma and increased the probability for a damaging earthquake.

Acknowledgments

This research was supported by the United States Geological Survey's National Earthquake Hazards Reduction Program. Source parameters determined in this study contribute to improving the understanding of earthquake hazard in Oklahoma and are available to research scientists and engineers from the USGS COMCAT system (<http://earthquake.usgs.gov/>). All waveform data used in this study, from both portable and permanent seismic stations, are archived and available for download from the IRIS Data Management Center (DMC). Earthquake hypocenter uncertainty was significantly reduced due to the high density of portable seismic stations. The RMTs benefited from high-quality broadband data recorded at permanent stations in the ANSS RSNs, Backbone, and Earthscope TA seismic networks. GMT was used to generate maps [Wessel and Smith, 2004] and ZMAP for earthquake FMD and Omori's law calculations [Wiemer, 2002]. The authors greatly appreciate the hard work of people that have responded to the evolving sequences. USGS field crews included Alena Leeds, Jim Allen, Steve Roberts, Dave Worley, M. Meremonte, and E. Cochran. We would also like to thank staff at IRIS PASSCAL, Oklahoma State University and the Oklahoma Geological Survey for material and logistical support. D. Ketchum provided easy access to waveform and meta-data. We also thank the NEIC analysts for initial single-event locations and phase picks. The manuscript greatly benefitted from editorial reviews by M. Zoback, R. Keller, R. Williams, O. Boyd, N. Vance, J. Rubenstein, J. McCarthy, and L. Gee.

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