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Key Points:
- Addition of approximately 200 new stress orientations in Texas enables us to map the complex stress field throughout the state
- Recent earthquakes in four study areas occurred on critically stressed faults in which slip was apparently triggered by industrial activity

Supporting Information:
- Supporting Information S1
- Table S1–S2

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State of stress in Texas: Implications for induced seismicity

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Abstract Compilation of almost 200 new maximum horizontal stress (S_{Hmax}) orientations in Texas reveals a complex intraplate stress field. A large extensional stress province is associated with extensive growth faulting from northeastern Mexico to Louisiana. S_{Hmax} is subparallel to the coastline, following the strikes of the growth faults. In contrast, we observe a strike-slip/normal faulting regime with S_{Hmax} approximately E-W in much of west Texas and the Texas Panhandle, similar to the stress fields observed in northeast New Mexico and north-central Oklahoma. Within the Fort Worth Basin in northeast Texas, S_{Hmax} is NNE-SSW. The faulting regime transitions from strike-slip/normal faulting in the northern part of the basin to normal faulting with subequal horizontal principal stress magnitudes further south. Recent sites of apparently injection-related seismicity near Snyder/Cogdell (west Texas), Karnes City/Fashing (south Texas), the Dallas-Fort Worth metroplex, and Timpson (east Texas) involves fault slip compatible with local stress fields.

1. Introduction

In this paper we discuss regional variations of the state of stress in Texas and active faulting associated with recent seismicity in the state. Approximately 200 new S_{Hmax} orientations reveal a complex stress field that has implications for understanding seismic hazard and the possibility of earthquake triggering throughout the state. Decades ago, compilations of crustal stress data revealed large provinces with remarkably consistent stress orientations and faulting regimes (relative stress magnitudes) [e.g., *Zoback and Zoback*, 1980, 1989; *Zoback*, 1992]. Despite continuous progress mapping stress orientations and relative magnitudes around the world [e.g., *Heidbach et al*., 2010], stress information in many areas remains sparse. Prior to this study, fewer than 30 reliable S_{Hmax} orientations were available in the World Stress Map database in Texas. In the sections below, we first briefly review the methods we employ for obtaining and analyzing the stress data and then present observations arising from the new data. We then utilize the new stress data to better understand faulting associated with apparently triggered earthquakes at four sites.

2. Stress Map of Texas

We employ established techniques for determining in situ S_{Hmax} orientations from drilling-induced tensile fractures and borehole breakouts observed in wellbore image logs, maximum horizontal shear wave velocity from crossed-dipole sonic logs, and hydraulic fractures from microseismic data (see review in *Zoback* [2010]). Most of our S_{Hmax} orientations (Table S1) were measured in supracrustal rocks, but nearly all were collected at more than 1 km depth. We interpret faulting regime (e.g., normal, strike-slip, or reverse) from in situ measurements, geologic data, and moment tensors from Saint Louis University [*Herrmann et al.,* 2011] and local studies [*Doser et al.,* 1991; *Hornbach et al.,* 2015] (Table S2). We categorize faulting regime using the A_φ system of *Simpson* [1997], in which increasing A_φ represents more compressive conditions, with 0 denoting radial extension (normal faulting with $S_V \gg S_{Hmax} = S_{hmin}$) and 3 denoting radial compression (reverse faulting with $S_{Hmax} = S_{hmin} \gg S_V$).

Figure 1 shows S_{Hmax} orientations and faulting regime compiled across Texas and surrounding areas. S_{Hmax} orientations include previously obtained measurements in Oklahoma compiled by *Alt and Zoback* [2016] and three unpublished measurements from the World Stress Map compilation (O. Heidbach, personal communication, 2016). We exclude single moment tensor solutions used to obtain approximate principal stress orientations. Relative stress magnitudes (A_φ values) in central Oklahoma are from moment tensor inversions by *Walsh and Zoback* [2016]. In addition, we conducted a formal inversion of Saint Louis University (SLU) moment tensors in the Raton Basin using the iterative joint inversion method of *Vavryčuk* [2014], and we include other relative stress magnitudes from outside of Texas compiled by *Hurd and Zoback* [2012] in order

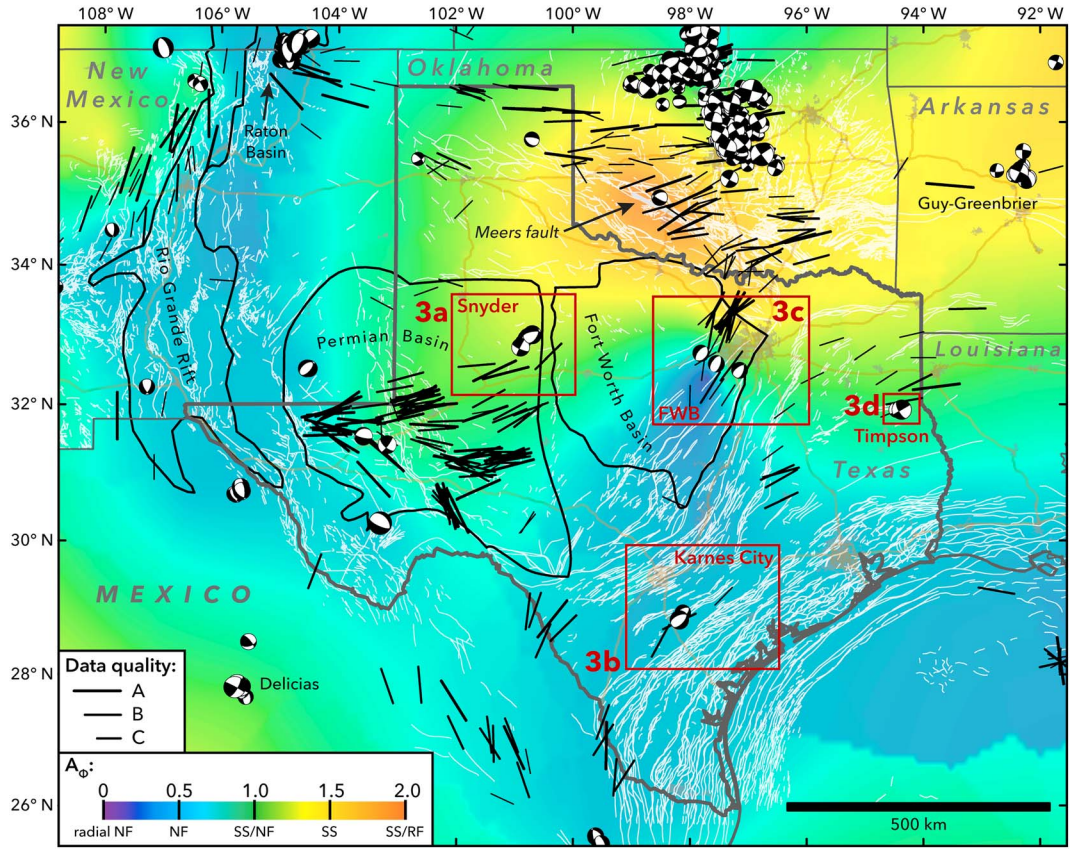


Figure 1. Stress Map of Texas showing maximum horizontal stress (S_{Hmax}) orientations and faulting regime categorized using the A_φ system of *Simpson* [1997] (see text for details). Basin boundaries are from the U.S. Energy Information Administration. The Rio Grande Rift boundary was compiled from *Seager and Morgan* [1979] and *Perry et al.* [1987]. RF, reverse faulting; SS, strike-slip faulting; and NF, normal faulting.

to limit edge effects. Fault traces are compiled from *Ewing et al.* [1990], *Ewing and Lopez* [1991], *Green and Jones* [1997], and *Darold and Holland* [2015].

From west to east in Figure 1, we see that S_{Hmax} is ~N-S in the vicinity of the extensional, ~N-S trending Rio Grande Rift in central New Mexico. S_{Hmax} transitions rapidly eastward to ~E-W in northeast New Mexico, the Texas Panhandle, and the Permian Basin of west Texas. Continuing eastward, S_{Hmax} rotates from E-W in the western Permian Basin to NNE-SSW (~N020°E) in the Fort Worth Basin of northeast Texas. S_{Hmax} then rotates sharply to nearly E-W in south-central Oklahoma, where there is excellent agreement between S_{Hmax} azimuths calculated from inversions of dozens of moment tensors (typically 5–6 km depth) and those measured in boreholes drilled in sedimentary rocks to depths of ~2.5 km [*Walsh and Zoback*, 2016]. The E-W S_{Hmax} in Oklahoma transitions further east to the generally NE-SW to NNE-SSW S_{Hmax} observed across most of the central and eastern United States, which experience strike-slip and reverse faulting [*Zoback and Zoback*, 1980; *Hurd and Zoback*, 2012]. In east Texas and western Louisiana, S_{Hmax} is distinctly more easterly than in the Fort Worth Basin.

In general, along the Gulf Coast of southern Texas and Louisiana and eastern Mexico, S_{Hmax} is subparallel to the coastline and extensive growth faulting accommodates extension of the post-Jurassic sedimentary succession into the Gulf of Mexico [*Zoback and Zoback,* 1980]. Approximately Gulf Coast-parallel S_{Hmax} continues northwestward into the southeastern part of the Permian Basin in west Texas. Intriguingly, in that area, S_{Hmax} changes rapidly from NE-SW in the south to NW-SE on the west (counter-clockwise rotation westward) and E-W further north in the Permian Basin (clockwise rotation northward).

Relative stress magnitudes also vary across Texas (Figure 1). Active ~E-W extension is associated with the Rio Grande Rift in New Mexico [*Ricketts et al*., 2014] and northeastern Mexico. In west Texas the faulting regime is

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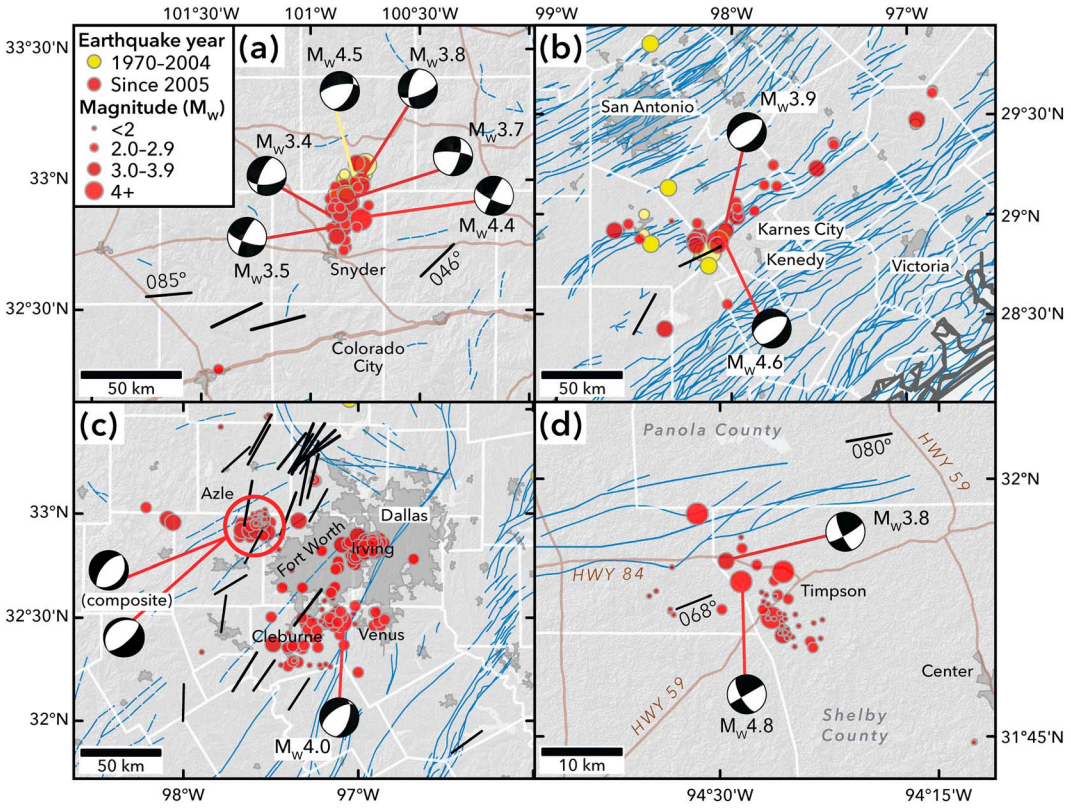


Figure 2. Maps of earthquakes in Texas compiled from *Frohlich et al.* [2011], *Frohlich and Brunt* [2013], *Gan and Frohlich* [2013], *Justinic et al.* [2013], *Frohlich et al.* [2014], *Hornbach et al.* [2015], *Walter et al.* [2016], and the U.S. Geological Survey National Earthquake Information Center. (a) Snyder/Cogdell; (b) Karnes City/Fashing; (c) Dallas-Fort Worth metroplex; (d) Timpson. Composite moment tensors in (Figure 2c) are from *Hornbach et al.* [2015]. Locations of these four areas are shown in Figure 1.

more compressional. East-west compression and both normal and strike-slip focal mechanisms are seen in the Texas Panhandle, north Texas near Snyder, and the western Permian Basin [*Doser et al.*, 1991; *Herrmann et al.*, 2011]. Two recent strike-slip focal mechanisms were recorded in east Texas near Timpson, together suggesting a strike-slip/normal faulting regime. *Fan et al.* [2016], and references therein, independently determined a strike-slip/normal faulting regime in a nearby borehole. Further west, in situ measurements and inversion of microseismic data show that the stress regime transitions northward in the Fort Worth Basin from normal faulting with nearly isotropic horizontal stress magnitudes ($A_\varphi = 0.18$) [*Vermylen and Zoback*, 2011] to strike-slip/normal faulting ($A_\varphi = 0.81$) (W. Kuang, personal communication, 2016) to strike slip ($A_\varphi = 1.50$) [*Sone and Zoback,* 2014]. The faulting regime becomes increasingly compressive northward into southwest Oklahoma, as paleoseismic studies [*Madole,* 1988; *Crone and Luza,* 1990] have shown that the Meers fault (Figure 1) produces oblique reverse/strike-slip earthquakes, although a single oblique strike-slip/normal faulting earthquake (M_w3.9) has been recorded nearby.

3. Implications for Faulting Associated With Seismicity

As in other parts of the central and eastern United States, the rate of seismicity in Texas has markedly increased since 2009 [*Frohlich et al.,* 2016]. Constraining the stress state enables retrospective analysis of earthquake triggering mechanisms, as well as quantitative assessment of the likelihood of slip on known faults due to fluid pressure perturbations. We apply our new stress data to conduct basic Mohr-Coulomb failure analyses for four areas that have experienced recent seismicity in Texas, and we calculate the pore pressure change, ΔP_P, that would have been required to trigger slip, assuming that perfectly oriented faults are in frictional equilibrium. Whether or not a given earthquake was triggered by injection-related pressure changes, the likely fault plane in any given focal plane mechanism is that most well oriented for failure in

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Table 1. Results of Geomechanical Analysis of the Snyder and Timpson, Texas, Earthquakes

Earthquake	Nodal Plane Orientation	S_{Hmax} Orientation	ΔP_P to Failure (MPa/km)	ΔP_P to failure at 5 km depth (MPa)
		Snyder, Texas		
16 June 1978	260°/60°	N046°E	1.48	7.40
M_w4.5		N066°E	0.72	3.59
		N085°E	0.79	3.93
	031°/41°	N046°E	2.88	14.39
		N066°E	4.28	21.39
		N085°E	6.88	34.41
11 September 2011 M_w4.4	115°/70°	N046°E	8.16	40.81
		N066°E	2.85	14.24
		N085°E	0.44	2.19
	207°/85°	N046°E	0.62	3.09
		N066°E	0.57	2.85
		N085°E	4.47	22.33
Earthquake/Fault	Nodal Plane Orientation	S_{Hmax} Orientation	ΔP_P to Failure (MPa/km)	ΔP_P to Failure at 2.5 km Depth (MPa)
		Timpson, Texas		
17 June 2012 M_w4.8	060°/90°	N068°E	2.70	6.76
		N074°E	1.54	3.85
		N080°E	0.72	1.81
	150°/60°	N068°E	12.23	30.59
		N074°E	10.60	26.50
		N080°E	8.93	22.34
10 June 2012 M_w3.8	060°/76°	N068°E	1.07	2.68
		N074°E	0.65	1.62
		N080°E	0.29	0.73
	155°/70°	N068°E	13.41	33.52
		N074°E	11.72	29.30
		N080°E	9.93	24.82
Mapped fault	138°/63°	N068°E	8.76	21.90
		N074°E	7.08	17.70
		N080°E	5.50	13.74

the current stress field. Equivalently, this plane would require the smallest ΔP_P if the event was triggered by fluid injection.

For each of the recent earthquake sequences considered here (Figure 2), at least one of the fault planes and senses of slip shown in the focal mechanisms is consistent with the local stress field and would have required relatively small changes of pore pressure to be triggered. The 1978–2016 earthquakes near Snyder, Texas, produced moment tensors with nodal planes striking mostly N and E for the strike-slip events and NE for the oblique normal faulting events, as well as a NNE-trending group of event locations (Figure 2a). These fault orientations are consistent with nearby in situ measurements showing NE-SW S_{Hmax} orientations. Most of the events occurring during and after 2006 in this area may have been triggered by injection of supercritical CO_2 in the Cogdell oilfield [*Gan and Frohlich*, 2013], and the earlier events may have been triggered by oilfield water flooding operations [*Davis and Pennington*, 1989]. We estimate the pressure perturbation (ΔP_P) needed to achieve failure for both nodal planes of the two largest earthquakes in this area (16 June 1978 M_w4.5 and 11 September 2011 M_w4.4, shown in Figure 2a), assuming hydrostatic pore pressure (P_P) and critically stressed conditions for $A_\varphi = 1.2$ (Figure 1). S_{Hmax} varies from N046°E to N085°E, which is a large enough range to change which of the two nodal planes is expected to represent the slipping fault in the case of the 2011 M_w4.4 event. Across this range of S_{Hmax} orientations at a reasonable hypocenter depth of 5 km, ΔP_P ranges from 3.6 to 7.4 MPa for the NW dipping nodal plane and from 14.4 to 34.4 MPa for the SE dipping nodal plane associated with the 1978 M_w4.5 earthquake (Table 1). At the same depth and range of S_{Hmax} orientations, we estimate ΔP_P of 2.8–22.3 MPa and 2.2–40.8 MPa, respectively, for the NW and SW dipping nodal planes produced by the 2011 M_w4.4 earthquake. These results demonstrate the sensitivity of earthquake triggering studies to variations in the local stress field. In Figure 3a, we show the estimated ΔP_P needed to produce slip on

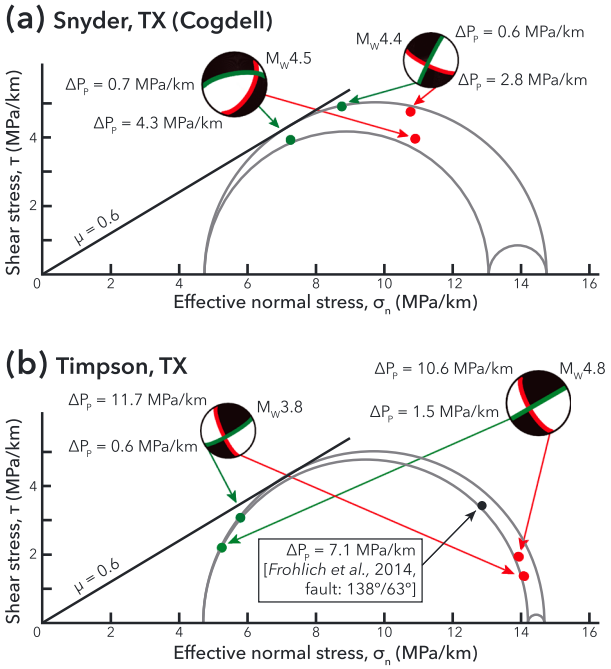


Figure 3. (a) Mohr circle showing stress conditions near Snyder, Texas. Saint Louis University (SLU) focal mechanisms are shown for the two largest events [*Herrmann et al.*, 2011], and resolved shear and normal stresses are shown for each nodal plane. (b) Mohr circle showing stress gradients in the Timpson area based on stress and pore pressure estimates from *Fan et al.* [2016].

each nodal plane for these two earthquakes assuming an average S_{Hmax} orientation of N066°E. In this figure, horizontal distance between a plane and the Coulomb failure line represents the ΔP_P needed to trigger fault slip. For this intermediate S_{Hmax} orientation at 5 km depth, we estimate that fairly modest P_P increases of 3.6 MPa and 2.8 MPa, respectively, were needed to trigger the 1978 M_w4.5 and 2011 M_w4.4 earthquakes.

Two earthquakes in 2008 and 2011 near Karnes City, Texas, which may have been triggered by production from wells in the Fashing gas field [*Frohlich and Brunt*, 2013], generated moment tensors that indicate slip on NE striking planes (Figure 2b). Normal slip on NE striking planes is in agreement with the NE-SW S_{Hmax} orientations and the trend of normal faults along this part of the Gulf Coast (Figure 1). Possibly triggered normal faulting earthquakes have also recently occurred in the Dallas-Fort Worth area, including a 2013-2014 sequence near Azle and a 2015 M_w4.0 event near Venus [*Hornbach et al.*, 2015, 2016]. These events involve normal faulting on NE striking planes that is consistent with both the stress field and the mapped faults in the region (Figure 2c). However, as noted above, the faulting regime in the Fort Worth Basin appears to change from mostly strike-slip north of Fort Worth, to normal/strike slip near Dallas and Fort Worth, to normal faulting further south (Figure 1). This transition presents important implications for seismic hazard analysis in the Dallas-Fort Worth metroplex because different sets of faults would be expected to be active in different parts of the basin (Figure 2c).

Finally, seismicity in 2012 near Timpson, Texas, produced two strike-slip moment tensors with NW and NE striking nodal planes, as well as a sequence of NW and NE trending aftershocks, suggesting slip along a previously mapped NW striking fault [*Frohlich et al.*, 2014, and references therein] and/or multiple NE striking faults. The original SLU focal mechanisms showed orthogonal *P* axes, suggesting that two earthquakes occurring days apart (10 June 2012 and 17 June 2012) were produced either from strike-slip on perpendicular faults or from opposite shear senses on parallel faults. This unusual scenario implied either a dramatically varying local stress field or slip on an unfavorably oriented fault induced by severely elevated pore pressure. Using a geomechanical model that accounted for poroelastic stress changes, *Fan et al.* [2016] found that slip on the NW striking mapped fault could have been triggered by a large pore pressure perturbation (12.9 MPa near 1800 m depth) resulting from nearby injection of saline wastewater. Our new stress data show that S_{Hmax} orientations are generally consistent across that area, ranging from N068°E to N080°E (Figure 2d). In addition, both moment tensors were subsequently recalculated on 23 June 2016 using a more refined local velocity model [see *Herrmann,* 2016], resulting in two strike-slip focal mechanisms with similar nodal plane and *P* axis orientations to one another (Figure 2d). Geomechanical analysis of the four nodal planes and the NW striking mapped fault (Figure 3b) shows that the NE striking nodal planes are near ideal orientations for slip in the local stress field. At the ~2.5 km top-fault depth shown by *Frohlich et al.* [2014], only 1.8–6.8 MPa ΔP_P in the case of the 17 June 2012 M_w4.8 earthquake and 0.7–2.7 MPa ΔP_P for the 10 June 2012 M_w3.8 earthquake were needed to trigger slip (Table 1). In contrast, the NW striking fault and nodal planes have highly unfavorable orientations, requiring a minimum 13.7 MPa pressure increase. *Fan et al.* [2016] demonstrate that poroelastic stress changes could allow P_P to build to the point that a severely misoriented fault could slip, but

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a requirement of their model is that no well-oriented faults are present. As shown above, only modest ΔP_P changes would be required to trigger slip on the well-oriented NE striking nodal planes. We consider it unlikely that a pore pressure perturbation large enough to trigger slip on the NW striking planes could occur without first hydraulically fracturing the formations near the well or triggering slip on the more well-oriented NE-ENE striking faults mapped nearby (Figure 2d). Moreover, we do not consider poroelasticity because modeling poroelastic stress changes is not straightforward if the P_P changes occur preferentially in fracture networks rather than being widely distributed in the formation.

4. Conclusions

The new stress measurements presented here reveal a complex but spatially coherent stress field in Texas, which allows us to better understand the triggering mechanisms of past earthquakes and to characterize the seismic hazard across the area. Although Texas is relatively seismically quiescent, several recent earthquakes are suspected to have been triggered by industrial activities (near Snyder/Cogdell, Karnes City/Fashing, the Dallas-Fort Worth metroplex, and Timpson). These earthquakes have nodal plane geometries consistent with the observed stress field, indicating that they are occurring on faults that are already likely to be active. At Timpson, aligned earthquake epicenters suggest slip along a NW striking and/or multiple NE striking planes [*Frohlich et al*., 2014]. Our analysis indicates that the NE striking planes are compatible with slip in the observed stress state despite being closer to parallel with S_{Hmax} than would be ideal for slip. In contrast, slip on the NW striking planes requires pore pressure perturbations in excess of the hydraulic fracturing pressure. Near the Dallas-Fort Worth metroplex, the stress regime transitions rapidly from strike-slip faulting north of Fort Worth to normal faulting to the south, implying that the orientations of faults most likely to produce earthquakes varies systematically across this area.

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Erratum

This paper has been corrected to remove 14 data points because permission was not granted to include them. Figure 1, Figure 2, acknowledgments, and the Supporting Table S1 have been updated. The present version may be considered the authoritative version of record. Please note that Jens-Erik Lund Snee's name has been changed to Jens-Erik Lundstern. This correction been made to the online version of this article, but not the PDF.

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