Summary of the North Texas Earthquake Study Seismic Networks, 2013–2018

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ABSTRACT

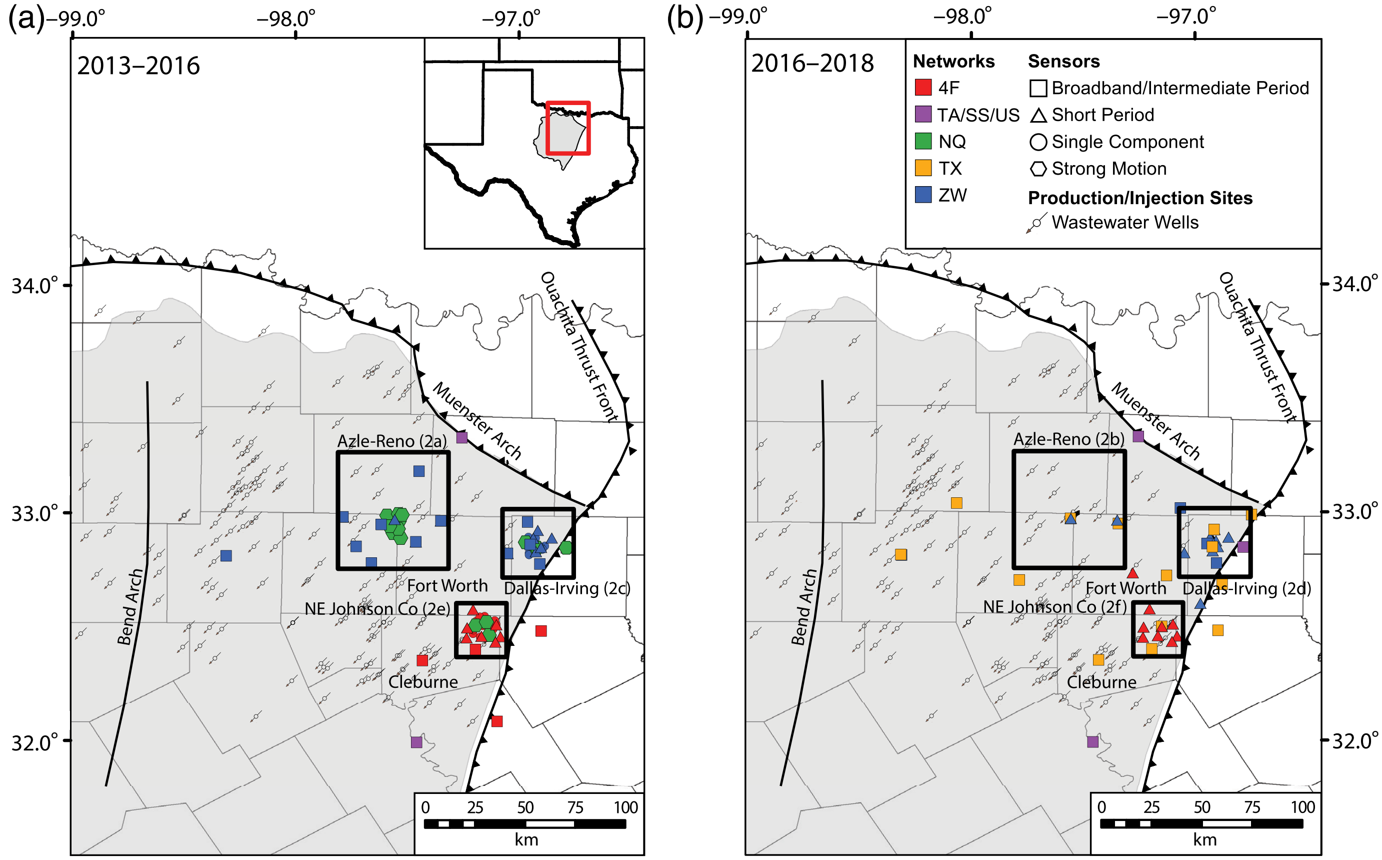
From 2013 to 2018, local seismic research networks operated by Southern Methodist University (SMU) have provided basic earthquake data needed to assess seismic hazard and to address the cause of the increased seismicity rates in the Fort Worth basin (FWB) and Dallas–Fort Worth metropolitan area, an area that was aseismic until 2008. This article summarizes the configuration, operation, and capability of the SMU FWB networks and documents how network geometries evolved in response to the onset of new earthquake sequences with instrumentation and funding availability constantly in flux. Network design strategies focused on providing accurate hypocenter and focal mechanism information while still constrained by the realities of dense urban environment operations. The networks include short-period single- and three-component sensors, broadband to intermediate period velocity sensors, and accelerometers. We document the complex metadata associated with the telemetered local seismic networks and provide necessary insights into temporal and spatial changes made to the networks from 2013 to 2018. The rich datasets contain local and regional earthquakes, anthropogenic and ambient noise, quarry blasts, and weather events. Prior publications document a causal link between earthquakes in the FWB and wastewater disposal and/or production activities associated with shale gas extraction, and the continuous waveform data described here allow for significant breakthroughs in understanding the physical mechanisms leading to induced earthquakes.

Electronic Supplement: Network design strategy and metadata for stations operating in the Fort Worth basin during 2013–2018.

INTRODUCTION

Felt earthquakes in the Fort Worth basin (FWB), north Texas, began with a series of events near the Dallas–Fort Worth (DFW) International Airport in late 2008 (e.g., Frohlich *et al.*, 2016). Over the next decade, a series of faults activated across the basin, and by 2018, more than 200 earthquakes ranging in magnitude (M) from 1.6 to 4.0 had been reported in the U.S. Geological Survey (USGS) Comprehensive Catalog (ComCat). The intensity and number of felt ground motions in a major U.S. metropolitan area, combined with the increased earthquake rates and magnitudes across Texas, raised significant community and local government concerns about the hazards, risks, and potential causes of these earthquakes. In response, Southern Methodist University (SMU) and collaborators began deploying temporary seismic networks focused on individual earthquakes sequences (Fig. 1). We provide a summary of the local seismic networks deployed from 2013 to 2018 as part of the North Texas Earthquake Study (NTXES) to encourage broader use of the data and to provide a framework for understanding network details of importance to data users. Older networks operated between 2008 and 2011 have been previously documented (Frohlich *et al.*, 2010, 2011; Justinic *et al.*, 2013).

There are five well-studied, and hence named, earthquakes sequences in north Texas, among others, that are recorded by the NTXES local seismic networks (Fig. 1). The 2008–2009 DFW Airport earthquakes were probably triggered by the onset of a nearly collocated wastewater disposal well (Frohlich *et al.*, 2010, 2011; Reiter *et al.*, 2012), but not all authors agree (Janská and Eisner, 2012). The Airport sequence continued into at least 2015 slowly migrating northeast along the causative fault (Ogwari *et al.*, 2018). The 2009 Cleburne earthquakes in southwest Johnson County and south of the DFW metroplex (Fig. 1) also occurred near wastewater disposal wells (Justinic *et al.*, 2013). SMU deployed and operated seismic stations over these early sequences with instrument support provided by the Incorporated Research Institutions for Seismology (IRIS), and data are archived under International Federation of Digital Seismic Networks (FDSN) code X9 (2008–2011). The USArray Transportable Array passed through the FWB with a 70-km station spacing between November 2009 and September 2011. Frohlich (2012) documented 60+ earthquakes down to magnitude 1.5 occurring across the basin in discrete clusters, nearly eight times the rate reported in ComCat over the same time period. After 2011 and continuing through 2013, only regional stations recorded seismicity within the basin, and



▲ **Figure 1.** Map views of the Fort Worth basin (FWB) showing all stations that were active during the periods of (a) November 2013–July 2016 and (b) August 2016–August 2018. Black boxes denote areas shown in Figure 2. Gray shaded area is the extent of the Barnett Shale; the basin is bounded by the Bend arch, Muester arch, and Ouachita front in this region. All symbols and place names are otherwise denoted in the legend. (Inset) Texas and the Barnett Shale, with the box denoting study area. The color version of this figure is available only in the electronic edition.

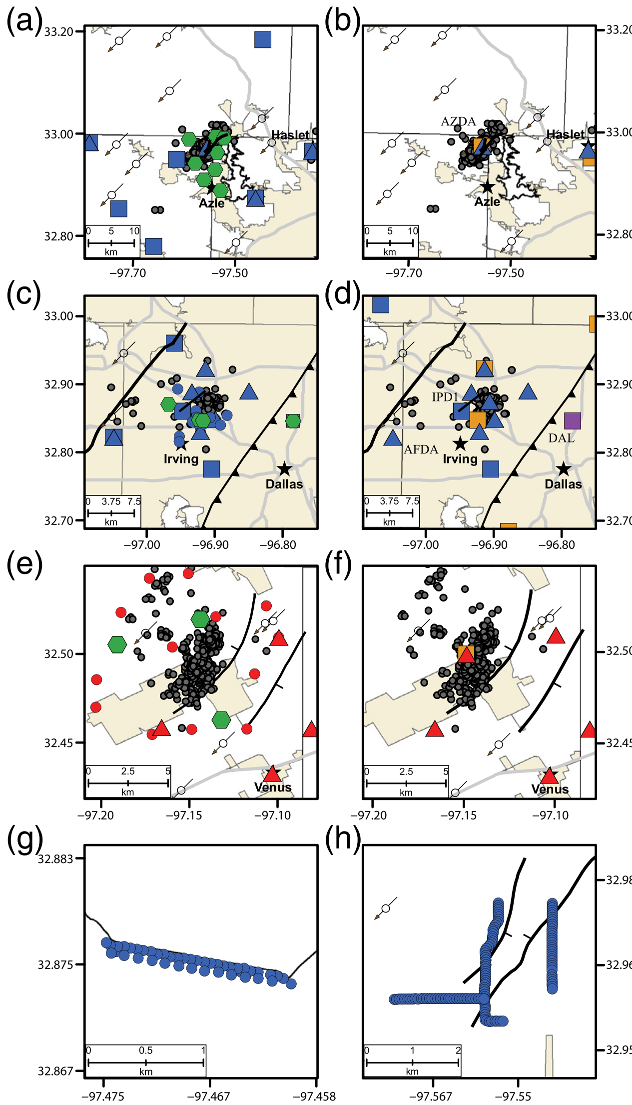
occasional felt earthquakes were reported in ComCat, primarily near the airport and south of the metroplex, with none exceeding M 3.5.

Beginning in November 2013 near the towns of Azle and Reno (northwest of Fort Worth, Fig. 2a,b), a swarm of earthquakes of $M_{\mathrm{b\_}Lg}$ 3.5 and greater prompted SMU's deployment of a local seismic network to record the Azle–Reno earthquake sequence (FDSN ZW 2013–2018; Figs. 1 and 2a,b). In January 2015, this network was expanded in response to an $M_{\mathrm{b\_}Lg}$ 3.6 and 3.5 doublet along a newly activated fault segment (Figs. 1 and 2c,d). In May 2015, an M_{w} 4.0 earthquake in northeast Johnson County near Venus, currently the largest recorded FWB earthquake, prompted a rapid response aftershock deployment (FDSN 4F 2015–2018; Figs. 1 and 2e,f). In late 2016, the Texas Seismic Network (TexNet, FDSN TX) deployed additional regional broadband and strong-motion stations in the FWB. The SMU-operated networks in the FWB include a wide mix of instruments provided by SMU, USGS NetQuakes program (FDSN NQ), IRIS Portable Array Seismic Studies of the Continental Lithosphere, and others and remain operational through 2018 (Fig. 1).

All continuous seismic data are telemetered in near-real time to the IRIS Data Management Center (DMC) without embargo or restriction. This decision limited station sites to those with commercial power and open internet access for NetQuakes stations and/or good cell coverage for stations on solar power. An exception to real-time open access was made for short-term and/or rapid deployments of single-component stations. The open access decision provided all interested parties, including the USGS, state regulators, and industry scientists, immediate access to the continuous waveform data.

INSTRUMENT DEPLOYMENT AND DETAILS

The 2013–2018 NTXES networks are designed to resolve depth for small magnitude ($M < 2.5$) local earthquakes and to provide mechanism and source parameter data for the three individual earthquake sequences (Azle–Reno, Irving–Dallas, and Venus). The networks are not designed for regional earthquake monitoring in the FWB, although other users have incorporated the continuous network data available at the DMC into regional operations. Network design details are discussed



▲ **Figure 2.** Station maps for the (a,b) Azle–Reno, (c,d) Irving–Dallas, and (e,f) Venus, northeast Johnson County earthquake sequences. See Figure 1 for the legend. Note that the Airport fault, active in the original 2008–2009 Dallas–Fort Worth Airport sequence, appears in the maps for the Irving–Dallas sequence. Gray circles, the North Texas Earthquake Study (NTXES) earthquake catalog. (a,c,e) Stations active between November 2013 and July 2016. (b,d,f) stations active between August 2016 and August 2018. (g) The Texan deployment along Eagle Mountain Lake dam (see a,b for lake location) and (h) the NodalSeismic deployment near the Azle–Reno epicenters are also shown. The color version of this figure is available only in the electronic edition.

in the Ⓔ electronic supplement to this article. Sample rates are 100 or 200 samples per second because of the study interest in high-frequency small-magnitude earthquakes. Ⓔ Table S1 provides station, site, sensor, and sampling rate information for all sites located in the FWB from 2013 to 2018. Because the networks evolved in response to developing earthquake sequences, some time periods have substantial variations in station locations, instrumentation, and uptime during operation (Fig. 3; detailed description available in the Ⓔ electronic supplement).

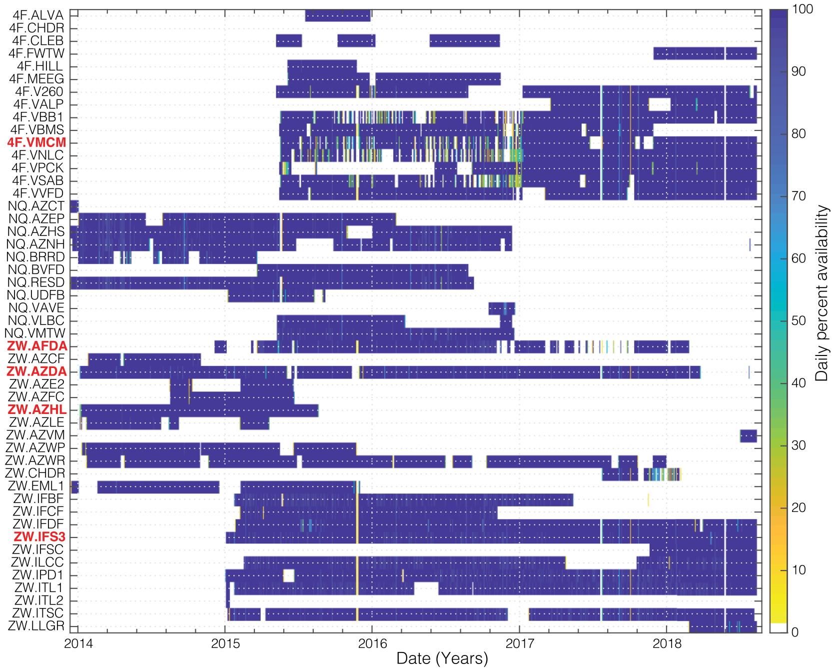
Network ZW began as an effort to record the 2013–2014 Azle–Reno earthquake sequence (Hornbach *et al.*, 2015; Figs. 1 and 2a,b). In late November 2013, the USGS contacted SMU for aid in deploying four NetQuakes strong-motion sensors. The strong-motion stations were placed to surround ComCat locations but proved to be south of the earthquakes after initial analysis was complete; intensity reports to the USGS proved more effective than the preliminary locations in understanding absolute earthquake locations prior to deployment of local seismic stations. NetQuakes and stations provided by SMU were moved and added through late January 2014, resulting in a complex spatiotemporal history to the station geometry (detailed description available in the Ⓔ electronic supplement). At peak station density in 2014, 20 stations reported continuous seismic data for the Azle–Reno sequence, and from 2014 to 2016, 15+ stations maintained continuous operations (Fig. 3).

In November 2014, a series of felt events, including an M_{b_Lg} 3.3 event reported to the USGS "Did You Feel It?" (Wald *et al.*, 1999) by more than 1000 people in the DFW area, prompted SMU to review *S-P* times at SS.DAL, a long-term broadband station located on the SMU campus. Based on the SMU review, the 2014 event was located to the east of the DFW Airport and closer to DAL. Station X9.AFDAD, located south of the DFW Airport, was reinstalled as ZW.AFDA on 8 December. On 5 January 2015, a short-period station using a quickly available Sprengnether S6000 was added in Irving (station IPD1; Fig. 2c).

On 6 January 2015, earthquakes of M_{b_Lg} 3.5 and 3.6 within a 4-hr period were felt within the Dallas metroplex. Both earthquakes were well recorded by stations in Azle, 60 km to the west, but peak motions clipped at IPD1. These two earthquakes prompted a rapid response and major expansion of the ZW network (Fig. 2c,d). SMU deployed 13 single-component RT125 Texan recorders on 7 January and within 10 days began deploying a mix of NetQuakes and three-component broadband and short-period sensors (detailed description available in the Ⓔ electronic supplement). The Irving–Dallas sequence was monitored by 13–16 stations through late 2017 (Fig. 2c) and then reduced to 10 stations operated by SMU, including DAL, and 4 TexNet stations over 2018 (Fig. 2d).

On 7 May 2015, an M_w 4.0 event occurred in northeast Johnson County near the town of Venus in a primarily rural setting (Scales *et al.*, 2017; Fig. 2e,f). SMU in collaboration with the USGS responded to the earthquake in a similar manner to the Irving–Dallas sequence. Fourteen Texans were sited and deployed on 10 May and replaced by a smaller number of short-period and broadband stations (detailed description available in the Ⓔ electronic supplement). A new FDSN network code 4F was assigned to the deployment. The 4F network consistently recorded with 10–12 sensors from May 2015 onward (Fig. 3).

Two unique short-period datasets were also collected for the Azle–Reno sequence in February 2014 and archived with ZW (Fig. 2g,h). A set of 40 Texans was placed on the Eagle



▲ **Figure 3.** Data availability for the NTXES networks (ZW, 4F) and NetQuakes (NQ) stations in the FWB. Discussion of major outages and power issues with stations in 4F are discussed in the Ⓔ electronic supplement of this article. Stations shown in Figure 4 are bolded. The color version of this figure is available only in the electronic edition.

Mountain Lake (EML) dam from 23 February to 1 March 2014. Sensors were buried along the top and bottom of the dam at 50- and 100-m spacing, respectively (Fig. 2g). In addition, on 25 February, NodalSeismic in cooperation with SMU installed and operated 130 vertical 10-Hz recorders at 50-m spacing distributed along three lines within a few kilometers of the epicenters and collected 10 days of continuous seismic recordings (Fig. 2h). During the time of the high-density recordings by the nodes and at the dam, three local earthquakes in the Azle area were detected by the network; however, correlation processing on the dense network detected more than 100 clearly visible events (Hayward *et al.*, 2014). We completed ambient noise tomography with the Azle node dataset, but we have not conduced additional work with the EML dam dataset.

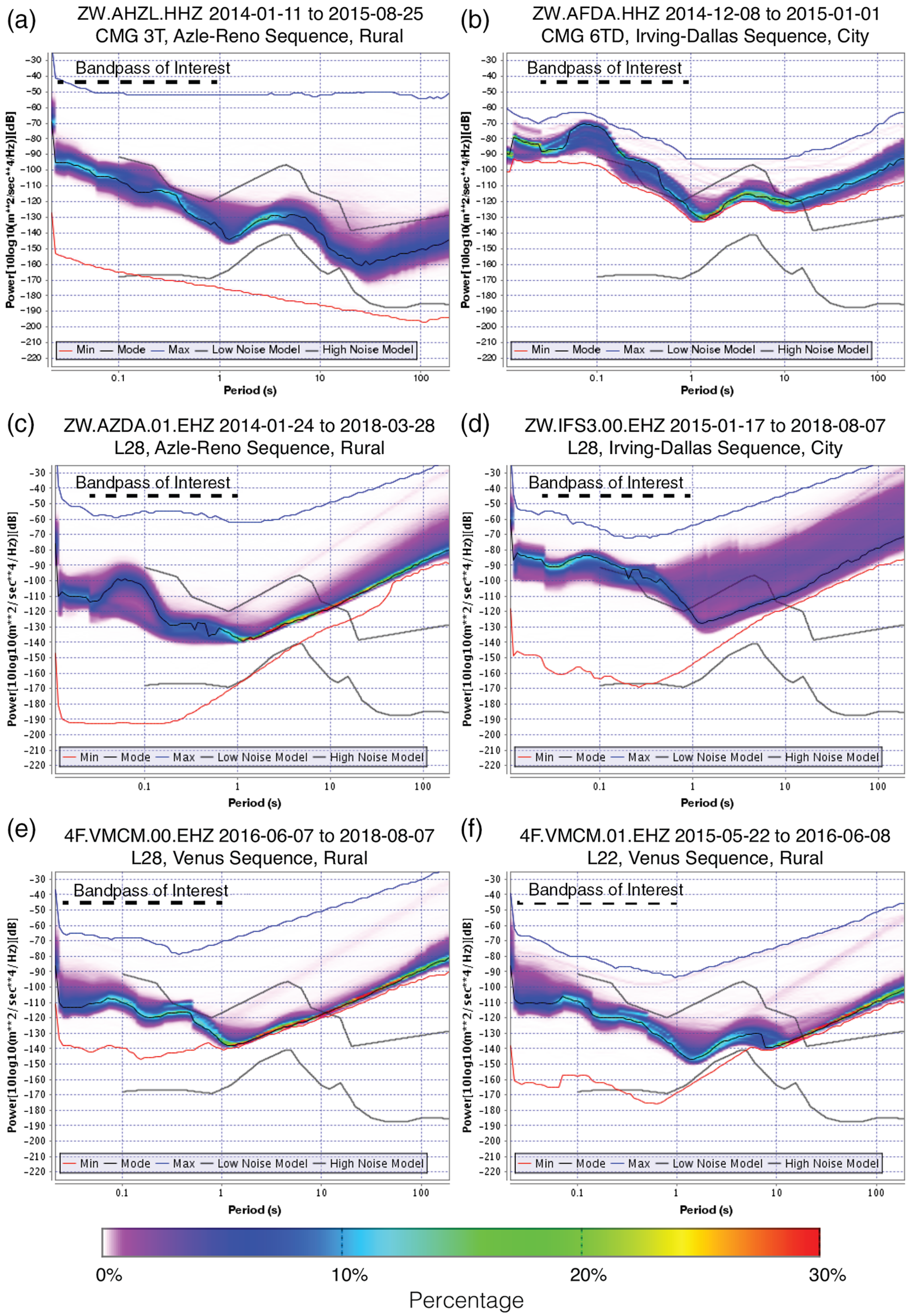
OVERALL DATA QUALITY AND AVAILABILITY

In the north Texas area, as a result of its population of nearly 7 million, even the most rural of stations is seismically noisy. For example, broadband station ZW.AZHL is one of the quietest sites (Fig. 4a). The seismometer was inside a small concrete building, and noise levels in the 1- to 50-Hz band of interest are only 10 dB below the new high noise model (NHNM; Peterson, 1993). In contrast, station ZW.AFDA, which is located next to two highways near DFW airport, exhibits noise levels well above the NHNM (Fig. 4b). Despite this, because the station is the closest station to the DFW airport earthquakes, ZW.AFDA remains a critical station for linking 2008–2009 local seismic data to 2013+ data and resolving event depth (Ogwari *et al.*, 2018). ZW.AZDA, a rural station with a 4.5-Hz short-period instrument, has lower noise levels below 1-s periods but would still be considered a high-noise station (Fig. 4c). Station ZW.IFS3, a short-period instrument buried at a fire station, shows noise typical of some of the urban systems (Fig. 4d). Not only is the noise at 10 Hz 25 dB higher than 4F.VMCM (Fig. 4e), a similar but rural system, but there is also a greater variance in noise levels throughout the band, which is a likely result of stronger diurnal variance in anthropogenic activity. Finally, changes in the instrument models during the experiment mean that site-specific self-noise may be different for different time periods; for example, 4F.VMCM in 2016 used an L28 4.5-Hz instrument compared with an L22 2-Hz instrument deployed at the site in 2015 (Fig. 4e,f).

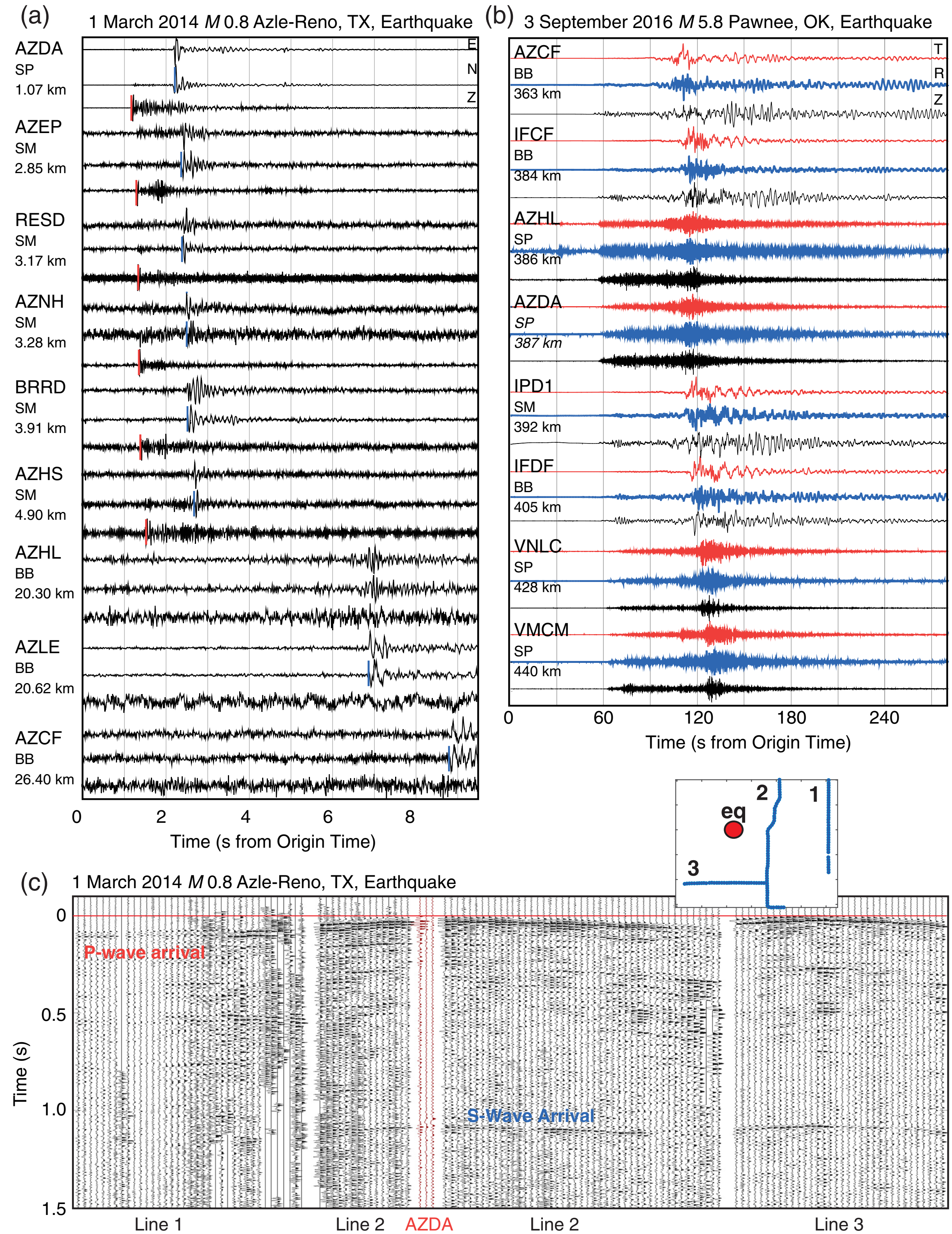
Even with these high noise levels, earthquakes of less than 0.0 magnitude had clearly identifiable *P* and *S* arrivals across NTXES stations. It is only when using instruments for regional detection that instrument noise at longer periods limits some kinds of measurements. Figure 5 shows example recordings of a local and a regional earthquake across the NTXES networks. The Azle–Reno example earthquake was M_L 0.8 and was recorded by the Azle stations and by the nodal array (Fig. 5a,c). Recordings at ZW.AZDA typify the high-frequency characteristics of the data with impulsive *P* and *S* signals. The strong-motion stations, which are naturally noisier, are sufficient at near (< 5 km) distances to pick *P* and *S* arrivals. Broadband stations at 20- to 25-km distance can detect events and provide *S*-wave data but less reliably provide *P*-wave data at this example magnitude. Two features common to north Texas earthquakes are (1) converted energy on the vertical channel between the *P* and *S* arrivals (see station ZW.AZEP, Fig. 5a) and (2) little to no *S*-wave energy on the vertical channel (all stations < 5 km, Fig. 5a). Vertical-only stations such as the nodes and the Texans used in NTXES cannot be reliably used to interpret *S* waves. Regional earthquakes such as the 2016 M_w 5.8 Pawnee, Oklahoma, event are well recorded on the network (Fig. 5b). Because of the mix of sensors, the NTXES stations provide an excellent tutorial on the effect of sensor corner frequency on earthquake recording. As shown in rotated displacement records, ZW.AZCF, a 120-s CMG3T, displays body and surface waves of the Pawnee event, but the 4.5-s corner of the short-period L28 sensors filters out the long periods, revealing only higher frequency body waves.

INITIAL OBSERVATIONS

The NTXES networks provide a dataset for a largely urban area previously considered aseismic with sufficient coverage of



▲ **Figure 4.** Power spectra density probability density functions extracted using the Incorporated Research Institutions for Seismology Data Management Center Modular Utility for STAtistical kNowledge Gathering webservices. Noise characteristics of broadband and short-period stations and contrasting rural and urban stations are discussed in the Overall Data Quality and Availability section. The color version of this figure is available only in the electronic edition.



▲ **Figure 5.** Example earthquake waveforms, shown normalized to maximum amplitude. (a) A local earthquake of M_L 0.8 recorded on the Azle–Reno network. Note that waveforms are continuous velocity (SP, short-period; BB, broadband) or acceleration (SM, strong motion) recordings. BB stations are high-pass filtered using a Butterworth filter with corner at 0.1 Hz. (b) The 2016 M_w 5.8 Pawnee earthquake recorded on selected NTXES stations. Instrument response is removed and displacement data are rotated in radial, transverse, and vertical components. (c) The M_L 0.8 Azle–Reno earthquake as recorded across the array of one-component NodalSeismic 10 Hz nodes. The color version of this figure is available only in the electronic edition.

individual earthquake sequences to conduct high-resolution hypocenter and source parameter studies and to assess local seismic hazard. The networks record the targeted local distance events. Additionally, the networks record a range of regional natural events, including storms, tornados, and earthquakes in Texas and Oklahoma, as well as anthropogenic signals such as quarry blasts and traffic. The NTXES networks provide a ground-truth dataset for investigations of regionally tuned cross-correlation detectors, especially those using station WMOK, which at 250-km distance is remarkedly sensitive to earthquakes in the North Texas area (e.g., Frohlich *et al.*, 2010).

Derived products from the NTXES seismic data have been used for a range of studies. Primary use produced the SMU NTXES earthquake catalog (Fig. 2), iterations of which are described in publications on the Azle–Reno (Hornbach *et al.*, 2015) and Venus (Scales *et al.*, 2017) earthquake sequences. High-resolution relative earthquake catalogs, template and correlation data, focal mechanisms, and source parameters are available for some individual sequences (Frohlich *et al.*, 2010, 2011; Justinic *et al.*, 2013; Hornbach *et al.*, 2015; Scales *et al.*, 2017; Ogwari *et al.*, 2018; Quinones *et al.*, 2018). Stress drop, corner frequency, moment, and moment magnitude relationship studies are near completion. Causative normal faults in the FWB strike north-northeast–south-southwest to northeast–southwest and appear well oriented for failure in the modern stress regime (Lund Snee and Zoback, 2016; Magnani *et al.*, 2017; Quinones *et al.*, 2018). The derived products have also been used to provide constraints for pore fluid pressure diffusion modeling (Hornbach *et al.*, 2015; Ogwari *et al.*, 2018, Zhai and Shirzaei, 2018), and waveform data have been used to characterize near-surface velocities (Zalachoris *et al.*, 2017). The NTXES networks allow researchers to better develop testable hypotheses and physical mechanisms that link oil and gas activities in the basin to the recent increase in earthquake rate (Frohlich *et al.*, 2016; Hornbach *et al.*, 2016; Goebel and Brodsky, 2018).

SUMMARY

Studies of the physical mechanism(s) linking oil and gas operations to earthquakes on basement faults below the sedimentary basins require high-quality absolute location of hypocenters and auxiliary datasets best provided by local seismic networks. Fundamentally, earthquake depth is best resolved when *P*- and *S*-arrival times from three-component stations span a wide range of takeoff angles with at least one arrival at a station within the equivalent of a focal depth distance (i.e., Husen and Hardebeck, 2010). Template matching and relative relocation, although powerful techniques, do not replace the basic data quality constraints necessary to resolve earthquake depth in the inverse problem, and these techniques require a high-quality earthquake catalog to succeed. Induced earthquakes across the United States have been shallow (< 10–km depth), and efforts to collect local distance earthquake records, not limited to networks discussed in this article, should provide key information to move forward with improved understanding that provides a basis to mitigate induced earthquakes.

The 2016 USGS one-year seismic hazard forecast for the central and eastern United States (Petersen *et al.*, 2016) showed increased hazard for north Texas, with a 1%–5% chance of experiencing modified Mercalli scale VI ground motions. Subsequent releases for 2017 and 2018 reduced the hazard caused by decreases in seismicity rates in the FWB (Petersen *et al.*, 2017, 2018). We continue to study causal factors for the decreased seismicity rates. The FWB is now regionally monitored by both permanent and portable stations associated with TexNet, and care has been taken to place a TexNet station as the central station for each of the major sequences in the FWB. Recent activity in 2017 and 2018 outside of the five named sequences has already prompted new SMU deployments of single stations to supplement TexNet regional coverage and improve depth resolution. SMU operation of NTXES stations under network codes ZW and 4F will remain in place over active earthquake sequences in the basin as funding allows.

DATA AND RESOURCES

Southern Methodist University (SMU) deployed a combination of SMU, U.S. Geological Survey (USGS), Incorporated Research Institutions for Seismology–Program for the Array Seismic Studies of the Continental Lithosphere (IRIS-PASSCAL), and Texas Seismic Network (TexNet) instruments. The recorded seismograms on these instruments are part of an ongoing study focused on the seismicity in the eastern part of the Fort Worth basin (FWB). Data for the FWB are available at the IRIS Data Management Center at ds.iris.edu under Federated Digital Seismic Network codes NQ (USGS; doi: 10.7914/SN/NQ), ZW (SMU 2013+; doi: 10.7914/SN/ZW_2013), 4F (SMU 2015+; doi: 10.7914/SN/4F_2015), and TX (TexNet 2016+; http://www.beg.utexas.edu/texnet-cisr/texnet, last accessed August 2018). We used the IRIS Modular Utility for STAtistical kNowledge Gathering (MUSTANG) webservices (Casey *et al.*, 2018; http://services.iris.edu/mustang/, last accessed August 2018) and the USGS Comprehensive Catalog (https://earthquake.usgs.gov/data/comcat/, last accessed August 2018).

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