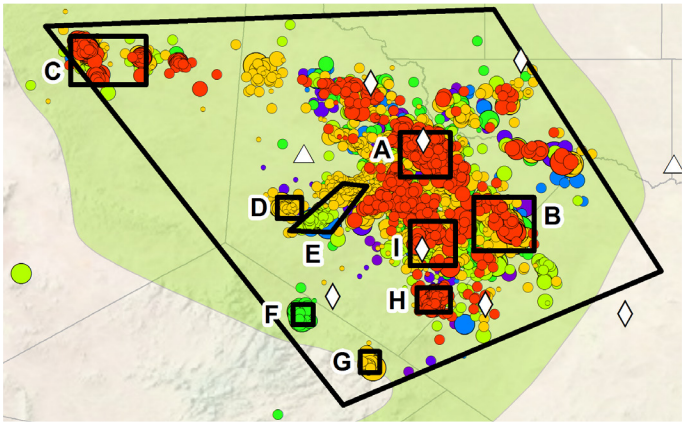
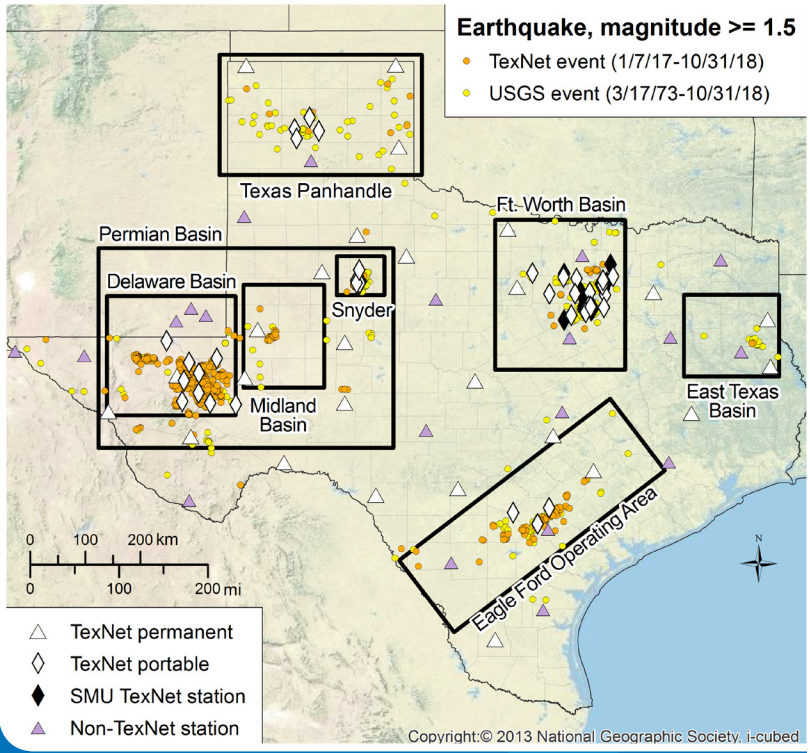
2018 Biennial Report on Seismic Monitoring and Research in Texas

November 28, 2018





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TexNet | Bureau of Economic Geology

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Executive Summary

In 2008, the rate of seismicity began to significantly increase across the southern Midcontinent of the United States, including parts of Texas. This increase led to the 2016 creation of the Texas Seismic Monitoring Program (TexNet) at the Bureau of Economic Geology (Bureau), The University of Texas at Austin (UT Austin), with a $4.471 million appropriation from the State of Texas. For the 2018–19 biennium, $3.4 million of funding was made available to TexNet. With these funds, TexNet completed the deployment of the network, operated the network to detect and locate earthquakes, and performed research to better understand seismicity in Texas. The following list represents key points from the work performed by TexNet over the last 2 years and summarized in this report:

- Texas now has a state-of-the art seismic network with a consistent ability to monitor earthquakes statewide. We can detect earthquakes across Texas below the felt level and locate these events with improved accuracy. A continuously updated, publicly available catalog of seismicity across the state is available at **http://www.beg.utexas.edu/texnet-cisr/texnet/earthquake-catalog**, providing near real-time earthquake information to all Texas residents.
- Increased seismicity began before the installation of the TexNet seismic network, with the seismicity ramping up in key areas around 2008–9.
- Most of the state is not experiencing earthquakes, but seismic activity *is* occurring in four main areas: the Delaware Basin in West Texas, Dallas–Fort Worth area, Eagle Ford Shale area of South Texas, and Cogdell Field near Snyder. Additionally, on October 20, 2018, a magnitude 4.4 (M 4.4) event occurred in the Panhandle near Amarillo. Although seismic activity has been recorded, almost all earthquakes are below the level commonly felt by people. No damage to date has been reported in these areas (to our knowledge), and currently the risk is deemed to be low to moderate.
- Ongoing research by TexNet is dedicated to understanding the causes of earthquakes in Texas, identifying mitigation strategies, and evaluating the potential seismic risk to, or impact on, Texans. Research takes advantage of state resources at UT Austin, Texas A&M University (TAMU), Southern Methodist University (SMU), The University of Texas at El Paso (UTEP), The University of Texas at Dallas (UT Dallas), and the University of Houston.
- TexNet leadership meets regularly with the TexNet Technical Advisory Committee and the Railroad Commission of Texas to discuss data collection and research outcomes, both of which are important for regulatory decision making. Leadership also meets with various stakeholder groups, including city councils, citizen groups, and oil and gas operators.
- Of the $3.4 million allocated for operation and maintenance of TexNet and associated research activities, approximately 45 percent has been spent through August 31, 2018. We anticipate full spend-out for both TexNet Operations and TexNet Research by the end of the 2019 fiscal year.

Recommendations: TexNet and its associated research program provide improved monitoring of seismicity across the State of Texas and enable research that advances our understanding of seismicity in Texas. This work provides a basis for assessing earthquake hazards, minimizing earthquake activity associated with human activities, and reducing the impact of possible future earthquakes on the people and infrastructure of Texas. It is critical to fund TexNet on an ongoing basis and as a stand-alone item in the state budget. **Continued funding of $3.4 million for the 2020–21 legislative cycle will allow the State of Texas to maximize its current investment in the earthquake monitoring network and extend our understanding of earthquake risk in the state.**

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1.0 Introduction

Summary: The main goals of TexNet are to provide high-quality earthquake data and to perform research to understand the causes of earthquakes in Texas. As of August 2018, TexNet has deployed 58 new seismic stations across the state. From January 2017 through October 2018, a total of 4,638 earthquakes have been reported by TexNet, with the vast majority (97 percent) being smaller than M 2.5, the magnitude above which events are typically felt by people. TexNet collaborates broadly with entities statewide and nationally to maintain a state-of-the art seismic network and ensure high-quality research.

1.1 Overview of TexNet Seismic Monitoring and Research

The goal of TexNet is to provide high-quality data and information to evaluate the location, frequency, and likely causes of earthquakes in Texas. As of August 2018, TexNet has deployed a total of 58 new seismic stations (25 permanent, 33 portable) across the State of Texas. These stations, along with 18 existing stations, form an evenly spaced, backbone seismic network across the state that allows for the accurate detection of earthquakes. The 33 portable stations have been specifically deployed across four areas of the state that have recently experienced clustered seismicity and represent regions of high socioeconomic importance. A data management system is used to detect, analyze, and locate earthquake events. A continuously updated, publicly available catalog of seismicity across the state is available at **http://www.beg.utexas.edu/texnet-cisr/texnet/earthquake-catalog**.

The research being conducted with TexNet funding is focused on understanding the potential causes of these earthquakes, including the potential relationship with subsurface industrial activity such as the injection of fluids. The TexNet seismic network, the foundational component of this research program (Figure 1.1),

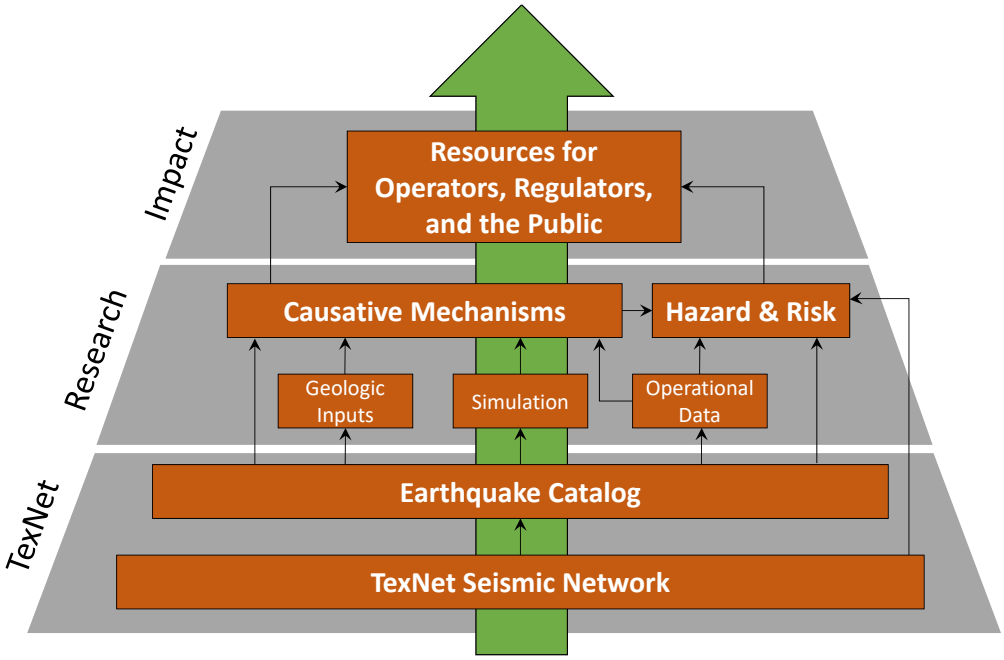

Figure 1.1 Integration of TexNet seismic network and TexNet research.

records ground shaking from earthquakes, which allows for the determination of the location and size of the earthquakes. The resulting catalog of earthquake locations/sizes is used throughout the research program. Integrating geologic inputs, coupled geomechanical/reservoir modeling, and operational data from oil/gas activities with the earthquake catalog allows for research related to the potential causative mechanisms of earthquakes in Texas. The research on causative mechanisms is integrated with operational data and earthquake data to better quantify seismic hazard and risk to the people and infrastructure of Texas. Together, the various research components provide resources and knowledge used by operators, regulators, and the general public to minimize the impact of earthquakes in Texas. The goals of the TexNet seismic network and associated research program have been endorsed by the Academy of Medicine, Engineering and Science of Texas in their Shale Development Report (TAMEST, 2017).

TexNet was established and funded in Section 16 of House Bill 2 (HB2) of the 84th Texas Legislature (2016–17). This legislation provided $4,471,800 over the 2016–17 biennium to the UT Austin Bureau of Economic Geology to establish and operate the TexNet seismic monitoring network, to perform research related to the modeling of reservoir behavior for wells in the vicinity of faults, and to establish a Technical Advisory Committee (TAC). During the 85th Texas Legislature (2018–19), House Bill 2819 (HB2819) revised the makeup of the TexNet Advisory Committee and described the committee's role in overseeing the operation of the TexNet seismic monitoring network and associated research related to seismicity in Texas. However, no funds were directly appropriated to the Bureau in 2018–19 for continued operation of the TexNet seismic network or to support the associated research program. Rather, $3.4 million of funding was made available to TexNet by the Office of the President of UT Austin via the "hold harmless" funding provided to the university by the 85th Legislature.

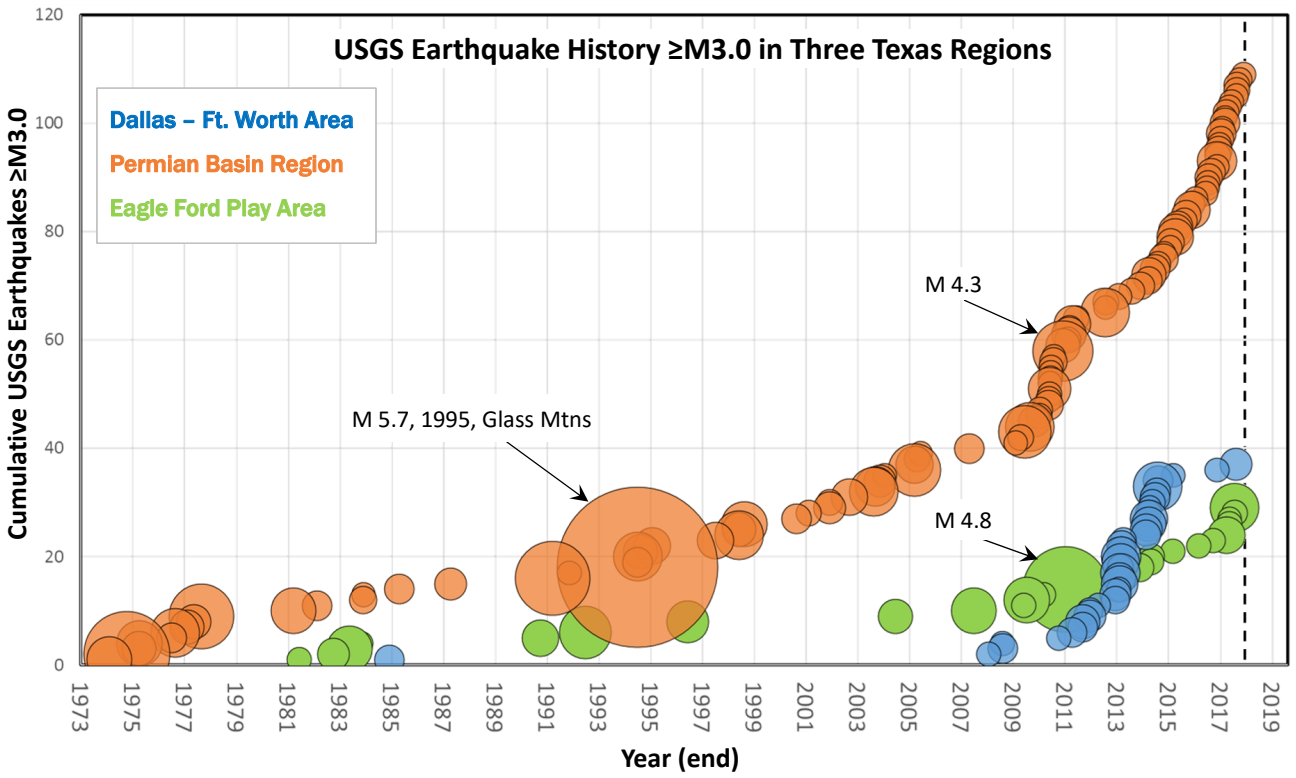

Figure 1.2 Cumulative seismicity for M ≥ 3.0 in the Dallas–Fort Worth area, Permian Basin region, and Eagle Ford area since 1973. Data from USGS/ANSS ComCat. Size of symbols correlates to recorded magnitude of event. The 1995 "Glass Mtns" event depicted in figure was a natural event occurring near Alpine, Texas.

1.2 Overview of Seismicity in Texas

A clear increase in the rate of recorded seismicity in Texas was observed beginning around 2008 (Frohlich et al., 2016). Prior to that time, an average of one to two earthquakes per year of M ≥ 3.0 were recorded. Since 2008, the rate has increased to approximately 15 events per year, on average.

Figure 1.2 shows the cumulative number of earthquakes greater than M 3.0 recorded in three specific areas of Texas (Dallas–Fort Worth, Permian Basin, and Eagle Ford play) from 1973 to 2018, as reported in the USGS Advanced National Seismic System (USGS/ANSS) Comprehensive Catalog (ComCat). Based on the data shown in Figure 1.2, seismicity rates started to increase in the Dallas–Fort Worth area around 2008, in the Permian Basin area around 2010, and in the Eagle Ford play area around 2017. The increase in seismicity in the Dallas–Fort Worth area is what initiated the creation of TexNet.

TexNet became operational in January 2017. The earthquakes detected by TexNet (Figure 1.3) are mainly clustered around four areas: the Fort Worth Basin, the Delaware Basin in West Texas, the Eagle Ford area,

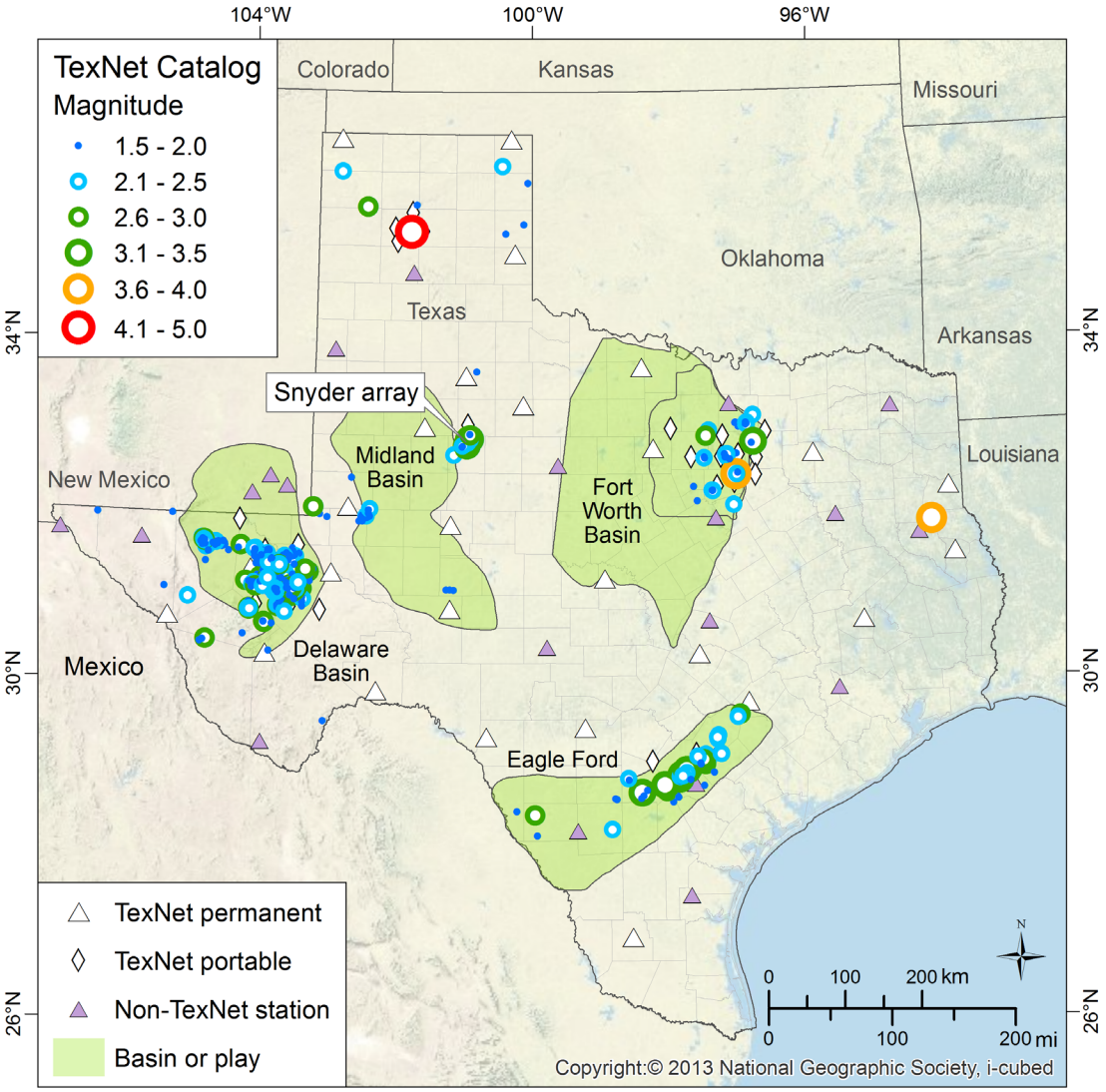

Figure 1.3 Earthquakes larger than M 1.5 recorded by TexNet between January 2017 and September 2018. Deployed TexNet permanent and portable seismic stations as of September 2018 are shown.

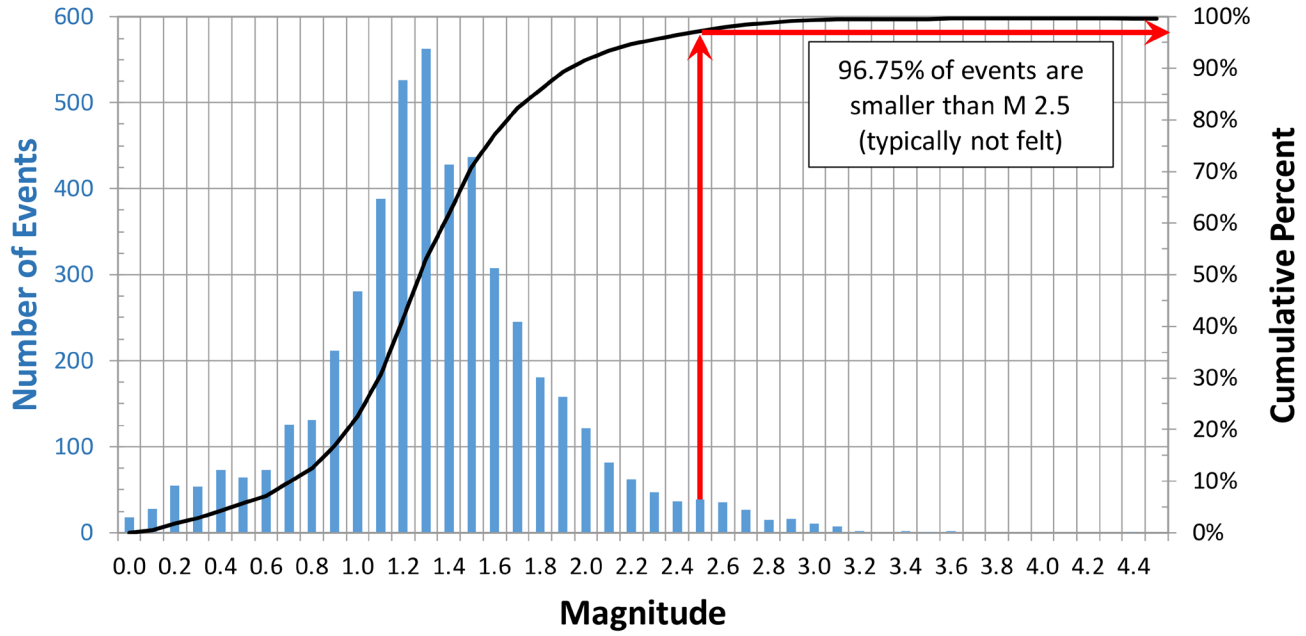

Figure 1.4 Magnitude distribution of earthquakes publicly available from TexNet.

and Cogdell Field near Snyder. The Delaware Basin has generated the largest number of earthquakes. The largest event, however, was an M 4.4 earthquake that occurred on October 20, 2018, near Amarillo—outside of the main areas of clustered seismicity.

From January 2017 through October 2018, a total of 4,638 earthquakes were reported through TexNet, with 1,835 events above M 1.5 and 148 events above M 2.5. These values are consistent with the understanding that the number of earthquakes generally increases about 10 times as the magnitude decreases by one unit. The magnitude distribution of the events publicly available from TexNet is shown in Figure 1.4. As expected, there are considerably more small earthquakes than large earthquakes; the vast majority (97 percent) are smaller than M 2.5, the magnitude above which events are typically felt by people.

1.3 TexNet Collaborations

TexNet is currently collaborating with SMU to support the operation of their network. In return, TexNet has real-time access to SMU data and uses it in earthquake detection and location. Similarly, TexNet has, at no cost, access to data from monitoring networks in neighboring states (e.g., Oklahoma and New Mexico) for use in earthquake detection/location. Data sharing occurs through the Data Management Center at the Incorporated Research Institute for Seismology (IRIS).

TexNet is also collaborating with specific groups across the state and nationally on seismology research to investigate seismicity in different parts of Texas. TexNet works with SMU to study the Dallas–Fort Worth area, the University of Houston to study the Midland Basin, UTEP to study the Delaware Basin, and the UT Austin Institute for Geophysics (UTIG) to study the Eagle Ford area. In addition, TexNet collaborates with TAMU, the Southwest Research Institute (SWRI), and Golder Associates on geomechanical analysis and reservoir modeling in the Fort Worth Basin. These collaborations are all supported by the TexNet research budget.

Research on seismicity is also funded through the Bureau's Center for Integrated Seismicity Research (CISR), which is sponsored by oil and gas operators in Texas who are keen to understand the causes of seismicity in

Texas and the steps that can be taken for mitigation. CISR funding broadens and deepens TexNet research, and improves earthquake monitoring in the border areas adjacent to neighboring states by collecting data for locating earthquakes in Texas. These sponsors interface with Bureau researchers and their collaborators through the CISR Science Advisory Committee, which meets quarterly for updates and annually for a comprehensive review. Sponsors provide access to proprietary data and collaborate on research, as appropriate, further boosting the comprehensive research program.

Various collaborations take place between TexNet and other entities that do not entail funding through TexNet. For example, TexNet collaborates with the Stanford Center for Induced and Triggered Seismicity to characterize the seismicity potential of subsurface faults in the Fort Worth Basin. TexNet also collaborates with the USGS on seismicity analyses and generation of different seismic-related products, such as ShakeMaps. TexNet leadership meets regularly with the Railroad Commission of Texas to discuss data collection and research outcomes, both of which are important for regulatory decision making. Leadership also meets with various stakeholder groups, including city councils, citizen groups, and oil and gas operators, to educate this broad constituency on earthquakes and their implications for Texas.

Finally, TexNet collaborates with the states of Oklahoma, Kansas, New Mexico, and Arkansas—in cooperation with the U.S. Department of Energy and the Ground Water Protection Council—through the recently created Regional Induced Seismicity Collaborative (RISC). RISC focuses on facilitating research already being conducted by these states by creating more effective pathways to move information and insights between the research groups, to the states' regulatory communities, and to the public.

2.0 TexNet Budget and Ongoing Cost

Summary: The FY 2018–19 TexNet budget included $1.4 million to operate the seismic network and $2.0 million to support research. Operation costs support the deployment and maintenance of the network, as well as the detection and reporting of earthquakes. Research includes projects that improve understanding of the causes of earthquakes in Texas and their potential effect on the people and infrastructure of the state. For the FY 2020–21 biennium, we request funding of $3.4 million to continue network operations and TexNet research, building on the existing infrastructure investment and supporting the mitigation of earthquake effects on the citizens of Texas.

2.1 Budget and Spending for TexNet Operations

TexNet operations (Project 1) include deployment and maintenance of sensors; telecommunications; operation of TexNet Hub servers; and the detection, location, and reporting of earthquakes across the state. The majority of TexNet operations are housed in the Bureau, with a small subcontract ($104,660) with SMU initiated to help link data from their 19 stations in the Fort Worth Basin to the TexNet network.

Table 2.1 shows a breakdown of costs for specific TexNet elements. As indicated, equipment spending in FY18 was nominal and limited to equipment and servers. We anticipate that equipment costs in FY19 will remain nominal, resulting in a total cost this biennium of $100,000. The majority of spending has been on deployment and operations. These costs include personnel to operate and maintain existing seismometer stations; redeploy portable seismometers to locations of clustered seismicity (in consultation with the TexNet TAC); and analyze data collected from seismometer stations to detect, locate, and report events in Texas. Note that FY18 costs are actual spending amounts; FY19 costs are expected.

Table 2.1 Costs for TexNet Operations during the 2018–19 biennium

TexNet Seismic Network	Equipment	Deployment and Operations					Subtotals by Cost
	TexNet Hardware	SMU Subcontract	Materials & Services	Personnel	Computer Usage	Travel	
TexNet FY18 Cost (actual)	$ 34,467	$ 14,820	$ 166,366	$ 357,942	$ 5,071	$ 34,467	$ 613,133
TexNet FY19 Cost (expected)	$ 65,533	$ 89,840	$ 110,734	$ 486,240	$ 10,729	$ 25,603	$ 788,679
Subtotals by Category	**$ 100,000**	**$ 104,660**	**$ 277,100**	**$ 844,182**	**$ 15,800**	**$ 60,070**	
Totals	**$ 100,000**	**$**				**1,301,812**	**$ 1,401,812**

2.2 Budget and Spending for TexNet Research

Research conducted under TexNet during the 2018–19 biennium includes a portfolio of projects designed to investigate topics needed to better understand the causes of earthquakes and their potential effect on the people and infrastructure of the state. These research activities were developed and funded in consultation with the TexNet TAC and were categorized into technical themes—Seismology, Geologic Characterization, Fluid Flow and Geomechanics, Seismic Hazard and Risk Assessment, and Results/Info Distribution—that effectively mirrored the workflow of raw-data collection to data analysis to geologic research/insight to communication.

Research activities and budgets are itemized in Table 2.2. Summaries of the research associated with the projects are included in Section 4 of this report. The research portfolio includes projects at several research

Table 2.2 Costs for TexNet Research during the 2018–19 biennium

Theme	Project Title	Institution/ Unit	Personnel	Materials & Services	Sub-contracts	Computer Charges	Tuition	Travel	Special Equipment	FY18/19 Project Total	FY19 Remaining
Seismology	**Project 2:** Texas Seismology Studies	UT-BEG	$ 250,952	$ 19,000	$ -	$ 14,011	$ 3,000	$ 35,000	$ 15,000	$ 336,963	$ 225,270
	Project 2a: Fort Worth Basin Seismicity and Integrated Studies	SMU			$ 210,874					$ 210,874	$ 183,446
	Project 2c: Midland Basin Seismicity Monitoring and Analysis	U Houston			$ 110,094					$ 110,094	$ 103,838
	Project 2d: Delaware Basin Seismicity Monitoring and Analysis	UT El Paso			$ 194,974					$ 194,974	$ 194,974
	Project 2e: High-Resolution Crustal Imaging in the Delaware Basin	UT Dallas			$ 70,489					$ 70,489	$ 70,489
	Project 2b: West Texas Seismicity Using Lajitas Array	UT-IG	$ 62,946	$ -	$ -	$ -	$ -	$ 5,776	$ -	$ 68,722	$ 37,500
Geologic Characterization	**Project 3:** Texas Injection and Production Analytics	UT-BEG	$ 33,961	$ 2,140	$ -	$ 1,000	$ -	$ 5,000	$ 8,085	$ 50,186	$ 15,467.0
	Project 4: Ft Worth Basin Geologic/Mechanistic Characterization	UT-BEG	$ 135,777	$ 3,084	$ -	$ 5,278	$ -	$ 8,172	$ -	$ 152,310	$ 11,014.8
		SWRI			$ 39,966					$ 39,966	$ -
	Project 5: Permian Region Geological Characterization	UT-BEG	$ 117,122	$ 9,070	$ -	$ 10,700	$ -	$ 4,000	$ -	$ 140,892	$ 24,220
Fluid Flow and Geomechanics	**Project 6:** Ft Worth Basic Hydrogeologic Modeling	UT-BEG	$ 165,120	$ 38,705	$ -	$ 4,480	$ -	$ 4,355	$ 6,227	$ 218,886	$ 12,116
		GOLDER			$ 50,000					$ 50,000	$ 17,701
	Project 7: Azle Coupled Geomechanical Modeling	UT-TAMU			$ 104,495					$ 104,495	$ 6,545
	Project 8: Ft Worth Basin Fast Marching Pore Pressure Simulation	UT-TAMU			$ 50,000					$ 50,000	$ 50,000
	Project 9: Geomechanics of Fault Reactivation	UT-BEG-PGE	$ 115,564	$ 4,557	$ -	$ 5,007	$ -	$ 6,115	$ -	$ 131,243	$ 4,812
	Project 10: Fluid Injection and Earthquake Size in Faulted Reservoirs	UT-PGE	$ 37,874	$ 77	$ -	$ -	$ 17,119	$ 4,237	$ -	$ 59,308	$ 3,541
Seismic Hazard and Risk Assessment	**Project 11:** Time Dependent Seismic Hazard	UT-CAEE	$ 105,905	$ 790	$ -	$ -	$ 4,973	$ 6,000	$ -	$ 117,668	$ 107,428
	Project 12: Refining Texas Velocity Models over the Top 500 m	UT-CAEE	$ 70,005	$ 12,578	$ -	$ -	$ 18,933	$ 17,500	$ -	$ 119,016	$ 82,018
	Project 13: Infrastructure Vulnerability	UT-CAEE	$ 88,921	$ -	$ -	$ 9,000	$ 31,402	$ 1,000	$ -	$ 130,323	$ 85,938
Results and Info Distribution	**Project 14:** Geodatabase	UT-BEG	$ 45,159	$ 5,000	$ -	$ -	$ -	$ -	$ -	$ 50,159	$ 42,490
									TOTAL	$ 2,406,571	$ 1,278,808

units within UT Austin—including Petroleum and Geosystems Engineering (PGE) and Civil, Architectural and Environmental Engineering (CAEE)—as well as projects with SMU, TAMU, UT Dallas, UTEP, and the University of Houston. The SWRI and Golder Associates are subcontractors on two of the research projects, totaling $39,966 and $50,000, respectively. The total research budget of $2,406,571 exceeds the $2 million allocated for the 2018–19 biennium by residuals following the 2016–17 biennium. As of August 31, 2018, approximately 47 percent of the research budget has been spent; we expect to fully spend out the research budget by the end of FY19.

2.3 Request for FY 2020–21 Funding

The costs to continue operating and maintaining the TexNet seismic network over the 2020–21 biennium will remain at $1.4 million. Funding requested to maintain the complementary TexNet research program is $2.0 million.

Table 2.3 provides projected costs for the 2020–21 biennium. Costs requested for Equipment assume replacement/expansion of two stations per year. Operations and Maintenance are calculated for the biennium for the four categories shown, which are similar to those presented in Table 2.1 for the 2018–19 biennium.

As summarized in Table 2.2 and discussed later in Section 4, the TexNet research program spans an array of geologic and engineering topics that increase understanding of all of the following: subsurface conditions in geologic basins in Texas, which can help to explain earthquake processes across the state; geomechanical

properties of faults and how they reactivate; pore-pressure conditions needed to rupture existing faults, including reservoir-modeling approaches to simulate complex dynamic subsurface processes; and how earthquakes could impact infrastructure. Specific research projects that will be undertaken with future TexNet funding will be discussed and agreed upon by the researchers and the TexNet TAC.

This integrated research program takes maximum advantage of the data acquired by the seismic network, as well as of the subsidiary geologic data, and provides the basis for understanding seismicity in Texas, mitigating the results of this activity, and minimizing the financial and social impacts of these events to the State of Texas.

Table 2.3 Costs for TexNet, 2020–21 biennium: Equipment, Operations and Maintenance, and Research

TexNet Seismic Network	Equipment	Operations and Maintenance				TexNet Operations	TexNet Research	Subtotals
		Materials & Services	Personnel	Computer Usage	Travel			
TexNet FY20	$ 50,000	$ 110,000	$ 500,000	$ 7,500	$ 35,000	$ 702,500	$1,000,000	$ 1,702,500.00
TexNet FY21	$ 50,000	$ 95,000	$ 510,000	$ 7,500	$ 35,000	$ 697,500	$1,000,000	$ 1,697,500.00
Subtotals by Category	**$ 100,000**	**$ 205,000**	**$ 1,010,000**	**$ 15,000**	**$ 70,000**	**$ 1,400,000**	**$2,000,000**	
							Biennium Total	**$3,400,000**

3.0 TexNet Seismic Monitoring Network

Summary: The TexNet seismic network is a system of permanent and portable stations deployed across the State of Texas. The permanent stations form a backbone network while the portable stations are deployed in areas where seismicity is spatially clustered, requiring more detailed characterization. The presence of TexNet generally allows earthquakes above approximately M 1.2 to be detected in areas with portable array deployments and their location to be assessed with low uncertainty, 1.5 km (0.9 miles) in the horizontal direction and 2.5 km (1.5 miles) in the vertical direction. The location and characterization of small earthquakes is critical to understanding larger earthquakes.

3.1 Network Configuration

The TexNet seismic network includes a total of 58 new broadband seismic stations across the State of Texas: 25 permanent stations and 33 portable stations (Figure 3.1). The 25 permanent stations, along with 18 existing stations operated by others (e.g., the USGS), form an evenly spaced backbone seismic network across the state that allows for the accurate detection of earthquakes. Permanent station installations consist of a highly sensitive broad frequency band seismometer, placed within a 20-ft-deep cased and cemented borehole. Each location is permitted under a 10-year license agreement with the landowner. A critical component of high-performance seismic stations is the identification of low-noise sites—a guiding principle for TexNet that is now reflected in the high-quality data that the network is returning.

Portable stations are deployed in areas of seismicity to enhance data quality and earthquake detectability, reducing location uncertainties and, in particular, allowing for better estimates of earthquake depth. TexNet deployed and maintains 33 portable stations and partially supports SMU's 19 stations, as well. Portable stations consist of direct-burial broadband seismometers and accelerometers to characterize ground motion from nearby events. These stations have shorter-term lease agreements (2 years) to more quickly relocate stations in case of shifts in seismicity. As of October 2018, TexNet portable stations are deployed in the following areas of spatial-cluster seismicity (Figure 3.1):

- 15 stations in the Fort Worth Basin, Dallas–Fort Worth area
- 8 stations in the Delaware Basin
- 3 stations in the Eagle Ford operating area
- 7 stations in the vicinity of Cogdell Field, northeast of Snyder

Additionally, following the M 4.4 event on October 20, 2018, near Amarillo, four portable stations were deployed to the Panhandle (Figure 3.1). These instruments were taken from the set of reserve instruments maintained at the Bureau for rapid deployment after notable events.

A continuously updated, publicly available catalog of seismicity across the state is available at **http://www.beg.utexas.edu/texnet-cisr/texnet/earthquake-catalog**.

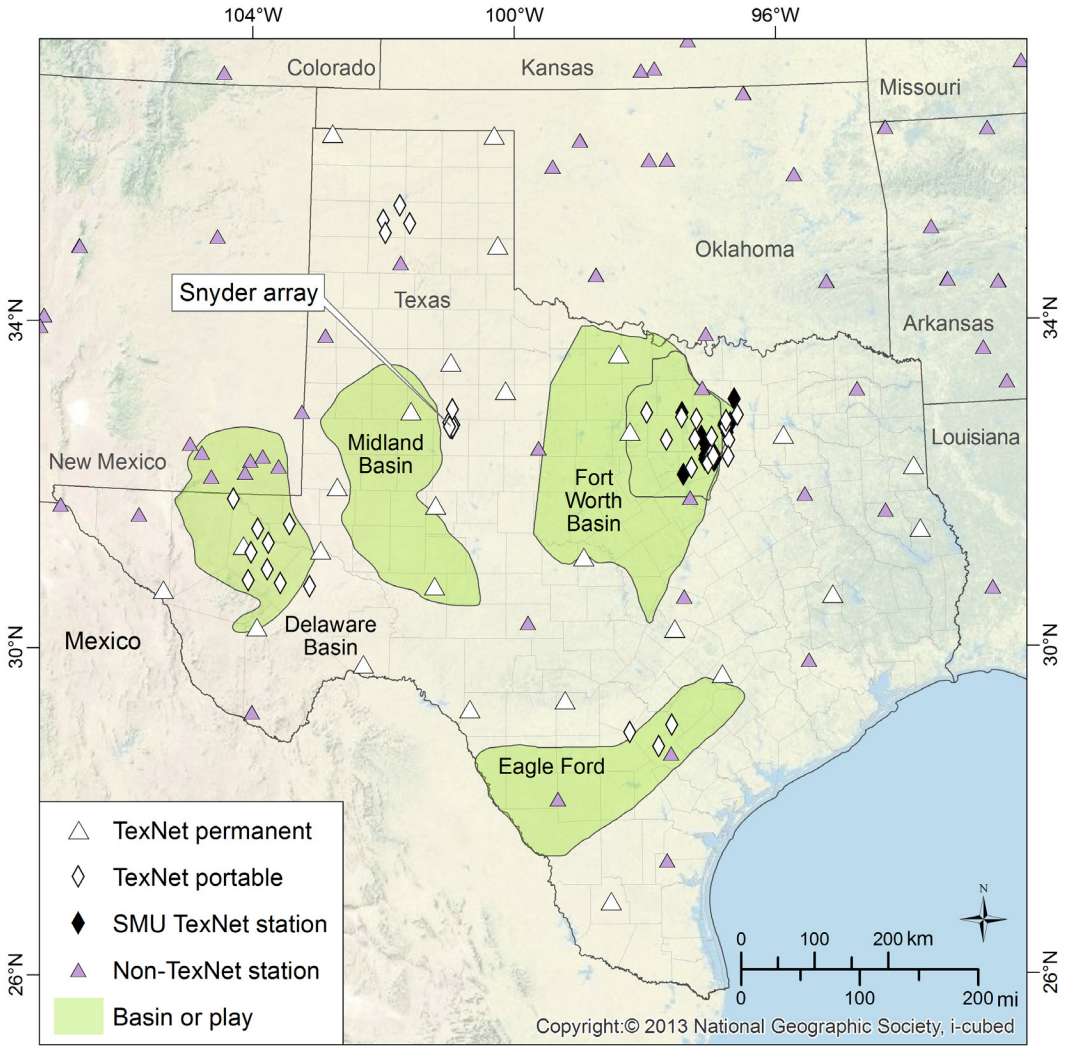

Figure 3.1 Map of TexNet permanent and portable stations, along with TexNet-supported SMU stations and non-TexNet stations that are used in detection and analysis of earthquakes by TexNet staff.

3.2 Network Performance

Magnitude of Completeness (Mc)

A key characteristic of a seismic monitoring network is the magnitude above which one can confidently state that all earthquakes were detected. This threshold is known as the *magnitude of completeness* (Mc). A lower Mc enhances the assessment of current and future seismicity. Generally, more closely spaced stations and more sensitive instruments lead to a smaller Mc. Before TexNet was deployed, the Mc across Texas was estimated to be between 2.7 and 3.0. The full deployment of TexNet and its portable stations has significantly reduced the Mc to between 1.1 and 1.2, as shown by the magnitude-frequency distribution in Figure 3.2.

General Statistics of Location Uncertainty

Earthquakes locations are reported in terms of their horizontal location on Earth's surface (i.e., epicenter) and their depth below the surface (i.e., hypocenter). Similar to Mc, more-accurate earthquake locations are obtained with a denser network of sensors. Reducing uncertainties is vital for accurately identifying

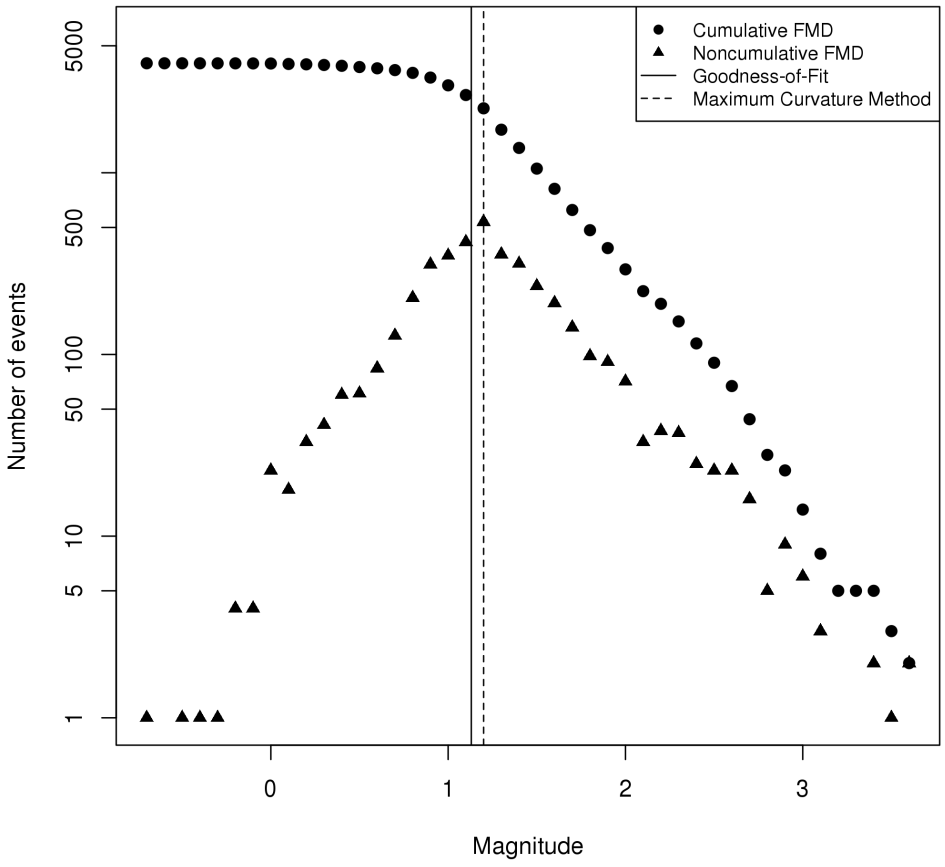

Figure 3.2 Estimated Mc for TexNet, based on the noncumulative frequency magnitude distribution (FMD) of earthquakes with magnitudes identified between January and September 2018.

earthquake location; accurate earthquake locations are critical for relating specific earthquakes to potential geologic faults, wastewater disposal wells, or other factors and for assessing their proximity to communities and critical infrastructure.

During the 2017–18 period of TexNet operations, the largest number of earthquakes were recorded in the Delaware Basin in West Texas (Figure 3.1). Therefore, we use Delaware Basin seismicity to illustrate how network density affects the horizontal and depth uncertainties in the earthquake locations. For this assessment, the total number of detected earthquakes for the Delaware Basin (2,248 events) provided by the TexNet catalog were reanalyzed for their location using (1) only pre-TexNet stations; (2) pre-TexNet stations and TexNet backbone stations; or (3) pre-TexNet stations, TexNet backbone stations, and TexNet portal stations.

The analysis shows that, when using only pre-TexNet stations, only 1,468 of the 2,248 events could be located; for these events (Figure 3.3a) most of the horizontal uncertainties were larger than 5 km (3.1 miles) and depth uncertainties were larger than 7 km (4.3 miles), making it difficult to associate the earthquakes with specific subsurface faults. The addition of the TexNet backbone stations (Figure 3.3b) reduced horizontal uncertainty to a median of 2.6 km (1.5 miles) and depth uncertainty to a median of 4.2 km (2.5 miles); the number of events that could be located increased to 2,210. Finally, the further addition of portable stations (Figure 3.3c) reduced median horizontal uncertainty to 1.5 km (0.9 miles) and median depth uncertainty to 2.6 km (1.5 miles), and increased the number of located events to 2,248. These smaller uncertainties and larger numbers of located earthquakes (even though most are too small to be felt by people) illustrate the value of increasing the number of seismometer stations in the state.

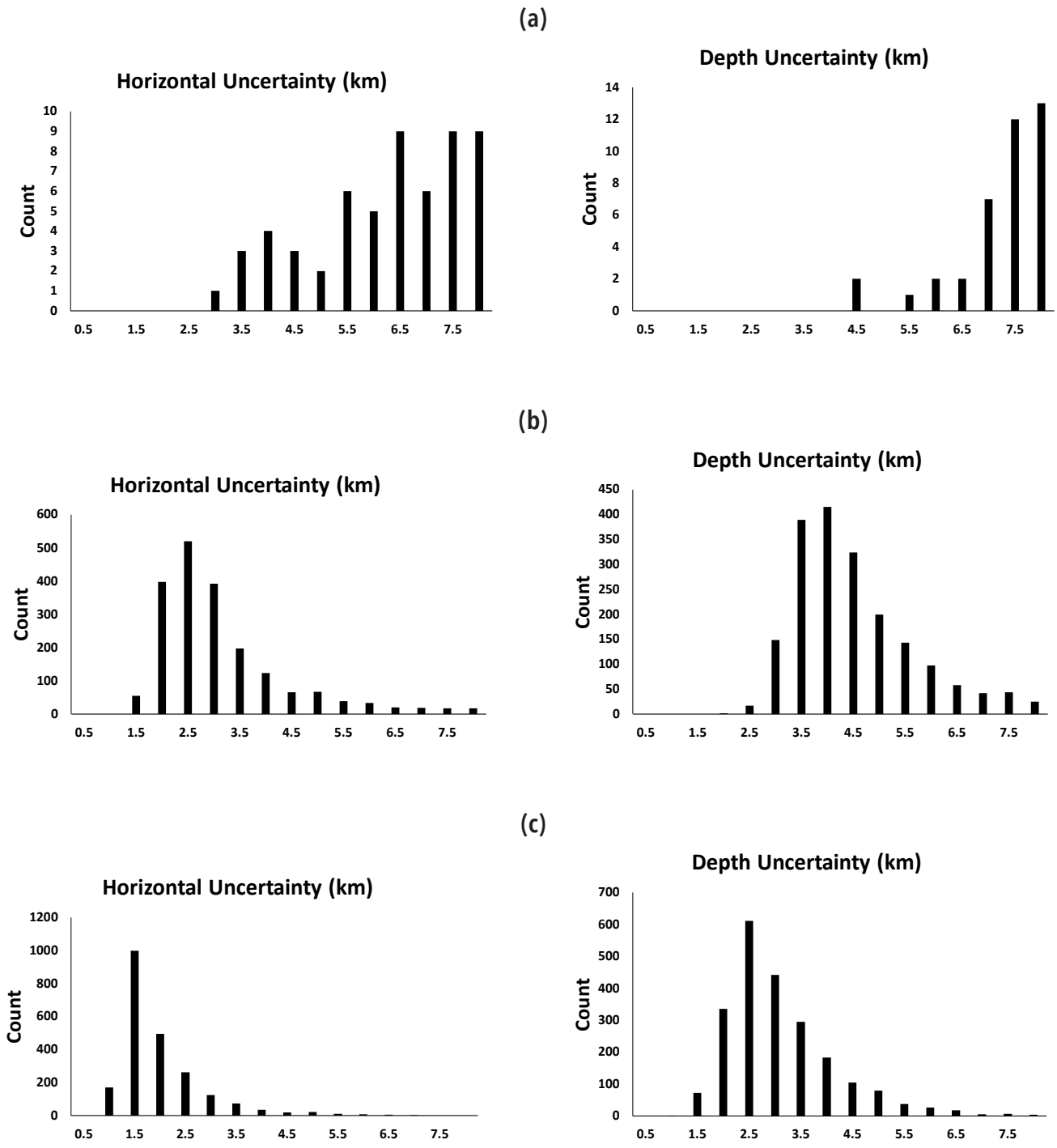

Figure 3.3 Histograms of horizontal and depth uncertainty of earthquake locations in the Delaware Basin for earthquakes analyzed using **(a)** only pre-TexNet stations; **(b)** pre-TexNet stations and TexNet backbone stations; and **(c)** pre-TexNet stations, TexNet backbone stations, and TexNet portal stations.

4.0 Summary of TexNet-Funded Research

Summary: TexNet research integrates TexNet earthquake information and complementary data into analyses and models that provide a better understanding of the causes of seismicity in Texas and its potential impact on the people and infrastructure of the state. As integrated analyses in the Dallas–Fort Worth area—where earthquake rates have diminished but active clusters persist—are nearing completion, it is becoming clear that deep injection of wastewater is the most likely cause of the earthquakes, although production may play a role in some cases. The Panhandle of North Texas has both natural and induced earthquakes. The geologic and operational habitat of earthquakes in other areas—such as West Texas and South Texas, where earthquake rates have increased compared to historic norms—is considerably more complex, but the TexNet research plan takes this into account and integrated studies are underway. The pace of delivery of quality data on earthquakes, and the publication of research findings, has increased over the current biennium and will continue to accelerate as per the developed research plan.

4.1 Introduction

Individual projects in the TexNet research portfolio form an integrated strategy to contribute leading science to better understand earthquakes in Texas. These studies are working to assess whether subsurface operations may be contributing to seismicity and, if so, the extent of this contribution. Two vital goals of this research are to use the results to devise appropriate mitigation strategies, when possible, and to better understand the seismic risk. In this section, we review the composition and progress of TexNet-funded research, providing a summary of composition and progress of the projects.

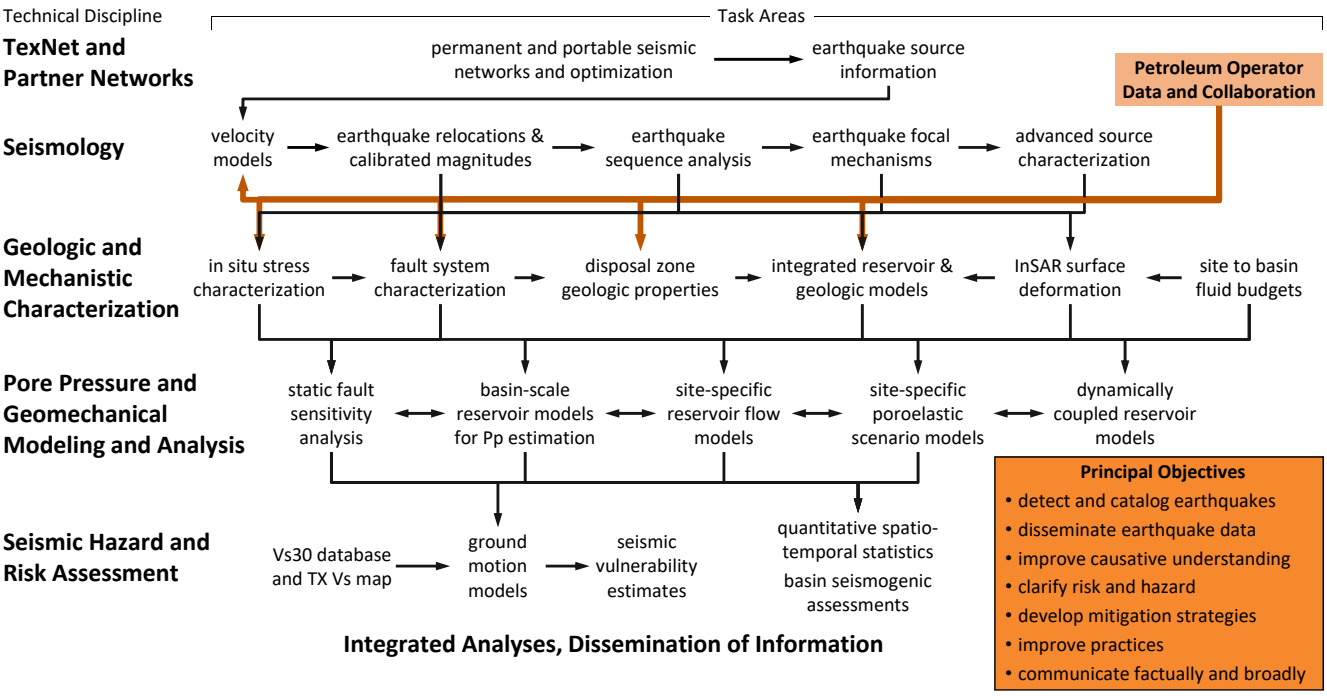

Figure 4.1 Chart showing how technical areas and projects are connected.

The principal products of TexNet projects are (1) high-quality data, and (2) analyses and models that explain subsurface behavior and aboveground consequences. Once finalized, data for individual earthquakes are made available publicly through the TexNet Earthquake Catalog. Analyses and models, however, must undergo independent scientific peer review before being made public, a process that typically involves presenting and vetting material at technical conferences and workshops, and publishing research findings in peer-reviewed scientific journals. The publication process can often take 1–2 years to complete. A partial listing of publications from research funded by TexNet can be found in Section 6.

The TexNet research portfolio is defined by technical areas that include **Seismology, Geologic and Mechanistic Characterization, Pore Pressure and Geomechanical Modeling and Analysis,** and **Seismic Hazard and Risk Assessment** (Figure 4.1), as well as tasks that add value to the information needed to pursue the following principal objectives: (1) cataloging earthquakes, (2) disseminating earthquake data, (3) improving causative understanding, (4) clarifying risk and hazard, (5) developing mitigation strategies, (6) improving practices, and (7) communicating facts and findings to different stakeholders. Figure 4.1 shows connections between the technical subdisciplines and the 14 specific research projects that are listed in Table 2.2 of Section 2. Some TexNet projects are applied statewide and others are focused geographically (Figure 4.2).

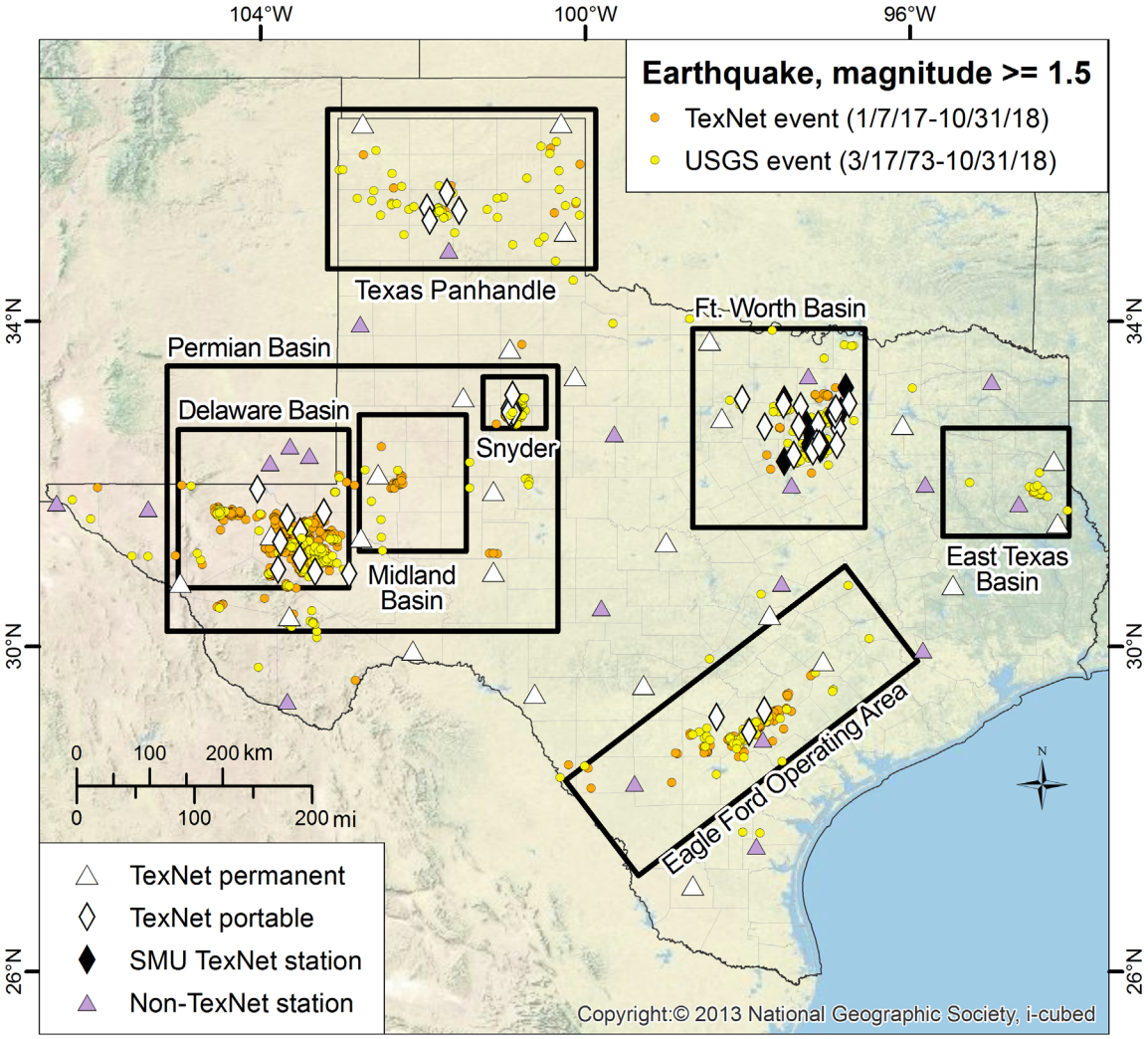

Figure 4.2 Seismicity in Texas as cataloged by the USGS and TexNet, deployed seismic stations, and TexNet research study areas.

Seismology Research Projects

Project 1 describes the statewide development and maintenance of the TexNet seismic network and the operational elements required to detect and locate earthquakes and distribute the data to the public (Table 2.1). See Section 3 for a summary of Project 1 progress. Project 2 and its subprojects represent a suite of seismologic studies, in partnership with other universities in Texas, that include earthquake monitoring in specific regions using dense local seismic networks.

Geologic and Mechanistic Characterization Research Projects

Projects 3, 4, and 5 focus on characterizing subsurface geology as it pertains to earthquakes: Texas Injection and Production Analytics (Project 3), and two separate projects characterizing geologic/mechanical properties (i.e., state of stress, faulting, permeability) of strata in the Fort Worth Basin (Project 4) and of the Delaware Basin area of the greater Permian Basin (Project 5). These projects clarify the potential hazard of fault reactivation and provide information for comprehensive models used for dynamic analysis.

Pore Pressure and Geomechanical Modeling and Analysis Research Projects

Assessing the potential relationship between earthquakes and subsurface oil and gas operations requires understanding the extent to which these operations change subsurface fluid pressures and the stress state acting on faults, as well as understanding the depths/locations of the oil/gas operations relative to those of the earthquakes. This work includes hydrogeologic and geomechanical reservoir modeling and analysis. Projects in this area include regional-scale analyses of the Fort Worth Basin (Projects 6 and 8), smaller-scale analyses of specific earthquake sequences (Project 7), and theoretical analyses designed to assess the subsurface conditions of geologic faults that are more likely to slip and cause an earthquake (Projects 9 and 10).

Seismic Hazard and Risk Assessment Research Projects

Projects in the area of seismic hazard and risk are designed to better understand the potential impacts of earthquakes on the people and infrastructure of Texas. This work involves developing models describing the time-dependent nature of observed seismicity and associated level of ground shaking (Project 11), refining the near-surface velocity structure that affects the levels of ground shaking and earthquake event location (Project 12), and evaluating the vulnerability of typical infrastructure in Texas (Project 13).

Dissemination Projects

As TexNet research projects accelerate in producing data, analyses, and models, it is critical to organize that information so that the public can easily retrieve it. Thus, the goal of Project 14 is to develop a digital repository where all TexNet data, and peer-reviewed models and publications, can be rapidly shared and integrated into other research.

A summary of research progress is provided in the section that follows; scientific peer-reviewed publications are listed in Section 6.

4.2 Summary of Research Progress

Research Progress for Dallas–Fort Worth Area and Fort Worth Basin

- Injection of wastewater into deep disposal layers is the most likely cause of earthquakes in the region. Withdrawal of fluids, both water and hydrocarbons, also contributed to increased seismicity in the region.
- Earthquake characterization for 2014–18 is complete; advanced studies continue.
- SMU has developed a comprehensive earthquake catalog for the region from 2008 to the present, which has been provided to TexNet for inclusion in its historical earthquake catalog.
- Analysis of saltwater injection and hydrocarbon production is complete and available upon request.
- Geologic characterization of injection zone is complete and pending publication.
- Fault interpretation and fault-slip-potential analyses are complete and pending publication.
- Integrated geologic model is complete and pending publication.
- Coupled geomechanical models for the Azle sequence are complete. Results from TAMU are published and results from the Bureau are pending publication.
- Hydrogeologic modeling by the Bureau and TAMU will be finalized in FY19.

The five largest earthquake sequences in the basin that have been studied and presented in the peer-reviewed scientific literature are (1) the 2008–09 DFW International Airport; (2) the 2009–10 Cleburne; (3) the 2013–present Azle–Reno; (4) the 2014–present Irving–Dallas; and (5) the 2015–present M 4.0 Venus sequences. During 2017 and 2018, seismicity occurred broadly across the Fort Worth Basin region. The 2018 M 3.4 earthquake in Venus and the 2017 M 3.0 earthquake in Irving–Dallas were the largest events in the reporting period (Figure 4.3). This seismicity included continued activity of the Azle–Reno, Irving–Dallas, and Venus sequences, with small M < 3.5 earthquakes between 2017 and 2018 but seismicity rates notably reduced compared to 2015–16. The 2018 Venus earthquake and 2017 Irving–Dallas earthquake led to 343 and 574 felt reports (reported by the USGS "Did You Feel It?" program), respectively. The 2017 M 2.8 earthquake in the Azle–Reno region led to 117 felt reports. In addition to these three sequences, a significant number of earthquakes have occurred near the cities of Fort Worth and Lake Lewisville, and to the west of Cleburne (Figure 4.2). These events have been preliminarily interpreted to represent new sequences on newly active faults. Additional stations have been recently deployed in those areas to better resolve location and depth.

Scientific consensus indicates that the increase in the rate of seismicity in the Fort Worth Basin beginning in 2008 and continuing through the present has been most likely caused by saltwater disposal (SWD) and oil and gas production. Injection of wastewater into deep disposal layers is the most likely cause, but withdrawal of fluids, both water and hydrocarbons, has also contributed to the increased seismicity. Monitoring has shown a decrease in the rate of seismicity since 2015, as the monthly rate of SWD decreased to pre-2007 levels, concurrent with a slowdown in the rate of development of the Barnett Shale. In work that is pending publication, we explain that the basin has many more faults than previously recognized and that many of the faults are sensitive to dynamic changes in the reservoir due to fluid injection and withdrawal. In some cases, faults in close proximity to wells with high rates and volumes of wastewater injection have caused earthquakes. In other cases that remain poorly understood, faults at greater distances from injection and production have reactivated, causing earthquakes; while faults located near areas of high-rate and high-volume injectors have not been reactivated.

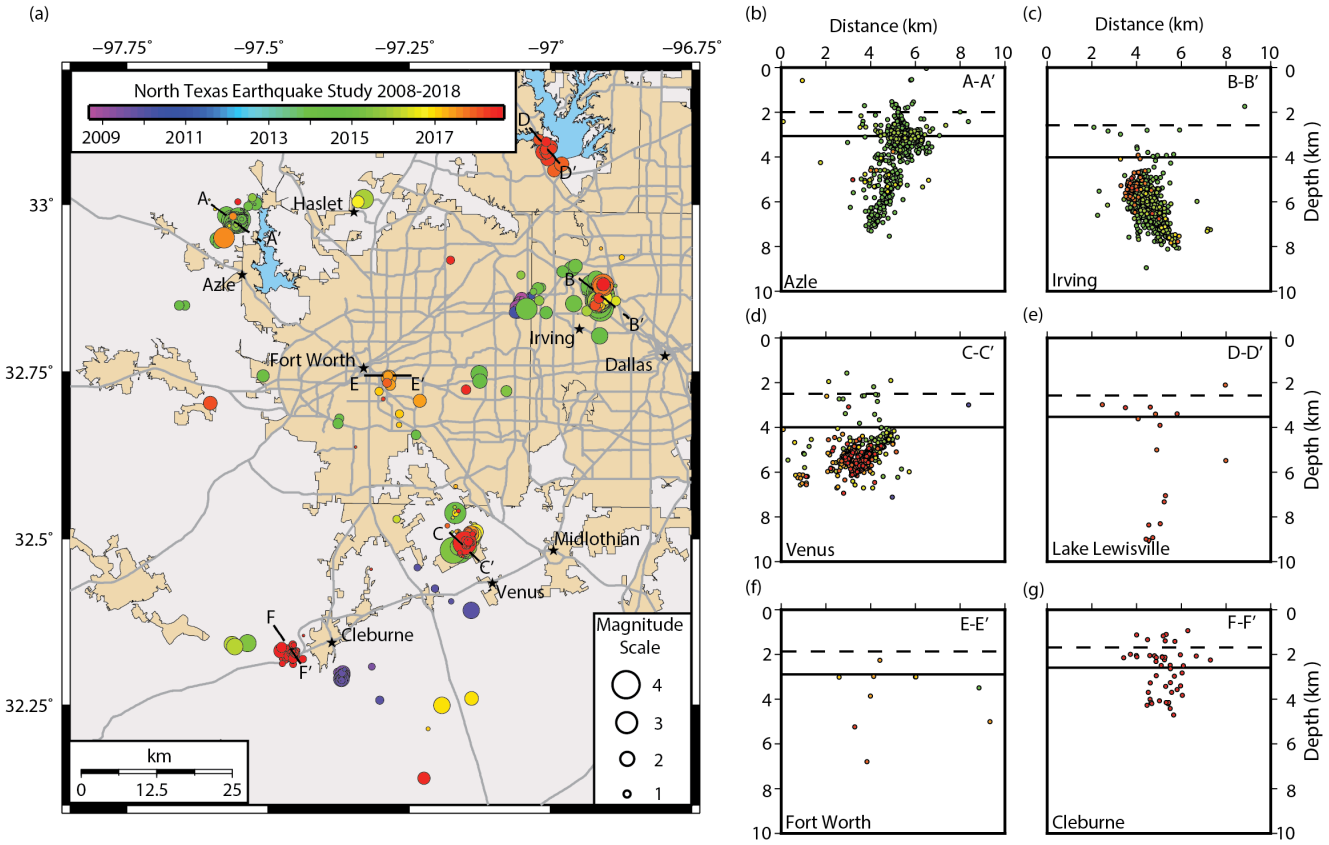

Figure 4.3 (a) Map view of SMU earthquake catalog showing locations of earthquakes (circles) scaled by their magnitudes and colored by origin times. Also shown are locations of injection wells (brown diamonds) active during period of observation. **(b–g)** Cross-sectional views of seismically active portions of basin, with their given sequence names shown at bottom left and cross-section line designations shown at top right. Cross-section lines are labeled on map view (a) and shown as dashed black lines (Quinones et al., in review).

Significant questions currently being addressed by ongoing TexNet research projects:

- What magnitudes of fluid-pressure change are most closely linked to earthquakes?
- What is the nature of the seismogenic faults?
- What are the most likely mechanisms for the inducement of earthquakes at great distances from areas of injection and production?
- What is the spatiotemporal change in earthquake hazard and what areas of the basin are the most sensitive to hydrocarbon operations using current practices?

Research Progress for West Texas

- The Permian Basin region of West Texas is geologically and operationally complex, with 11 active earthquake clusters: 9 in the Delaware Basin, 1 in Snyder, and 1 in Midland.
- The rate of earthquakes in the Delaware Basin increased in 2010 and again in 2017.
- Each earthquake cluster may have a unique mix of operational and natural influences.

- Detailed earthquake analysis is underway in the region using data from TexNet, and the number of monitoring stations being placed in strategic locations continues to grow.
- Locally dense monitoring of key earthquake clusters is either underway or planned.
- A new 3D velocity model will soon further reduce earthquake hypocenter uncertainty.
- Analysis of saltwater injection and hydrocarbon production is complete and available upon request.
- Work supporting integrated earthquake assessment is focused on the Delaware Basin.
    - Preliminary geologic characterization of shallow injection and shallow earthquakes is complete and being used for hydrogeologic modeling and geomechanical analysis.
    - A new 3D model of Delaware Basin structure and faults will be complete in FY19 and will be used for analysis of fault stress and fault-slip potential.
    - Site-specific assessment of key earthquake clusters will commence in FY19.

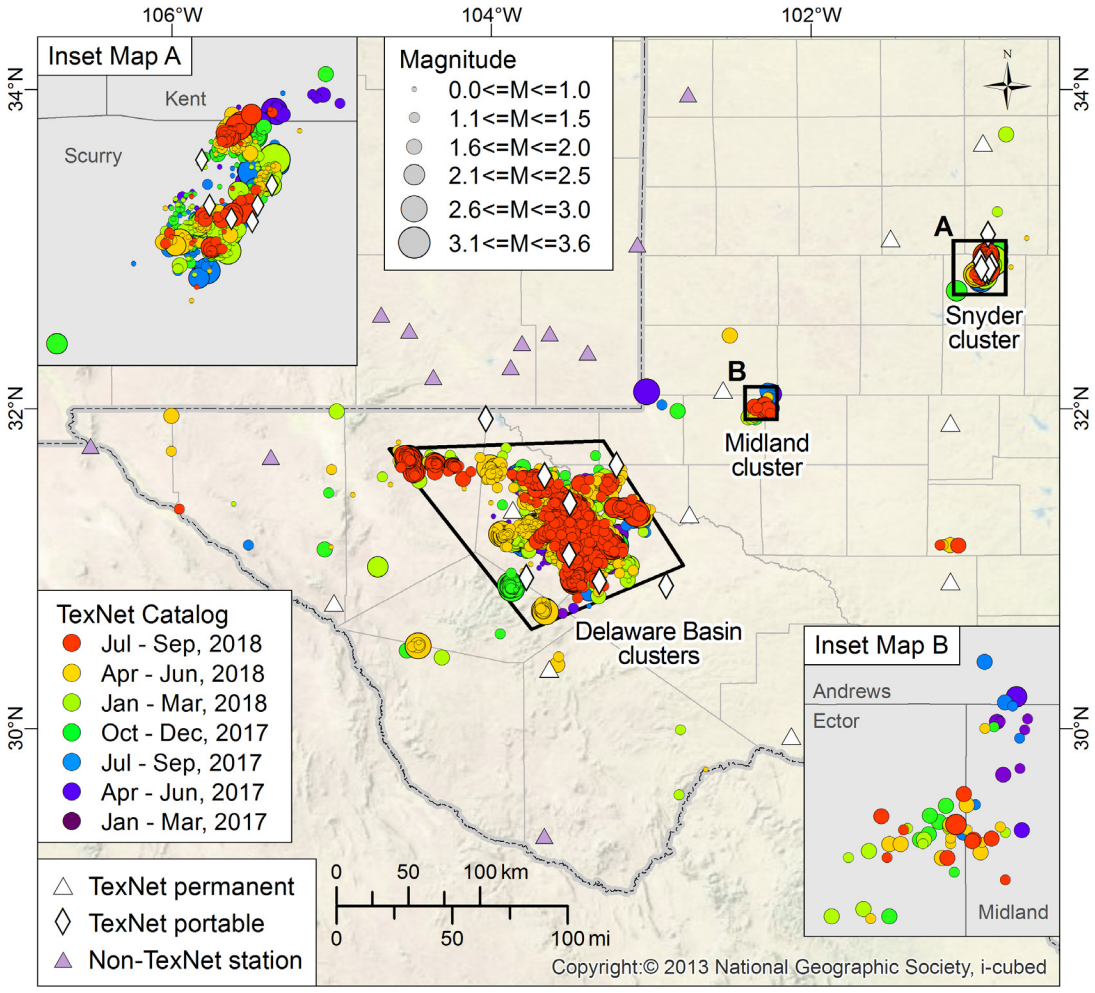

Figure 4.4 Map of the over 4,000 earthquakes cataloged by TexNet in West Texas from January 1, 2017, to September 30, 2018. Circles represent earthquakes, and color and size correspond to time and magnitude of event, respectively.

In contrast to the less-complicated earthquake situation of the Fort Worth Basin, where injection is primarily in Ordovician intervals and earthquakes are primarily in the Precambrian basement along NE-striking faults, the Permian Basin region of West Texas is far more complex, with 11 active earthquake clusters (Figures 4.4 and 4.5). The areas are each distinct with regard to geology and operational history. Natural earthquakes also occur in the region. The Snyder cluster is being monitored by a local TexNet monitoring array. The Midland cluster and Delaware Basin "A" cluster will also be monitored by local arrays beginning in FY19. Earthquake depth estimates still carry considerable uncertainties, but a new 3D velocity model for the region and more instruments will reduce uncertainty.

Even with the current uncertainty in depth, some Delaware Basin earthquake clusters likely are occurring dominantly in the shallow sedimentary realm (e.g., "A" cluster, Figure 4.5). Others are occurring in the deeper geologic basement along previously identified faults (e.g., "B" cluster, Figure 4.5). Soon-to-be-published data in the Delaware Basin region suggest that the ramp-up of seismic activity began in 2010 and increased markedly in 2017. Information with higher confidence will become available for these clusters in FY19 as more TexNet stations are added, local arrays are put into service, and controls on velocity structure are improved. At present, different causative mechanisms, each with a mix of operational and natural influences, may be needed to explain each earthquake cluster.

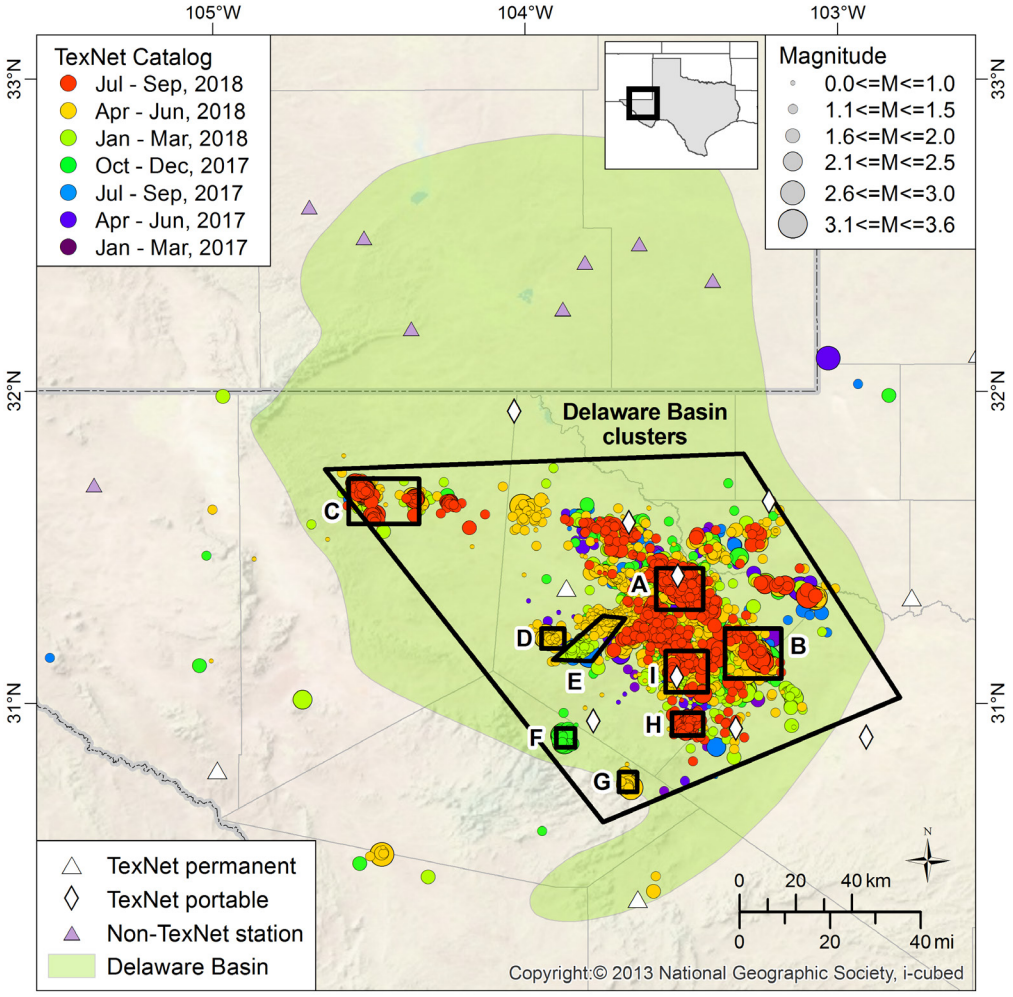

Figure 4.5 Enlarged area (from Figure 4.4) showing primarily Delaware Basin. Areas labeled with letter represent spatial clusters of seismicity.

The research study plan for 2019–20 will focus on the Delaware Basin, where the rate of seismicity is the greatest in the region. Here, geologic data sets are being assembled, integrated models are being constructed, and scoping-level hydrogeologic and geomechanical models have begun. The goals of the first phase of work are to identify the most likely factors contributing to earthquakes in each studied cluster area and to then use those preliminary results to determine the most appropriate research strategies to gain quantitative understanding. Significant questions remain:

- What is the recent history of earthquakes in the region, and how might it change in the future?
- What is the depth of the various earthquake clusters, and are the depth ranges limited or broad?
- What are the most likely mechanisms for inducing earthquakes, and how do natural causes fit in?
- What data and information will be most beneficial to inform steps for mitigation?

Research Progress for South Texas (Eagle Ford Area)

- Earthquakes in South Texas occur along a NE-trend broadly spanning the Eagle Ford area (Figure 4.6).
- Currently, an insufficient number of monitoring stations are available for reliable information on earthquake depth, though we are confident that earthquakes cataloged by TexNet have occurred in both the geologic basement and the overlying sediment.
- Saltwater injection and hydrocarbon production data sets are complete and available for use.
- An integrated geologic model is being developed and will achieve preliminary status in 2019.
- A locally dense seismic-monitoring network will become active in 2019.

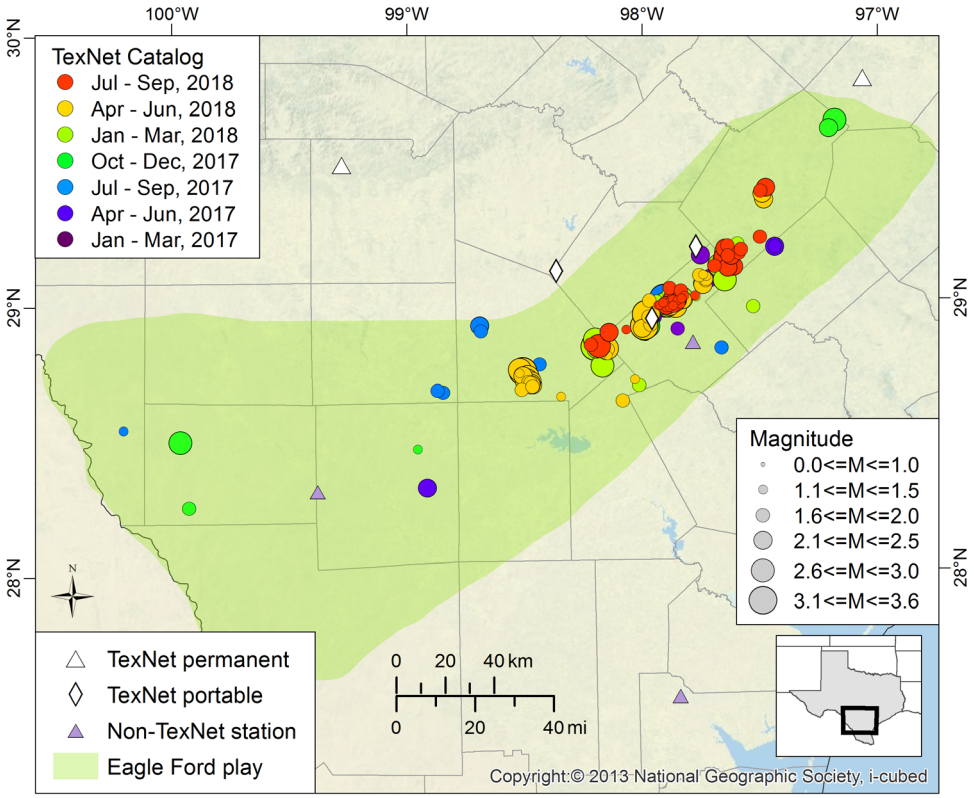

Figure 4.6 Map of the 132 earthquakes cataloged by TexNet in southern Texas from January 1, 2017, to September 30, 2018. Circles represent earthquakes, and color and size correspond to time and magnitude of event, respectively.

The research plan for South Texas in 2019–20 is to acquire more-detailed data on earthquake location, depth, and characteristics using the current TexNet seismic network and locally dense monitoring; build and maintain a database of operational activity for both oil and gas production and SWD; and construct an integrated geologic model with increasing completeness and capability over time. Mechanistic analyses to assess earthquake cause and mitigation options will begin in 2020 when earthquake and geologic data sets are satisfactorily complete.

Research Progress for Texas Panhandle

- The strongest earthquake cataloged thus far by TexNet occurred in the Texas Panhandle on October 20, 2018.
- The region is moderately seismically active, with both natural and possibly induced earthquakes.

The M 4.4 earthquake event indicated above occurred 12 miles northeast of Amarillo, adjacent to other studied clusters (Walter et al., 2018) (Figure 4.7). Within a week of that event, TexNet deployed four temporary monitoring stations in the region surrounding the event location to monitor for aftershocks. No further study is planned at this time.

Research Progress for East Texas

After a period of quiescence since the 2012–13 Timpson sequence, two earthquakes have been recently cataloged by TexNet, including an M 3.6 event recorded on September 4, 2018, approximately 5 miles west of Timpson, Texas. TexNet researchers are monitoring this area to determine if a more concerted study should be prioritized.

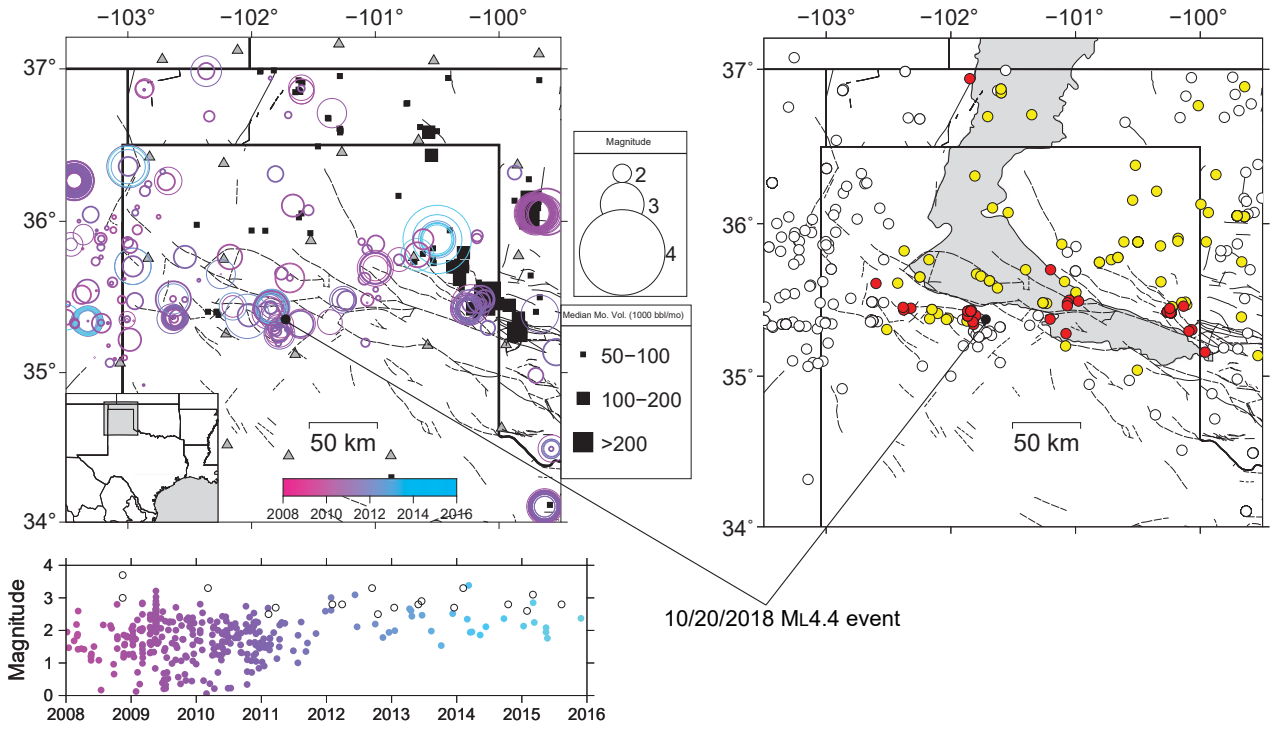

Figure 4.7 (Left) Earthquakes (circles) and wastewater injection wells (filled squares) in the Panhandle region. (Right) Map of earthquakes ranked by the method of Frohlich et al. (2016), with colors showing the strength of available evidence of inducement: white, score 0.0–1.0 (event not induced, or very little evidence available); yellow, score 1.5–2.0 (event possibly induced); red, score 2.5–3.0 (event probably induced). From Walter et al. (2018).

5.0 Future Plans for TexNet

Summary: TexNet will continue to improve network quality by repositioning, adding, and upgrading stations. TexNet will collaborate with other universities in Texas to deploy local dense arrays in areas of clustered seismicity. TexNet funded research will continue to focus on seismicity in the Dallas–Fort Worth, Permian Basin, and South Texas priority areas.

5.1 TexNet Seismic Monitoring Network

The earthquake locations provided by TexNet from 2017 through 2018 have quantified temporal changes in seismicity across Texas to a degree never previously understood. These results motivate the need to assess network performance with the capability to reposition individual stations as our understanding of Texas seismicity improves. TexNet has quantified the dynamic characteristic of seismicity in Texas, fueling the need for a flexible instrumentation plan going forward that will leverage the portable instrumentation component of the program. To continually improve the network, stations will be repositioned and added as needed to enhance data quality, improve earthquake detectability, and minimize uncertainties in earthquake location. Some examples of current plans for changes to the network are provided below.

Delaware Basin: Five additional stations, procured with funding from internal sources, will be installed to better locate events in this area of clustered seismicity. Specific sites will be chosen as close as possible to locations directly above the centers of specific seismicity clusters in the region. Additionally, UTEP will be installing an array of dense, portable stations over the next year to better understand the seismicity.

Fort Worth Basin: Results have shown that three existing sites in the region are too noisy; therefore, more-suitable sites are being evaluated that are closer to the active earthquake clusters. SMU will continue to operate their stations.

Eagle Ford Area: A portable station installed near detected seismicity was recently reinstalled. The sensor was initially installed in a 23-ft (7-m) deep borehole to reduce ambient noise but will be deepened to 47 ft (12 m) in 2019 to further improve data quality. This portable station will then become part of the TexNet permanent seismic network.

TexNet collaborations with the following Texas academic institutions involved in managing local dense arrays will continue in 2019:

- SMU, which operates 19 stations in the Fort Worth Basin close to active earthquake clusters
- UTEP, which will deploy 25 portable stations in late 2018 in the Delaware Basin near Pecos, Texas
- The University of Houston, which will deploy 7 seismic stations in late 2018 and early 2019 in the Midland Basin
- UTIG (with Bureau personnel), which will install an additional 25 stations in the Eagle Ford area

5.2 Research

TexNet-funded research will continue to focus on Dallas–Fort Worth, Permian Basin, and South Texas as priority areas (Figure 5.1). These priorities will be reevaluated as earthquake trends evolve and our understanding of the earthquakes improves.

Research work in the Dallas–Fort Worth area is entering concluding phases, with numerous publications submitted, or soon to be, and summary analyses and reporting scheduled for 2019 (see Section 6). Interim research products are available now for operators, regulators, and the public; final versions will become available beginning in 2019.

Concerted research work in the Permian Basin began in 2018 with a focus on improving the regional velocity model for locating earthquakes and integrating geologic analysis of the Delaware Basin, centered on the city of Pecos. The current focus of analysis in this area will include the shallow earthquake clusters; subsequent analysis of deeper earthquake clusters will begin in 2019.

Research on other seismically active areas of Texas such as the Midland Basin; the area northeast of Snyder, Texas; and the Eagle Ford area will also begin in coming years. However, background work for research in these additional areas is already underway, including local seismic monitoring, analysis of operational data on oil and gas production and wastewater injection, and assembly of geologic data and 3D models.

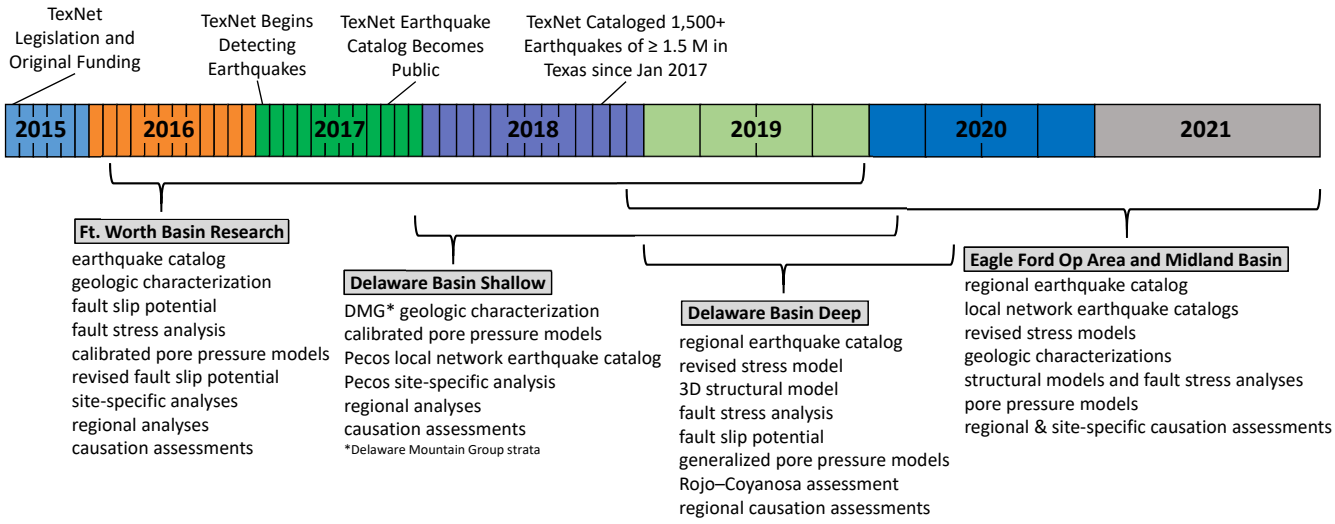

Figure 5.1 Generalized timeline for principal geographic application areas of TexNet research.

6.0 TexNet Research Publications

Summary: TexNet is funding high-quality research that receives independent, scientific peer review in an effort to provide the best research products for the State of Texas. Over 100 separate scientific conference presentations and peer-reviewed publications have resulted thus far from work funded or co-funded by TexNet. Table 6.1 lists peer-reviewed conference and journal papers published, accepted, or submitted. A list of conference abstracts from TexNet work can be found at the TexNet website.

Table 6.1 Peer-reviewed conference papers and journal papers from TexNet-supported research, published and planned. Project numbers listed are defined in Section 2.

No	Year	Type	Status	Project	Authorship, Title, and Publishing Information
1	2016	Journal Paper	Published	9	Fan, Z., Eichhubl, P., and Gale, J. F. W., 2016, Geomechanical Analysis of Fluid Injection and Seismic Fault Slip for the MW4.8 Timpson, Texas, Earthquake Sequence, Journal of Geophysical Research-Solid Earth, 121 (4), p. 2798–2812, doi:10.1002/2016JB012821.
2	2017	Journal Paper	Published	11	Zalachoris, G., Rathje, E., and Paine, J. 2017, VS30 Characterization of Texas, Oklahoma, and Kansas Using the P-Wave Seismogram Method, Earthquake Spectra, Earthquake Engineering Research Institute, 33 (3), p. 943–961, doi:10.1193/102416EQS179M.
3	2018	Journal Paper	Published	2a	Ogwari, P. O., DeShon, H. R., and Hornbach, M. J., 2018, The Dallas-Fort-Worth Airport Earthquake Sequence: Seismicity Beyond Injection Period, Journal of Geophysical Research, 123, p. 553–563, doi:10.1002/2017JB015003.
4	2018	Journal Paper	Published	2a	Quinones, L. A., DeShon, H. R., Magnani, M. B., and Frohlich, C., 2018, Stress Orientations in the Fort Worth Basin, Texas, Determined from Earthquake Focal Mechanisms, Bulletin Seismological Society of America, 108 (3A), p. 1124–1132, doi:10.1785/0120170337.
5	2018	Journal Paper	Published	2	Walter, J., Frohlich, C., and Borgfeldt, T., 2018, Natural and Induced Seismicity in the Texas and Oklahoma Panhandles, Seismological Research Letters, 89 (6), p. 2437–2446, doi:10.1785/0220180105.
6	2018	Journal Paper	Published	1	DeShon, H. R., Hayward, C. T., Ogwari, P. O., Quinones, L., Sufri, O., Stump, B., and Magnani, M. B., 2018, Summary of the North Texas Earthquake Study Seismic Networks, 2013–2018, Seismological Research Letters, doi:10.1785/0220180269.
7	2019	Journal Paper	Accepted	11	Zalachoris, G., and Rathje, E., in press, Ground Motion Model for Small-to-Moderate Earthquakes in Texas, Oklahoma, and Kansas, Earthquake Spectra, doi:10.1193/022618EQS047M.
8	2018	Journal Paper	Submitted	9	Fan, Z., Eichhubl, P., and Newell, P., in review, Basement Fault Reactivation by Fluid Injection into Sedimentary Reservoirs: Poroelastic Effects, Journal of Geophysical Research-Solid Earth.
9	2018	Journal Paper	Submitted	2a	Jeong, S.-J., Stump, B. W., and DeShon, H. R., in review, Spectral Ground Motion Characteristics for Induced Earthquakes in the Fort Worth Basin, Texas, Bulletin of the Seismological Society of America.
10	2018	Journal Paper	Submitted	13	Khosravikia, F., Clayton, P., and Nagy, Z., in review, An Artificial Neural-Network Based Framework for Ground Motion Prediction Equations for Small to Moderate Earthquakes in Texas, Oklahoma, and Kansas, Seismological Research Letters.

No	Year	Type	Status	Project	Authorship, Title, and Publishing Information
11	2018	Journal Paper	Submitted	4	Smye, K. M., Lemons, C. R., Eastwood, R., McDaid, G., and Hennings, P. H., in review, Stratigraphic Architecture and Petrophysical Characterization of Formations for Deep Disposal in the Fort Worth Basin, TX, Interpretation.
12	2018	Journal Paper	Submitted	1	Quinones, L. A., DeShon, H. R., Jeong, S.-J., Ogwari, P., Scales, M. M., and Kwong, K. B., in review, Tracking Induced Earthquakes in the Fort Worth Basin: A Summary of the 2008–2018 North Texas Earthquake Study Catalog, Bulletin of the Seismological Society of America.
13	2018	Journal Paper	Submitted	4	Hennings, P. H., Lund Snee, J.-E., Osmond, J. L., DeShon, H. R., Dommisse, R., Horne, E. A., Lemons, C. and Zoback, M. D., in review, Slip Potential of Faults in the Fort Worth Basin of North-Central Texas, USA, Geophysical Research Letters.
14	2018	Journal Paper	Submitted	1	Savvaidis, A., Young, B., Huang, D.-G., and Lomax, A., in review, TexNet: A Statewide Seismological Network in Texas, Seismological Research Letters.
15	2018	Journal Paper	Submitted	2	Huang, G.-C. D., Savvaidis, A., and Walter, J. I., in review, Mapping the 3D Lithospheric Structure of the Greater Permian Basin in West Texas and Southeast New Mexico for Earthquake Monitoring, Journal of Geophysical Research.
16	2017	Conference Paper	Presented	11	Zalachoris, G. and Rathje, E., 2017, Ground Motion Models for Earthquake Events in Texas, Oklahoma, and Kansas, 3rd International Conference on Performance-Based Design in Earthquake Geotechnical Engineering (PBD-III), Vancouver, Canada, July.
17	2017	Conference Paper	Presented	11	Zalachoris, G., Rathje, E., Cox, B., and Cheng, T., 2017, Application of the P-Wave Seismogram Method for Vs30 Characterization of Texas, Oklahoma, and Kansas, 3rd International Conference on Performance-based Design in Earthquake Geotechnical Engineering (PBD-III), Vancouver, Canada, July.
18	2018	Conference Paper	Presented	2	Savvaidis, A., Rathje, E., Cox, B., Zalachoris, G., Tiwari, A., Yust, M., and Young, B., 2018, Site Characterization of TexNet Seismic Stations Using Different Geophysical Approaches, Geotechnical Earthquake Engineering and Soil Dynamics V, Austin, Texas, June.
19	2018	Conference Paper	Presented	12	Yust, M. B., Cox, B. R., and Cheng, T., 2018, Epistemic Uncertainty in Vs Profiles and Vs30 Values Derived from Joint Consideration of Surface Wave and H/V Data at the FW07 TexNet Station, Geotechnical Earthquake Engineering and Soil Dynamics V, Austin, Texas, June.
20	2019	Conference Paper	Presented	7	Chen, R., Xue, X., Yao, C., Datta-Gupta, A., King, M. J., Hennings, P., and Dommisse, R., 2018, Coupled Fluid Flow and Geomechanical Modeling of Seismicity in the Azle Area North Texas, SPE 191623, Presented at 2018 Annual Technical Conference, Dallas, Texas.
21	2018	Conference Paper	Presented	11	Grigoratos, I., Bazzurro, P., Rathje, E., and Savvaidis, A., 2018, A Framework to Quantify Induced Seismicity Due to Wastewater Injection in Oklahoma, 11th US National Conference on Earthquake Engineering, EERI, Los Angeles, June.
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