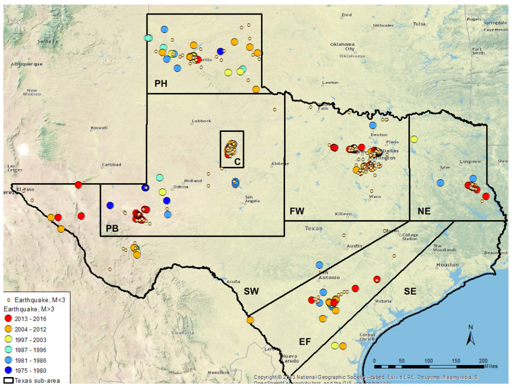
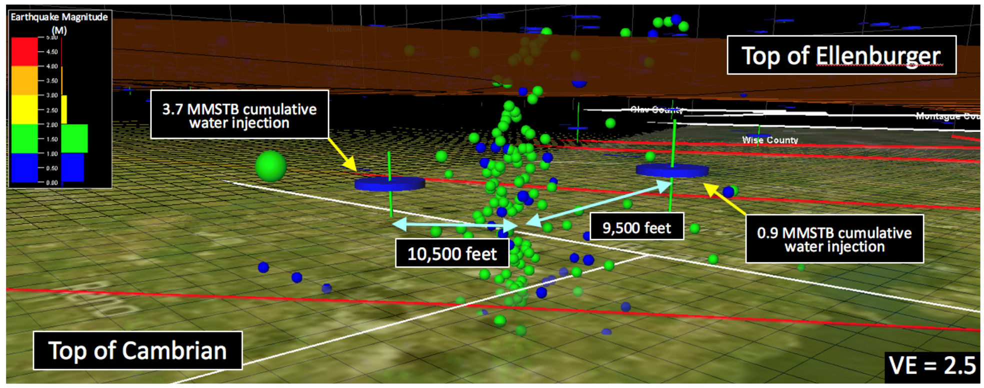
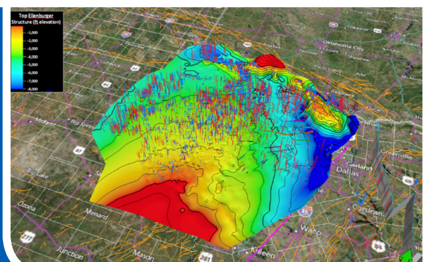
Report on House Bill 2 (2016–17)
Seismic Monitoring and Research in Texas

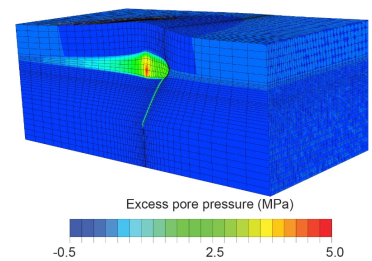
December 1, 2016





The University of Texas at Austin
Bureau of Economic Geology
Scott W. Tinker, Director





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Executive Summary

Beginning in 2008, the rate of seismicity significantly increased across the southern mid-continent of the United States, including parts of Texas. A broad spectrum of stakeholders from the public, governments and regulators, petroleum energy and service companies, and academic researchers need information to understand the causes of this increased seismicity and how these events might be better understood and potentially mitigated.

The State of Texas responded proactively by providing $4.471 million to The University of Texas at Austin Bureau of Economic Geology (BEG, Bureau) to develop and manage a new earthquake monitoring system in Texas and to conduct research into seismicity across the state. The research activities fall into two main categories. First, the Bureau was directed to design and implement the TexNet Seismic Network to measure earthquake activity and report on the locations and magnitudes of the events; $2.9 million was dedicated to this activity. Second, to understand *why* the earthquakes, both natural and potentially human-induced, are occurring, the Bureau designed a portfolio of research projects; $1.571 was dedicated to this activity.

The research is reviewed by the TexNet Technical Advisory Committee (TAC), which was appointed March 24, 2016. The committee has endorsed the proposed use and allocation of funds. TAC and TexNet research leaders meet regularly to discuss network implementation, research strategies and tactics, and use of funds. Status of the network and descriptions of the research projects are discussed herein.

The funding legislation, contained in House Bill 2 (HB2) of the 84th Legislature, specifies that a progress report be delivered on or before December 1, 2016, and that it discuss (1) how the money has been and is being used, (2) data collected on earthquakes, (3) the ongoing cost of operating TexNet, and (4) preliminary reservoir modeling (and subsurface analysis) results.

1 **TexNet funding allocation.** As discussed in Section 2 of this report, the Bureau used these funds to design TexNet, a monitoring program that, when fully installed in 2017, will add 22 permanent, high-quality seismic monitoring stations to the 18 existing stations in Texas, providing a robust network for monitoring seismicity across the state. In addition, 36 portable stations, each with the added ability to measure ground motion, will be used to monitor ongoing earthquake sequences such as those that have occurred in the Dallas–Ft. Worth area in the last few years. Section 3 of this report discusses the technical specifics of the TexNet budget. The recruiting of highly qualified staff, network design, vendor selection, equipment acquisition, and creation of the real-time TexNet Data Hub are complete. The majority of sensors will be deployed by mid-2017. As of October 31, 2016, just over 50% of the $2.9 million budget for this activity has been spent or accrued. We anticipate full spend-out by the end of August 2017.

Research funding allocation. As discussed in Section 4, $1.571 million was allocated for use by the Bureau—in partnership with other University of Texas units, Texas A&M University, and Southern Methodist University—to design, staff, and initiate a portfolio of research projects to characterize seismicity throughout Texas; to understand its causative mechanisms; and to use TexNet data and our future research products to help regulators, policy makers, planners, resource developers, and others to develop strategies for mitigation. As of October 31, 2016, 60% of these appropriated research funds have been spent or are contractually obligated. With recruiting and staffing now complete, we are on pace to spend the remaining 40% by the end of August 2017.

2 **TexNet Seismic Network and earthquake data.** As discussed in Section 3, the selection of suitable sites for permanent stations is nearly complete. Selection of permanent sites is a time-intensive process involving up

to 15 site options for each permanent site, with multiple field visits, noise testing and landowner discussions. Installation of portable sites has also begun and data are now streaming from the array of TexNet portable stations in the Dallas–Ft. Worth area. We are focused on identifying appropriate sites with cooperative landowners, which has been a lengthier process than initially planned. Parameters needed to accurately locate and characterize earthquakes using TexNet are being tested and fine-tuned. The catalog of seismic events in Texas will become publicly available in early 2017.

3 **Ongoing cost of TexNet and essential research.** As discussed in Section 3, we estimate that operation and maintenance of TexNet for the September 2017 to August 2019 biennium will require an appropriation of $3.4 million from the State of Texas, stemming from the upcoming 85th Legislative Session. This amount breaks down to $700,000/yr for network operations and maintenance, and $1.0 million/yr for research. This general level of biennial expenditure can be anticipated beyond 2019, with occasional potential equipment upgrades and replacements.

4 **Preliminary modeling results.** As discussed in Section 4, and as required by HB2, we have initiated a portfolio of TexNet research and modeling studies. Research conducted on the diverse geologic conditions across Texas will allow us to fine-tune how TexNet data are used, to minimize the location and depth uncertainty of earthquakes and to use the characteristics of earthquakes quantitatively in models. We have been constructing advanced geologic models to determine the architecture, properties, and fluid pressures of the subsurface. By assessing the nature of faults where the earthquakes are occurring, we can narrow down potential causes. We are also constructing and testing advanced reservoir computational models that simulate subsurface processes, and that can provide insights into whether fluid injection is triggering fault rupture and how injection strategies could be tailored to mitigate this behavior. Given that a very small percentage (<1%) of injection wells in Texas are potentially associated with seismicity, we are working to determine why some isolated areas appear to be more sensitive to injection than others. These research goals—which address very complex geologic and fluid systems and behaviors—will take many years to evolve and improve.

Our progress in establishing the TexNet Seismic Network and launching the studies required to understand seismicity in Texas includes these advances:

- We have recruited and engaged top scientists and technicians to develop and lead the program.
- We have designed, acquired, and initiated installation of the 58-station TexNet Seismic Network.
- Data from stations in the Dallas–Fort Worth area are streaming live to the TexNet Data Hub.
- Robust collaboration between numerous units at The University of Texas, Texas A&M University, and Southern Methodist University has been established, and seven integrated research projects have been initiated.
- Earthquake characterizations using historical data of the Fort Worth Basin, Permian Basin, Panhandle region, and East Texas are nearing completion.
- Assembly of data and models for simulation of wells in the vicinity of faults is well underway, and the construction and testing of the preliminary models has commenced.

Through the establishment of the TexNet Seismic Network and a portfolio of multiyear and ambitious research projects, the State of Texas has positioned itself to be a leader in the study of seismicity, which will lead to stronger safeguards for its citizens and its infrastructure.

We anticipate that by 2019, sufficient earthquake data from TexNet will be available to fully support subsurface characterization and modeling. We seek and recommend continued funding of $3.4 million for the 2018–19 legislative cycle.

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1. Introduction

Legislation Establishing TexNet

TexNet was established and funded as part of House Bill 2 (HB2) of the 84th Texas Legislature (2016–17), specifically Section 16, which states:

SECTION 16. THE UNIVERSITY OF TEXAS AT AUSTIN: BUREAU FOR ECONOMIC GEOLOGY.

(a) In addition to amounts previously appropriated for the state fiscal biennium ending August 31, 2015, $4,471,800 is appropriated out of the general revenue fund to The University of Texas at Austin for the two-year period beginning on the effective date of this Act for the purchase and deployment of seismic equipment, maintenance of seismic networks, modeling of reservoir behavior for systems of wells in the vicinity of faults, and establishment of a technical advisory committee.

(b) From the money appropriated in Subsection (a) of this section, the Bureau for Economic Geology shall use an amount as determined by the technical advisory committee to enter into collaborative research relationships with other universities in Texas, including the Texas A&M Engineering Experiment Station, for the purpose of modeling of reservoir behavior described by that subsection and other data analysis.

(c) The technical advisory committee established using money appropriated in Subsection (a) of this section must be composed of nine members appointed by the governor, at least two of whom represent higher education institutions and have seismic or reservoir modeling experience, at least two of whom are experts from the oil and gas industry, and at least one of whom is a Railroad Commission of Texas seismologist. The technical advisory committee shall advise on the use of the money appropriated in Subsection (a) of this section and on preparation of a report to be delivered not later than December 1, 2016, to the governor, the House Energy Resources Committee, and the Senate Natural Resources and Economic Development Committee. The report must:

(1) include an analysis of how money appropriated in Subsection (a) of this section has been used;

(2) provide the monthly data collected by the seismic equipment described in Subsection (a) of this section and transmitted to the Incorporated Research Institutions for Seismology [IRIS] database;

(3) identify the equipment and personnel costs necessary to maintain the TexNet Seismic Monitoring program after 2016; and

(4) describe preliminary reservoir modeling results.

Purpose of TexNet and Related Research

The funding of $4,471,800 provided to the Texas Bureau of Economic Geology and its partner institutions, and the language of the bill, directs that funds be used to develop and install a seismic network throughout Texas; collect, analyze, and catalog the data and make it publicly available; and conduct research leading to an understanding of the nature of the seismicity (e.g., earthquakes) and its cause(s).

The existing network of 18 operating seismic monitoring stations, irregularly distributed across Texas, is insufficient to detect, locate, and properly characterize seismicity in our state at a level of accuracy necessary to understand either what caused the event or if any actions can be taken to reduce the recurrence of such events. TexNet, the new seismicity monitoring system funded by HB2, is a network of stand-alone broadband seismometers that are being installed in suitable locations throughout Texas in two configurations, permanent and portable. TexNet is installing 22 permanent and 3 auxiliary stations that, when integrated with the existing 18 stations, will compose the back-bone seismic network of 43 stations, enabling us to monitor and catalog seismicity across Texas, at magnitudes to M2.0 in some cases. In addition to this backbone network, 36 portable seismic monitoring stations also have been acquired. Deployment of these portable stations will allow for detailed site-specific assessments of areas of active seismicity. These stations were designed to use broadband seismometers and accelerometers, which allow for the detailed characterization of ground motion when earthquakes are relatively close. Ten of these portable stations are now deployed in the Dallas–Fort Worth metropolitan area and are on-line. Data from the TexNet seismic stations will stream in real time to the TexNet Data Hub, installed at the Bureau, for analysis and subsequent distribution to IRIS and the U.S. National Earthquake Information Center (NEIC), operated by the United States Geological Survey (USGS). Earthquake data and analyses will be available to the public through IRIS and the TexNet Data Hub.

The research being conducted using TexNet funds, as specified in the legislative language, is focused on under-standing the potential relationship between the subsurface injection of fluids and earthquakes in the vicinity of faults. These narrow yet highly complex research goals cannot be accomplished without also performing more fundamental research tasks. Therefore, the TexNet research portfolio consists of a tightly integrated group of proj-ects, including seismicity analysis, geologic characterization, fluid-flow modeling, and geomechanical analysis. Our TexNet research collaboration spans three units at The University of Texas at Austin (Bureau of Economic Geology [BEG], Institute for Geophysics [UTIG], Department of Petroleum and Geosystems Engineering [UT-PGE]), and also includes the Department of Petroleum Engineering at Texas A&M University (TAMU-PE) and the North Texas Earth-quake Studies Group at Southern Methodist University (SMU).

Development of the TexNet Seismic Network and the scope and strategy of the research portfolio are guided by the TexNet Technical Advisory Committee (TAC), a group of outstanding leaders on this topic from academia, private industry, and government who have been appointed by the governor of Texas.

Seismicity in Texas

Instrumental seismology for earthquakes in Texas began in 1970, when the first seismic station was deployed in the state. **Figure 1.1** shows earthquakes recorded in Texas from 1975 to August 2016, as reported in the USGS Advanced National Seismic System (USGS/ANSS) catalog. Based on this catalog, and on studies conducted by the TexNet research team as described in Section 4 of this report, seismicity in Texas is divided into eight regions of differing scientific and socioeconomic implications, which will be monitored by TexNet and studied following the research plan described in Section 4.

In an earthquake catalog, the magnitude of completeness (Mc) is the minimum magnitude above which all earth-quakes within a certain region are reliably recorded. The TexNet research team's current analysis of Mc is described in the subsection on Instrumental Seismicity in Section 4 of this report. Since the existing Texas earthquake catalog has

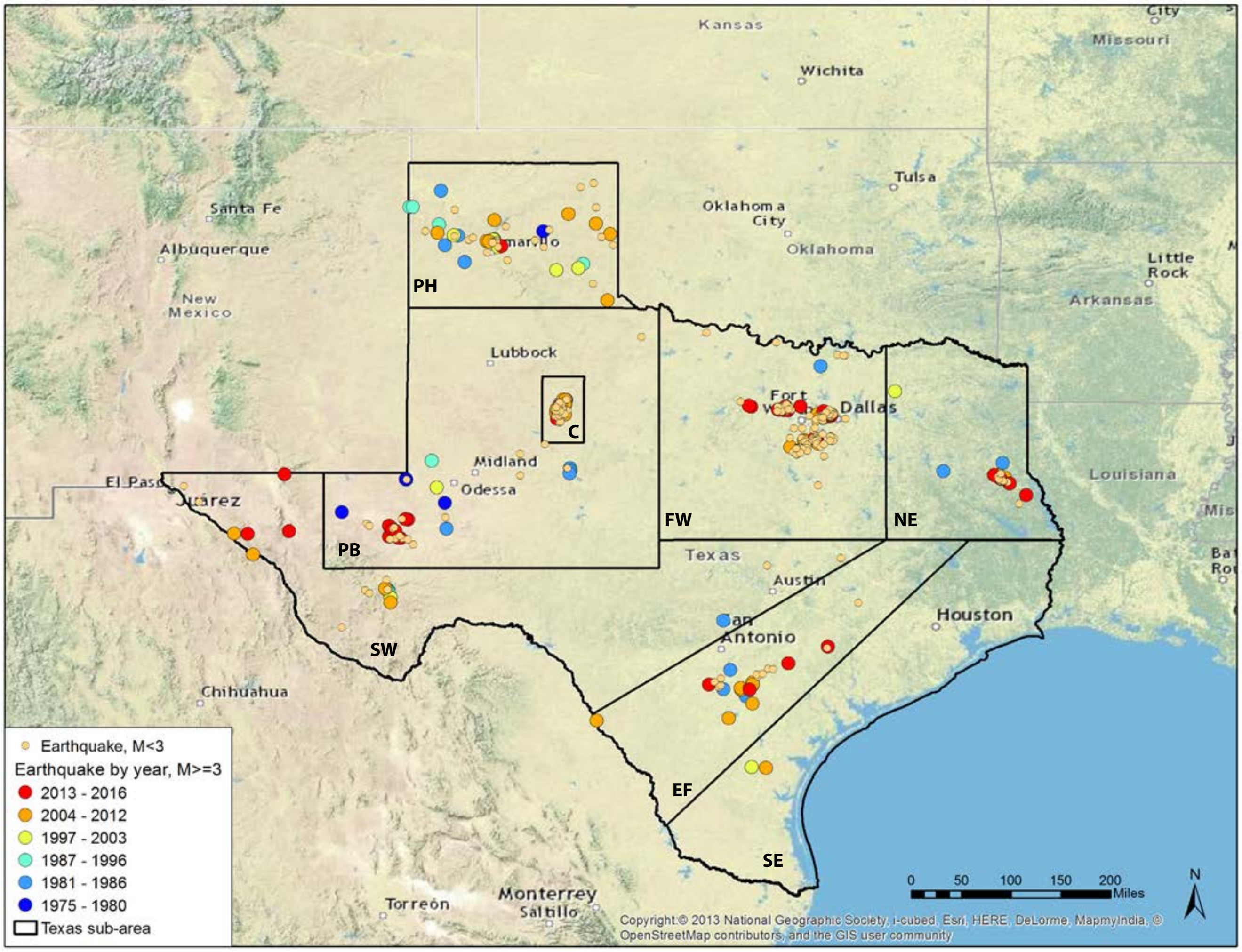


Figure 1.1 Instrumental seismicity map of Texas as reported from the USGS/ANSS. Different seismicity regions are denoted with polygons: Panhandle (PH), Permian Basin (PB), Cogdell Field (C), South West (SW), Eagle Ford (EF), South East (SE), North East (NE), and Fort Worth Basin (FW).

a mix of magnitude types, the TexNet research team will in 2017 develop an adjusted moment-magnitude catalog (Petersen and others, 2014) so that the historic magnitude of completeness for Texas can be quantitatively assessed.

The frequency and cumulative occurrence of earthquakes in Texas with M≥3 is shown in **figure 1.2**. It is clear that there has been an increase in the rate of recorded seismicity beginning in about 2008. Prior to that time, there were, on average, one to two earthquakes per year of M≥3. Since 2008, that rate has increased to around 15 per year on average. This plot should be considered preliminary until the TexNet research team has finished implementing appropriate declustering methods for this earthquake data. It should also be noted that in that same time period, the number of seismometers in Texas increased from 1 to 18. However, we do not think that this increase has impacted the frequency count because the magnitude of completeness, as discussed in Section 4, has been calculated at M2.7 for the catalog, and the plot in **figure 1.2** is for M≥3. **Figure 1.3** shows the seismicity from January 2015 through October 2016 in Texas and Oklahoma, with data taken from the USGS/ANSS catalog. TexNet will begin providing earthquake data for Texas in early 2017.

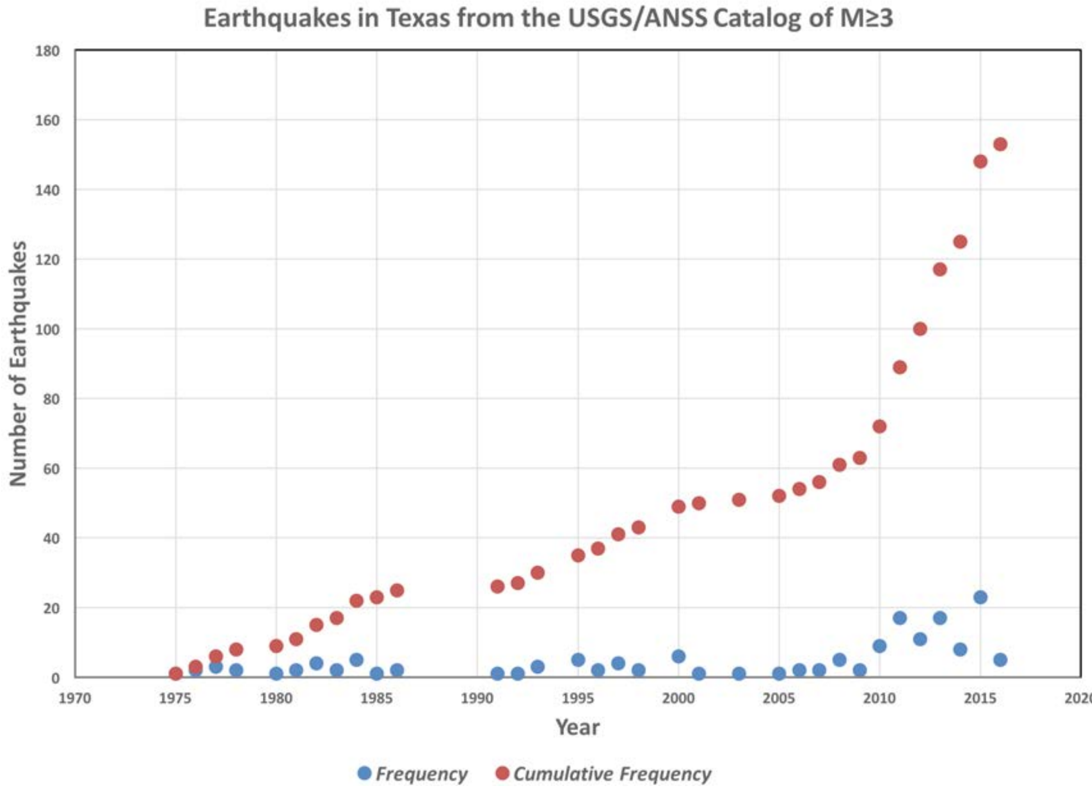


Figure 1.2 Frequency and cumulative frequency plots with time for M≥3, from the earthquake catalog presented in figure 1.1.

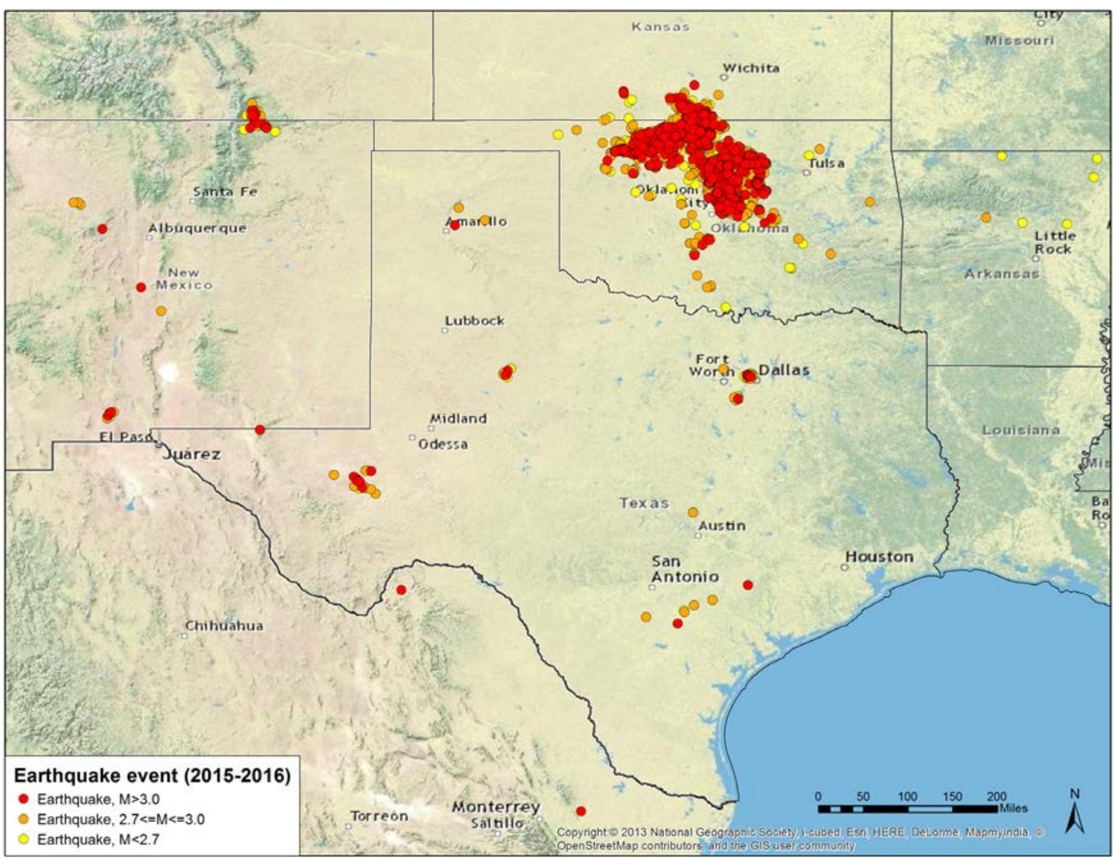


Figure 1.3 Seismicity of Texas and neighboring states as reported from the USGS/ANSS, for events from January 2015 through October 2016.

2. TexNet Budget and Ongoing Cost

TexNet Budget and Spending FY 2016–17

Budget and Spending for TexNet Acquisition, Installation, and Operation

The TexNet Seismic Network was proposed during the 84th Texas legislative session and signed by Governor Abbott on June 22, 2015. The amount funded by the State of Texas is $4,471,800. As specified in HB2, Section 16, the Bureau was directed to purchase and deploy seismic equipment, maintain a seismic network, model reservoir behavior for systems of wells in the vicinity of faults, and establish a technical advisory committee. This section will describe allocation of funds to achieve the tasks specified by HB2.

Regarding the purchase, deployment, and operations of seismic equipment: After HB2 was signed into law, the Bureau and its collaborators developed hardware specifications for the seismic monitoring network. The specifications are vital to ensure that the hardware is capable of detecting a wide range of earthquakes across the State of Texas and that the data are deemed acceptable by the international community (e.g., Incorporated Research Institutions for Seismology, or IRIS—specifically mentioned in HB2), which warehouses and uses seismicity data worldwide.

Following State of Texas purchasing guidelines, the Request for Proposals for TexNet hardware was issued on October 10, 2015, and proposals were evaluated in an open and transparent process by UT-Austin personnel, including those from the UT-Austin Purchasing Office. The proposal for TexNet hardware submitted by Nanometrics (Ontario, Canada) was officially approved on March 31, 2016.

Table 2.1 shows a breakdown of costs for grouped elements of the final and approved proposal. Note that costs include installation of permanent seismometers that require the drilling and completion of boreholes, into which the seismometers are lowered and secured. Borehole installation, which improves the signal/noise ratio, is a vital way of detecting low-magnitude events occurring across Texas that are necessary to detect and analyze.

Table 2.1 Costs for TexNet, 2016–17 biennium: Equipment, and Deployment and Operations

TexNet Seismic Network	Equipment		Deployment and Operations						Subtotals by Cost
	Seismic Stations and Installation	TexNet HUB Hardware	Software	Borehole Subcontract	Materials & Services	Personnel	Computer Usage	Travel	
Nanometrics (1 time cost)	$1,636,500		$23,420	$317,900	$18,700				$1,996,520
TexNet (1 time cost)		$65,000							$65,000
TexNet Year 1 Cost					$61,500	$210,875	$8,700	$41,100	$322,175
TexNet Year 2 Cost					$128,100	$312,867	$13,200	$45,000	$499,167
Sub Totals by Category	**$1,636,500**	**$65,000**	**$23,420**	**$317,900**	**$208,300**	**$523,742**	**$21,900**	**$86,100**	
Totals		**$1,701,500**						**$1,181,362**	**$2,882,862**

Equipment (light tan cells in **table 2.1**) includes field hardware for the monitoring program (seismometers, solar panels, batteries, data loggers, and so on) and the computer hardware needed to collect, analyze, store, and transmit seismometer data. Costs shown in the first row are those included in the contract approved for Nanometrics ($1,996,520). The field equipment, in the process of being deployed, includes 22 permanent and 36 portable seismometer stations. Costs for Deployment and Operations (light green cells) are subdivided into (1) one-time costs for software needed to operate the field-data loggers and analyze seismic responses, and (2) subcontracts (initiated by Nanometrics) and Materials and Services needed by Nanometrics to perform field-related operations. Costs for the first 2 years of TexNet operations are shown in rows 3 and 4. These costs include personnel to assist in deployment and to lead operations and maintenance (O&M) of the nearly 60 seismometer stations around the state. Year 1 costs are approximately 50% of Year 2 costs because deployment did not fully begin until late in the 2015–16 fiscal year.

Budget and Spending for TexNet Research

Included with costs for acquisition and deployment of the monitoring network are those associated with data analysis and research needed to analyze seismic signals and place them into a geologic and reservoir context allowing researchers and others to determine causal mechanisms for earthquakes, including natural causes and, potentially, wastewater injection. After HB2 was signed, BEG and collaborators at UTIG, UT-PGE, SMU, and TAMU-PE initiated research across three themes and seven projects. **Table 2.2** breaks down these analytical themes, including project titles, lead institution, and itemized (budgeted) costs, represented through the 2016–17 biennium. Note that specific explanations of each project are included in Section 4 of this report. Each project includes costs for personnel (researchers, faculty, students, and their tuition [when applicable]), computer costs, travel, and so on. All projects have been discussed, vetted, and approved by the Technical Advisory Committee.

Table 2.2 Costs for TexNet, 2016–17 biennium: Equipment, and Deployment and Operations (green), Research (red, blue, and yellow)

Theme	Project Title	Institution/ Unit	Personnel	Materials and Services	Computer Charges	Tuition	Equipment	Travel	Total	Percentage of Total Budget
Seismic Network	TexNet Deployment and Operations	UT-BEG	$ 523,742	$ 549,620	$ 21,900	$ -	$1,701,500	$ 86,100	$ 2,882,862	64%
				Research Projects						
Seismology	Texas Seismicity Studies	UT-IG	$ 159,494	$ 4,200	$ 4,800	$ 11,112	$ -	$ 8,472	$ 188,078	
Seismology	Ft Worth Basin Earthquake Characterization	SMU	$ 180,909	$ 2,100	$ -	$ 6,912	$ 1,000	$ 9,622	$ 200,543	
Faults and Geomodels	Ft Worth Basin Fault Characterization and Reservoir Model Inputs	UT-BEG	$ 166,735	$ 2,500	$ 4,800	$ -	$ -	$ 4,000	$ 178,035	
Hydrology	Hydrology: Fluid Budget Protocols, Data and Analysis	UT-BEG	$ 162,486	$ 3,100	$ 22,920	$ -	$ -	$ 2,400	$ 190,906	32%
Geomechanics	Geomechanics of Fault Reactivation	UT-BEG	$ 165,931	$ 1,400	$ 16,920	$ -	$ -	$ 8,000	$ 192,251	
Reservoir Modeling and Geomechanics	Pore Pressure Estimation and Fault Rupture Modeling	UT-PGE	$ 134,130	$ 400	$ -	$ 48,000	$ -	$ 8,000	$ 190,530	
Reservoir Modeling and Geomechanics	Coupled Fluid Flow and Geomechanical Modeling	TAMU-TEES	$ 259,033	$ 6,000	$ 3,000	$ 22,967	$ -	$ 9,000	$ 300,000	
								Total	$ 4,323,205	
								HB2 Budget	$ 4,471,800	
								Contingency	$ 148,595	3%

Request for FY 2018–19 Funding

Cost of Network Operations and Management

This section presents costs for ongoing operation and maintenance of the network, as well as analysis of subsurface characterization and modeling data collected from the network, which is needed to explain the cause of seismic events. The research activities described here are intended to support the State's proactive investment in creating TexNet and to continue addressing the original mandate of HB2 from the 84th legislative session, which directed the Bureau to model reservoir behavior for systems of wells in the vicinity of faults.

Table 2.3 provides costs for the 2018–19 biennium, subdivided by Equipment, Operations and Maintenance, and Research. Costs requested for Operations and Maintenance are calculated for the biennium for the four categories shown in green, which are similar to the categories presented for the 2016–17 biennium. In brief, O&M costs include data collection and transfer to IRIS; analysis of seismic responses that help geologists and seismologists assess location and magnitude of events; and field visits to maintain each station, ensuring that the data quality is the highest possible and worthy of the confidence that stakeholders and colleagues have placed in TexNet.

Table 2.3 Costs for TexNet, 2018–19 biennium: Operations and Maintenance, and Research

TexNet Seismic Network 2018-19	Operations and Maintenance					Research	Yearly Total
	Materials & Services	Personnel	Computer Usage	Travel	Total		
TexNet FY18 Cost	$160,400	$475,850	$18,750	$45,000	$700,000	$1,000,000	$1,700,000
TexNet FY19 Cost	$160,400	$475,850	$18,750	$45,000	$700,000	$1,000,000	$1,700,000
Subtotals by Category	**$320,800**	**$951,700**	**$37,500**	**$90,000**	**$1,400,000**	**$2,000,000**	
						Biennium Total	**$3,400,000**

Cost of Research

The funding required to maintain the research program initiated in the 2016–17 biennium is projected to be $1.0 million per year. As described throughout this report, the advanced analyses and research conducted during the current biennium spans geologic and engineering topics from seismogenic potential of geologic basins in Texas, to geomechanical properties of faults and how they reactivate, to pore-pressure conditions needed to rupture existing faults, including reservoir-modeling approaches needed to portray the complex subsurface conditions that lead to earthquakes. These research themes, along with additional research related to understanding the potential impact of seismic events on the people and infrastructure of Texas, are expected to continue into the 2018–19 biennium and beyond. The specific projects to be undertaken with future funds will depend on many factors that are difficult to know a priori; but the research team led by BEG and implemented by scientists and engineers across multiple departments at UT-Austin and at Texas A&M and SMU are closely collaborating to accelerate the pace of our research and constantly improve ways to best manage our talents and resources.

3. TexNet Seismic Monitoring Network

Design Criteria

A seismic network is designed with specific criteria based on its intended purpose. The goals of the TexNet Seismic Network (TexNet) are twofold: (1) to monitor, locate, and catalog seismicity across Texas; and (2) to facilitate the investigation of ongoing earthquake sequences by deploying portable seismic monitoring stations. These site-specific assessments are most critical for events in or near urban areas and for events co-located where earthquakes may be related to human activities.

Based on these goals, TexNet includes both permanent and portable stations that are deployed as described below. The following are considered in selecting the locations of the new permanent stations: the locations of the 18 existing permanent TexNet Seismic Network stations in Texas, the locations of seismic stations in neighboring states, and the historical seismicity in Texas (as reported by the USGS/ANSS). The proposed locations for the permanent TexNet stations are presented in **figure 3.1**. Once deployment is complete in 2017, Texas will have 22 new permanent stations and 3 auxiliary semi-permanent stations. The purpose of the auxiliary stations, which will utilize portable-station hardware but have a more long-term plan of deployment, is to fill in the gaps of the permanent array. Together, the existing and new stations are located over an approximately evenly spaced grid that will provide optimal assessment of the seismicity across the entire state of Texas. The stations shown in **figure 3.1** represent the TexNet "backbone" network. The site-specific assessment for each of the 22 new permanent-station locations has occurred within a buffer zone with a radius of 25 miles. Numerous sites were evaluated within these buffer zones to determine the optimum location for station installation.

Considerations for portable-station deployment included recent seismicity (from 2013 on), as well as the scientific and socioeconomic implications (**fig. 1.1**) of the region. A plan of deploying 33 portable stations through the end of 2017 is underway at the following locations:

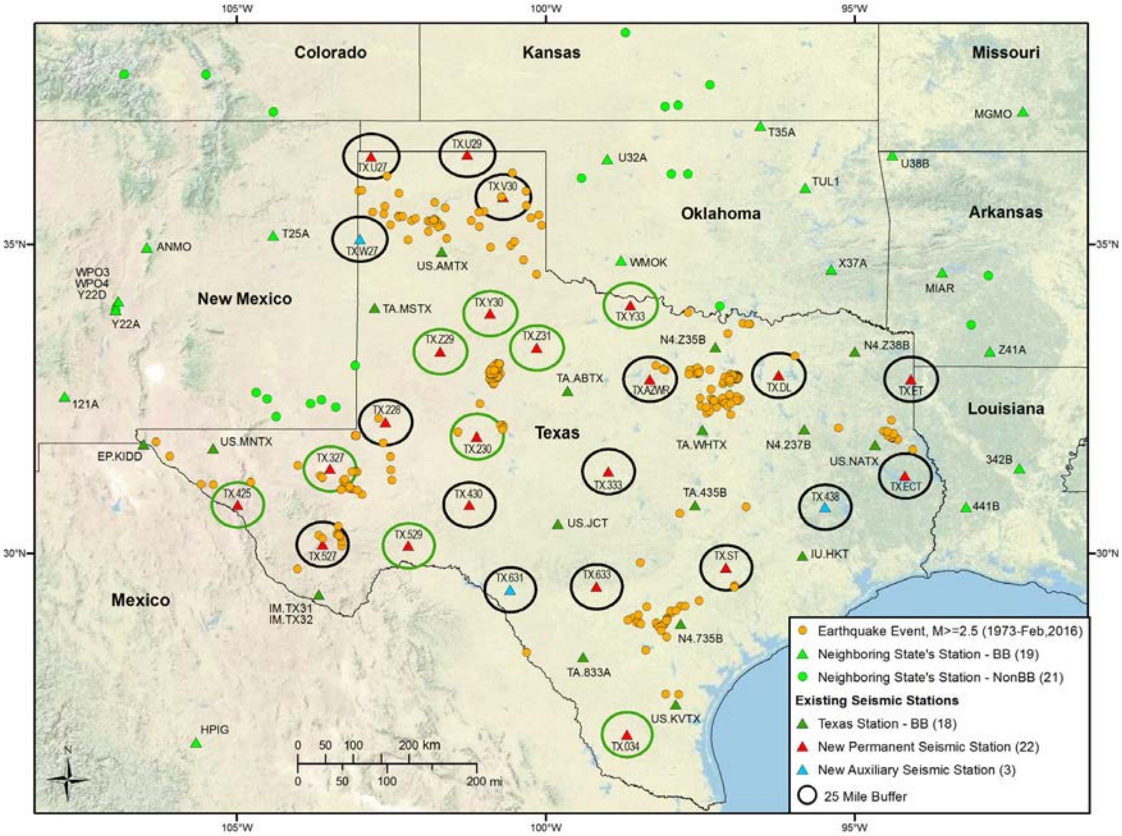
- 12 stations in the Fort Worth Basin
- 9 stations in the vicinity of Cogdell Field
- 6 stations in the Permian Basin
- 3 stations Eagle Ford operating area
- 3 to be used as auxiliary stations augmenting the network of permanent stations
- 3 stored at the BEG in Austin for rapid deployment

For 2018, we plan to demobilize the stations from Cogdell and maintain or increase portable deployments as follows:

- 12 stations in the Fort Worth Basin
- 9 stations in the Permian Basin
- 6 stations in the Eagle Ford operating area
- 3 stations in northeast Texas
- 3 to be used as auxiliary stations augmenting the network of permanent stations
- 3 stored at the BEG in Austin for rapid deployment

Three portable stations will be available for any immediate deployment complementary to existing TexNet deployments. The portable-station deployment plan will be reevaluated after mid-2017.

(a)



(b)

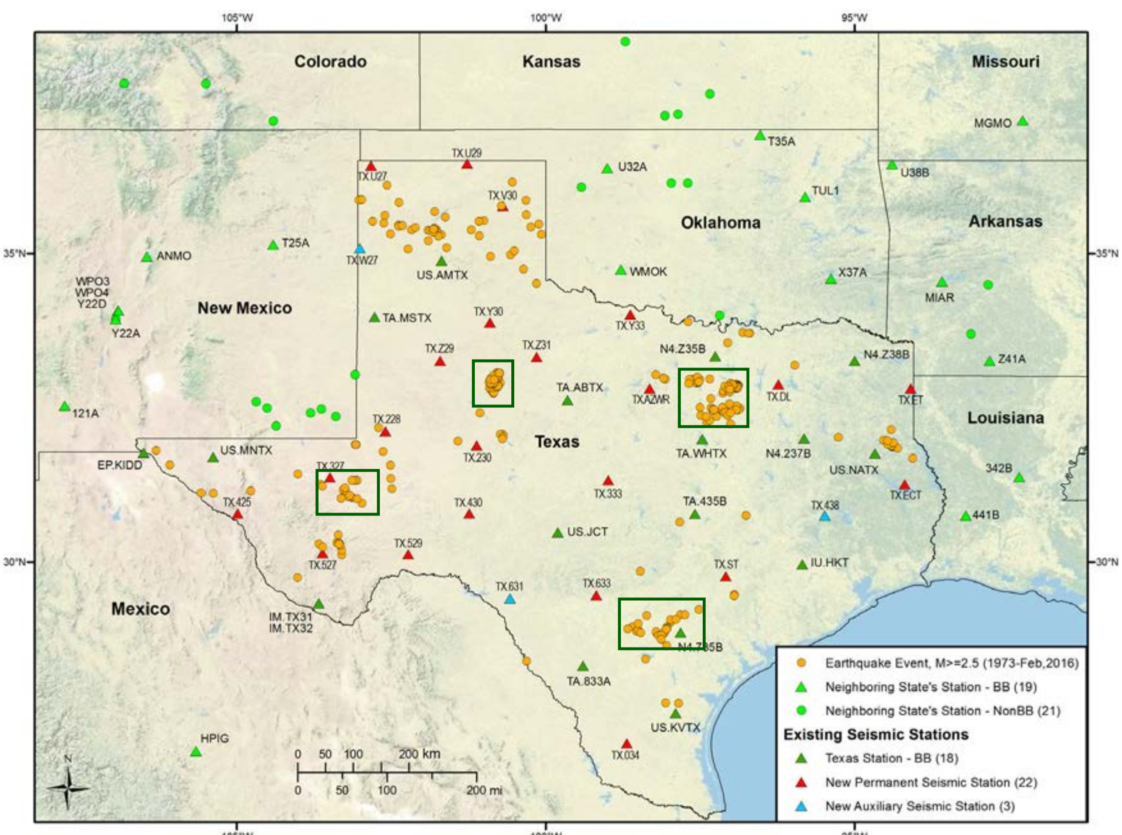


Figure 3.1 (a) Existing and new stations in Texas that will form the TexNet "backbone" seismic network. Green circles indicate stations with executed license agreements (as of December 1, 2016). **(b)** Green boxes indicate areas with planned portable-station deployments for 2016–17.

Equipment Specifications

Specifications of the equipment conform to the practices of international seismic observatories for both permanent and portable stations, which include the following:

Permanent Stations

Sensor performance

- Three-component seismometer with nominally flat velocity response across 100 (or 120) seconds (100 Hz)
- Median local nighttime noise at least 20 dB below USGS high-noise model for all frequency bands (Peterson, 1993)

Telemetry

- Coordination with BEG staff to identify cell-modem telemetry hardware compatible with the central TexNet Data Hub to transmit sensor data to the TexNet computer network; University maintenance of telecommunication contracts
- SeedLink server capable of delivering mini-seed files to central TexNet Data Hub
- Six-channel data logger capable of transmitting data over Ethernet to telemetry

Installation

- Installation of sensors in a 20-ft-deep steel-cased borehole. Although boreholes are expected to be dry, sensor hardware should be waterproof.

Power

- Autonomous operation through solar power ensured if main power is unavailable

Warranty

- Minimum 5-year warranty. For any permanently installed monitoring station whose median nighttime noise routinely exceeds limit of 20 dB below USGS high-noise model for all frequency bands, contractor must correct problem by applying the following remedies: (a) re-engineering existing borehole; (b) re-installing station in a new borehole; or (c) moving installation to an alternate site located within 15 km of the initial site.

Portable Stations

Sensor performance

- Short-period response with 1 Hz or 2 Hz natural-frequency three-component seismometer, three-component accelerometer, and six-component data logger

Telemetry

- SeedLink server capable of delivering mini-seed files to central TexNet Data Hub
- Data logger capable of transmitting data over Ethernet to telemetry provided by TexNet

Installation

- Water-tight enclosure consisting of a stormproof, plastic case either pole mounted or with mountable solar panel on top; enclosures to remain functional during deployments lasting at least 2 years or longer

Power

- Autonomous operation through solar power ensured for a minimum of 2 years

Warranty

- Contractor to provide a minimum 5-year warranty to cover operation of sensor, data logger, power system, and communications hardware

Vendor Selection Process and Performance

To ensure an objective assessment of vendor proposals, four criteria were identified to rate each proposal quantitatively: (1) Cost, (2) Vendor Experience, (3) Seismic Array Design, and (4) Vendor Project Approach. A score of 1 to 5 was awarded depending on how the vendor proposal addressed the targeted specifications and responded to the above criteria. A procurement committee evaluating the supplier proposals was established prior to the proposals being submitted, and no external stakeholders were allowed to participate in the review. In addition, supplier bids and allocated costs were evaluated exclusively by a dedicated UT-Austin purchasing department such that the research team would remain unbiased and focused on the technical evaluation of the proposals. The percentage weights used in assessing the vendors were specified as the following:

(1) Cost (30%)

(2) Vendor Experience (20%)

(3) Seismic Array Design (20%)

(4) Vendor Project Approach (30%)

The schedule of vendor selection and acquisition was as follows:

(1) Begin generating specifications for the network: 7/1/15

(2) Request for proposals (RFP) available to public: 10/28/15

(3) Bid submittals due: 11/10/15

(4) Evaluation completed by procurement committee: 11/23/15

(5) Contractor selected: 12/13/15

(6) Nanometrics awarded contract and final approvals obtained: 3/31/16

Nanometrics, one of five vendors bidding for the equipment, was awarded the contract for the hardware acquisition and installation of the 22 permanent TexNet "backbone" seismic stations and the 36 portable seismic stations. For over 30 years, Nanometrics has provided mission-critical seismic monitoring networks to governments and academic communities around the globe.

Field teams from Nanometrics and the BEG performed 24-hr noise tests at the 22 permanent sites during August and September 2016.

All equipment required for station installation was received from Nanometrics on or before October 11, 2016.

Nanometrics and their subcontractors will begin installation of TexNet permanent stations in December 2016.

Site Selection Criteria

TexNet Seismic Network stations have to meet specific site selection criteria. Both permanent and portable station sites share some common criteria, including that (a) stations will be deployed at sites with low ambient noise, and (b) where possible, the selected sites will be in bedrock or otherwise stiff substrate. Because of the different time-spans of station deployment (6+ months for portable and 10+ years for permanent) and different spacing (close spacing for portable and regional spacing for permanent), site selection criteria and installation methods for the two types of deployment differ.

Permanent Sites

Permanent seismic station installations include placing seismometers in 20-ft-deep cased and cemented boreholes (**fig. 3.2**). Once potential sites were identified for permanent installations, the corresponding landowners were contacted to request access to the locations identified and begin the initial site assessment. The agreement between TexNet (The University of Texas) and willing landowners utilizes a 10-year license agreement for the sites ultimately selected for installation.

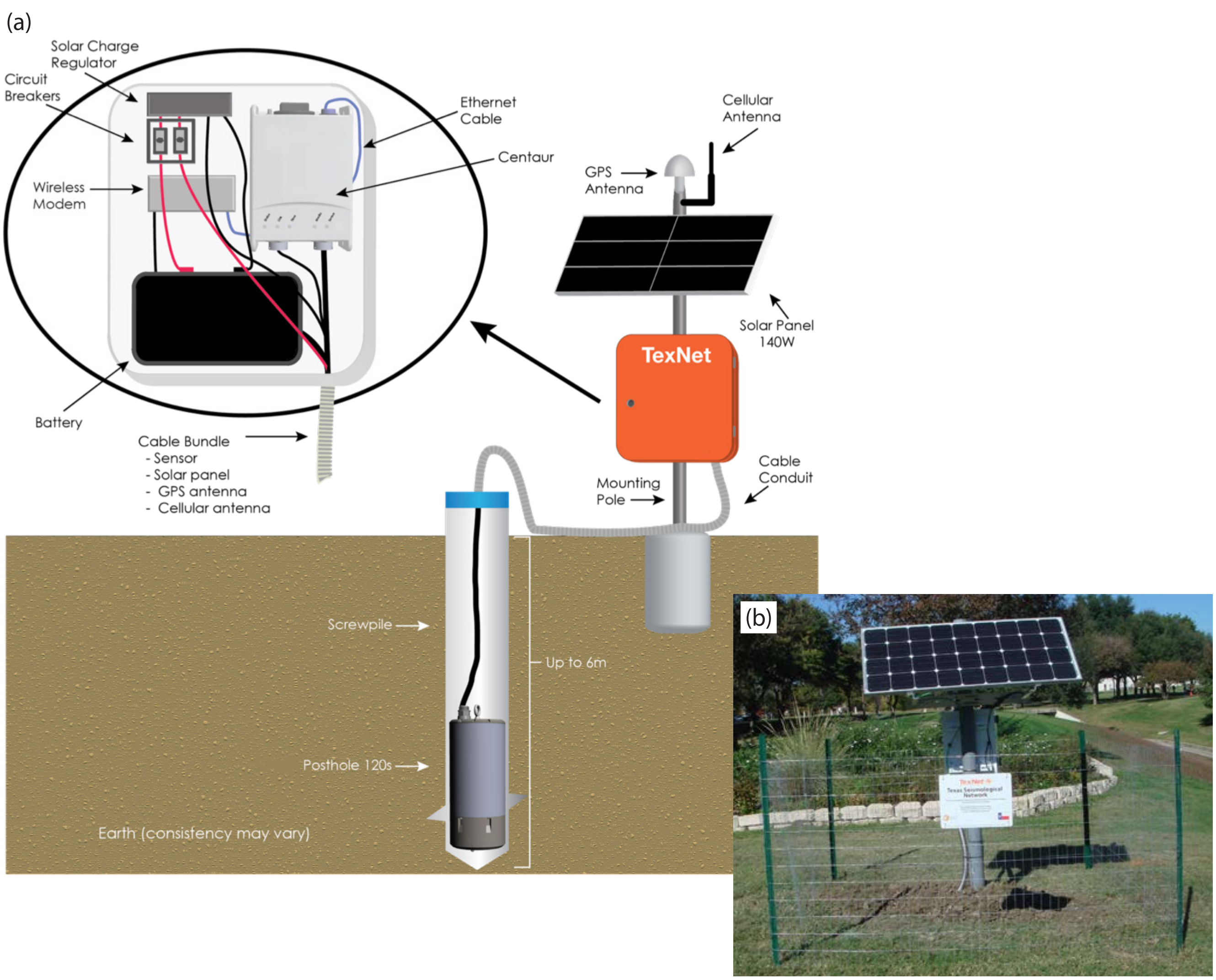


Figure 3.2 (a) Schematic representation of the components and installation of TexNet permanent seismic stations. **(b)** Photograph of a TexNet portable-station deployment at the University of Texas at Dallas.

For each station indicated in **figure 3.1**, numerous alternative sites were identified and screened within a 25-mile search zone, as denoted by the black circles. To facilitate site selection, the performance of transportable array (TA) sites from EarthScope's USArray program, which swept across Texas in 2008–11, was used to assess ambient noise and earthquake-monitoring effectiveness. TA sites that were potentially suitable to be reoccupied for TexNet permanent sites were assessed by considering the performance of the site as indicated by analysis of TA data, the geologic description of the site, the cellular data coverage and strength, and the calculated shear wave velocity (Zalachoris and others, 2016).

Especially useful from the TA data are the power density function (PDF) plots provided by IRIS for each station. In addition, the published geologic and topographic information of the area inside the 25-mile buffer zone was used to identify and investigate sites with the firmest bedrock, as it is expected that stiff material will reduce noise and allow for better detection of earthquakes. Additional considerations for site suitability include verifying mobile data network coverage for fast data upload and remote equipment communication, and verifying drilling-rig accessibility to the site for station installation and routine maintenance.

Each potential permanent station site was screened for excessive ambient noise using a 24-hr test performed by Nanometrics. One criterion of the test was that the site's median nighttime noise must not exceed the level of 20 dB below the USGS high-noise model for all frequency bands. For example, noise-test results for potential site ET6 (of permanent station ET) show that the median nighttime noise is higher than the specified limit (**fig. 3.3**); therefore, the site was rejected from deployment consideration. **Figure 3.4** shows the stations that passed the noise test and the four that failed it.

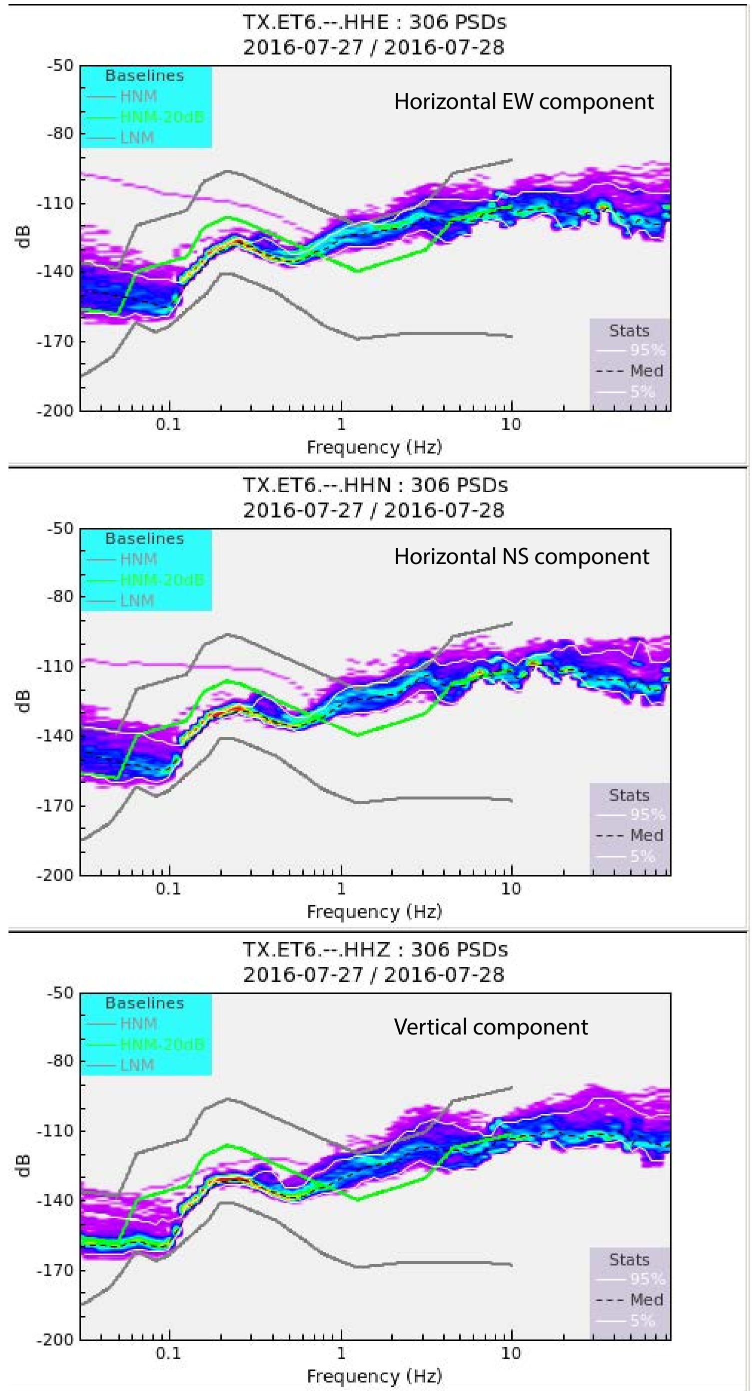


Figure 3.3 Ground-motion noise level at site ET6, which failed the 24-hr test. Noise-level limit is denoted with a green line. PDF plot color scale is ordered from low to high probabilities as a gradient from white (0%) to magenta (>0%), blue (6%), turquoise (12%), green (18%), yellow (24%), and red (30% +). Minimum (red), maximum (blue), and mode (black) curves are also presented. New high and low noise models (Peterson, 1993) are denoted with dark gray curves. The upper panel is the east axis, middle panel is the north, and lower panel is vertical.

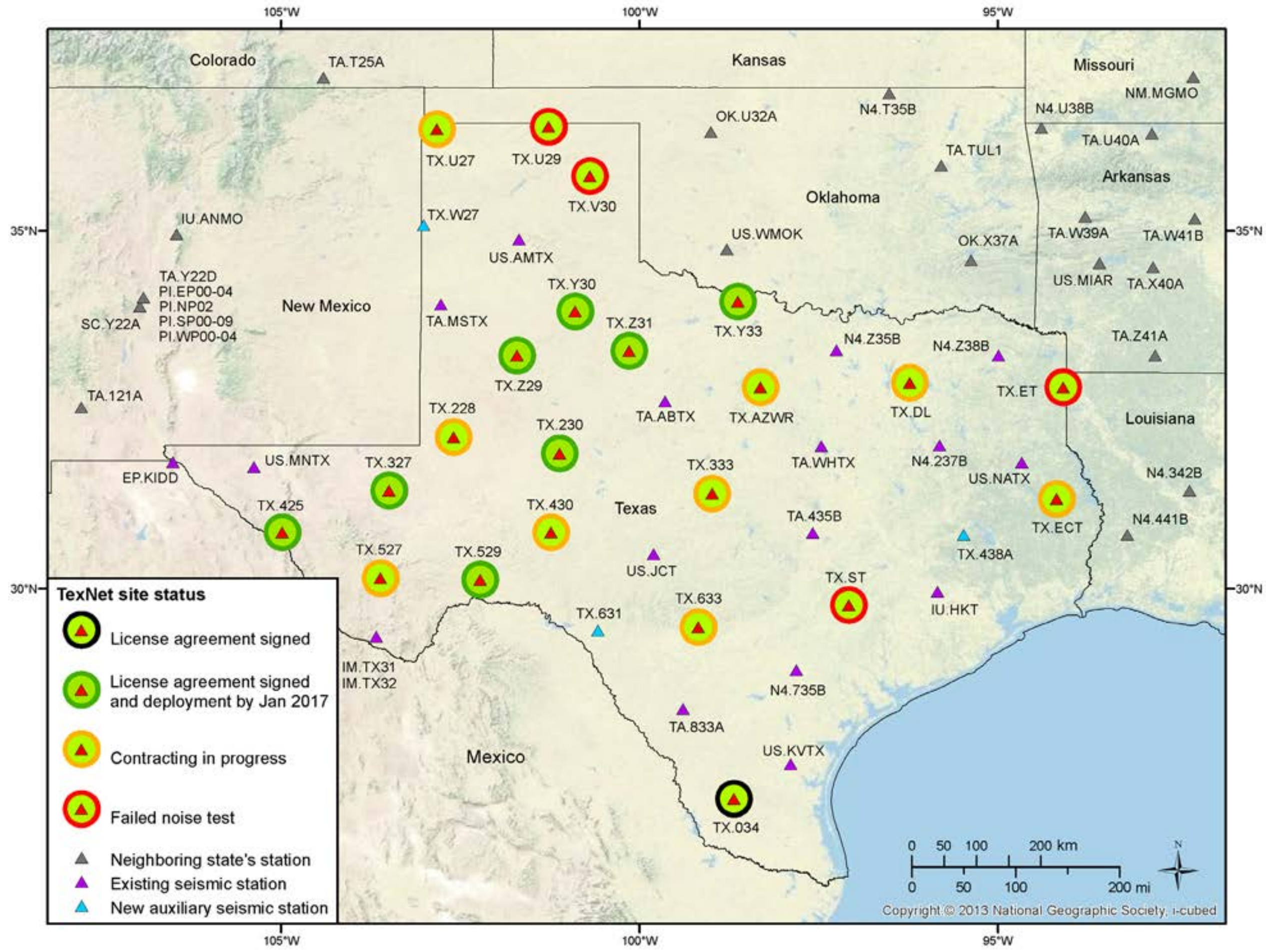


Figure 3.4 Map showing permanent seismic station status (as of December 1, 2016). The existing broadband seismic stations in Texas (18) and neighboring states are also presented.

To proceed with the installation of the equipment, a 10-year license agreement with the landowners must be signed for each permanent-station installation. The rate of identification of landowners and their responsiveness has proved to be a key control on the pace of permanent-station site assessment.

Portable Sites

Portable sites are selected based on two principal criteria: (a) the ability to provide low uncertainty of hypocentral information for seismically active areas, and (b) the capability of fast deployment to new areas of seismic activity, including physical accessibility of the site. Since a portable network covers a relatively small area compared to that of a permanent network, there is limited flexibility to reposition sites away from sources of surface noise. The identification and availability of willing landowners is a key aspect of portable-site selection.

Site Evaluation

Permanent Stations

For the initial selection of permanent sites, information from the transportable array (TA) site location was assessed, as were PDF plots provided by IRIS for each station. Taking into consideration the PDF, the geologic description of the site, the cell coverage map, and the Vs(z) calculated (Zalachoris and others, 2016), we decided which of the TA sites would be included in the assessment for each station. Different sites were identified based on geology, topography, distance from human-activity areas, and accessibility. Areas of higher altitude and stiffer formations where preferred over sites located in basins and recent sediments. Main traffic highways were avoided. To ensure the high detectability of seismic activity at permanent stations, a 24-hr noise test was performed at each site.

Our first step was to identify the landowners of each indicated site, which was implemented in collaboration with the appraisal office of each county through their web services or by personal communication. After identifying the landowners' contact information, the director of the Bureau of the BEG sent a letter to each landowner. By web data mining, we also tracked phone numbers to efficiently contact landowners, including follow-up calls to provide a description of TexNet to give landowners an understanding of our activities and a photo of the expected final site deployment covering a was provided. After a successful evaluation of all necessary information described above and agreement from the landowner, we proceeded with the license agreement and contract. A license agreement prepared by The University of Texas at Austin.

Field locations selected and visited in the process of identifying the best possible sites to install permanent stations are shown in **table 3.1**. In areas where nearby human activity might produce excessive noise, numerous sites and landowners were identified for consideration to provide more options for final site selection. In several cases, it was not possible to contact landowners, or landowners declined having a seismic station on their property; therefore, up to 13 potential sites were identified in the search for each final site location at each station. Once a suitable site

Table 3.1 TexNet permanent-seismic-station selection, testing, land contracting, and installation progress

Station Name	Sites Considered	Site Landowner Contacted	Sites Visited by BEG	Sites Approved by BEG	Sites Visited for the 24h Survey	Station Approved	License Agrement Signed	Borehole Drilling	Station Installation
TX.ET	8	8	7	7	7	Siting new positions			
TX.ECT	7	3	2	2	2				
TX.DL	13	6	4	2	2				
TX.ST	6	6	2	2	2	Siting new positions			
TX.Y33	6	6	2	4	4				
TX.AZWR	1	1	1	1	1				
TX.333	3	3	2	2	2				
TX.633	5	4	2	2	2				
TX.034	5	2	1	1	1				
TX.Z31	3	2	2	2	2				
TX.V30	6	6	3	3	3	Siting new positions			
TX.Y30	7	7	6	3	3				
TX.U29	5	4	1	1	1	Siting new positions			
TX.230	11	5	2	2	2				
TX.430	4	4	3	3	3				
TX.Z29	10	10	4	4	4				
TX.U27	2	2	2	2	2				
TX.228	2	2	2	2	2				
TX.529	5	5	3	2	2				
TX.327	5	4	2	1	1				
TX.527	10	8	1	1	1				
TX.425	1	1	1	1	1				
	125	99	55	50	50				

Progress Status
Completed
In Progress
No Go

was identified and tentative landowner permission was obtained, the site was evaluated with a 24-hr noise survey conducted by BEG and Nanometrics. Of the 50 sites suitable for permanent-station installation, 18 passed the 24-hr noise test. Of these 18 sites, 9 have fully executed land-use contracts in place; the remaining 9 are moving through the contracting process. The 4 stations having sites that failed the 24-hr noise test (TX.ET, TX.ST, TX.V30, TX.U29) will be moved to the nearest possible alternative locations for evaluation and subsequent contracting.

Portable Stations

We evaluate sites for portable stations in a way similar to our evaluations for permanent stations, although there are some differences. For instance, because the distance between proposed portable sites could be of a few miles, it is not possible to move the possible deployment position away from the initial site. Also, a 24-hr noise test was not included in portable site evaluations because these station deployments are considered temporary and can be changed. For portable stations, noise is estimated by visual inspection of the area; in the case of a high noise level after station deployment, we will demobilize the station and deploy at a new site.

Deployment Status and Challenges

It has taken longer than anticipated to identify and contact landowners, to schedule discussions regarding TexNet's requirements, and to receive answers from landowners about their willingness to host a seismic station on their land. These issues have caused an installation delay of approximately 3 months.

Permanent Stations

Installation of TexNet permanent stations will occur in batches to minimize the cost of mobilization. Although 100% of the equipment required for station installation was received from Nanometrics by October 11, 2016, an insufficient number of executed land contracts were in place to warrant mobilization at that time. With sufficient land

Table 3.2 TexNet permanent-station installation process and status

Legend
Sites Selected
Site Landowner Contacted
Sites Visited by BEG
Sites Approved by BEG ❖
Sites Visited for 24-hr Survey
Station Approved ❖
Contracting in Progress
License Agreement Signed ❖
Borehole Drilling
Station Installation ❖

Permanent Station Name	2016												2017											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
	Actual												Planned											
TX.ET							❖						❖	❖	❖									
TX.ECT								❖		❖			❖		❖									
TX.DL							❖			❖			❖		❖									
TX.ST							❖						❖	❖	❖									
TX.Y33							❖			❖		❖												
TX.AZWR								❖		❖			❖	❖										
TX.333						❖				❖			❖	❖										
TX.633							❖			❖			❖	❖										
TX.034								❖		❖	❖			❖										
TX.Z31							❖			❖	❖	❖												
TX.V30						❖							❖	❖										
TX.Y30							❖			❖	❖	❖												
TX.U29						❖							❖	❖										
TX.230						❖				❖		❖												
TX.430							❖			❖		❖		❖										
TX.Z29							❖			❖	❖	❖												
TX.U27						❖				❖			❖	❖										
TX.228					❖					❖		❖		❖										
TX.529								❖		❖		❖												
TX.327						❖				❖		❖												
TX.527							❖			❖		❖		❖										
TX.425					❖					❖	❖	❖												

contracts in place at the time of this writing, installation of stations in the western half of Texas is scheduled for December 2016, with the remainder of the stations to be installed in early 2017. **Table 3.2** presents a detailed view of the site-installation process and status.

Portable Stations

The portable-station deployment process and status is shown in **table 3.3**. At the end of November 2016, 10 of the 12 portable stations planned for the Fort Worth Basin were deployed (**fig. 3.5**), and real-time data began streaming to the TexNet Data Hub and, from there, to IRIS. The remaining 2 stations of the Fort Worth Basin will be installed in December 2016.

The plan to install 9 stations in the region of Cogdell Field north of Snyder has been delayed by the inability to identify landowners willing to host portable seismic stations. Alternative sites are currently being evaluated.

Table 3.3 TexNet portable-station installation process and status

		2016												2017											
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
		Actual											Planned												
Legend	**Portable Stations**																								
Sites Selected	***Auxiliary (3)***											❖	❖	❖											
Site Landowner Contacted	*Identify Sites*																								
Sites Visited by BEG	*Identify Landowners*																								
Sites Approved by BEG ❖	*Contact Landowners*																								
License Agreement Signed ❖	*On-Site Visit and Assessment*											❖													
Station Installation ❖	*Contracting*																								
	Installation: # out of 3													❖											
	Fort Worth (12)								❖			❖	❖												
	Identify Sites																								
	Identify Landowners																								
	Contact Landowners																								
	On-Site Visit and Assessment								❖																
	Contracting												❖												
	Installation: # out of 12									4	9	10	12												
	Cogdell (9)								❖					❖	❖	❖									
	Identify Sites									LO Declined															
	Identify Landowners																								
	Contact Landowners																								
	On-Site Visit and Assessment								❖					❖											
	Installation: # out of 9														❖	❖									
	Permian Basin (6)												❖	❖	❖										
	Identify Sites																								
	Identify Landowners																								
	Contact Landowners																								
	On-Site Visit and Assessment												❖												
	Installation: # out of 6													❖	❖										
	Eagle Ford (3)															❖	❖								
	Identify Sites																								
	Identify Landowners																								
	Contact Landowners																								
	On-Site Visit and Assessment															❖									
	Installation: # out of 3																❖								

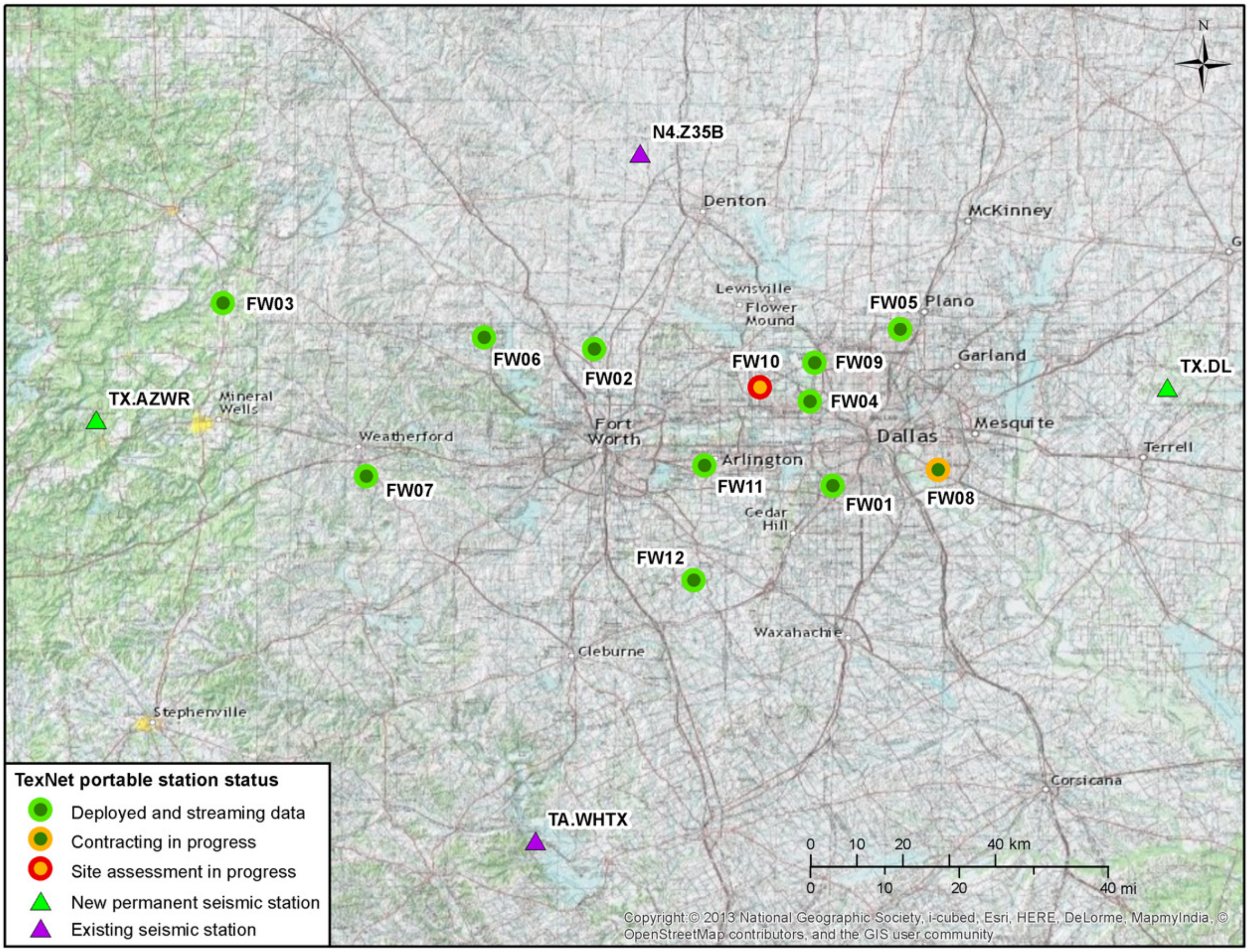


Figure 3.5 TexNet station deployments in the Fort Worth Basin.

Installation Challenges and Solutions

One of the greatest challenges for the development of TexNet was identifying landowners and creating among them an awareness of the importance and positive impact of a seismic network for the State of Texas. The process of identifying contact information for landowners and establishing first contact and permission to visit the sites has been time-consuming and difficult in many cases. Often, landowners have been unresponsive and apprehensive, and, in many cases, have declined to provide access to their land for a seismic station deployment. We identified 125 sites for probable seismic station installation and contacted 99 landowners (**table 3.1**). Only 55 landowners provided access to their property, permitting a site visit. In order to overcome these issues, we identified multiple sites for each targeted station location, reaching up to 10 potentially viable sites in some cases. Occasionally, for locations where direct access to landowners proved challenging, the aid of local landmen was employed to assist with site visits and establish a communication channel with landowners. Continuous communication with appraisal offices in each county where sites are located proved very important and a very efficient means of potential site preselection.

At two sites, we had to take extra measures to ensure adequate mobile-network coverage, using directional Yagi–Uda antennae. Also, at four permanent stations (see **table 3.1**), the 24-hr noise tests failed to reach acceptable noise-level limits as defined in the specifications. Subsequently, we have initiated the process of contacting local landmen to carry out the necessary 24-hr surveys for each site.

Network Data Hub and Earthquake Management System

Real-time ground-motion data (raw time series) are recorded from each sensor through the data logger and are archived locally for a period of at least 2 months as part of the data-backup strategy. The raw data are transferred through field-data modems to the TexNet Data Hub in real time. In case of network failure, the locally stored time-series data will be transmitted when the network connection is reestablished. This data will be backfilled within the archive of the TexNet Data Hub.

At the Data Management Center (DMC) of the TexNet Data Hub (**fig. 3.6**), data is stored for 4 months in a real-time ring buffer (Server 1), archived locally (Server 2), and also fed into the Earthquake Management System (EMS) (Server 3) for event identification. Backup 1 of the time-series data is stored on Server 3. After that, real-time data is stored in the SeedLink server (Server 4) and archived in the cloud (Backup 2). Through Server 4, earthquake data and related information are available to the public through the SeedLink protocol (real-time), ArcLink protocol (archive), and FDSN web services. IRIS is a consortium of over 120 U.S. universities dedicated to the operation of science facilities for the acquisition, management, and distribution of seismological data.

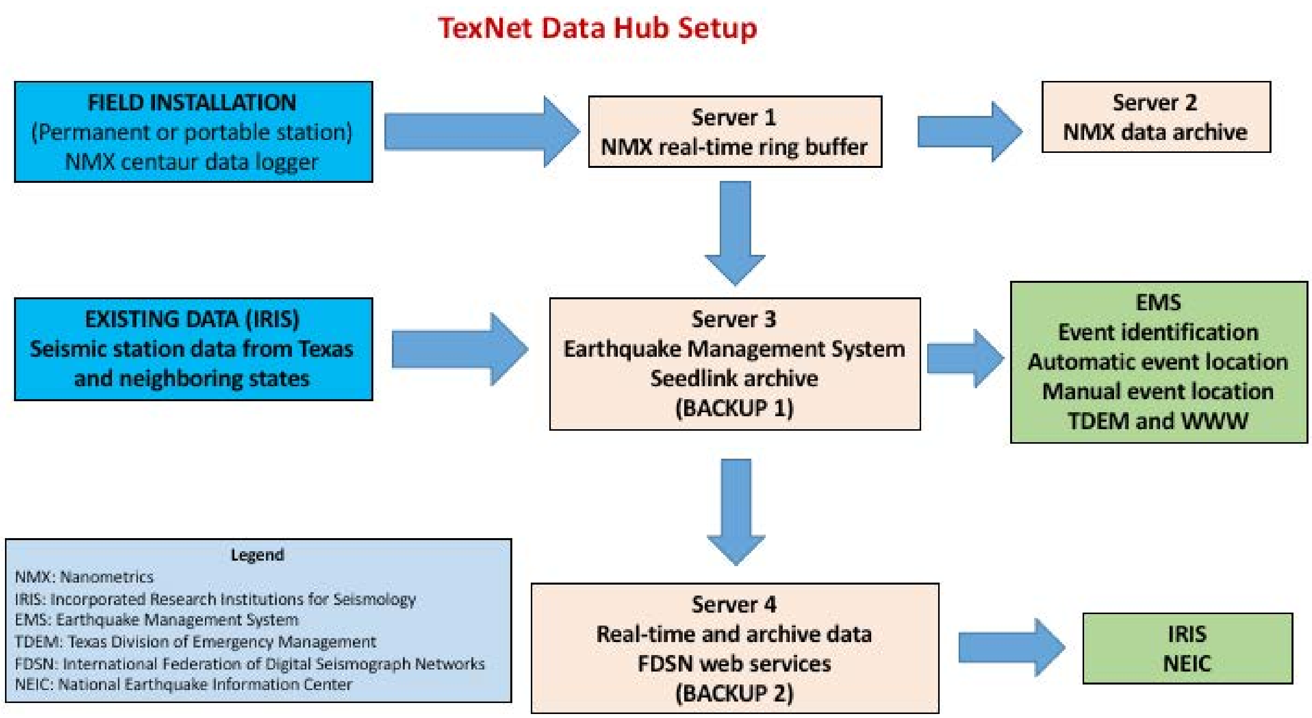


Figure 3.6 Schematic representation of TexNet Data Hub with data-flow information.

Ground-motion data from existing seismic stations in Texas and neighboring states are acquired from IRIS and used by the EMS. The latter employs an earthquake-event identification module that classifies in real time any new earthquake event. An automatic event location is calculated and an e-mail is sent automatically to the TexNet Operations team. A revised event location is provided by human intervention. Final earthquake source information is stored in the database of the EMS. Earthquake-location information will be available to the public in early 2017. A pathway for providing earthquake- location information and peak ground motion to the Texas Division of Emergency Management (TDEM) is already identified.

Station information for the 18 broadband seismometers located in Texas that provide real-time data through IRIS is presented in **table 3.4**. As shown, most of the sensors have been updated during the last 5 years. Through noise analysis, we identified a few stations, in South Texas, that provide noisy records. Ground-motion data from 40 stations located in neighboring states (**fig. 3.1**) and 28 stations through a temporary network in Fort Worth are acquired from IRIS. Depending on the availability and quality of the data, recordings of an earthquake event can be used at the earthquake location through the EMS. Nine portable TexNet stations deployed in Fort Worth are directly incorporated into the EMS through the TexNet Data Hub. Any additional TexNet station to be deployed in Texas will be included at the earthquake location in real time.

Table 3.4 TexNet stations with broadband seismometers providing real-time data through IRIS

Station Name	Owner	Operating since	Latest Sensor Update	Instrument	Operating by
EP.KIDD	UTEP Seismic Network	10/8/09	10/8/09	CMG-3T, 120 s, 1500 V/m/s-RT130, gain 1, 40 sps	UTEP
IM.TX31	International Monitoring System	1/3/72	11/18/13	KS54000=TX31=AIM24S_KS54K=TX31	TXAR Array, Lajitas, TX
IM.TX32	International Monitoring System	1/24/70	4/11/06	KS5400	TXAR Array, Lajitas, TX
IU.HKT	Global Seismograph Network (GSN - IRIS/USGS)	7/21/95	2/3/16	Streckeisen STS-1VBB w/E300	Albuquerque Seismological Laboratory (ASL)/USGS
N4.237B	Central and Eastern US Network	2/6/14	2/5/14	Streckeisen STS-2.5/Quanterra 330 Linear Phase Com	UC San Diego
N4.735B	Central and Eastern US Network	2/27/14	2/27/14	Streckeisen STS-2 G3/Quanterra 330 Linear Phase Co	UC San Diego
N4.Z35B	Central and Eastern US Network	2/10/14	2/10/14	Streckeisen STS-2 G3/Quanterra 330 Linear Phase Co	UC San Diego
N4.Z38B	Central and Eastern US Network	2/12/14	2/12/14	Nanometrics Trillium 240 Sec Response sn 0-399/Qua 330	UC San Diego
TA.435B	USArray Transportable Array (NSF EarthScope Project)	1/15/10	1/26/16	Guralp CMG3T/Quanterra 330 Linear Phase Composite	IRIS Transportable Array (IRIS_TA)
TA.833A	USArray Transportable Array (NSF EarthScope Project)	12/4/09	10/16/15	Streckeisen STS-2 G3/Quanterra 330 Linear Phase Co	IRIS Transportable Array (IRIS_TA)
TA.ABTX	USArray Transportable Array (NSF EarthScope Project)	2/12/09	10/16/15	Streckeisen STS-2 G3/Quanterra 330 Linear Phase Co	IRIS Transportable Array (IRIS_TA)
TA.MSTX	USArray Transportable Array (NSF EarthScope Project)	4/23/08	11/23/15	Streckeisen STS-2 G3/Quanterra 330 Linear Phase Co	IRIS Transportable Array (IRIS_TA)
TA.WHTX	USArray Transportable Array (NSF EarthScope Project)	2/11/09	10/16/15	Streckeisen STS-2 G3/Quanterra 330 Linear Phase Co	IRIS Transportable Array (IRIS_TA)
US.AMTX	United States National Seismic Network (USNSN)	9/29/02	5/2/11	STS2-I=80630=Gen=Q330SR=3521	Albuquerque Seismological Laboratory (ASL)/USGS
US.JCT	United States National Seismic Network (USNSN)	2/3/00	6/21/11	STS2-I=80219=Gen=Q330SR=0884	Albuquerque Seismological Laboratory (ASL)/USGS
US.KVTX	United States National Seismic Network (USNSN)	6/16/06	5/2/11	STS2-I=80434=Gen=Q330SR=1261	Albuquerque Seismological Laboratory (ASL)/USGS
US.MNTX	United States National Seismic Network (USNSN)	5/29/03	5/2/11	STS2-I=10440=Gen=Q330SR=3716	Albuquerque Seismological Laboratory (ASL)/USGS
US.NATX	United States National Seismic Network (USNSN)	5/12/04	7/8/15	Streckheisen STS2-I=80406=Gen=Q330SR=3522	Albuquerque Seismological Laboratory (ASL)/USGS

4. TexNet Research

Introduction

Earthquakes have the potential to negatively impact the people and infrastructure of Texas. Understanding the nature and causes of earthquakes is a challenging technical endeavor because they happen in the deep subsurface, which is very difficult to characterize physically, and they occur by mechanisms that are not well understood. The individual projects in the TexNet research portfolio are designed to contribute leading science to better understand earthquake causes and potential risks. These projects constitute components of an integrated strategy leading to a mechanistic understanding of the cause(s) of seismicity in Texas—naturally occurring and potentially caused by human activity. These studies will assess whether subsurface operations may be contributing to seismicity and, if so, the degree of this contribution. A vital goal of this research is to use the results to devise appropriate mitigation strategies, when possible, and to better understand the seismic risk.

Research Integration Plan and Timeline

To accomplish these ambitious research goals, a technical integration strategy has been developed that couples with a regional, site-specific application plan. Contributing to this strategy are three foundational technical areas funded by the State of Texas: TexNet (data) and Seismology, Geologic and Hydrologic Description, and Geomechanics and Reservoir Modeling.

Two additional critical areas of research—Seismic Hazard and Risk Assessment, and Seismic Risk Social Science—are being managed by the BEG but are not funded by the State of Texas (**fig. 4.1**).

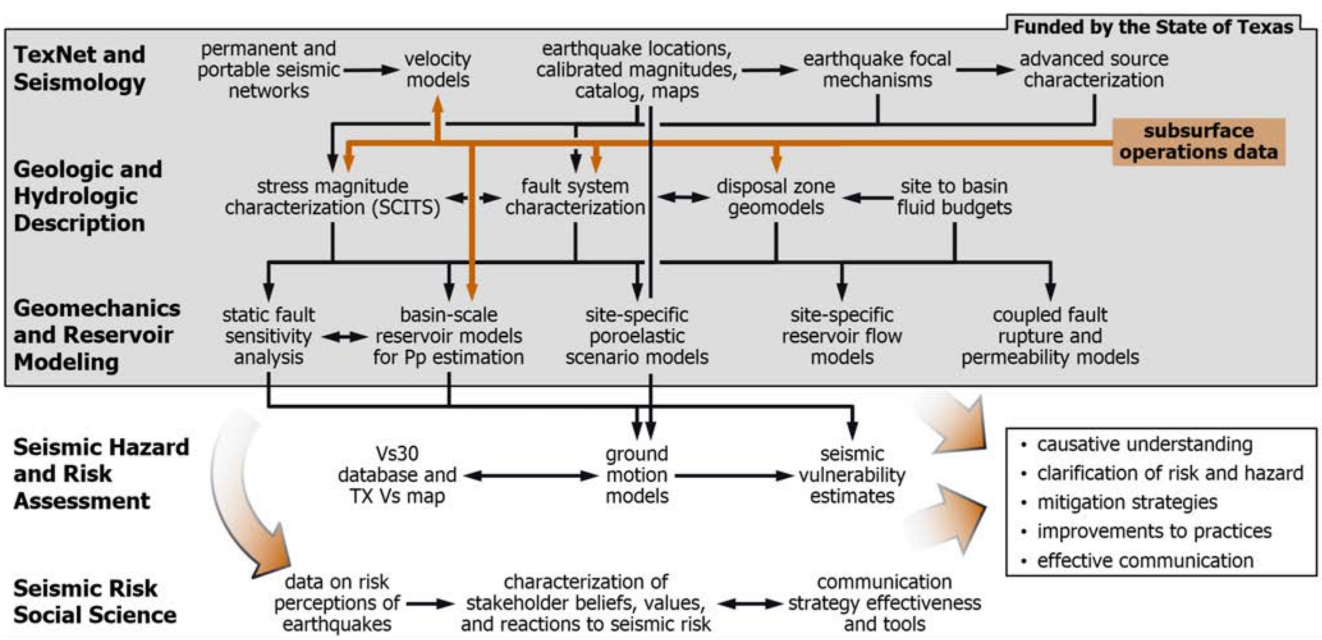


Figure 4.1 TexNet research area integration map.

The keys to this integration plan are that (1) accurate and precise data on earthquakes in Texas will be generated by the TexNet permanent monitoring network; (2) this information will be used to better identify areas for more-detailed monitoring using portable TexNet seismic stations; (3) earthquake data will be used to condition new quantitative geologic models of key areas; and (4) earthquake data and the quantitative geologic models will be used to develop physically realistic computational models to assess fluid-pressure change, reservoir mechanical behavior, and earthquake rupture mechanics.

While not specified in HB2, results from these integrated analyses will be used to develop methods for assessing seismic risk (i.e., the impacts of earthquakes on people and infrastructure) in Texas. Seismic risk assessment involves modeling the location and size of potential earthquakes, assessing the expected ground-shaking levels, and using this ground-shaking information to assess infrastructure vulnerability. The integrated research plan will help develop and assess strategies to mitigate induced seismicity, if and where it is determined to exist.

The legislative language in HB2 specifies the "modeling of reservoir behavior for systems of wells in the vicinity of faults." Therefore, the TexNet research portfolio emphasizes computational modeling of injection-zone fluid flow. Currently, four projects in the "Geomechanics and Reservoir Modeling" area are being pursued; all interface closely with the "Geologic and Hydrologic Description" areas (**table 4.1**). These projects address key topics of fluid pressure and stress evolution with injection, fault rupture/reactivation prediction, and the generation of seismic moment. The results of these studies will be pivotal in assessing mechanistically how the perturbance of ambient fluid pressure may cause fault reactivation, how assessment of pore-pressure evolution might guide future injection operations, and how injection can be conducted while mitigating the likelihood of inducing seismicity.

Table 4.1 Matrix description of the scope and attributes of the computational modeling projects being conducted in the "Geomechanics and Reservoir Modeling" research area of TexNet. The first four projects listed are currently active; the fifth will commence in 2017.

Group	Researcher or PI	Topic or Title	Code Source	Code Type	Fluids	Mechanical Properties	Fault Geometry	Earthquake Magnitude Prediction	Geologic Heterogeneity Capability	Size of Model Domain	Rupture Propagation	Outcome Emphasis
UT-PGE	**Gono**	Ft Worth Basin regional-scale pore pressure estimation and fault reactivation	CMG commerical reservoir simulator	3d, finite difference	Multiphase	Elastic	Must conform to rectilinear grid, many fractures	No	Maximum capability, compatible with industry geomodels	Reservoir to basin scale	No	Basinal interpretation of regional fault reactivation potential related to injection
UT-PGE	**Babazadeh**	Fluid injection and earthquake size in faulted reservoirs	Custom built	3d, boundary element fracture and 3d finite difference flow	Multiphase	Elastic	Arbitrary orientation, many fractures	Quasi-dynamic, rate and state friction model	Requires homogeneous mechanical properties	Single fault	Quasi-dynamic, temporal tracking of rupture/slip moving arbitrarily across fault as dictated by stress/loading	Process investigation, well-based history matching, understand physics of earthquake magnitude
UT-BEG	**Eichhubl**	Site-specific geomechanics analysis; basement fault reactivation	Commerical geomechanics code Abaqus	2d, 3d finite element, poroelastic	Single phase	Coupled poroelastic (but could also include plastic)	Arbitrary orientation, few fractures	No	High on local scale including few wells	Single well to reservoir scale	No	Fault-specific reactivation potential; well-based history matching; parameter sensitivity analysis; process investigation
TAMU-PETE	**Datta-Gupta**	Coupled fluid flow and geomechanical modeling of the Azle area	Commercial CMG reservoir simulator	3d finite difference	Multiphase	Elastic	Must conform to rectilinear grid, many fractures	Static estimate	Maximum capability, compatible with industry geomodels	Reservoir scale	Static, strain magnitude but not slip modeling	Fault-specific reactivation potential; well-based history matching/interpretation; flow visualization using streamlines
TAMU-PETE	**Kim**	Coupled fluid flow and geomechanical modeling: mechanisitic studies	Tough+ Geomechanics (LBNL-TAMU-inhouse code)	3d-finite-volume (flow)/finite element (geomechanics), cohesive zone model (fracture propagation)	Non-isothermal, Multiphase	Chemo-themo-poro-mechanics, including plasticity	Arbitrary orientation	Quasi-static	Heterogeneity (cell by cell input)	Reservoir scale	Fault actvation, fault slip modeling	Fault-specific reactivation potential; fault slip; senstivity analysis; mechanistic studies

The spatiotemporal strategy of the research integration plan includes topics that will improve the accuracy of TexNet in locating and characterizing earthquakes across all of Texas, as well as in providing region-specific emphases (**fig. 4.2**). The first focus area is the Fort Worth Basin region, where the recent increase in the rate of seismicity has been associated in the published literature with fluid injection (e.g., Hornbach and others, 2015, 2016; Frohlich and others, 2016a, b). The need to focus on this heavily populated metropolitan area was emphasized when the USGS identified an increase in the seismic hazard of the region due to the increased rate of seismicity (Petersen and others, 2016).

Once work in the Fort Worth Basin region satisfactorily progresses in 2017–18, the emphasis will shift to the greater West Texas Basin region, where development of unconventional reservoir systems has greatly increased in the last several years. Moreover, there is general consensus that the current pace of development will continue for the foreseeable future, especially in the Delaware Basin region. The pace of wastewater injection is also anticipated to increase substantially. Integrated analysis of the Eagle Ford operating area and other areas in Texas will then follow in succession.

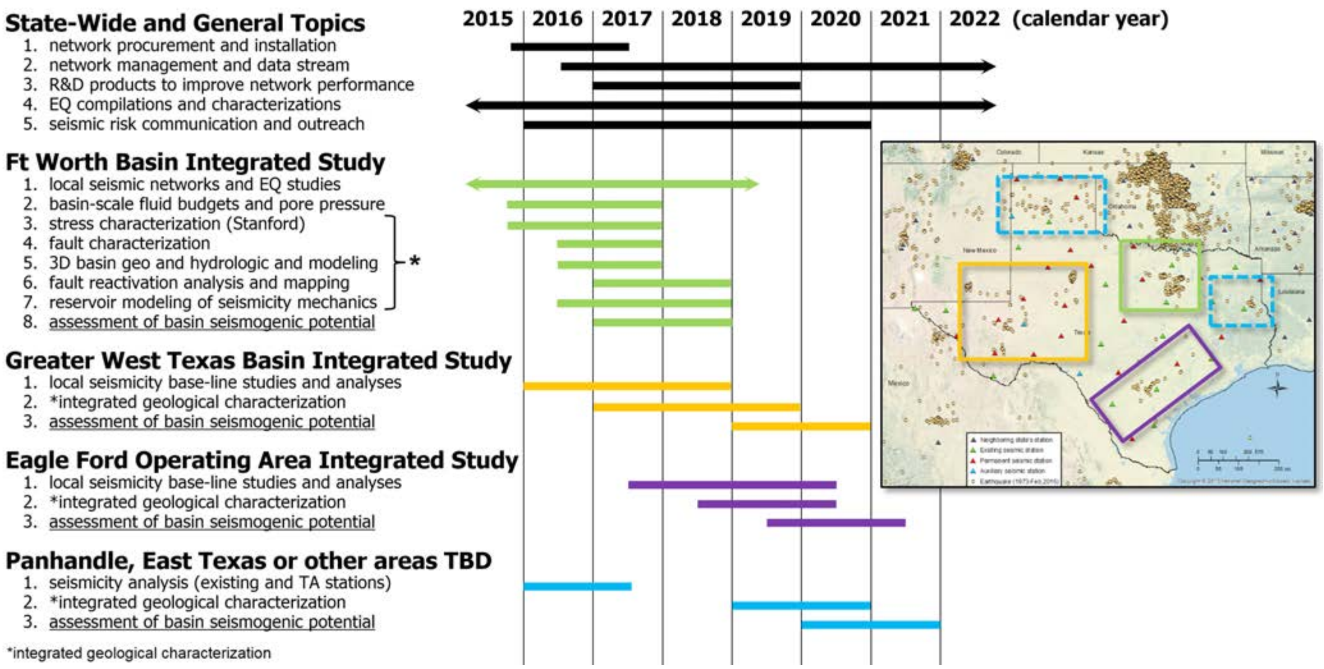


Figure 4.2 Timeline depicting TexNet research priorities in various Texas regions.

Research Projects

The State of Texas currently funds projects in the three areas listed above—TexNet and Seismology, Geologic and Hydrologic Description, Geomechanics and Reservoir Modeling—and found in **table 2.2**. These projects are considered pivotal in converting sometimes-raw data into information that will help achieve the goals set out for TexNet and HB2.

Texas Seismicity Studies (PI's: Jake Walter and Cliff Frohlich, UTIG)

Project Background

A primary activity of TexNet will be to accurately locate earthquakes at regional scales, with spatial (location) uncertainties of a few kilometers or less when using permanent stations and uncertainties of hundreds of meters when rapid-response (portable) stations are deployed. Research efforts will focus on developing and implementing cutting-edge methods to determine earthquake locations more accurately than possible with routine methods. For example, while arrival of seismometer signals sometimes can be identified automatically with some accuracy, ambiguous arrivals require careful reanalysis. Precise locations are achieved with these data and a locally tailored seismic velocity model, also to be developed using TexNet. Sometimes relocating aftershocks or clusters of earthquakes reveals new information about regional geology that has significance for seismic hazard analysis. For example, planar aftershock clouds may delineate previously unknown subsurface faults. Detailed spatial maps and temporal plots of seismic activity provide a baseline for all other aspects of TexNet research. These data will help constrain improved seismic velocity models that will be distributed to the broader community through peer-reviewed publications and the TexNet website.

Scientists at UTIG have been investigating past seismicity in Texas, focusing especially on reevaluating data collected across Texas between 2008 and 2011 by the National Science Foundation's EarthScope Transportable Array program. UTIG's investigations are helping to inform us on where to install TexNet permanent and portable stations and to assess the nature and potential cause(s) of historical seismicity in the state.

Historical and Regional Texas Seismicity (Cliff Frohlich, UTIG)

A literature review of historical Texas seismicity uncovers evidence that earthquakes associated with human activities have occurred as early as 1925 in several different regions of Texas (Frohlich and others, 2016a, 2016b; **fig. 4.3**). Since June 2015, research has focused on seismicity in four areas: the Panhandle, West Texas, East Texas, and the Fort Worth Basin. Results from TexNet seismometers and future research will improve on our understanding based on this earlier research.

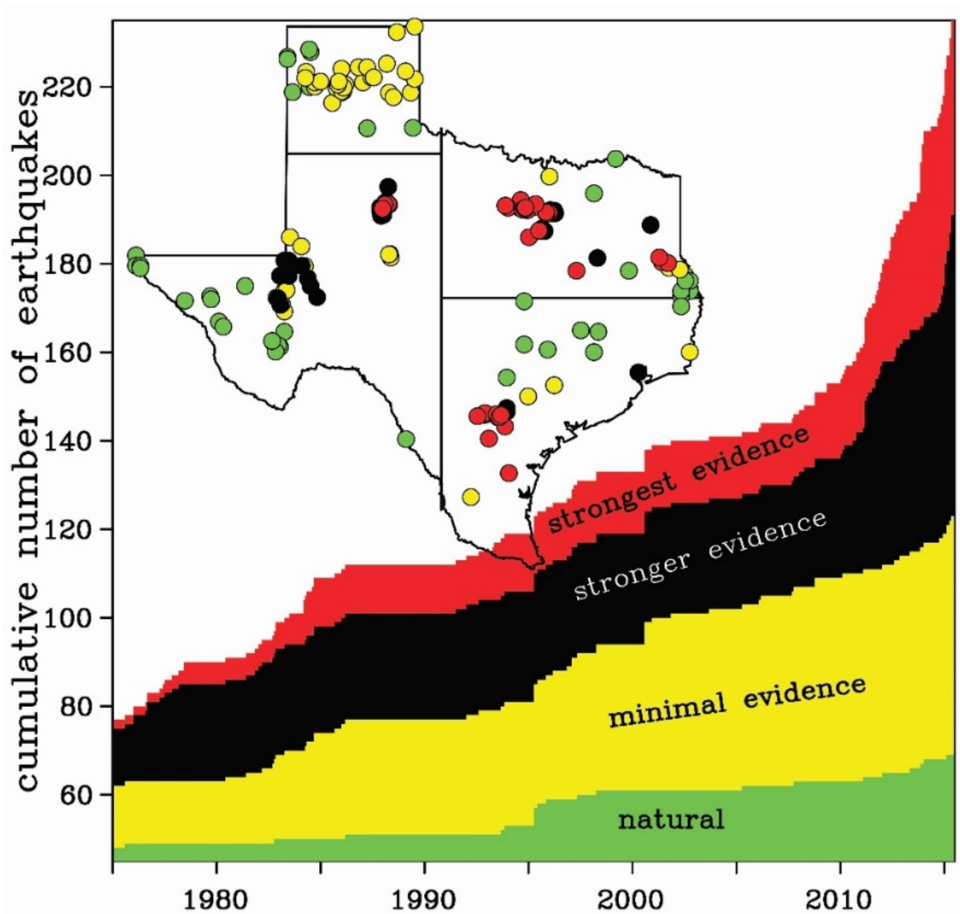


Figure 4.3 Historically reported earthquakes (circles) with magnitude M3.0 and greater, as listed in Frohlich and others (2016a), and strength of available evidence supporting the conclusion that these earthquakes have an induced cause. Reproduced from Frohlich and others (2016b).

Instrumental Seismicity (Alexandros Savvaidis, BEG)

A statistical analysis of the Texas USGS/ANSS catalog, following Mignan and Woessner (2012) and using several different methods, provides the magnitude of completeness (Mc) for reported earthquakes. In an earthquake catalog, the Mc is the minimum magnitude above which all earthquakes within a certain region are reliably recorded. **Figure 4.4** shows the frequency–magnitude distribution (FMD) of the catalog. Since the Texas earthquake catalog has a mix of magnitude types, the TexNet research team will in 2017 provide an adjusted moment magnitude catalog, as per Petersen and others (2014), so that the historic magnitude of completeness for Texas can be quantitatively assessed.

It is common practice to provide a declustered catalog by removing statistically dependent events such as foreshocks and aftershocks before use for statistical analysis (Petersen and others, 2014). Developing the adjusted Mc and declustering the catalog are considered to be important analysis steps in advance of developing hazard maps that include events of suspected induced origin (Petersen and others, 2016). For these reasons, **figure 1.2** should be considered preliminary.

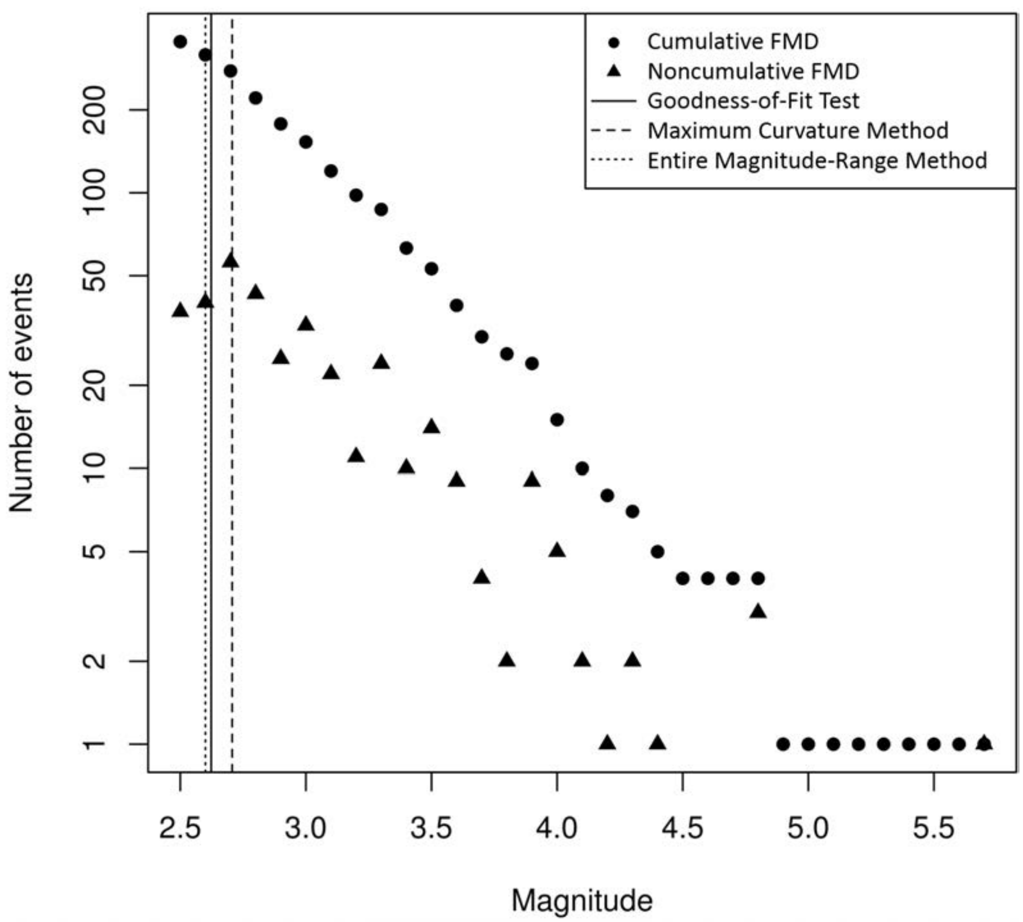


Figure 4.4 Texas earthquake frequency–magnitude distribution, USGS/ANSS catalog. Magnitude of completeness is denoted using different methods.

Texas Panhandle Seismicity (Jake Walter, UTIG)

In an ongoing investigation led by Jake Walter, an analysis of EarthScope Transportable Array records at stations in the Texas Panhandle has identified numerous small earthquakes in that area, mostly occurring from 2008 to 2012 (**fig. 4.5**). Some of these earthquakes appear to be associated with wastewater-injection wells. Walter's research, when completed and published, will be the first published investigation of Panhandle seismicity since Sellards (1939).

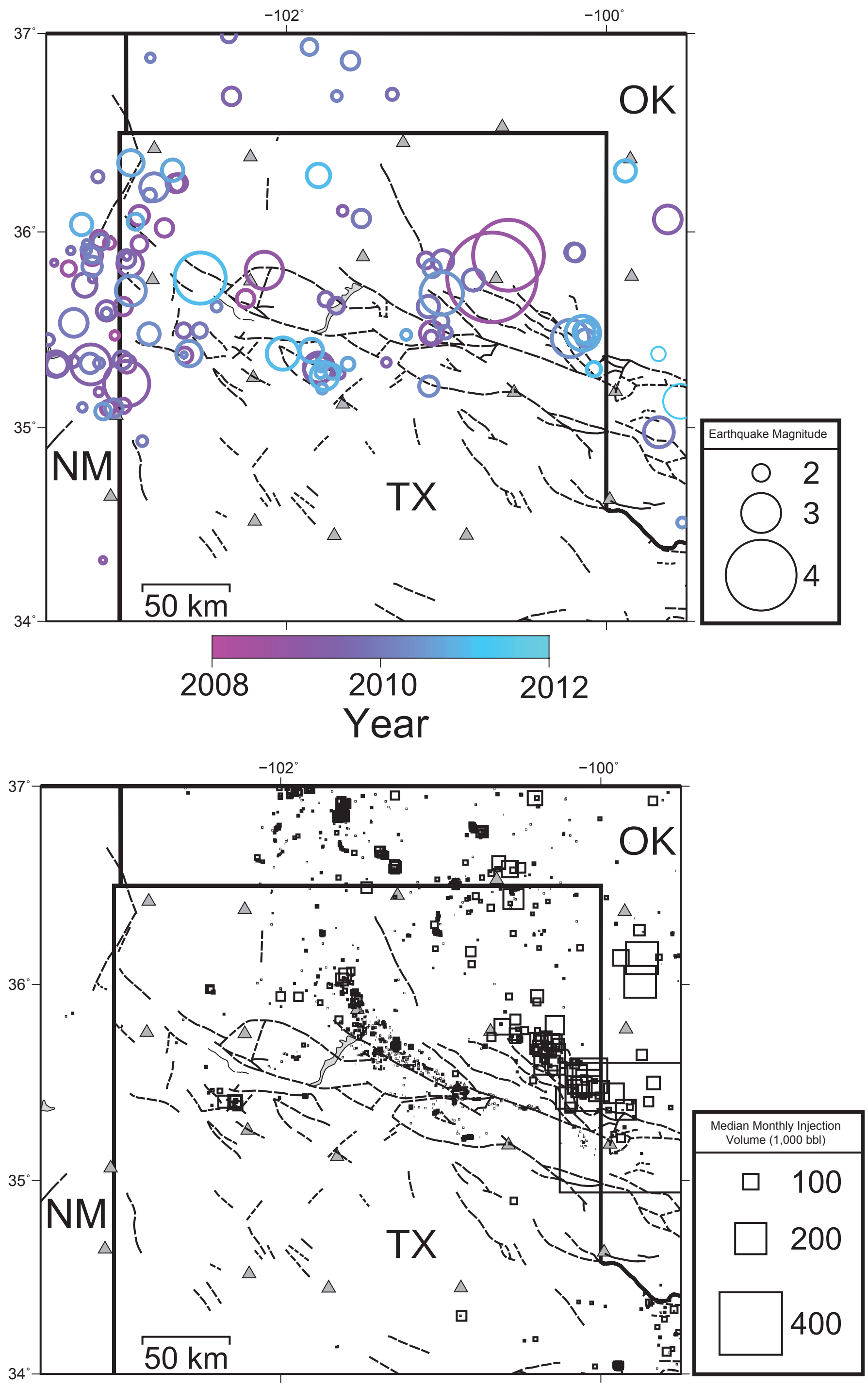


Figure 4.5 Earthquakes (circles) occurring from 2008 to 2012 and recorded by Transportable Array seismographs (triangles) in the Texas Panhandle. Squares are active injection wells. Dashed lines are subsurface faults (Ewing, 1990). Note that nearly all Transportable Array seismographs were removed after the study was completed. Figure courtesy of Jake Walter.

West Texas Seismicity (Jake Walter, UTIG)

In an ongoing investigation led by Jake Walter, an analysis of EarthScope Transportable Array records at stations in West Texas has identified numerous small earthquakes in that area, mostly occurring from 2008 to 2012 (**fig. 4.6**). Some of these earthquakes appear to be associated in space and perhaps in time with wastewater-injection wells.

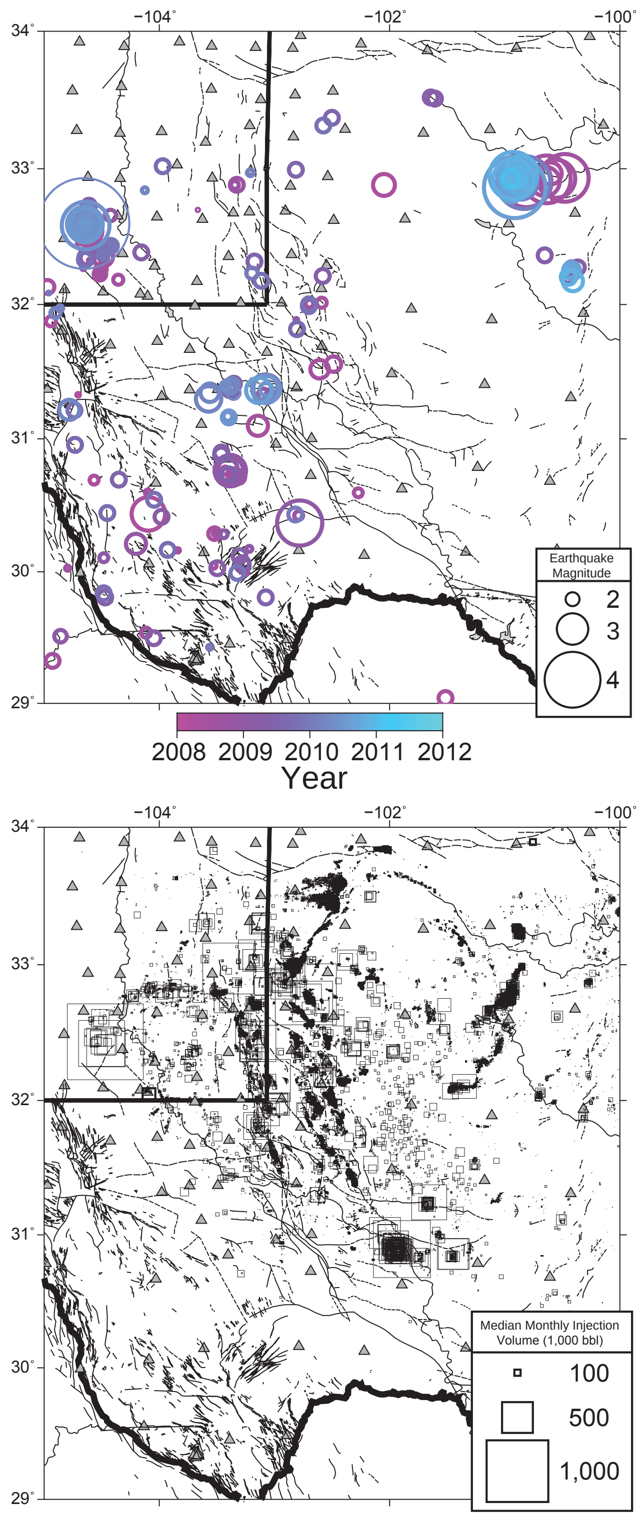


Figure 4.6 Earthquakes (circles) occurring from 2008 to 2012 and recorded by Transportable Array seismographs (triangles) in West Texas. Squares are active injection wells. Figure courtesy of Jake Walter.

East Texas Seismicity (Jake Walter, UTIG)

Using methods similar to, but updated from, those employed in the Frohlich (2012) survey of EarthScope Transportable Array records in the Fort Worth Basin, Walter and others (2016) evaluated small-magnitude earthquakes occurring from 2010 to 2012 in the vicinity of production from the Haynesville Shale in East Texas and Louisiana (**fig. 4.7**). They concluded that a sequence of earthquakes occurring in East Texas near Timpson (Frohlich and others, 2014) and some clusters of earthquakes in Louisiana were likely associated with wastewater injection. Fan and others (2016) undertook geomechanical modeling of stress and hydrological conditions near Timpson and concluded that injection-induced fault slip was plausible for this sequence. Again, results from TexNet seismometers and research should improve our understanding through time.

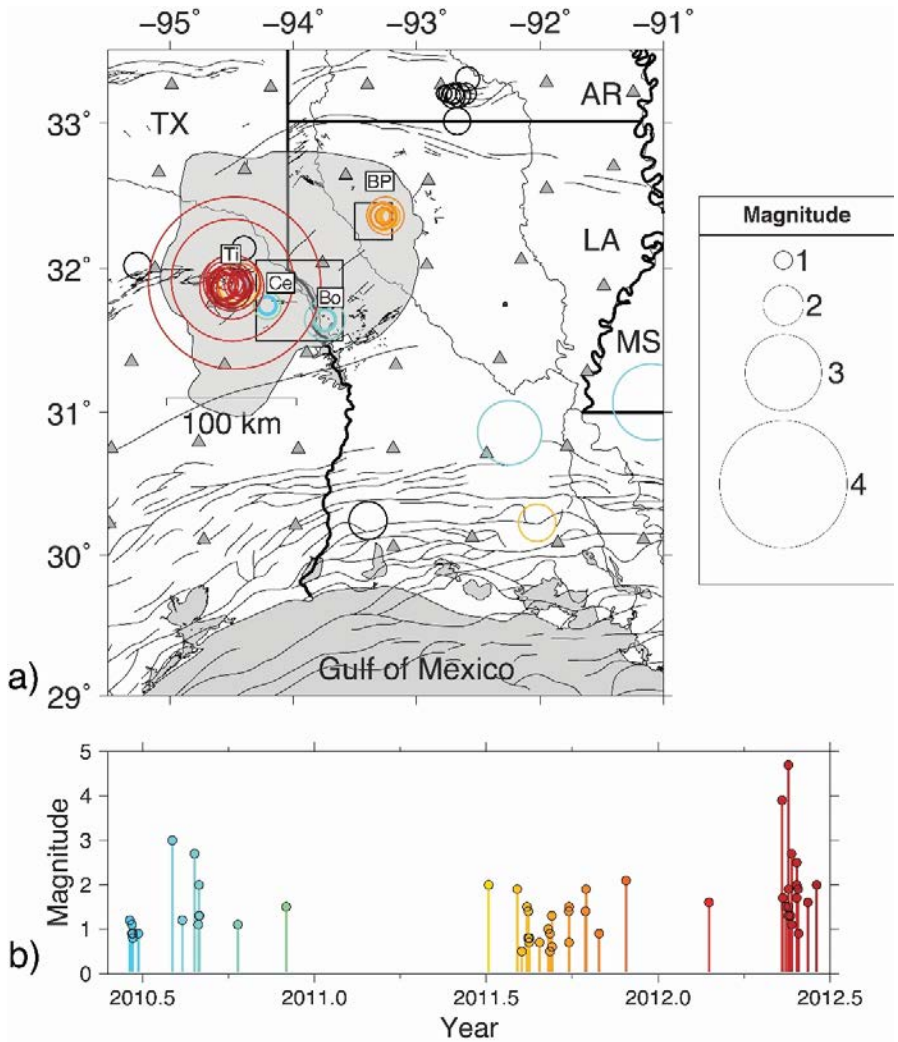


Figure 4.7 Earthquakes (circles) detected from 2010 to 2012 in East Texas and Louisiana and recorded by Transportable Array seismographs (triangles). Largest circle in East Texas is the M4.8 Timpson earthquake of 17 May 2012. Figure reproduced from Walter and others (2016).

Crustal Seismic Velocity Models (Taylor Borgfeldt and Jake Walter, UTIG)

Crustal seismic velocity models are used to locate earthquake hypocenters in routine earthquake location algorithms. Velocity models previously used in Texas to locate earthquakes were made with little regard to deeper geologic units because shallow earthquakes recorded by a localized seismic network only require velocity models of the upper crust. The aim of the new seismic velocity models is to refine both the shallow and deeper crust in relation to the geologic units present. The TexNet Seismic Network will require deeper crustal velocity models because locations will now use readings from stations across the entire state. Together with data from geologic provinces, tectonics, sonic logs, and newer seismological techniques, the updated regional velocity models of the State of Texas will allow researchers to more accurately locate earthquake hypocenters.

To produce velocity models of the entire state, we split the state into six regions based loosely on geologic and tectonic boundaries. From there, we first refined the layers of the 1D regional models with the geologic and geophysical datasets mentioned above. We then evaluated model performance at an earthquake location by comparing the differences in arrival time between predicted and observed travel times at each station (these time differences are known as *residuals* and represent errors in the model). In the future, we will evaluate how previously determined earthquake locations compare with those determined using the newly refined models, and we anticipate that our new 1D regional velocity models will be used by TexNet to locate earthquakes.

As of October 2016, four out of the six regional 1D velocity models are near completion. More datasets are being investigated for the remaining two models, as well as for enhancement of the nearly completed models. These results, and the sonic logs that were digitized to develop the shallow crustal models, will accompany a peer-reviewed publication.

Fort Worth Basin Earthquake Characterization (PI: Heather DeShon, SMU)

SMU scientists have deployed seismographs to monitor several earthquake sequences in the Fort Worth Basin. Their first deployment in the basin was in 2008, in response to events occurring near the Dallas–Fort Worth Airport (DFWA). In some of these efforts, SMU scientists have collaborated with scientists at the USGS and/or UT-Austin. Prior to 2015, station deployments focused on earthquakes near DFWA, Cleburne, and Azle (Frohlich and others, 2012; Justinic and others, 2013; Hornbach and others, 2015). Currently, 30 stations operate in the Fort Worth Basin (28 operated by SMU in collaboration with IRIS/USGS/TexNet, and 2 operated by USGS/ANSS). All data are streamed to a public archive in real time and used by USGS and TexNet to publicly report on earthquakes across North Texas. Monitoring by SMU is focused on three areas with active ongoing seismicity, specifically near Azle, Irving, and Venus (**fig. 4.8**).

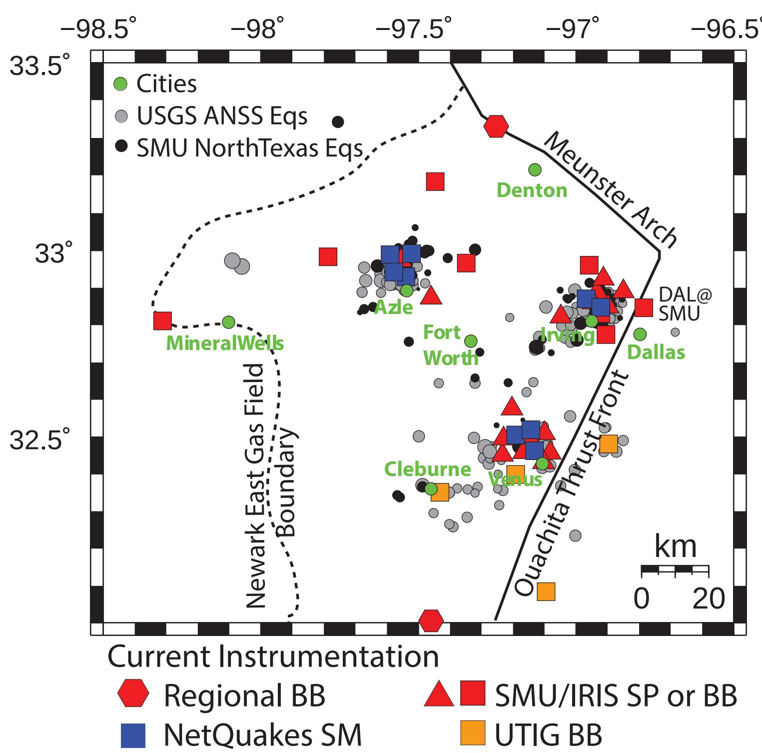


Figure 4.8 Seismograph stations currently operating in the Fort Worth Basin. Note concentrated clusters of stations near Azle, Irving, and Venus, with additional stations throughout the region to provide broad regional coverage. The USGS has reported 204 M1.8+ earthquakes in this region since 2008. SMU has reported over 1,500 small earthquakes ranging from M<0 to M4 since beginning network operations in late 2013. Figure courtesy of Heather DeShon.

Azle

Earthquakes have been a concern near Azle since November 2013, when a series of events occurred that included a M3.6 earthquake on 20 November 2013, followed by another M3.6 on 8 December 2013 (**fig. 4.9**). SMU and USGS seismologists installed seismograph stations to monitor this activity. Analysis of earthquakes recorded by this network showed that activity occurred along two steeply dipping normal faults extending from about 2 to 8 km in depth (Hornbach and others, 2015). Currently, 9 stations monitor seismicity near Azle, although seismic activity has decreased or nearly ceased, with the most recent Azle earthquakes detected in December 2015. The 17 December 2015 M3.0 Haslet earthquake occurred to the east of Azle on a different fault but was recorded by the stations near Azle. Earthquake magnitudes versus time are shown in **figure 4.12**.

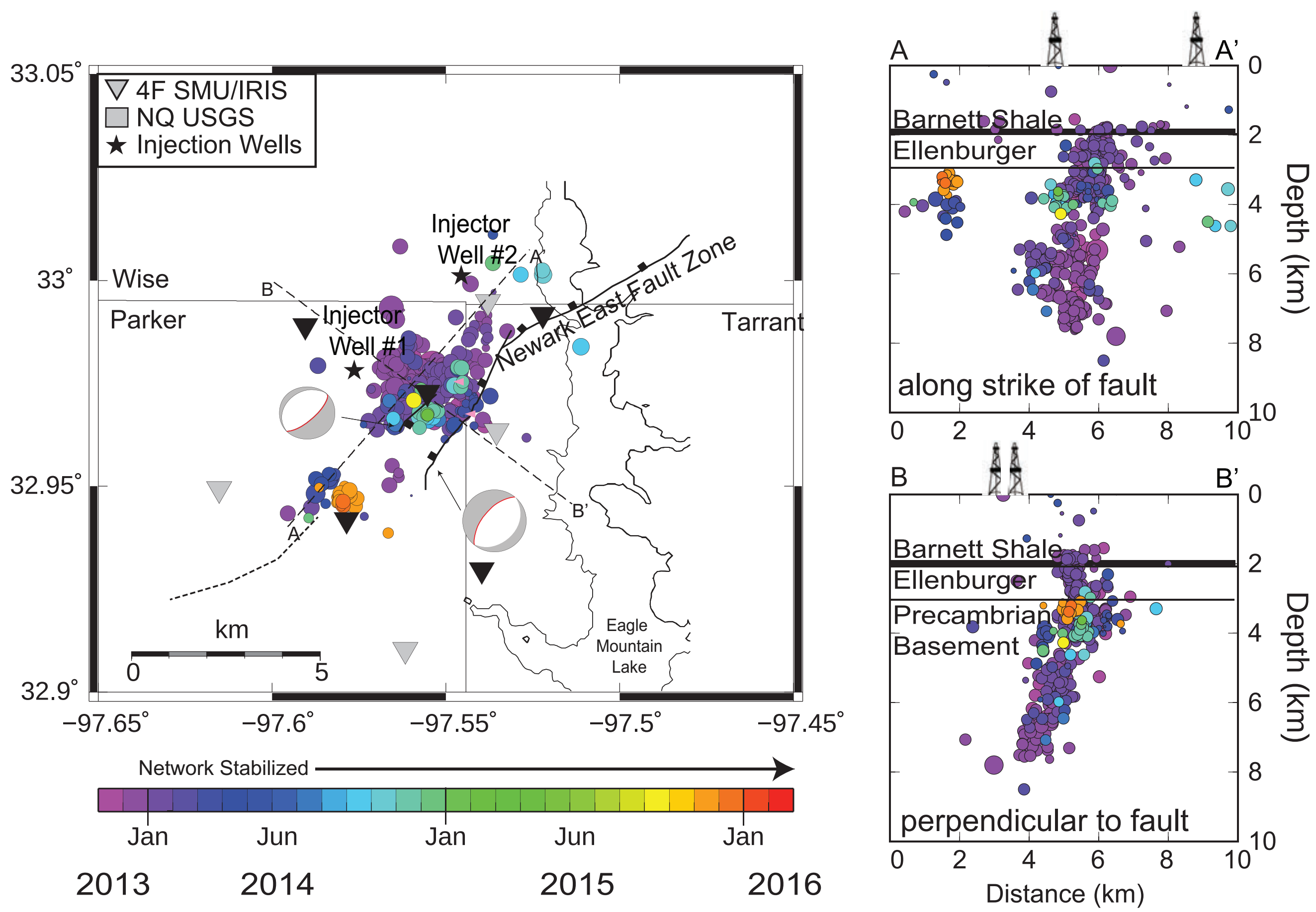


Figure 4.9 (left) Map of earthquakes 2013–16 (circles) and seismograph stations (other symbols) currently operating near Azle. Cross sections show seismic activity along-strike (top right) and perpendicular to fault (bottom right). Locations for earliest events (purple circles) are less accurate because they occurred prior to the installation of most stations.

Irving

Two earthquakes with magnitudes of 3.4 and 3.1 occurred near Irving on 30 September 2012 and were felt by local residents. Since seismograph stations were deployed here late in 2014, over 600 small earthquakes have been detected, including M3.5 and M3.6 events on 6–7 January 2015 (**fig. 4.10**). In all, 12 earthquakes at M3 or greater have occurred at this location. The better-located activity occurs at depths of 4–8 km along an eastward-dipping normal fault. Currently, 11 stations monitor seismicity in the Irving area. Hornbach and others (2016) recently published a paper that evaluated possible relationships between the Irving seismicity and wastewater injection into the Ellenburger Group, concluding a possible, but not definitely established, connection. Earthquake magnitudes versus time are shown in **figure 4.12**.

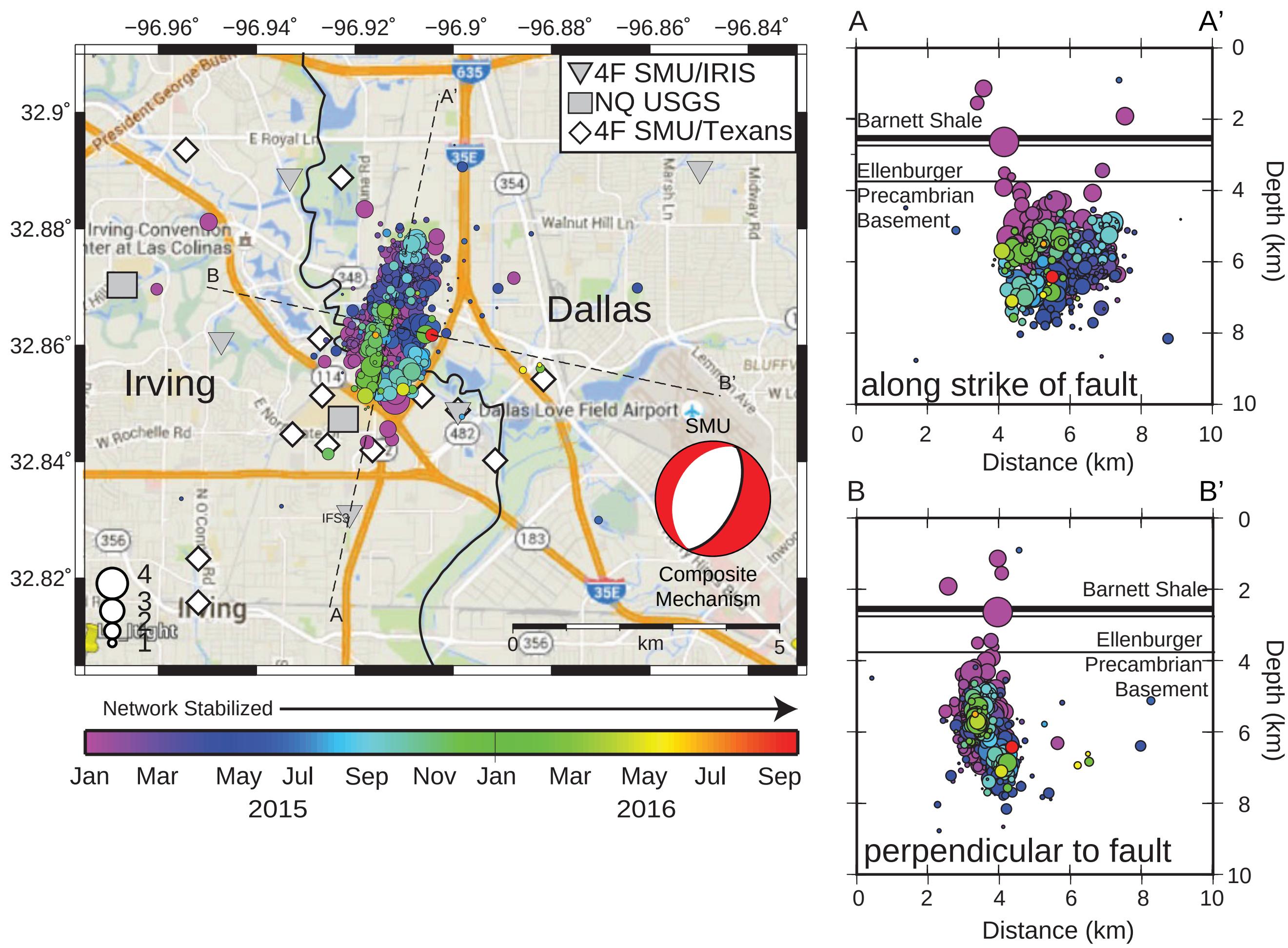


Figure 4.10 (left) Map of earthquakes 2014–16 (circles) and seismograph stations (other symbols) currently operating near Irving. Cross sections show seismic activity along-strike (top right) and perpendicular to fault (bottom right). Locations for earliest events (purple circles) are less accurate because they occurred prior to the installation of most stations.

Venus

Earthquakes have occasionally occurred near Venus since at least 2009 (Frohlich, 2012), including a M3 event on 17 July 2011. SMU and UT-Austin seismologists deployed several stations near Venus after a M4 earthquake occurred on 7 May 2015; 8 of these stations are still operational. Since May 2015, numerous (>280) earthquakes have been located, mostly along a steeply dipping normal fault extending 4–6 km in depth (**fig. 4.11**). Earthquake magnitudes versus time are shown in **figure 4.12**.

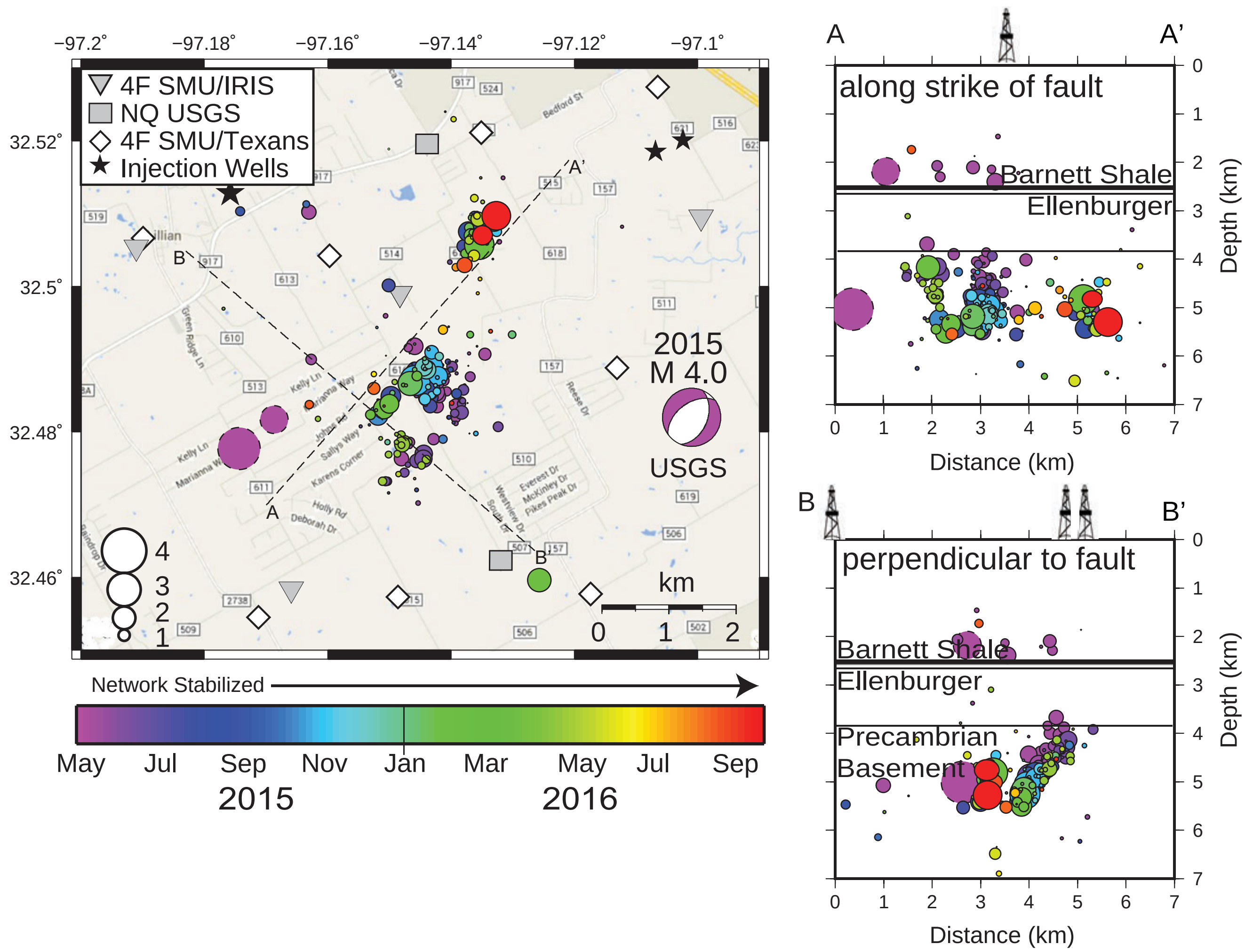


Figure 4.11 (left) Map of earthquakes 2015–16 (circles) and seismograph stations (other symbols) currently operating near Venus. Cross sections show seismic activity along-strike (top right) and perpendicular to fault (bottom right). Locations for earliest events (purple circles) are less accurate because they occurred before the installation of most stations.

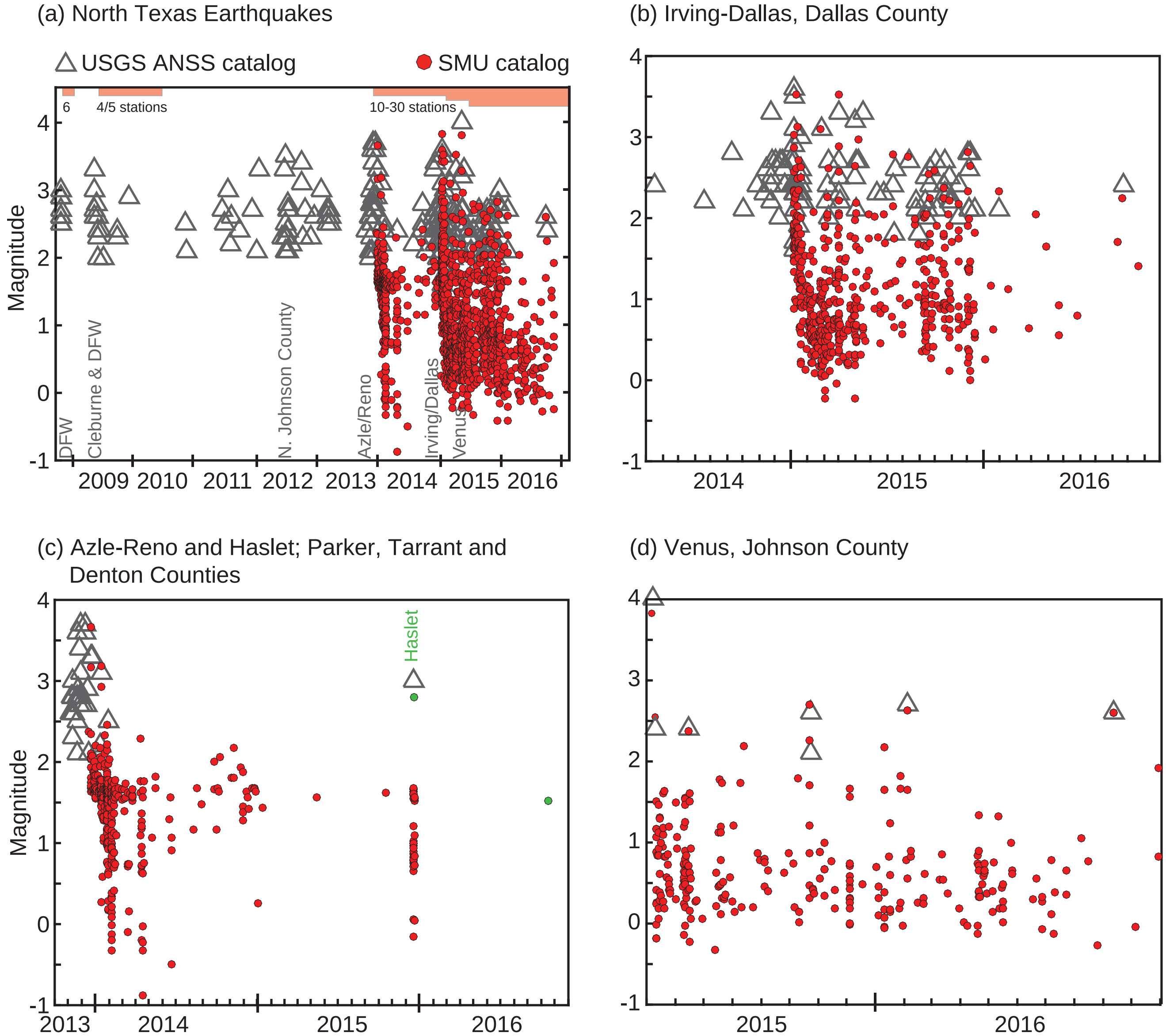


Figure 4.12 Magnitude versus time for North Texas earthquakes as reported by the USGS/ANSS Comprehensive Earthquake Catalog (triangles) and the SMU Earthquake Catalog from 2013 to present (circles). The SMU Earthquake Catalog magnitudes are reported as local magnitude (ml) calibrated to the ANSS regional body wave (mb_lg) magnitude. **(a)** North Texas from October 2008 to October 2016. SMU and collaborators deployed portable research seismic networks (red bars, number of stations in italics) in response to the DFWA, Cleburne (Johnson County), Azle–Reno, Irving–Dallas, and Venus (Johnson County) earthquake sequences. A series of earthquakes in northern Johnson County in 2012 were not recorded by local seismic stations. **(b)** Earthquakes associated with the Irving–Dallas earthquake sequence. The first local seismometers were deployed on 5 January 2016, one day prior to the onset of multiple M3.5+ earthquakes. **(c)** Earthquakes associated with the Azle–Reno (Parker County) earthquake sequence and the sequence near Haslet (Tarrant and Denton Counties). The first local seismometers were deployed in mid-December 2013. **(d)** Earthquakes associated with the M4.0 2015 Venus (Johnson County) earthquake sequence. The first local seismometers were deployed 3 days following the M4.0, which was widely recorded by stations already in place.

Hydrology: Fluid-Budget Protocols, Data, and Analysis (PI: Jean-Philippe Nicot, BEG)

Project Background

An understanding of fluid flow and fluid-pressure evolution is critical in studies assessing seismicity that may be potentially induced. Both the withdrawal and injection of fluids can result in pore-pressure changes and cause fault reactivation and seismicity, but reactivation due to injection has a more profound effect in areas where induced seismicity is assumed or being studied. This project has three principal objectives: develop fluid-budget data protocols, compile injection-volume relationships for Texas basins, and estimate basin-scale pore pressures using hydrologic modeling.

Obtaining and using public and proprietary fluid-injection data is a cumbersome task fraught with issues of data incompleteness and inconsistency. The first objective in this project is to develop robust fluid-injection data protocols that will provide a roadmap for researchers and research customers to efficiently obtain and organize fluid-injection data. The second objective is to produce quality-controlled injection datasets by zone and area in Texas that can be used to assess total volumes over given time periods, scrutinize injection by zone and area, make appropriate maps, and inform other TexNet projects. The collected data also will include injection intervals and permeability characteristics of the injection horizon and surrounding intervals. The third and most intensive objective of this project is to develop hydrologic flow models of key injection/seismicity areas to assess the degree of lateral and vertical connectivity of injection zones and to predict pore pressure at key time intervals. When possible, this hydrologic modeling will leverage framework and reservoir property inputs of key geologic models developed in other TexNet projects. Flow modeling will commence in the Fort Worth Basin in 2017 and move to areas of the Permian Basin in 2018.

Project Update: Fluid-Budget Protocols, Data, and Analysis (Casee Lemons, BEG)

The purpose of this protocol is to enable efficient data mining to characterize parameters that may influence the occurrence of seismicity. The protocol describes data-gathering procedures, how to perform quality control, and how to manage data leading to the creation and management of a fluid budget. Data types mined include geographic and subsurface locations of producing and injection zones, injection and production volumes, and rock properties. Products include a publicly available workflow on the TexNet website, a detailed protocol providing guidance for others to follow, and a single database to be used by TexNet research teams.

The Railroad Commission (RRC) of Texas permits both injection and disposal wells to inject fluid into the subsurface. Injection well type is classified by the RRC as: (1) disposal into a porous, nonproductive formation; (2) disposal into a porous formation productive of oil, gas, or geothermal resources; and (3) secondary recovery, which is an injection well used for enhanced oil recovery (commonly known as *waterflooding* [RRC, 2016a]). For injection or disposal wells, the RRC requires that injection volumes be reported annually and production volumes be reported both monthly and annually; for oil and gas wells, monthly reporting is required. For injection, disposal, and gas wells, volumes are reported on a single-well basis; for oil wells, volumes are summed and reported on the lease level. Fluid volumes are delineated on the basis of injection and disposal, hydraulic-fracturing stimulation fluids, and produced fluids (**fig. 4.13**).

Injection volumes are available for download from several sources. The RRC website is a public source that provides searchable forms and data for single wells to small numbers of wells. Injection information is also available from IHS Enerdeq®, which ingests injection data from the RRC, FracFocus®, and operators. Because the RRC data was not digitized before 1990, and much of IHS Enerdeq® Texas injection data comes from the RRC, the IHS Enerdeq® injection dataset is only partially complete before 1990. IHS Enerdeq® allows downloading of multiple wells in multiple formats, although access requires a subscription license. Monthly oil-, gas-, and water-production data are available

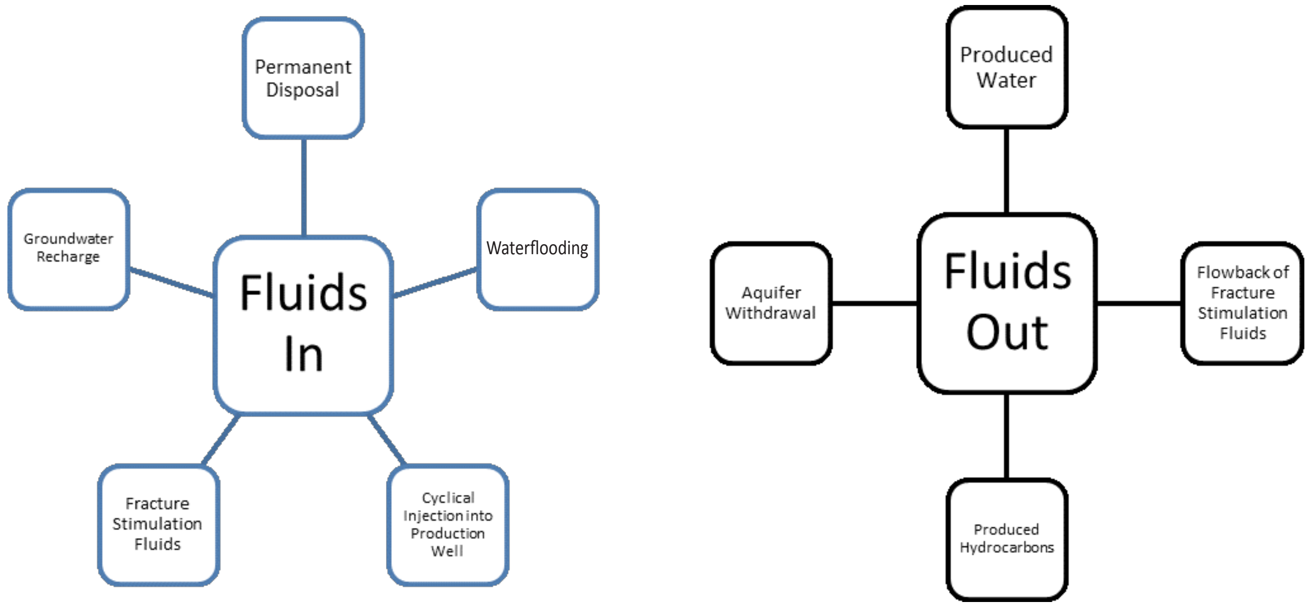


Figure 4.13 Relationships of fluid types within the total fluid budget.

from the RRC and IHS Enerdeq®. There is no official reporting of produced water volumes, which are estimated from periodic well tests. Historical and current production and injection volumes for multiple wells are most easily extracted from IHS Enerdeq®. Field-level production, however, is most easily gathered from the RRC Online Research Queries page (http://www.rrc.texas.gov/about-us/resource-center/research/online-research-queries/).

Because the State of Texas requires production values of oil wells to be reported only on a lease level, volumes from individual wells must be estimated. Operator-reported produced hydrocarbon volumes are downloaded from the RRC Online Research Queries page; however, these reports do not include water. IHS Enerdeq® offers its own algorithm for estimating individual oil-well production values based on lease-level volumes and well and production tests, as summarized by Smith and Catto (2015). Alternatively, Drillinginfo® has devised its own allocation algorithm based on a decision tree of reported well tests, production volumes, and completion dates. Drillinginfo® (2015) provides a detailed description of its allocation algorithm. IHS Enerdeq® estimates water volumes on a monthly basis from periodic well tests.

Standard methodology has established that injection- and production-volume updates are best performed on a quarterly basis for all well datasets larger than several hundred data points (wells) (pers. comm., R. Lafollette). We noted that the first 12 months of single-well production volumes (oil, gas, and water from oil wells) downloaded from IHS Enerdeq® can change by as much as 10% over a period of 4 months. Therefore, when updating fluid volumes in or out, it is recommended that all historical volumes be updated. These new findings also demand that the frequency of data update should be determined by the sample size, rather than by rule of thumb.

Project Update: Injection and Production Fluids in the Fort Worth Basin Area (Casee Lemons, BEG)

The project's current area of focus is the Fort Worth Basin, which, as a geologic structural unit, is smaller than the North Texas region undergoing active injection and seismic activity. These boundaries are defined as Texas Oil and Gas Districts 5, 7B, and 9 (**fig. 4.14**). Once data in these districts have been completely characterized and examined for other data types, the boundaries of interest are redefined into a smaller region representing the Fort Worth Basin and subbasin areas.

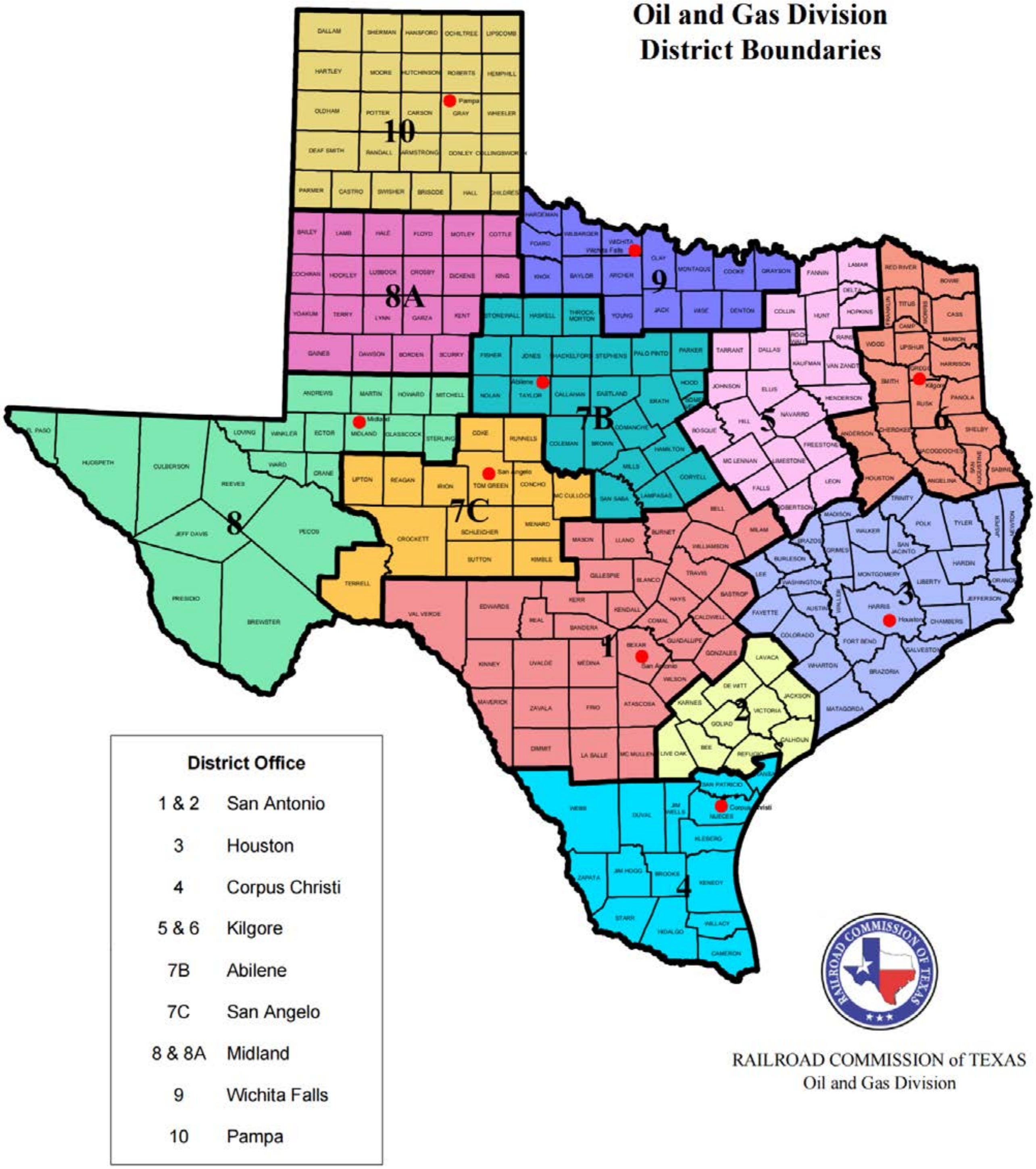


Figure 4.14 Texas Oil and Gas Districts map. The current extents of the study are Districts 5, 7B, and 9. Modified from RRC 2016b.

For the purpose of fluid budget and overall characterization, all wells from these districts reporting any monthly injection values were downloaded from IHS Enerdeq® and analyzed. In total, 21,653 individual wells (API's) reported monthly injection at some time from January 1983 to May 2016 (**fig. 4.15**).

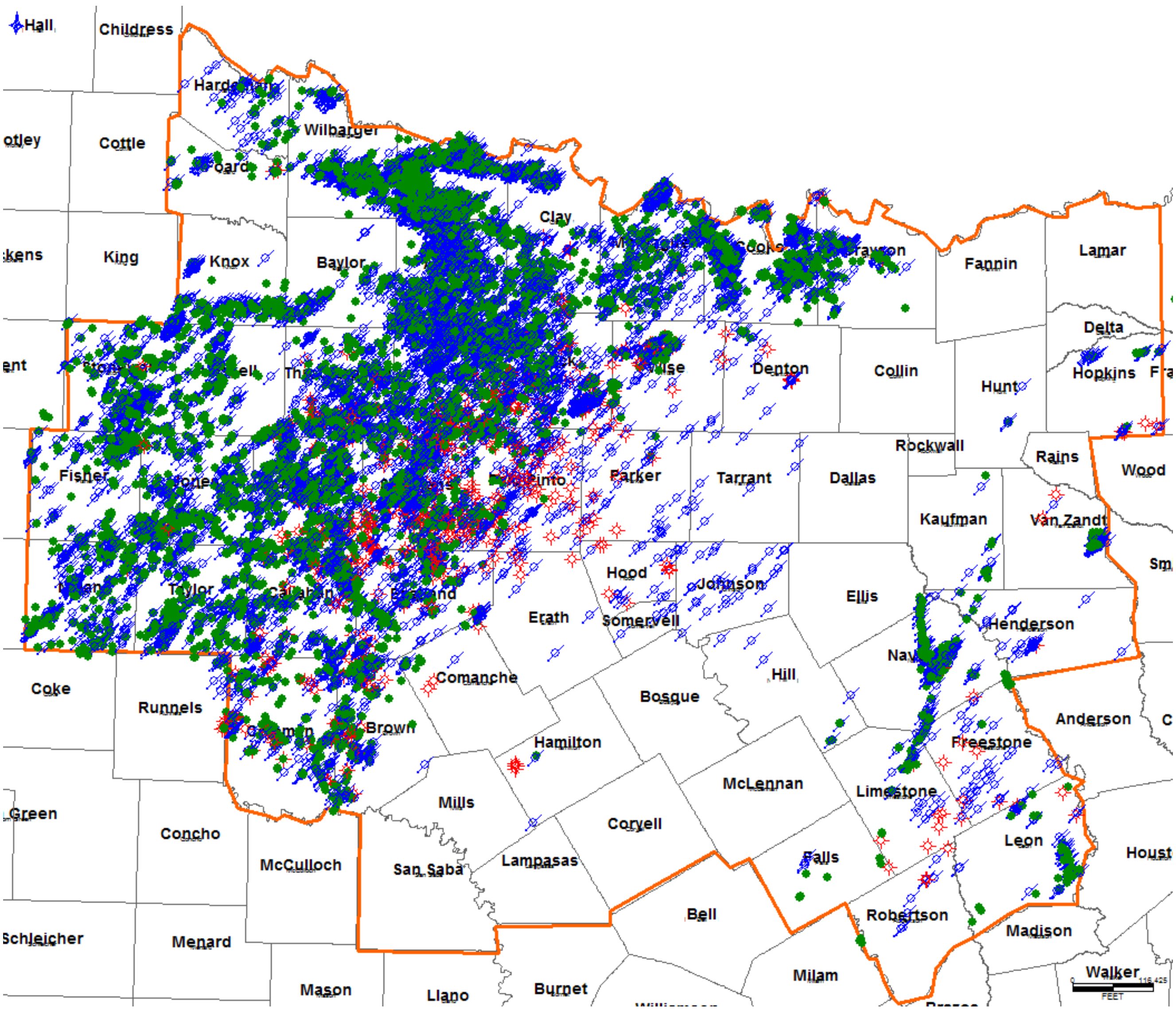


Figure 4.15 Map of 21,653 wells reporting any monthly injection volumes from January 1983 to May 2016 for the Fort Worth Basin region. Wells are represented as circles and colored by well type. Blue circles with line arrows are 9,644 injection wells; green circles are 11,476 injection wells classified as oil; red circles are 533 injection wells classified as gas. RRC districts 5, 7B, and 9 are bound in orange.

Quality control was performed on the Fort Worth Basin injection-volume dataset. Quality-control activities are done to identify and correct data that are erroneous or that warrant further investigation. For example, one source of error were erroneously large monthly values, presumably the result of data-entry errors. Thus, monthly reported values exceeding 500,000 bbl (approximately 10 times the overall injection-fluid average) were flagged and each then examined for per-well consistency with adjacent months. If the value was identified as erroneously large, it was replaced with the average of the 12 reported months of injection surrounding the erroneous value. Less than 1 percent of wells were identified as containing these sorts of erroneously large values. A second important consideration is interpretive error caused by the regulatory annual reporting cycle. In Texas, injection wells are required to report their monthly injection values once per year; the timing of the reports is determined by the field in which the well is located. Each field has a specific annual reporting due date, which means that across the region, fully reported values are current only up to 11 months before publication date. Additionally, there is generally a 3-month delay from the time of reporting to the time of publication, and then an expected additional 3-day delay from the time of RRC publication to the output by IHS Enerdeq®. Therefore, because data presented here were downloaded from IHS Enerdeq® (24 August 2016), the most recently completed database was from June 2015. After accommodating these and many other quality-control measures, the history of cumulative monthly injection over time was computed and charted from January 1983 to June 2015 (**fig. 4.16**). The year 1983 represents when monthly injection volumes began being reported in Texas. At some time in the RRC districts considered, 21,626 wells were identified as having actively injected fluids.

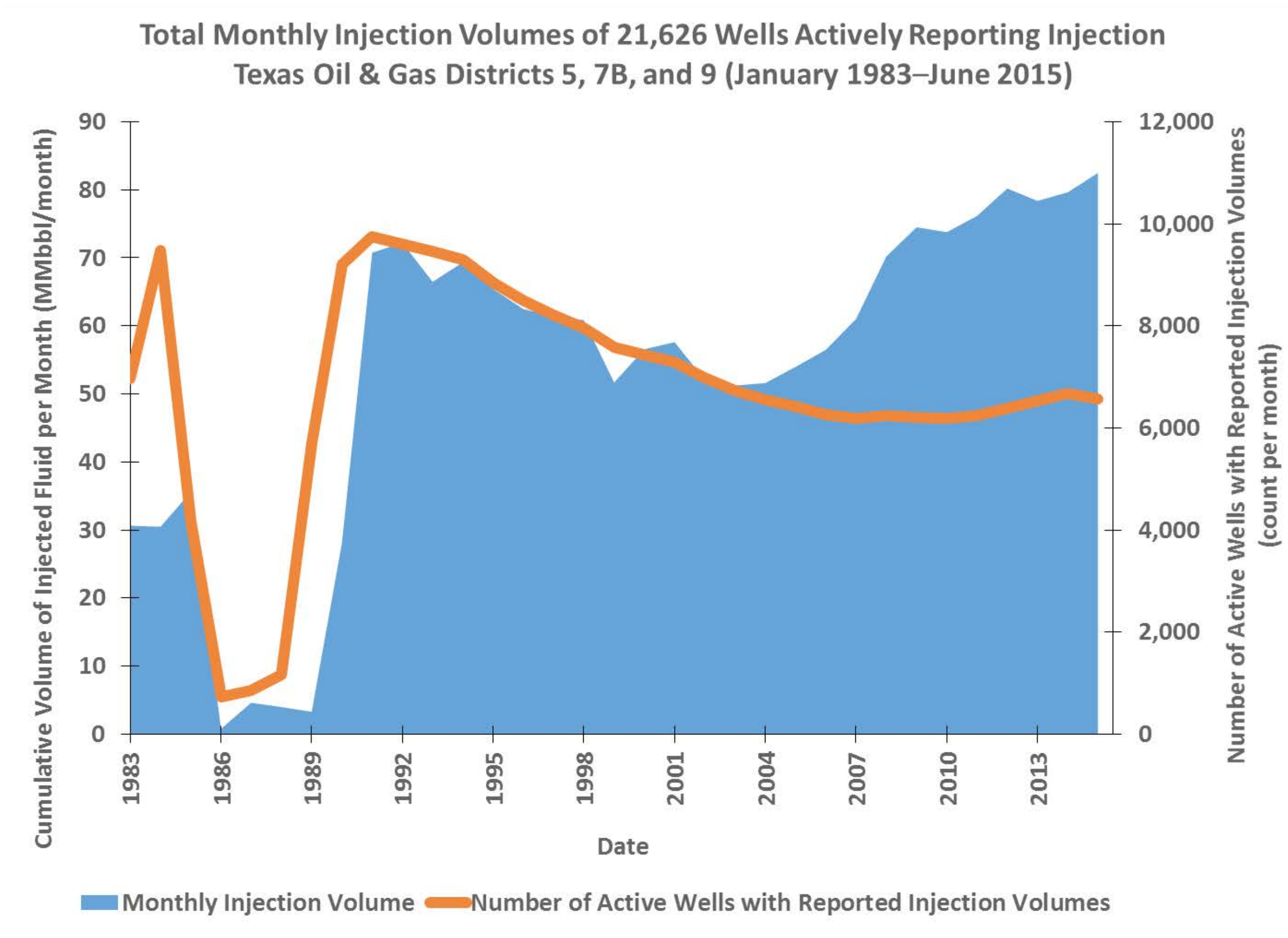


Figure 4.16 Cumulative monthly injection volume (blue area) and number of actively injected wells per month (orange line), January 1983 to June 2015.

For each active injection well, the probable formation receiving injection-fluid volumes was identified. Because the injected formation is not a required data field to be reported for wells and thus not clearly identified by users, it must be inferred. The first step to identifying the injected formation was to name it based upon the formation listed at well total depth (TD). For a disposal well, the deepest formation is typically equivalent to the injected formation. This formation at TD, provided by operators for some wells, is a data field available for download from IHS Enerdeq®. For all wells with no value listed in the formation at TD, the value for the producing formation was supplemented and assumed to be the formation at which the well perforations are located. The perforation-interval formation was selected as a secondary criterion because oil and gas wells are commonly completed in multiple formations, where the topmost formation is the one reported for the perforation interval. If neither the formation at TD nor the producing formation is reported, the probable injected-formation data field is considered unknown. In 2017, these unknown injection intervals will be analyzed by placing the well and the perforated intervals into our geologic model and interpreting the most likely injection intervals.

The injection formation was identified for 17,200 wells (79.4%), of which 775 (3.6%) are injecting into the Ellenburger Group (**fig. 4.17**). Within the subset of wells injecting into the Ellenburger Group, 120 wells are located in six counties in the eastern part of the Fort Worth Basin—closer to the areas that have experienced the recent increase in seismicity. Collectively, as much as 21 million barrels per month were injected into these wells in late 2011, an amount that has declined to approximately 14 million barrels per month in June of 2015 (**fig. 4.18**). A full characterization of the fluid budget and injection for the entire Fort Worth Basin will be released in early 2017. These data are vital for other TexNet research projects, especially those involving geomechanics and reservoir modeling.

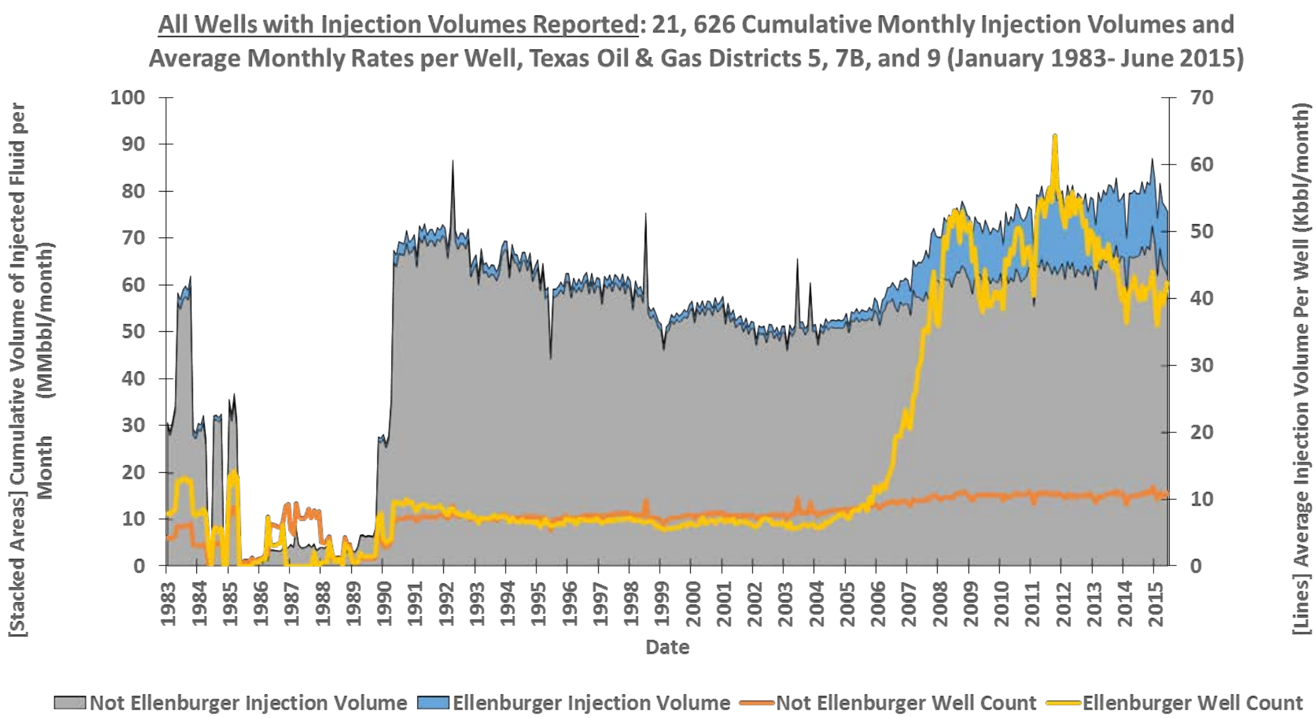


Figure 4.17 Monthly cumulative-injection volumes and monthly well counts of actively injecting wells. Ellenburger Group injection volumes charted in blue; all other formation volumes charted in gray. Total Ellenburger Group wells injecting is yellow curve; all other formations' well count is orange. Data downloaded from IHS Enerdeq® on 24 August 2016. Most complete dataset is through June 2015 because of annual reporting and 3-month delay in RRC public release. A production allocation query was performed for all wells with injection volumes; 21,626 well results total. Formations identified by bottomhole formation; all blanks supplemented with perforated formation.

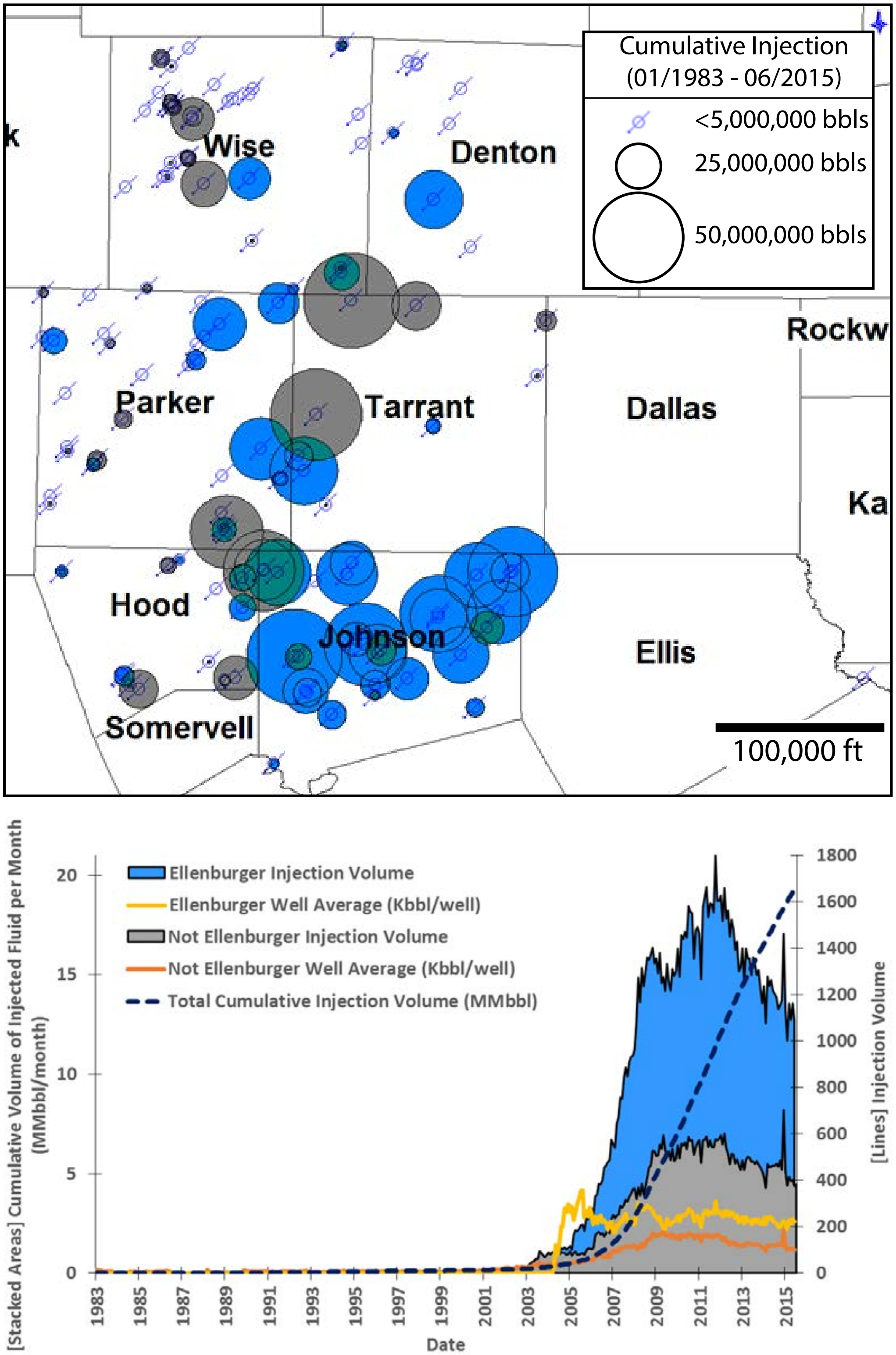


Figure 4.18 Cumulative well-injection volumes in six counties spanning eastern Fort Worth Basin near Dallas–Fort Worth metropolitan area for 120 wells that reported injection from January 1983 to June 2015 (most complete data available). Map at top shows cumulative injection volumes for wells disposing into the Ellenburger Group and Viola Formation (blue and green, respectively) and all other formations (gray). Chart shows total monthly injection volumes for the 120 wells (blue for Ellenburger Group and Viola Formation, and gray for all other formations), average disposal per well by zone, and total cumulative injection (over 1.6 billion barrels).

Faults and Geomodels (PI: Peter Hennings, BEG)

Project Background

Reactivation of faults produces earthquakes. Therefore, identifying the existence of faults in seismically sensitive basins and ascertaining their geomechanical characteristics is vital to assessing seismicity in Texas. Because recent experience in Oklahoma and elsewhere shows that the vast majority of potentially induced earthquakes have occurred on previously unmapped faults, it is critical to compile all possible indicators of faults to develop interpretations of fault geometry, timing, and depth/height from basement into the sedimentary cover. Fault system and growth characterizations to be studied include length, offset, gradients in displacement, linkage geometries, spacing, growth behavior, and reactivation history. Data to be considered include published information, industry seismic data (as available), seismicity data and characteristics, and outcrop. This work will begin in the region of the Fort Worth Basin and then move to other areas of Texas such as the Permian Basin, Panhandle, and Eagle Ford play area.

Deterministic data obtained from subsurface study in the Fort Worth Basin and informed by outcrop data from the flanks of the Llano Uplift will be used to stochastically generate realizations of spatial and volumetric intensity of the fault within the Fort Worth Basin as input into fluid flow and geomechanical models within other TexNet projects. With 3D deterministic models and stochastic realizations of faults within the Fort Worth Basin and, later, elsewhere, we will conduct fault-stress analysis to assess the static sensitivity of faults to reactivation, a task that will utilize in situ stress analysis as being undertaken by Stanford's SCITS research group. Once basinal pore- pressure data is available, assessments of area-specific fault-reactivation hazard will be assessed.

Project Update: Fort Worth Basin Geomodel (Peter Hennings and Robin Dommisse, BEG)

A geologic model of the principal disposal intervals in the Fort Worth Basin is being constructed from publicly available well data and information from existing publications. The model will constrain the structural architecture and fluid-flow properties of all sedimentary units underlying Barnett hydrocarbon-producing intervals (e.g., Viola and Simpson Formations, Ellenburger Group, and Cambrian formations). **Figures 4.19–4.21** show 3D models of the geologic model in progress. **Figure 4.19** shows the top of the Ellenburger Group, which is constrained by 320 wells. Once complete, this and other deeper surfaces, including basement, will be analyzed for the existence of faults and karst-collapse features, which will then be used as inputs for architectural and flow-property constraint for fluid-flow models. The 128 wells being analyzed penetrate through the Ellenburger Group and down to the crystalline basement. Petroleum operators in the Fort Worth Basin have been asked to share certain proprietary subsurface data, which would allow for a far greater ability to constrain the architecture and characteristics of potentially seismogenic faults, in situ stress conditions, pore-pressure measurements, and fluid-flow properties.

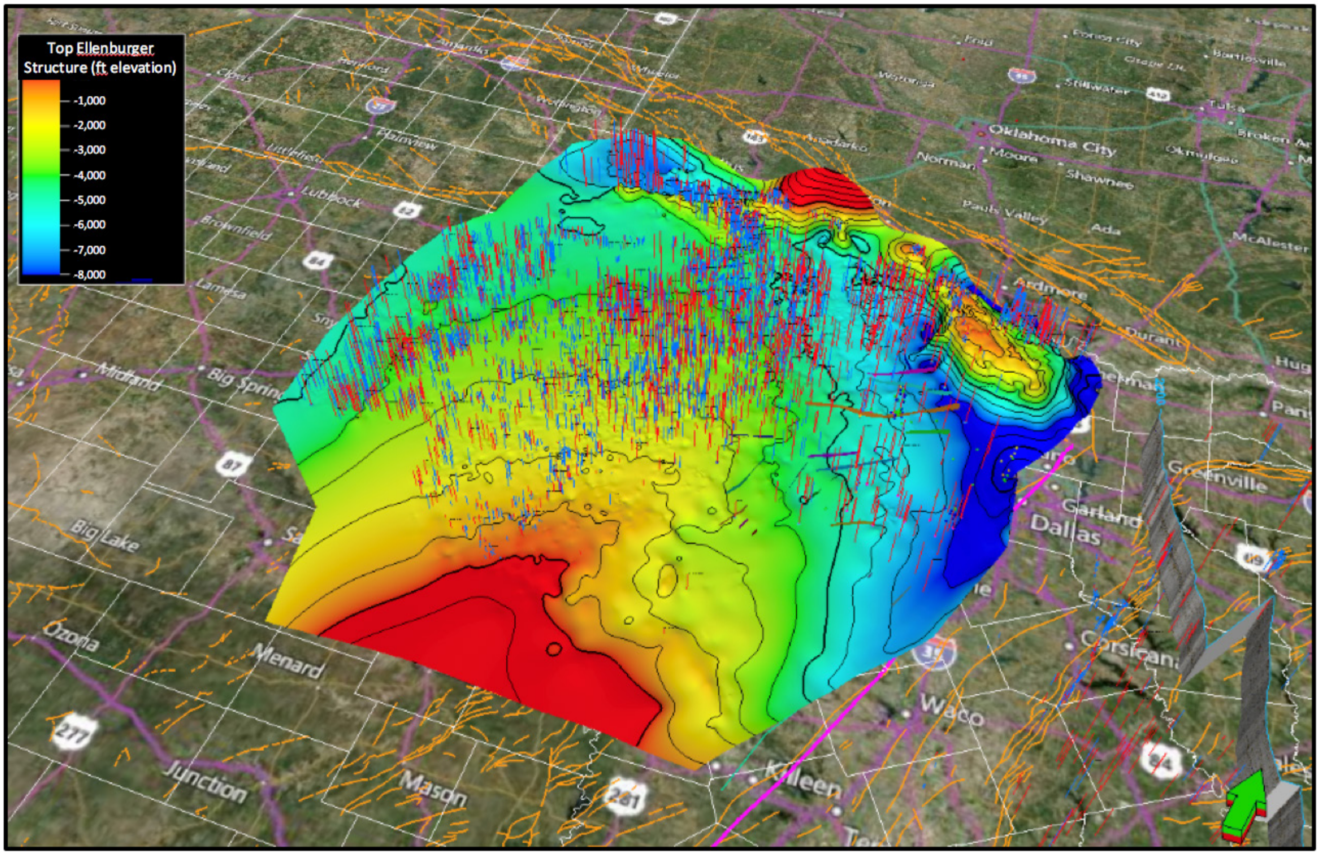


Figure 4.19 Oblique view northwest of the 3D geologic model, showing the top of the Ellenburger Group stratigraphic boundary which is, in general, the structural top of the intervals used for deep fluid injection in the Fort Worth Basin.

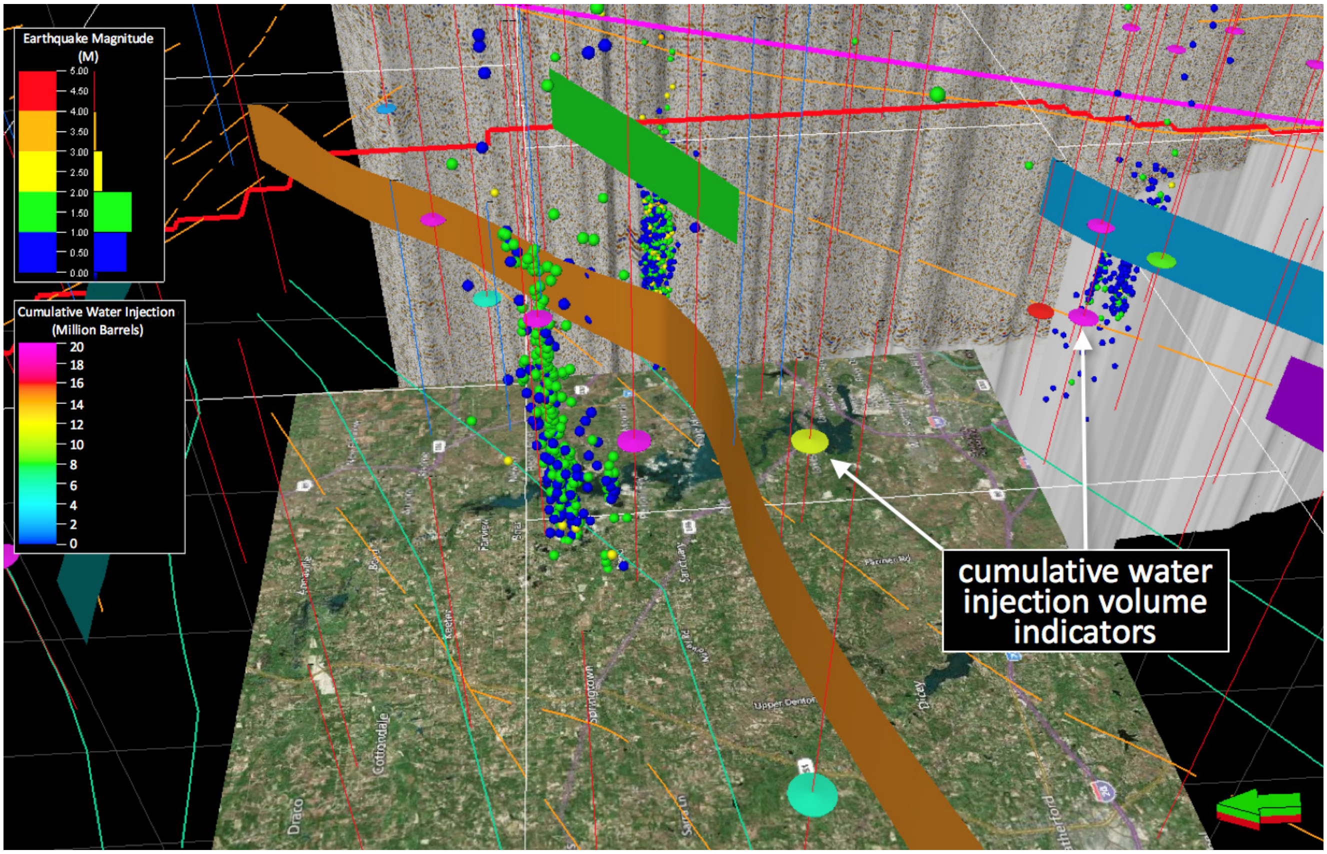


Figure 4.20 Oblique view east of the 3D geologic model, showing published fault surfaces, seismicity from the SMU North Texas Earthquake Catalog (spheres), and wells injecting into the Ellenburger Group indicating cumulative injected volume.

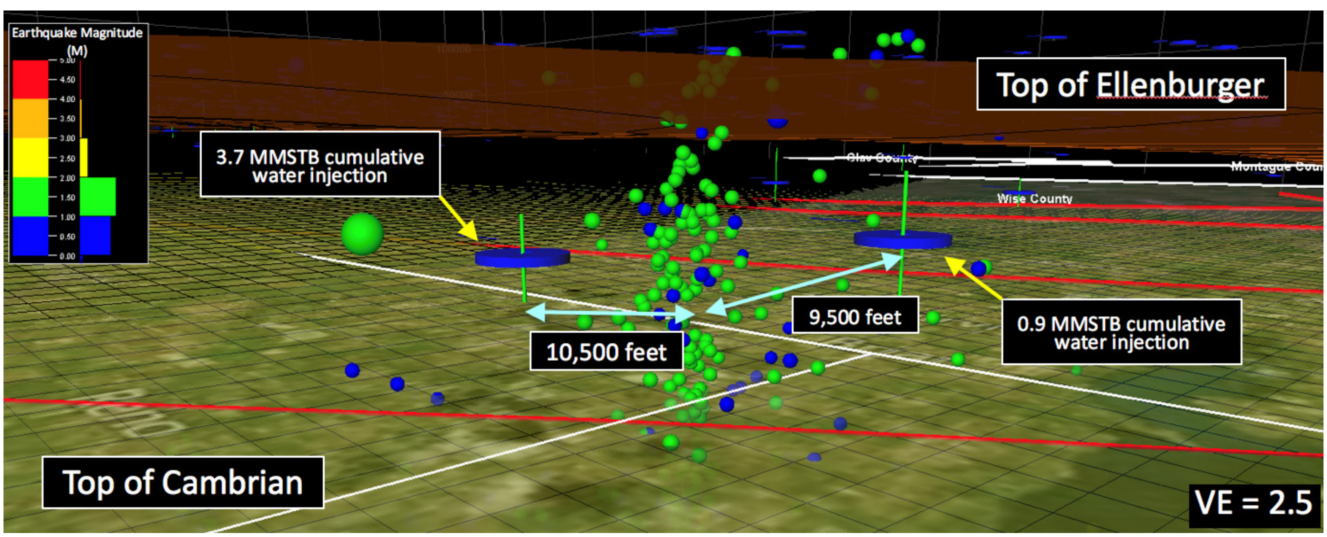


Figure 4.21 Lateral view north of the Azle seismicity sequence (spheres), showing events located within the Ellenburger Group injection interval and the location and distance to nearby injection wells.

Project Update: Llano Fault Zone Characterization (Peter Hennings and Johnathon Osmond, BEG)

Basement-rooted normal faults of the Llano Fault Zone are geologically continuous from the floor of the Fort Worth Basin southwest to surface exposures in the Llano Country of Central Texas, where they can be observed directly (**fig. 4.22a**). Several key outcrops identified in the area are being studied for fault architecture and fluid-flow characteristics (**fig. 4.22b**). The outcrops at Hoover Point are in a nested graben between faults that dip toward each other (**fig. 4.22c** and **d**). Using areal drone photography, the Hoover Point outcrop has been reconstructed as a 3D ortho-rectified geologic model for advanced characterization and modeling (**fig. 4.22e**). The outcrop displays a high density of small faults in Cambrian sandstones and limestones that, upon preliminary analysis, appear to be best classified as disaggregation zones indicative of faulting with limited overburden and a low clay content (Fisher and Knipe, 1998). Some clay-smear fault cores are observed, but many of these appear to have been diagenetically cemented with hematite, presumably from the abundant glauconite-bearing intervals interspersed within the faulted intervals.

Faults formed in these types of lithologies and under these burial conditions typically produce fault-permeability fabrics that moderately decrease across-fault permeability. Fault-parallel permeability may be enhanced relative to unfaulted rock. Given that the small faults in the Hoover Point graben are parallel in attitude to the larger faults of the system, we surmise that this fabric of deformation could (1) enable efficient hydraulic communication

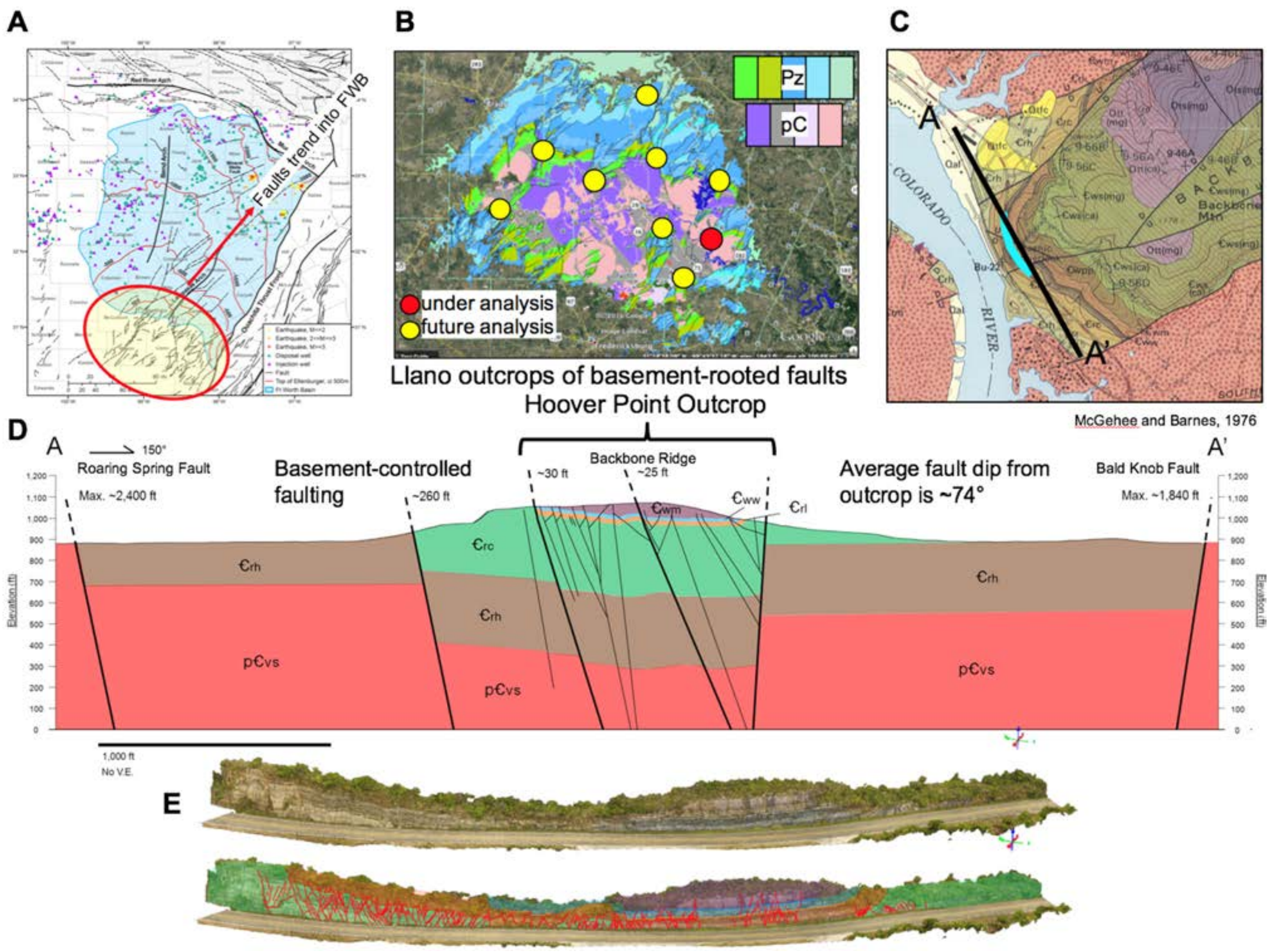


Figure 4.22 Graphics illustrating outcrop characterization work initiated in the exposures of faults in the Llano Country of Central Texas, where numerous faults of the Fort Worth Basin come to the surface and are observed as they cut the Ellenburger Group and cut down into the crystalline basement. **(a)** Map of faults at the surface and their continuity with the few documented faults in the Fort Worth Basin subsurface. **(b)** Location of outcrops scheduled for study; the red one (Hoover Point) is in progress. **(c)** Geologic map of the Hoover Point outcrop, where quantitative analysis is in progress. **(d)** New cross section through the Hoover Point area. **(e)** 3D outcrop model constructed from drone flight data.

vertically from overlying sedimentary intervals down into basement, and (2) produce significant lateral permeability enhancement parallel to the faults, which could produce permeability anisotropy whereby the permeability of the rock volume in the NE–SW direction could be significantly higher compared to that in the NW–SE direction. Given that the general strike of faults throughout the Llano Fault Zone, and into the Fort Worth Basin subsurface, is NE–SW, then the enhancement of permeability in the NE–SW direction may be further enhanced by the interaction of faults with the in situ stress state.

This work will progress vigorously in fiscal year 2016–17, leading to a 3D fault model of the exposed Llano Country faults and faults in the Fort Worth Basin subsurface, which will be analyzed for fault-reactivation likelihood, for their contribution to anisotropic fluid flow, and for how their effects will be geometrically and stochastically implemented in fluid-flow models.

Geomechanics of Basement Fault Reactivation (PI: Peter Eichhubl, BEG)

Project Background

An important aspect of evaluating seismic risk and devising approaches to minimize this risk is an understanding of reservoir fluid flow and its geomechanical implications. Numerical simulations of pore fluid pressure and in situ stress changes associated with fluid injection and production can be used to derive predictive models that relate natural processes and human activity to past and possible future earthquake activity. Geomechanical simulations can determine the plausibility of shear failure in certain areas depending on initial conditions and can provide guidance as to whether modified injection practices (e.g., lower rates or pressure, limits on total volumes) can reduce the potential for seismic events. Simulation also guides instrument deployment in the field and informs geologic and geophysical data-collection strategies.

This project will assess the effects of fluid production and injection on the stability of nearby faults using coupled poroelastic and thermoporoelastic numerical simulations. Using 2D and 3D finite-element simulations, we will assess the effect of multiple production and injection wells, heterogeneity in reservoir and fault permeability, and in situ stress state. Simulations will also investigate processes that may allow stress and pore-pressure transfer between porous injection horizons and underlying basement to assess the mechanics of earthquake nucleation in basement rocks. Simulations will be run with both generic fault and injection geometries, as well as with geometries informed by available subsurface structure and permeability information for recorded earthquake sequences with known injection and production history of nearby wells.

Project Update (Peter Eichhubl and Zhiqiang Fan, BEG)

Wastewater associated with oil and gas operations including formation brine and recovered hydraulic- fracturing fluids is routinely disposed of through reinjection into horizons of higher porosity and permeability than the producing reservoir. The recently observed increase in earthquake activity in a number of states including Texas has been linked to high-volume fluid injection (Horton, 2012; Ellsworth, 2013; Keranen and others, 2013; Kim, 2013; Frohlich and others, 2014; Fan and others, 2016). The common occurrence of earthquakes in the basement, far below the injection layer in the sedimentary unit, raises the question of why earthquake sequences nucleate in the basement before slip is induced in the injection layer (Nicholson and Wesson, 1990; Seeber and Armbruster, 1993; Seeber and others, 2004; Horton, 2012; Kim, 2013; Weingarten and others, 2015).

During fluid injection, pore pressure dissipates by fluid migration within the reservoir and possibly along the fault damage zone into the basement, resulting in a pore-pressure perturbation that is larger in the reservoir than in the basement. Therefore, pore pressure alone cannot account for the nucleation of seismicity in the deep crystalline basement induced by injection in overlying sedimentary formations. Fluid injection into reservoirs affects the stability of basement faults via two coupled processes: (1) raising pore pressure, thus decreasing effective normal stress and lowering resistance to fault reactivation, and (2) changing the shear and normal tractions acting on the fault because of poroelastic stress changes.

To test if basement-fault reactivation can occur before fault slip is induced in the injection reservoir, and to investigate the effects of stress regime and fault orientation on basement-fault reactivation, we developed 3D finite-element models using the code Abaqus, which couples fluid flow and geomechanical deformation with explicit representation of faults in the poroelastic rock matrix (**fig. 4.23**). The modeling domain consists of four layers and extends vertically from the surface to a depth of 6 km and horizontally to an 8 km × 16 km area. The 150-m-thick reservoir is situated between basement and a caprock layer that is overlain by 1,500 m of overburden. In all models, a fault cuts across the basement and penetrates into the overlying reservoir. The width of the fault is assumed to be 20 m, consisting of a 4-m fault core bounded by two 8-m-thick damage zones. The distance between the injection well and the upper tip of fault is 1 km. The fault has the same mechanical properties as the host rocks but different hydraulic properties. Based on representative laboratory data, we assume that the reservoir rock has a larger Biot coefficient and a smaller Poisson's ratio than the basement. We simulate the effects of continuous injection of water into the reservoir over 10 years at a constant injection rate of 60,000 m^3 /month.

The excess pore-pressure profile after 10 years of continuous injection for the normal-faulting stress regime is shown in **figure 4.24**. The maximum pore-pressure change at the bottom of the injection well is about 5 MPa after 10 years of continuous injection of water. The high-permeability fault-damage zone allows the pore pressure to propagate downward from the reservoir into the basement. The fault as modeled here serves as a barrier to flow across the fault because of the presence of a low-permeability fault core.

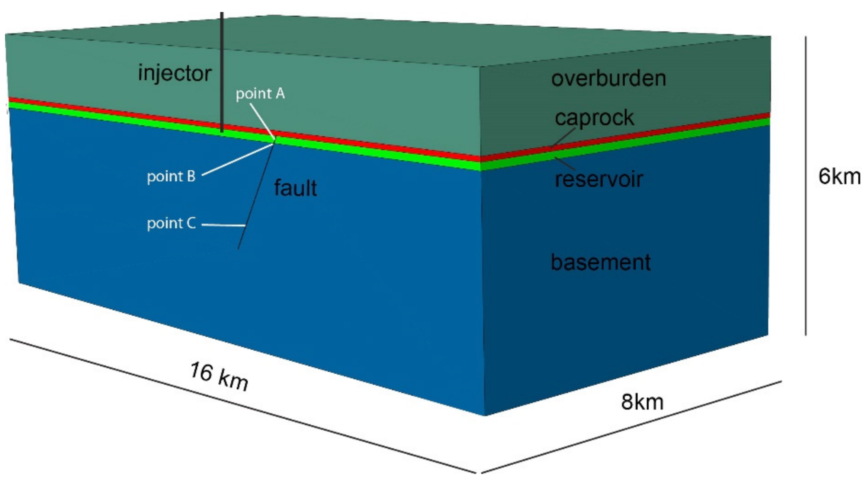


Figure 4.23 Schematic illustration of 3D finite-element model to simulate the temporal and spatial pore-pressure perturbations along faults. Coulomb failure stress on the fault is tracked at point A within the reservoir, at point B in the basement immediately below the reservoir, and at point C in the deeper basement.

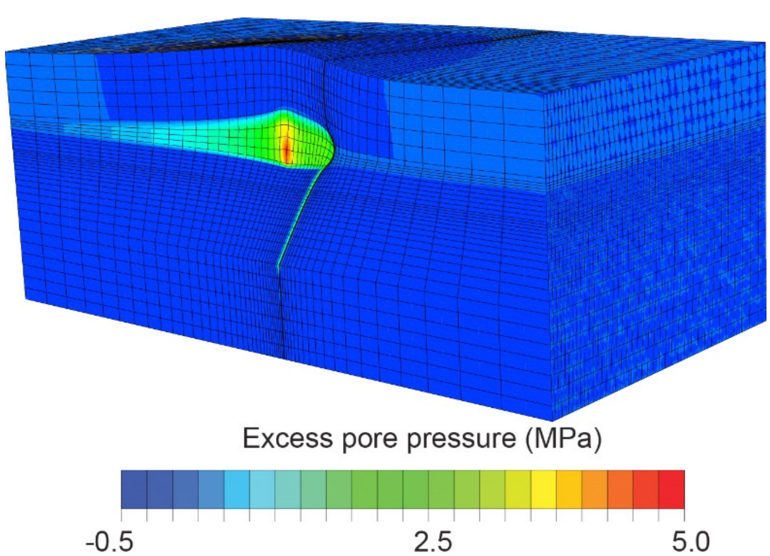


Figure 4.24 Excess pore-pressure profile after 10 years of continuous injection. Displacement induced by volumetric expansion of the reservoir is not to scale.

Coulomb failure stress (CFS) evolution is tracked for three points along the fault: one within the reservoir (point A, **fig. 4.23**) and two within the basement (points B and C, **fig. 4.23**). The temporal evolution of pore pressure and CFS at different points along the fault is shown in **figure 4.25**. The simulated pore pressure and CFS increase monotonically with time and follow a similar trend. At point C, poroelastic stress changes do not affect CFS significantly. At point B, which is located in the upper basement, the initial CFS prior to injection is lower than that at point A, which is located in the reservoir. However, the CFS at point B increases at a higher rate than that at point A and becomes positive earlier, thus allowing fault reactivation at point B before A, despite excess pore pressures being nearly identical at both points.

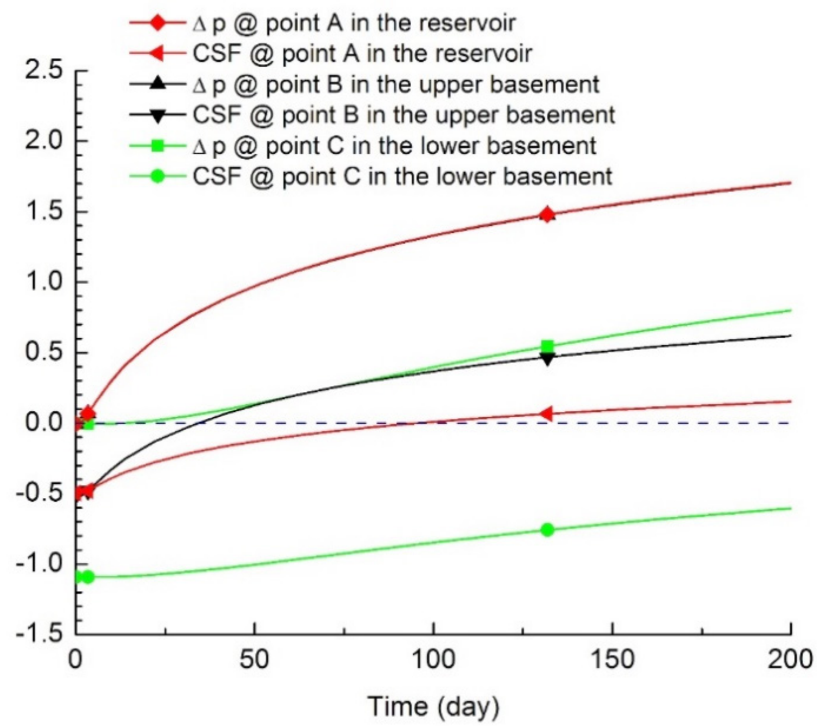


Figure 4.25 Evolution of excess pore pressure and Coulomb failure stress at points A, B, and C along fault segments in the reservoir and basement.

We explain this behavior through poroelastic stress changes. Induced normal tractions on the fault close to the injector are always positive (more compressive) as pore pressure increases and are counterbalanced by the increase in pore pressure. Because the reservoir rock has a larger Biot coefficient and a smaller Poisson's ratio than the basement, the increase in pore pressure leads to a more pronounced poroelastic effect in the reservoir. The induced normal traction is thus larger in the reservoir than in the basement, favoring slip in the basement.

Our results suggest that pore-pressure effects alone are insufficient to account for slip nucleation in the basement underlying the reservoir. Instead, slip nucleation along basement faults is governed by the combined effects of pore-pressure changes and resulting poroelastic stress perturbations, which highlights the importance of considering coupled poroelasticity in fault-stability analysis.

Pore-Pressure Analysis of Fort Worth Basin and Fault Rupture Modeling (PI: Jon Olson, UT-PGE)

Project Background

The mechanism for earthquakes to be induced by wastewater injection is the reduction of frictional resistance on the faults due to pore-pressure increase (Zoback and Healy, 1984). Although initial stress and pore-pressure data are sparse, we make an assessment of mapped faults in the Fort Worth Basin to determine whether they are critically stressed prior to injection. Important fault attributes are orientation, initial pore pressure, and horizontal stress magnitudes.

Project Update (Valerie Gono, Jon Olson, Rich Schultz, UT-PGE)

Gono (2015) performed a basinwide pore-pressure modeling study that included 374 wastewater injection wells across the Fort Worth Basin (**fig. 4.26**). Going forward, the goal is to perform geomechanical analyses on mapped faults that may be associated with earthquake events in the Fort Worth Basin, and to couple those analyses with previous basinwide pore-pressure modeling results to better understand why some areas of increased pressure have increased seismicity and others do not.

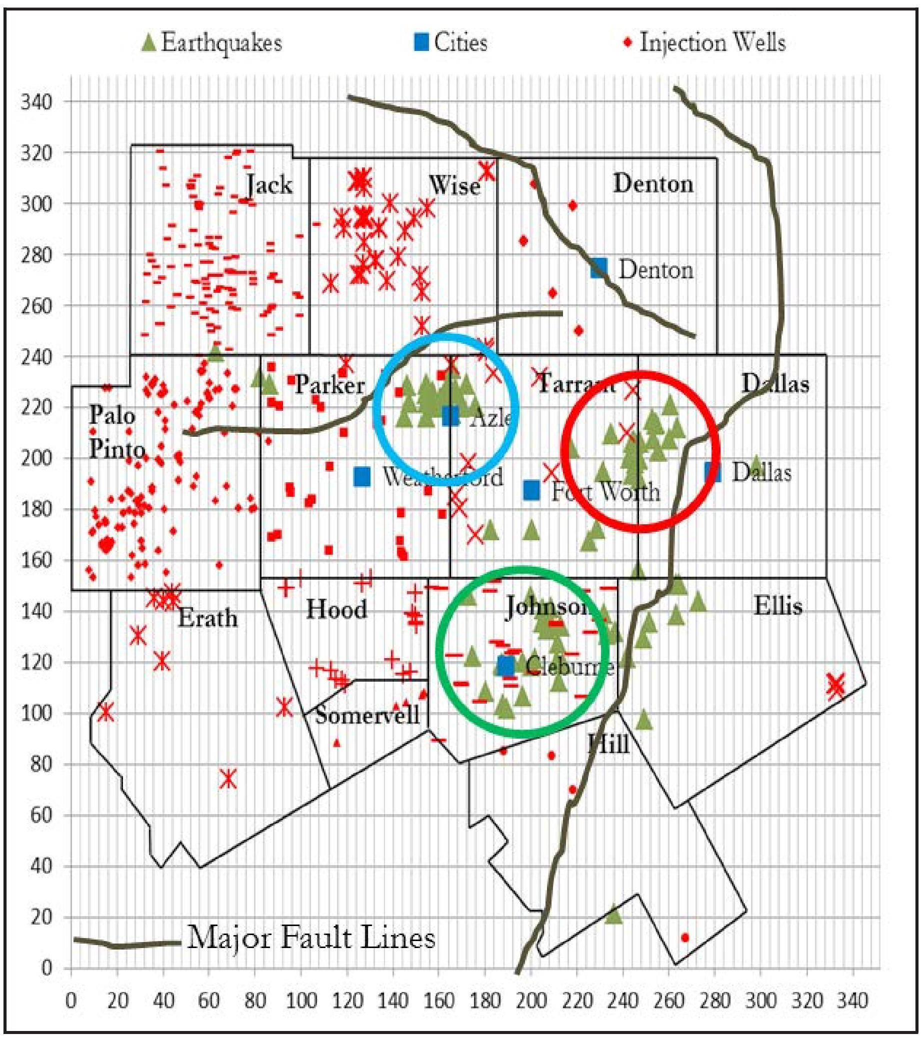


Figure 4.26 Discretized well-placement map showing where clusters of earthquakes occurred. Green triangles represent earthquake epicenters, blue squares represent cities, and red markers of various shapes represent locations of injection wells. Injection wells shown with the same marker shape are located in the same county. Red circle shows the Dallas–Fort Worth Airport earthquakes, green circle shows the Cleburne earthquakes, and blue circle shows the Azle earthquakes.

Preliminary basinwide pore-pressure modeling (Gono, 2015) indicates that for three earthquake clusters in the Fort Worth Basin—DFW Airport (DWFA), Cleburne, and Azle—spatial and temporal associations exist between wastewater injection and earthquake epicenters (**fig. 4.27**). Our multilayer flow model showed increased pore pressure in various formations throughout the Fort Worth Basin over an injection period from December 1997 to June 2014. The goal of our current work is to incorporate much more detail based on parallel geologic-mapping efforts. The previous geologic model was not detailed enough to adequately characterize formation-flow characteristic heterogeneity below the county scale.

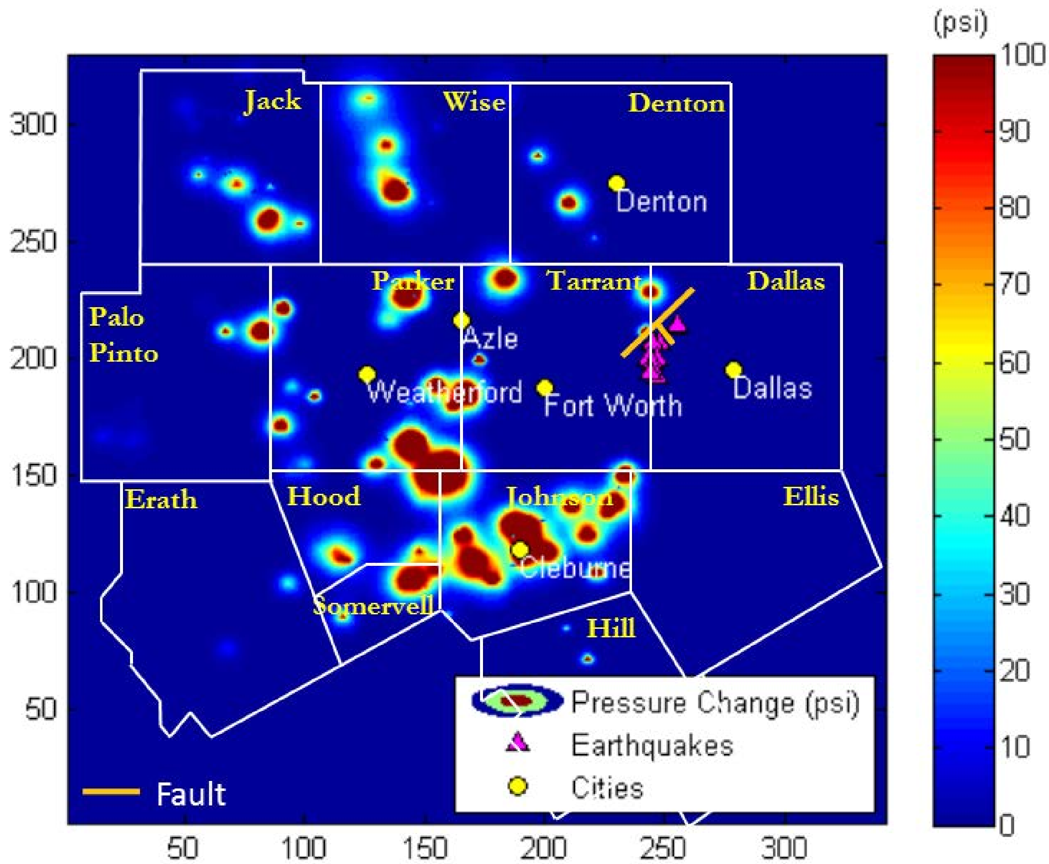


Figure 4.27 Pore-pressure increase plot for the Dallas–Fort Worth Airport (DFWA) earthquakes on 1 November 2008. The fault associated with the DFWA earthquakes is oriented at 33° in the NE–SW direction. The fault dip angle is 64° to the southeast. The maximum horizontal stress, S_{Hmax}, in the region is oriented NE–SW at 45°.

An example of a case needing more detailed geologic characterization is the fault associated with the DFWA earthquakes. The fault strikes N33°E with a dip angle of 64° to the southeast. The maximum horizontal stress in the region, S_{Hmax}, is oriented 12° clockwise from the fault strike (N45°E). Comparison of fault attributes and stress orientation shows that the fault is not critically stressed and should have been locked prior to injection. Flow-modeling results include some scenarios that can cause slip on the DFWA fault, but whether injection can cause slip is highly dependent on initial pore pressure in the region, horizontal-stress magnitudes, and formation permeability and thickness. In an effort to assess slip risk, we will perform a sensitivity analysis of key parameters that could drive induced seismicity. This analysis should highlight which parameters are most crucial for risk evaluation and indicate to what level of accuracy they need to be quantified.

Further work on the Fort Worth Basin is planned to assess the slip potential on other mapped faults. Another factor to be included is the flow capacity of the faults themselves, which is thought to be a factor in controlling how seismicity can move from sedimentary cover to basement rocks. All of this modeling work will be measured against actual injection-well histories and recorded earthquakes.

Theoretical Analysis of Controls on Size of Earthquakes Induced by Fluid Injection (PI: Jon Olson, UT-PGE)

Project Background

We will develop a model that couples fluid mechanics and earthquake-rupture physics, which will allow us to examine sensitivities between injection volume, injection rate, injection pressure, distance between injection site and fault, reservoir properties, and other controlling factors. Expecting to gain a physical understanding of fundamental processes that impact earthquake size, timing, and location, we will benchmark our model by running it against situations where injection is thought to have triggered earthquakes. Based on model results, we hope to provide a set of mitigation strategies that can be used to delay or impede earthquake nucleation.

Project Update (Mohsen Babazadeh, Jon Olson, and Rich Schultz, UT-PGE)

The objectives of the present study are to (1) investigate the causative relationships between fluid injection and seismicity suggested in the literature, and (2) generate a suite of recommended practices to mitigate induced seismicity.

The causality of earthquakes induced by wastewater injection is likely due to the interaction of fluid flow with existing faults. Wastewater injection increases underground fluid pressure, and increased fluid pressure reduces frictional resistance on the fault, possibly inducing sliding displacement. Whether fault slip generates measurable seismicity depends on fluid pressure and stress factors (initial reservoir pressure, in situ stress, rate of fluid pressure increase, and so on), as well as on fault-plane characteristics (orientation relative to principal stress directions, fault strength, weakening and strengthening of the fault during rupture, and so on) (Terzaghi, 1943; Barton and others, 1995; Ellsworth, 2013; National Research Council, 2013; Dieterich and others, 2015).

We couple a 3D geomechanical model to a 3D reservoir simulator to model the nucleation and propagation of an induced slip event on a preexisting fault. A 3D finite-difference reservoir simulator solves for pressure diffusion through the formation and on the fault surface. The fault is discretized into boundary-element patches with initial frictional strengths given by the Coulomb criterion. A rate and state friction relation is then implemented to account for unstable and stable rupture growth. The results should enable the correlation of the magnitudes of induced seismic events with injection parameters such as rate, volume, and pressure. An adaptive time-stepping is used in order to optimize efficiency and accuracy.

The tool as described is now operational, and we are starting to investigate some of the basic relationships between fluid flow and slip induced on faults. The first results suggest that for a critically stressed fault 100 m in height and length located within 100 m of a 10,000 bbl/day injection well, slip events that have a Richter measurement of M1 to M2 can be generated. Earthquake magnitude is calculated from seismic moment, which is a function of formation stiffness (shear modulus), slip magnitude, and area (length x height) of the slipped fault segment (Hanks and Kanamori, 1979).

The propagation of a slip event is illustrated in **figure 4.28**, which shows the distribution of slip velocity at seven successive timesteps. The figure shows that the maximum velocity occurs at slip initiation in the center of the fault (0.3 m/s), and that the slip then propagates out to the fault tips at a diminishing rate. The details of the slip velocity history may be used to validate the model against documented earthquakes and will help in devising slip mitigation strategies related to controlling injection-well parameters.

Ongoing investigations will further explore the importance of other factors such as injection volume, reservoir properties, multiple interacting faults, and ground motions (e.g., for shake maps and deformation monitoring). We will also compare our earthquake-source physics model with simpler approaches like Mohr–Coulomb for earthquake size and extent on the fault. We will then run several case studies to identify steps that could be used to mitigate the occurrence of large induced events.

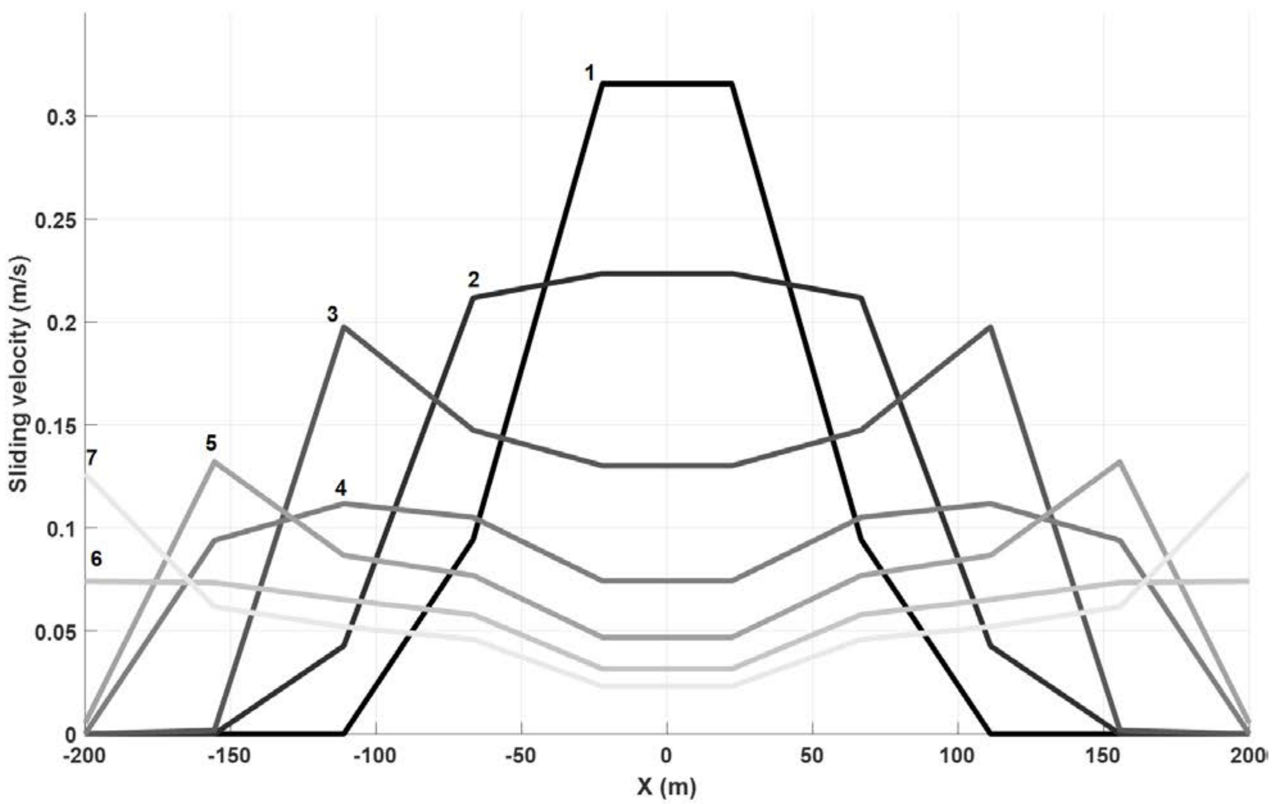


Figure 4.28 Evolution of sliding velocity through time for the fault's middle strip of slipping patches. The shading of the lines becomes lighter, indicating the progression of time, and the numbering is based on time, as well. This plot shows how slip cascades along the fault.

Coupled Fluid Flow and Geomechanical Modeling (PI's: Akhil Datta-Gupta, Michael King, Jihoon Kim, TAMU-PE)

Project Background

In November 2013, a series of earthquakes occurred near a fault system in Azle, Texas. This seismicity is suspected to have been induced by brine production and wastewater injection in the vicinity of the fault system. Small changes in stress near changes in pore pressure can activate a fault system, especially if the fault is almost critically stressed. This phenomenon can be modeled using coupled fluid flow and geomechanics. However, no systematic modeling of coupled flow, geomechanical effects, and induced seismicity has been carried out for the region near the Azle site. We are conducting modeling of fluid flow through complex faulted systems, visualizing transport across faulted systems using streamlines, assessing fault activation using coupled fluid flow–geomechanical simulation, and calculating potential induced seismicity through calculation of seismic moments.

A coupled geomechanical and fluid-flow reservoir simulation may capture the interaction of the mechanisms described above. However, the predictive ability of the model will be limited by our knowledge of formation characteristics, which includes structure, stratigraphy, local and regional stress state, fault geometry, fault seal, and petrophysical and geomechanical properties. Some of these characteristics may be known or estimated by prior geologic modeling but with considerable uncertainty. The impact of these characteristics will need to be evaluated using sensitivity studies that should acknowledge three scales of unknowns. The regional scale will control the stress-boundary conditions on the geomechanical calculation. The stratigraphic scale will describe the systematic variation of properties throughout the formation. The local scale of heterogeneity will describe the variability of properties within the strata of a formation. All may influence the impact of predictions of fault activation and induced seismic activity.

Project Update (Rongqiang Chen, Xu Xue, Jaeyoung Park, Hyun Yoon, TAMU-PE)

One previous study based on pore-pressure models indicated brine production and wastewater disposal as the likely causes of the November 2013 series of earthquakes near Azle (Hornbach and others, 2015). Geomechanical modeling and rock-failure conditions were not included in this work.

For this study, our focus is to develop a detailed simulation model for coupled fluid flow and geomechanical modeling of fluid injection/production, potential fault activation, and history matching of seismic events. We will then utilize this calibrated model to perform sensitivity studies with respect to rock-failure conditions (fault activations) for a broad range of reservoir and geomechanical parameters.

The workflow for this study is described in **figure 4.29**, and a simple model with two tilted intersected faults is created to test the workflow. Our test geologic model as shown in **figure 4.30** has one primary normal fault extending down-dip through the crystalline basement (strike 225°, dip 60–70°) and a more steeply dipping (~70–80°) shallow conjugate normal fault (Hornbach and others, 2015; RRC 2015a, 2015b).

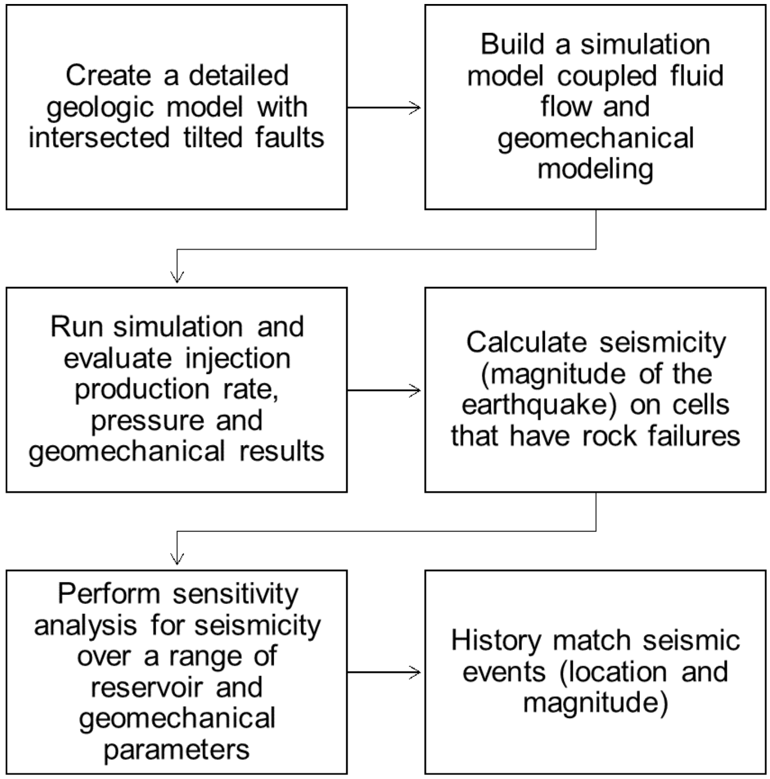


Figure 4.29 Workflow for seismicity sensitivity using coupled fluid flow and geomechanical modeling simulation.

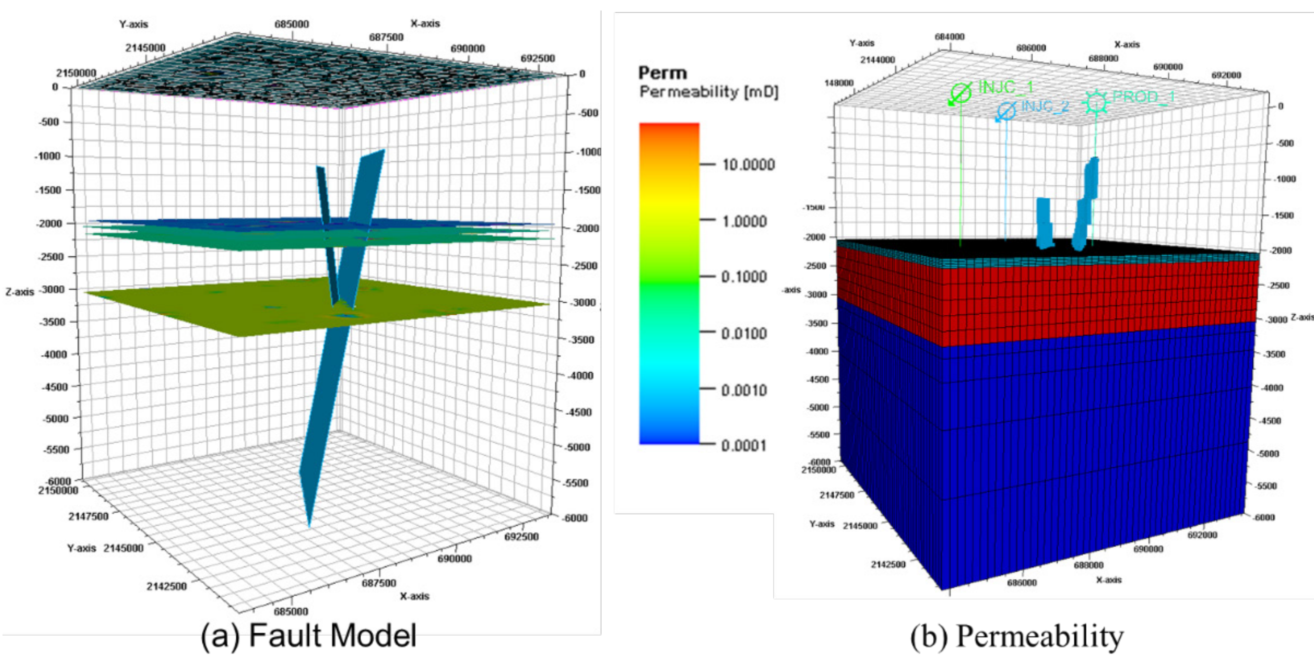


Figure 4.30 (a) Fault and horizon model; **(b)** simulation model with permeability.

A three-zone (Barnett Formation, Ellenburger Group, and basement) test simulation model is created with homogeneous reservoir and geomechanical properties in each zone. This single-phase model has 49 × 49 × 15 grids with an XY dimension of 200 m × 200 m. The model has two injectors and one major producer; simulation time is 8 years. **Figure 4.31** lists the simulation-model input data and corresponding sources. The near-critical initial stress conditions and typical rock geomechanical properties of the Timpson field are used for this initial study. There are high uncertainties related to this input. **Figure 4.32** shows the aerial view of fluid flow and geomechanical simulation results at the end of the simulation run. Rock failures occur in both the Ellenburger Group and the basement from layer 6 to layer 15. After the simulation run, and using geomechanical outputs, the rock-failure indicator for each cell is calculated.

	Barnett	Ellenburger	Basement	Fault	Reference
Permeability (md)	1e-3 – 1e-4	10-100	1e-4 – 1e-5	Transmissibility Multiplier = 0.1	Hornbach et al. 2015
Porosity	0.06	0.055	0.05	Transmissibility Multiplier = 0.1	
Pore Pressure	23 kPa @ 2046 m				Fan et al. 2016
Z Effective Normal Stress	12.76 kPa/m				
X Effective Normal Stress	12.76 kPa/m				
Y Effective Normal Stress	2.66 kPa/m				
Young's Modulus (kPa)	4.0e7	6.0e7	4.3e7	4.0e7	Wang 2000
Poisson's Ratio	0.23	0.2	0.27	0.2	
Cohesion (kPa)	2.0e4	2.0e4	2.0e4	1.5e3	
Friction Angle (Deg)	30	30	30	30	
Dilation Angle (Deg)	25	25	25	25	

Figure 4.31 Test simulation-model input.

The sensitivity-analysis result is shown in **figure 4.33**. As shown, the reference case of the test model results in a M1.6 earthquake. For the wide range of parameters tested, the seismic moment ranges from 0.7 to 2.9. Rock geomechanical properties such as cohesion and Young's modulus near the basement are the most sensitive parameters in this sensitivity study; they are also the most uncertain input parameters in the model.

In summary, a detailed workflow for the Azle-area seismicity sensitivity study has been developed and tested using a simple simulation model with coupled flow fluid and geomechanical effects. Our next step is to build a more detailed geologic model with BEG that includes well logs and fault-picks data. We will also include all production wells in the simulation model. The simulation-predicted seismic events will then be history matched with the actual seismicity data for sensitivity analysis and uncertainty assessment.

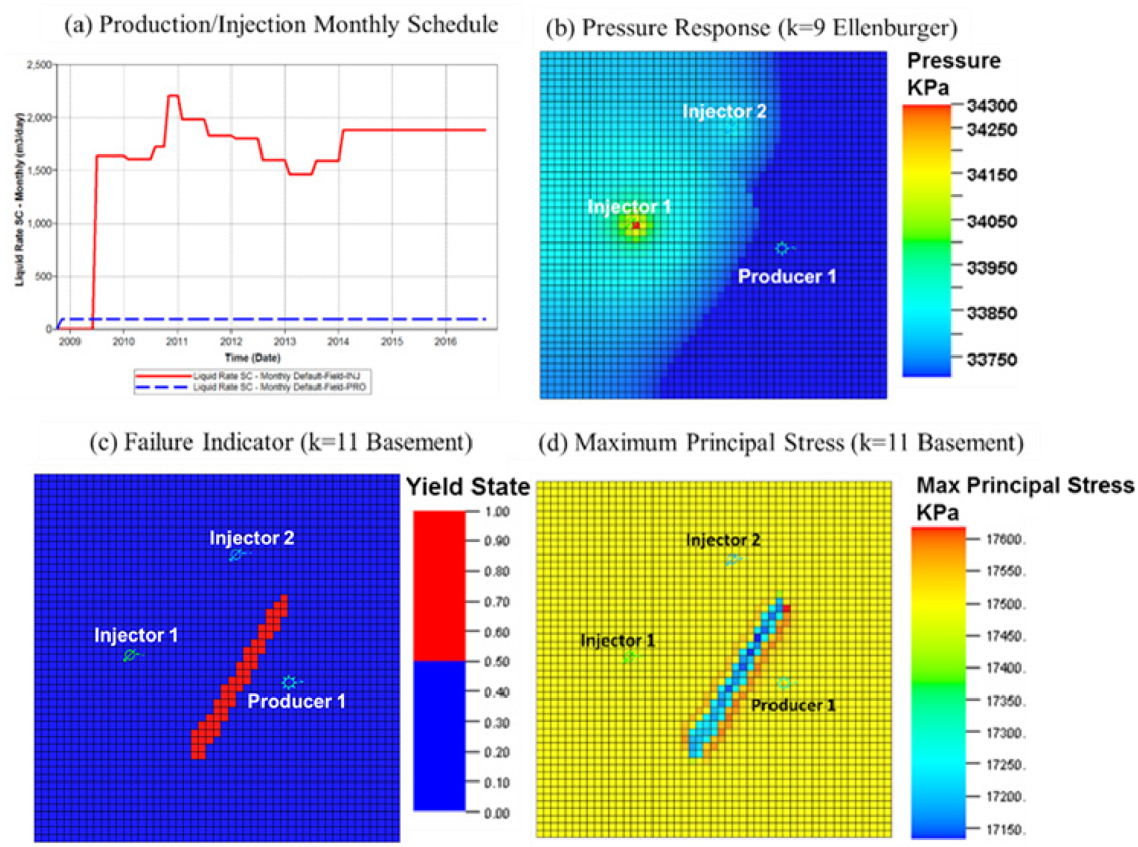


Figure 4.32 Example fluid-flow and geomechanical-simulation results.

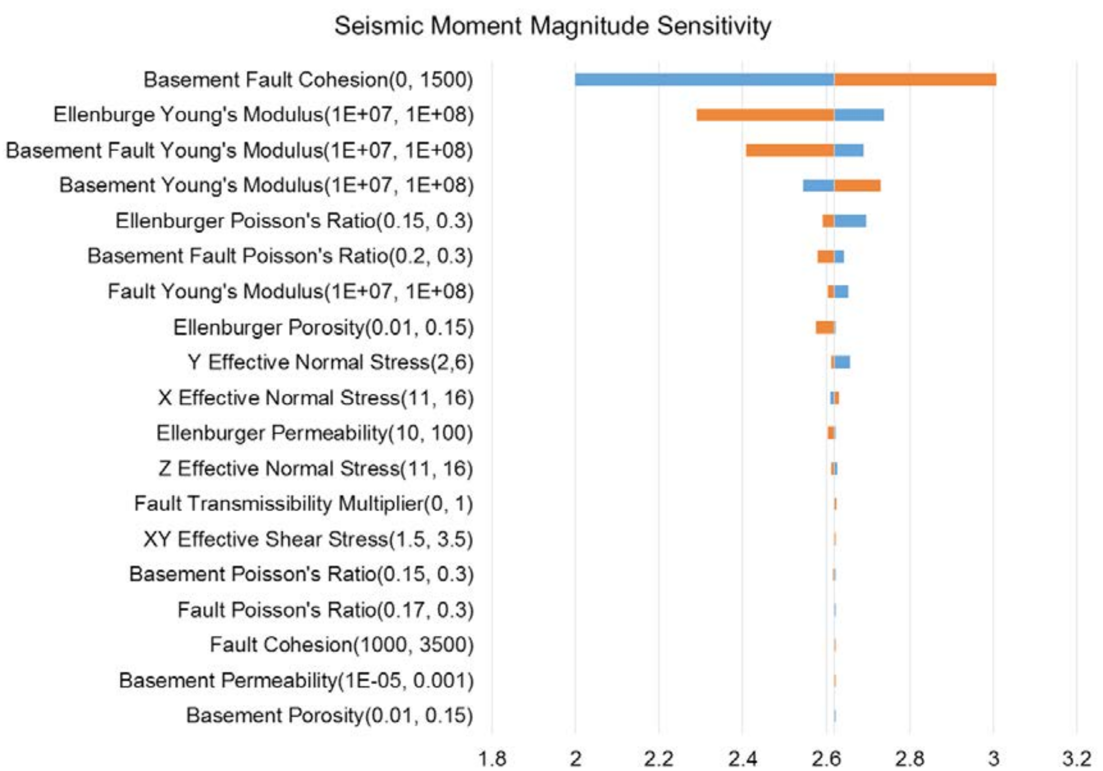


Figure 4.33 Seismic moment sensitivity analysis.

Summary

Using funds provided by the State of Texas, the Bureau of Economic Geology and its research partners have designed the TexNet Seismic Network and implemented a portfolio of studies to understand the nature and causes of seismicity in Texas. Several key staff positions were filled with hires from international searches, and a broad collaboration was established with notable scientists and engineers from units at The University of Texas, Texas A&M University, Southern Methodist University, and other institutions both within and outside Texas. The TexNet Technical Advisory Committee has provided valuable advice, direction, and oversight of this process and progress.

Acquisition of the necessary equipment and deployment of TexNet seismic stations is proceeding according to plan and budget. The network will add 22 new permanent broadband seismic stations to the existing 18 stations to create the TexNet seismic "backbone." The permanent stations–which require an in-depth process of site visits and landowner discussions for each station–will be fully installed by mid-2017. In addition, 36 portable stations, which also include accelerometers to study ground motion when earthquakes are nearby, are being added to the network. Ten of these portable seismic stations have been installed in the Dallas–Fort Worth area already and their data are currently streaming live, recording earthquakes both within and outside of Texas.

Once completed in 2017, the TexNet Seismic Network, with up to 76 stations (58 TexNet and 18 existing) deployed at any given time, will provide monitoring capabilities unparalleled in the United States for a network of its scope and scale. TexNet seismologists will use these data to study earthquakes in Texas to determine their essential characteristics. This information will be used by an interdisciplinary team of scientists and engineers who are moving beyond associative, and developing a mechanistic understanding of the cause(s) of the seismicity. Research conducted by this team has begun on seven integrated projects spanning the disciplines of seismology, geology, geomechanics, and reservoir engineering. Their research will enable us to better quantify the potential impacts of these earthquakes and the technical steps that can be taken to mitigate occurrences of future seismicity. Funding from the State of Texas is tracking closely with this progress and with the status in the biennium; as of October 31, 2016, the total spent is $2,285,257, or 51.1%, of the budgeted amount of $4,471,800.

The TexNet research team is making solid research progress as described in this report. We anticipate that by 2019, sufficient earthquake data will be available to fully support subsurface characterization and modeling. Therefore, it is vital that funding for TexNet operations and research be continued. We seek and recommend continued funding of $3.4 million for the 2018–19 legislative cycle.

The TexNet team at the Bureau of Economic Geology, along with our research partners, are honored to be leading this important project for the State of Texas and look forward to our continued work helping to safeguard Texas citizens, and providing a Texas example for other states to follow.

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TexNet Technical Advisory Committee

Introduction

Governor Greg Abbott has appointed Dan Hill, Chris Hillman, Dana Jurick, Hal Macartney, Kris Nygaard, Craig Pearson, Brian Stump, Scott Tinker, and Robie Vaughn to the Technical Advisory Committee to the Bureau of Economic Geology at The University of Texas at Austin (UT) for terms at the pleasure of the governor. Vaughn has been designated as presiding officer of the Committee. House Bill 2, passed by the Texas Legislature during the 84th legislative session, created the Advisory Committee and appropriated $4.47 million to UT for the purchase and deployment of seismic equipment, maintenance of seismic networks, and modeling of reservoir behavior for systems of wells in the vicinity of faults. The Committee will advise the Bureau of Economic Geology on the use of the funding, including the TexNet Seismic Network and collaborative research relationships with other universities in Texas, and on the preparation of a status report to the governor and Legislature.

Mission Statement

The mission of the Technical Advisory Committee ("TAC") is to fulfill the responsibilities as established in House Bill 2, passed by the Texas Legislature during the 84th Legislative Session, and to continuing related efforts as directed by the State of Texas and the Governor.

The TAC will advise the Bureau of Economic Geology ("BEG") on the use of the funding, including the TexNet Seismic Monitoring Program and collaborative research relationships with other universities in Texas, and on the preparation of a status report to the Governor and Legislature.

The TAC will further advise BEG and TexNet on the work to establish high quality recordings of seismic events occurring within the boundaries of the State of Texas. These data, when integrated with geological, hydraulic, and geomechanical characteristics and combined with reservoir modeling near faults, shall provide a basis for understanding both the spatial distribution and the source mechanisms of earthquakes statewide, so that the Citizens of Texas and State officials are proactively informed and prepared for the future.

Advisory Committee

Members

Robie Vaughn, Chair. Robie Vaughn of Dallas is the owner of Vaughn Capital Partners, LLC. He is a member of The University of Texas System Chancellor's Council Executive Committee, the McDonald Observatory and Department of Astronomy Board of Visitors, the Athletics Longhorn Educational Foundation Advisory Council, and the Culver Educational Foundation Board of Trustees. He is also a life member of The University of Texas at Austin Development Board, President's Associates, Texas Exes, and Texas Cowboys Alumni Association. Vaughn served on The Commission of 125 as co-chair of the Resources and Infrastructure Committee for The University of Texas at Austin in 2003–04. He received a Bachelor of Business Administration from The University of Texas at Austin.

Dan Hill. Dan Hill of College Station is a professor and the Stephen A. Holditch Department Head Chair of the Harold Vance Department of Petroleum Engineering at Texas A&M University. He is a Distinguished Member of the Society of Petroleum Engineers (SPE) and a member of its board of directors. Hill received a Bachelor of Science from Texas A&M University and a Master of Science and Doctor of Philosophy from The University of Texas at Austin.

Chris Hillman. Chris Hillman of Irving is city manager for the City of Irving. He is a member of the International City/County Management Association and the Texas City Management Association. Hillman received a Bachelor of Arts and Master of Public Administration from Brigham Young University.

Dana Jurick. Dana Jurick of Houston is manager of Seismic Analysis for the Geoscience and Reservoir Engineering Organization at ConocoPhillips Company. He is a member of the Society of Exploration Geophysicists, and he was honorably discharged from the United States Army Reserve. Jurick received a Bachelor of Science from Syracuse University and a Master of Science from the University of Texas at El Paso.

Hal Macartney. Hal Macartney of Irving is geoscience manager of Sustainable Development for Pioneer Natural Resources. He is a member of the American Association of Petroleum Geologists, American Geophysical Union, Seismological Society of America, Rocky Mountain Association of Geologists, and the Society of Petroleum Engineers. Macartney received a Bachelor of Arts from Dartmouth College.

Kris Nygaard. Kris Nygaard of Houston is senior stimulation consultant for ExxonMobil Upstream Research Company. He is a member of the Society of Petroleum Engineers, Society of Mechanical Engineers, Seismological Society of America, and the Tau Beta Pi National Engineering Honor Society. Nygaard received a Bachelor of Science, Master of Science, and Doctor of Philosophy from the University of Arizona.

Craig Pearson. Craig Pearson of Midland is the State Seismologist for the Railroad Commission of Texas. He is a member of the American Geophysical Union, Seismological Society of America, American Association of Petroleum Geologists, and the International Society of Explosives Engineers. Pearson received a Bachelor of Science from the University of Texas of the Permian Basin and a Master of Science and Doctor of Philosophy from Southern Methodist University.

Brian Stump. Brian Stump of McKinney is a professor and the Albritton Chair of Geological Sciences at Southern Methodist University. He is a member of the Seismological Society of America, Society of Exploration Geophysicists, International Society of Explosives Engineers, and the American Geophysical Union. He is also a fellow of the Royal Astronomical Society and the American Association for Advancement of Science. Stump received a Bachelor of Arts from Linfield College and a Master of Arts and Doctor of Philosophy from the University of California, Berkeley.

Scott Tinker. Scott Tinker of Austin is the State Geologist of Texas, director of the Bureau of Economic Geology, acting Associate Dean of Research and Edwin Allday Endowed Chair of Subsurface Geology and professor at The University of Texas at Austin Jackson School of Geosciences. He is a past president of the American Association of Petroleum Geologists, Association of American State Geologists, and American Geosciences Institute. Tinker received a Bachelor of Science from Trinity University, Master of Science from the University of Michigan, and Doctor of Philosophy from the University of Colorado.

TexNet Web Resources

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