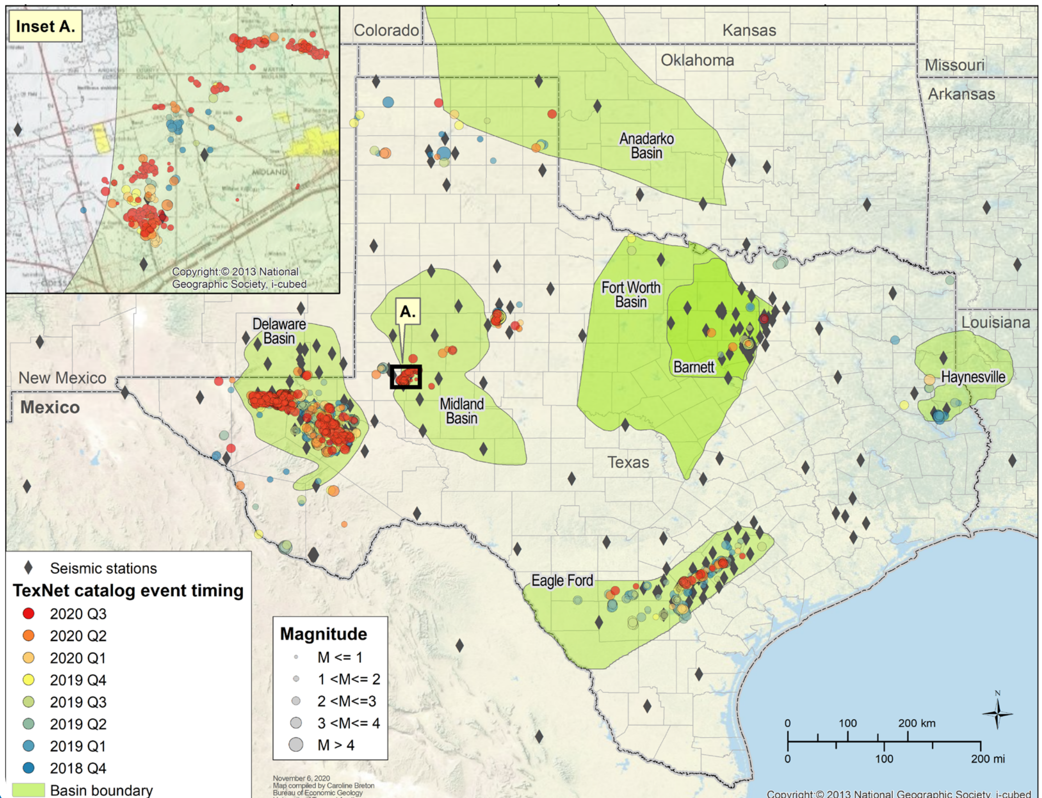
2020 Biennial Report on Seismic Monitoring and Research in Texas

November 30, 2020

The University of Texas at Austin

Bureau of Economic Geology

Scott W. Tinker, Director



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TexNet | Bureau of Economic Geology

TexNet Mission Statement and Objectives

Provided by the Technical Advisory Committee, July 28, 2020.

Mission Statement

Serve as an independent scientific body that measures and analyzes earthquakes and associated data, and distributes and communicates these data and related products to government, industry, and the public for their benefit and the benefit of the State of Texas.

Objectives

- Maintain a network of seismometers capable of accurately recording earthquake data across Texas.
- Exceed the network technical performance metrics established in consultation with the TexNet Technical Advisory Committee (TAC), USGS, and other authoritative bodies.
- Continuously strive to increase the accuracy of hypocenter location analyses and report with uncertainties.
- Maintain high-quality electronic databases of all event catalogs and products and make them available as appropriate.
- Seek to understand causes of seismic activity in Texas.
- Seek to understand and quantify the impact and risk to public safety and infrastructure.
- Distribute data and analyses to stakeholders effectively and in a timely fashion, recognizing their different needs. Stakeholders include:
    - Railroad Commission of Texas (timely, mission-critical supporting information)
    - Texas Division of Emergency Management, Texas Department of Transportation, Texas Commission on Environmental Quality, University Lands (rapidly for large events)
    - Local Communities
    - Oil and Gas Industry
    - Academic Research Community
    - General Public
    - Media
- Receive and utilize input from the stakeholders

TexNet Technical Advisory Committee Members

Brian Stump, Committee Chair – SMU (Southern Methodist University)
Mark Boyd, Committee Member – ConocoPhillips
Cal Cooper, Committee Member – Apache (retired)
David Ferrill, Committee Member – SwRI (Southwest Research Institute)
Chris Hillman, Committee Member – City of Irving
Alika Valdez, Committee Member – Texas Division of Emergency Management
Jeff Nunn, Committee Member – Chevron
Kris Nygaard, Committee Member – ExxonMobil Upstream Integrated Solutions
Scott Mitchell, Committee Member – Deep Blue Midstream
Aaron Velasco, Committee Member – UTEP (The University of Texas at El Paso)
Scott Tinker, *ex officio*

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1.0 Executive Summary

The Texas Seismic Monitoring and Research Program (TexNet) at the Bureau of Economic Geology was created by the 84th Texas Legislature to address the increase of seismicity in Texas that began in 2009. TexNet was appropriated $3.4 million for the current biennium by the 86th Legislature. With these funds TexNet expanded the network seismic stations, decreased the time for cataloging and reporting earthquakes, and conducted research to better understand seismicity in the state. The most significant accomplishments of TexNet during the current biennium:

- USGS approved TexNet as a self-supporting Advanced National Seismic System member based on extensive technical qualification review.
- TexNet continues to determine the causes of Texas earthquakes and help to limit the damage from any future Texas earthquakes.
- A healthy and safe Texas oil and gas industry is vital to the state's continued prosperity, and TexNet plays a key supporting role in enabling and building that prosperity. With companies, state agencies, and public and private state universities as partners, TexNet helps the oil and gas industry to operate safely within the state, ensuring continued production from Texas plays and the associated stream of state production-tax revenue.
- TexNet provides uninterrupted high-quality waveform data, continually cataloging earthquakes and improving their location accuracy, freely available to all. A timely, updated earthquake catalog is available at **https://www.beg.utexas.edu/texnet/catalog**, providing near-real-time earthquake information to all Texans.
- TexNet distributes earthquake information 24/7 in less than 20 minutes from the time of occurrence for all events with magnitude greater than or equal to 3.0.
- TexNet's field crews successfully continue to provide seismic station maintenance while following strict COVID-19 safety protocols.
- TexNet is documenting and assessing ongoing seismic activity in seven main areas (see Figure 5.1): the Delaware Basin and the Midland–Odessa area of West Texas; the Panhandle; the Dallas–Fort Worth area; East Texas; the Eagle Ford area; and Cogdell field near Snyder. All these areas have experienced at least one felt earthquake event with magnitude higher than 3.0 since September of 2019.
- During 2019, the highest-magnitude event (M_L 4.2) occurred on September 30, near Snyder (in the Midland Basin). In 2020 (through October), the highest magnitude event (M4.9) occurred in the Delaware Basin along the Culberson–Reeves County line. From March to July 2020 (the onset of COVID and oil price decline), seismicity dropped except in the Permian Basin. Seismicity began to increase in August 2020 in the Eagle Ford, Permian, and Snyder areas, illustrating the critical importance of real-time monitoring across the state.
- Based on TexNet research results and peer-reviewed publications, we conclude that recent seismicity in the Delaware Basin is most likely induced by a combination of hydraulic fracturing and saltwater disposal.
- Although the seismic risk in the Dallas–Fort Worth urban area decreased during the current biennium (consistent with a decrease in measured seismicity), seismic risk increased in the Midland–Odessa region, where 13 events with magnitude greater than or equal to 3.0 have occurred (compared with none in the previous biennium).
- Consistent with its mission to serve the State of Texas, TexNet leadership meets regularly with the TexNet TAC and the Railroad Commission to discuss the direction of data collection and future research outcomes, both important for regulatory decision-making. Leadership regularly meets with various stakeholder groups, including city councils, citizens' groups, and oil and gas operators.
- TexNet monitoring program was reviewed by an external peer-review panel in 2019. The panel included members from academia and industry. The peer-review team overwhelmingly endorsed the work that has been achieved in a short period of time. Also, the TexNet-CISR Annual Research Review was a success, with up to 120 attendees throughout the day. During the review, TexNet-CISR research teams presented the groundwork, studies, and findings evaluating seismic activity and how it has affected the State of Texas.

Recommendations: TexNet produces freely available data sets and associated analysis products that quantify in near-real-time seismicity in Texas. Both the data and data products are used by many to advance the overall understanding of Texas earthquakes. These products are critical to the assessment of earthquake hazards in Texas and support the mitigation of earthquake activity linked to human activity while assessing hazards and risks from future Texas earthquakes.

These critical, legislatively mandated tasks allow the State of Texas to remain prepared for earthquakes while ensuring the safety of the contributions of the oil and gas industry to its prosperity. This effective use of past resources invested in TexNet and its support of both the citizens of Texas and the oil and gas industry motivates ongoing TexNet funding as a stand-alone item in the state budget. In order to provide critical support for the citizens of Texas as well as maintain a robust oil and gas industry, and to extend understanding of earthquake risk by expanding the network and its vital capabilities, a budget of $3.4 million for the FY 2022–23 legislative cycle is proposed. This proposed state investment is based on ongoing activities as well as external and independent assessments by state agencies, the oil and gas industry, and citizens.

2.0 Impact of TexNet Program for State of Texas

TexNet directly contributes to the safety and prosperity of Texas. By providing earthquake information used by the oil and gas industry, its regulatory agencies, and other stakeholders, the network facilities help to facilitate ongoing production activities that directly support the flow of production-tax revenue. By so doing, TexNet provides critical support for safe operations and builds prosperity for all Texans. Ongoing monitoring and research by TexNet is designed to analyze earthquake activity, understand the causes of this seismicity, quantify hazards and future impacts, and provide quantitative data to enable risk mitigation for the socioeconomic safety of the state (Figure 2.1). State investment in the research is uniquely leveraged by partnerships with UT-Austin, Southern Methodist University, The University of Texas at El Paso, The University of Texas at Dallas, and the University of Houston. This cooperation provides a Texas-centric unified effort as illustrated by cohesion among the diverse research groups across Texas efficiently sharing one another's resources.

The implementation of a disaster recovery system safeguards the availability of the data to our stakeholders and to earthquake analysts for uninterrupted earthquake detection and manual relocations. Seismic monitoring across the state, and the ability to document earthquake source information 24/7 for events with magnitude greater than or equal to 3.0 in less than 20 minutes, safeguards people and infrastructure from earthquake hazards. Continuous monitoring and evaluation of ongoing seismicity with reporting by the next business day delivers governmental and nongovernmental stakeholders critical information for decision-making. The TexNet Earthquake Catalog has become the primary source for earthquake information for researchers, for state regulators making policy decisions, and for operators, thus maximizing industry best practices in the state. The world-class accuracy and timeliness of the TexNet system is recognized by the U.S. Geological Survey (USGS), who has responsibility for national earthquake monitoring, as the primary authoritative network for Texas. Specifically, the timely publication of earthquake locations, i ncluding estimates of bias and a decrease in the uncertainty of these estimates, improves regulatory judgments while simultaneously supporting national earthquake hazard reduction.

Compilation, maintenance, and quality control of the Earthquake Catalog, available geophysical information, and other operational factors provide timely data sets to stakeholders so each can assess the causality and implications of recent seismicity. Development and maintenance of fault maps, evaluation of areas prone to earthquakes, and establishment of factors that impact future earthquakes based on operational data, statistical analysis, and physics-based models improve risk mitigation of these natural hazards. In addition to understanding the causes of the seismicity, TexNet also evaluates the procedures and approaches necessary to assess the hazards resulting from earthquakes using collected data sets and existing models.

This work provides essential applied research products to mitigate risk in areas of increased seismicity or expected increase in oil and gas operations. Minimizing earthquake activity associated with human activities provides a basis for reducing impacts on the people and infrastructure of Texas. Finally, conducting educational programs that provide information and outreach to the public facilitates understanding and awareness of these processes and improves public safety.

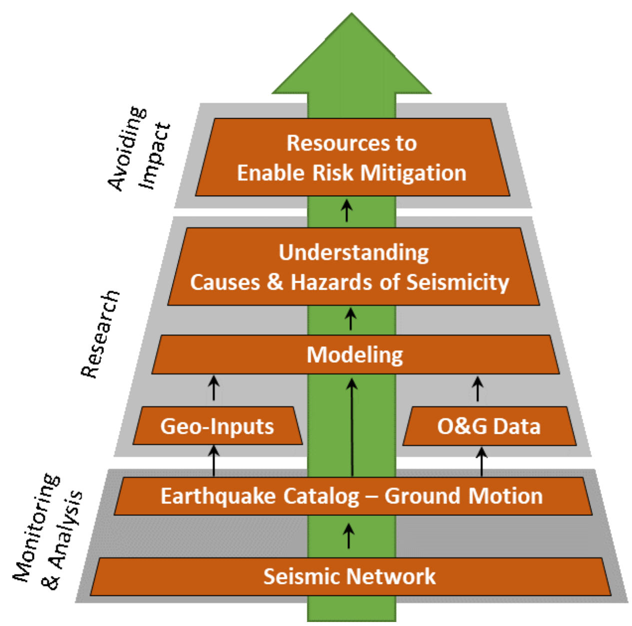


Figure 2.1. TexNet processes, products, and resources to the State.

3.0 TexNet Budget Utilization: Spending and Next Biennial Request

Summary: The FY 2020–21 TexNet budget includes $1.4 million used to operate the seismic network and $2 million to support research. Costs support the deployment, maintenance, and operations of the network, as well as the detection and reporting of earthquakes. Research includes projects that improve the understanding of the causes of earthquakes in Texas and quantify their potential impact on the citizens and infrastructure of Texas.

For the FY 2022–23 biennium, TexNet requests total funding of $3. 4 million to support network operations and TexNet research capabilities, building on the state's investment in the network's infrastructure and supporting the mitigation of earthquake impacts.

These funds will provide:

- Replacement of seismic instrumentation and limited expansion of the network and its IT infrastructure
- High quality of data available promptly to TexNet stakeholders
- Improved technical performance of the network
- Advanced earthquake analysis
- Improved knowledge on causes of seismicity
- Expertise on hazards and impacts of seismicity
- Production information to enable risk mitigation

Current FY 2020-2021 Funding

The TexNet seismic network project includes deployment and maintenance of sensors; use of telecommunications; purchase and operation of TexNet Hub Servers; and detection, location, and reporting of earthquakes across the state.

Table 3.1 below provides a breakdown of specific TexNet costs. As indicated, equipment (seismic and IT) spending in FY20 was $122,032. Based on initial network design work, we anticipate costs in FY21 will remain nominal at $106,579, resulting in a total cost this biennium of $228,611. The majority of expenses to date have been used for equipment deployment and operations. These costs include personnel to operate and maintain existing seismometer stations and to redeploy portable seismometer stations to maximize the capability to detect, locate, and report events in the state. Costs for the TexNet T1 project include materials and services at $210,578, personnel at $879,724, computer usage at $39,184, and travel at $41,903, for a subtotal of $1,400,000.

Table 3.1. TexNet during in the 2020–21 biennium.

TexNet	Equipment	Operations and Maintenance				TexNet Seismic Network	TexNet Research	Subtotals
		Materials & Services	Personnel	Computer Usage	Travel			
TexNet FY20 (actual)	$122,032	$118,310	$422,780	$18,304	$21,903	$703,329	$996,671	$1,700,000
TexNet FY21 (expected)	$106,579	$92,268	$456,944	$20,880	$20,000	$696,671	$1,003,329	$1,700,000
Subtotals by Categories	**$228,611**	**$210,578**	**$879,724**	**$39,184**	**$41,903**	**$1,400,000**	**$2,000,000**	
							Biennium Total	**$3,400,000**

TexNet research costs are $2,000,000 in total for this biennium. Appendix B contains a summary of the research funding, documenting collaboration and broad participation in research activities conducted across Texas.

During the current biennium, TexNet has used modest funds to develop a cost-efficient program and achieve its objectives. Concurrently, the high-quality data, Earthquake Catalog, and applied research have increased the impact of both the raw data and the research products to a variety of Texas-based groups' stakeholders (e.g., oil and gas industry, Railroad Commission of Texas, research groups). The USGS is now using TexNet waveform data in real time for earthquake detection and location, thus further providing critical external assessment of TexNet, which is leading to improvements in data collection and processing. Also, Incorporated Research Institutions for Seismology (IRIS), the Center for Integrated Seismicity Research (CISR), and the Stanford Center for Induced and Triggered Seismicity (SCITS), along with other research-community participants, are leveraging the data and products of TexNet. Finally, the Railroad Commission of Texas, Texas Division of Emergency Management, and other stakeholder groups (industry, U.S. Army Corps of Engineers, and others) are utilizing the data and are updating TexNet products on a daily basis. These products are critical for decision-making.

U.S. Geological Survey Advanced National Seismic System (USGS-ANSS) has awarded TexNet to be the authoritative network for seismicity in Texas. TexNet provides earthquake locations to USGS and are included in the ANSS ComCat (Comprehensive Earthquake Catalog).

Request for FY 2022–23 Funding

For TexNet to continue operating the seismic network and providing research, we propose a budget of $3.4 million for the 2022–23 biennium. The costs to continue operating the network will remain at $1.4 million. Funding requested to maintain the complementary TexNet research program is $2.0 million.

Table 3.2 provides projected costs for the 2022–23 biennium. Costs related to equipment correspond to maintenance of seismic instruments and limited expansion of the network and TexNet's IT infrastructure. Operations and maintenance costs include necessary expenses for station visits, earthquake management system services, and personnel to support and coordinate all necessary actions for a statewide seismic network and 24/7 availability of data and earthquake locations. A detailed description is provided in section 4.0.

As discussed and agreed upon with the TexNet TAC, the TexNet research program integrates geological, geophysical, data analytics, and engineering topics that increase our knowledge of the following: improving the performance of the network and advanced earthquake products, enhancing the knowledge on causes of seismicity, producing expertise on hazards and impact of seismicity, and contributing information to stakeholders to enable risk mitigation. Specific research projects that will be undertaken with future TexNet funding will be discussed and agreed upon with the TexNet TAC.

The consolidated research program takes advantage of the data acquired by the seismic network as well as the supplemental geoinformation and provides the basis for understanding seismicity in Texas, minimizing the financial and social impacts of these events to the State of Texas.

Table 3.2. Costs for TexNet, 2022–23 Biennium: equipment, operations and maintenance, and research.

TexNet	Equipment	Operations and Maintenance				TexNet Seismic Network	TexNet Research	Subtotals
		Materials & Services	Personnel	Computer Usage	Travel			
TexNet FY22	$75,000	$110,000	$470,000	$20,000	$25,000	$700,000	$1,000,000	$1,700,000
TexNet FY23	$60,000	$120,000	$470,000	$20,000	$30,000	$700,000	$1,000,000	$1,700,000
Subtotals by Categories	**$135,000**	**$230,000**	**$940,000**	**$40,000**	**$55,000**	**$1,400,000**	**$2,000,000**	
							Biennium Total	**$3,400,000**

4.0 TexNet Seismic Monitoring

TexNet has established standards for seismic monitoring stations in order to ensure that a real-time high-quality network provides ground-motion data and associated analytical results for daily earthquake analysis. TexNet, in the current biennium, has deployed 68 additional stations (as of December, 2020; Figure 4.1) to better monitor seismicity in key areas based on industrial operations or spatiotemporal seismicity patterns.

Specifically, in addition to past deployment, during the current biennium TexNet deployed 28 stations in the Eagle Ford Play area, 1 station in East Texas, 2 stations in the Panhandle, 6 stations in the Midland Basin, and 31 stations in the Delaware Basin. Also, three stations in Snyder were relocated to better monitor the seismicity south of the existing earthquake cluster. Five of the six new deployments in the Midland Basin are near Midland–Odessa, in response to the recent increase in seismicity near urban areas.

To achieve real-time availability and archiving of waveform data for more than 150 TexNet stations, we purchased additional IT hardware systems. We plan to purchase and deploy a full replicate system (Colo) of the TexNet Hub that will be brought online in case of disruption of services in the primary site. If full failure occurs at the primary site, the Colo will be brought online to minimize data-availability downtime.

As of March 2020, TexNet has added on-call staffing to its operations to meet USGS standards and to provide earthquake source information to its stakeholders faster. To attain this objective, we post on our Catalog's website all earthquake information for events of $M_L \geq 3.0$ in less than 20 minutes from the time of occurrence. Earthquakes of $M_L 1.5$ or less to $M_L < 3.0$ are cataloged on the next business day.

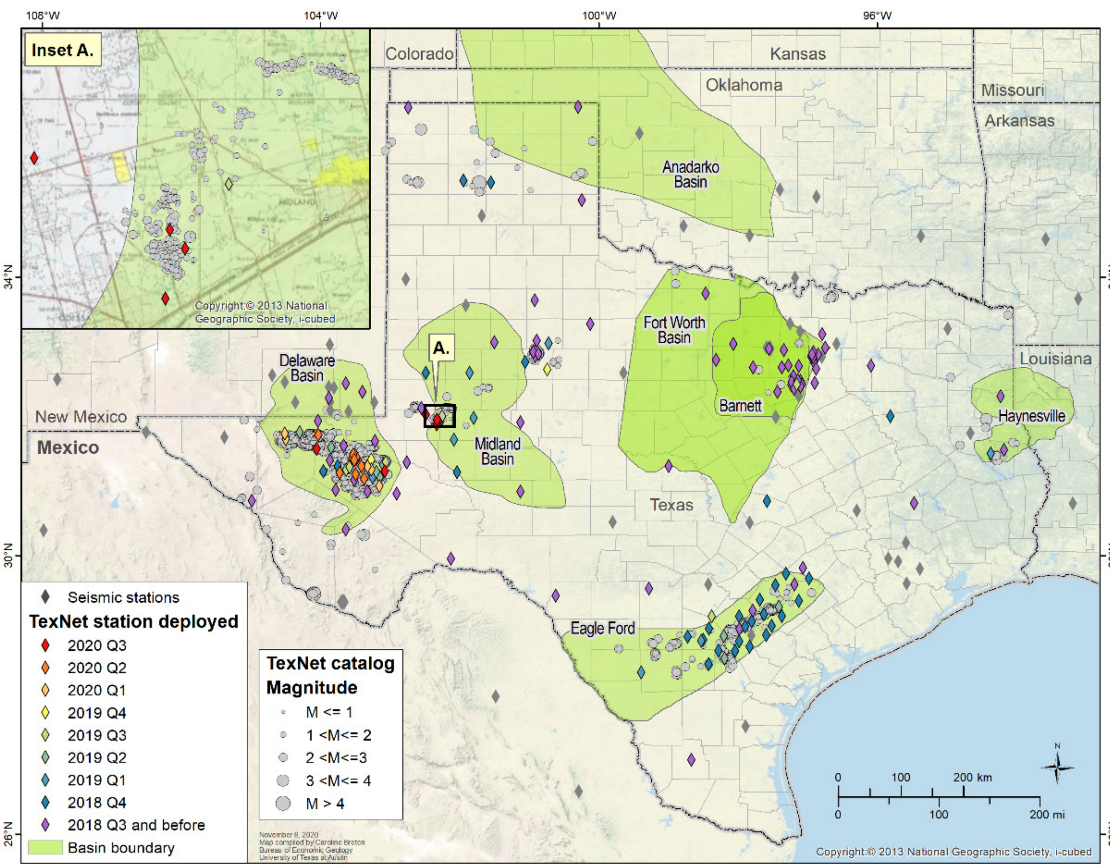


Figure 4.1. Seismic stations providing real-time waveform data to the TexNet Hub for seismicity monitoring.

5.0 Seismicity in Texas

Using ground-motion information from our seismic monitors and following a peer-reviewed reference, TexNet researchers have calibrated the local magnitude (M_L) calculation. On October 19, 2020, TexNet magnitude values available through the earthquake web catalog were aligned with USGS standards.

In Figure 5.1, we present the seismicity across the state that occurred from the last quarter of 2018 until Q3 of 2020. Currently, the highest rate of seismicity is in Culberson County (West Texas), where TexNet cataloged 61 events with $M_L \geq 2.5$. The second-highest rate of seismicity is north of Midland–Odessa, with a rate of 20 events cataloged for the same period and magnitude range. Seismicity rates have dropped in Snyder and in the Eagle Ford area to 1 and 11 events, respectively. In the Eagle Ford, the seismicity rate has drastically dropped during Q1 & Q2 of 2020, with a total of 5 events with $M_L \geq 2.5$. In a similar way, seismicity has dropped in Snyder, where in 2019 there were two events of $M_L \geq 4.0$. This reduction in seismicity may be related to COVID-19; during this time in the pandemic, the industry partially paused its operations.

In the Culberson County area and along the border with Reeves County, from January through October 2020, TexNet cataloged four earthquakes having $M_L \geq 4.0$. The highest-magnitude earthquake (M_L4.9) was reported on March 26, 2020, along the county line.

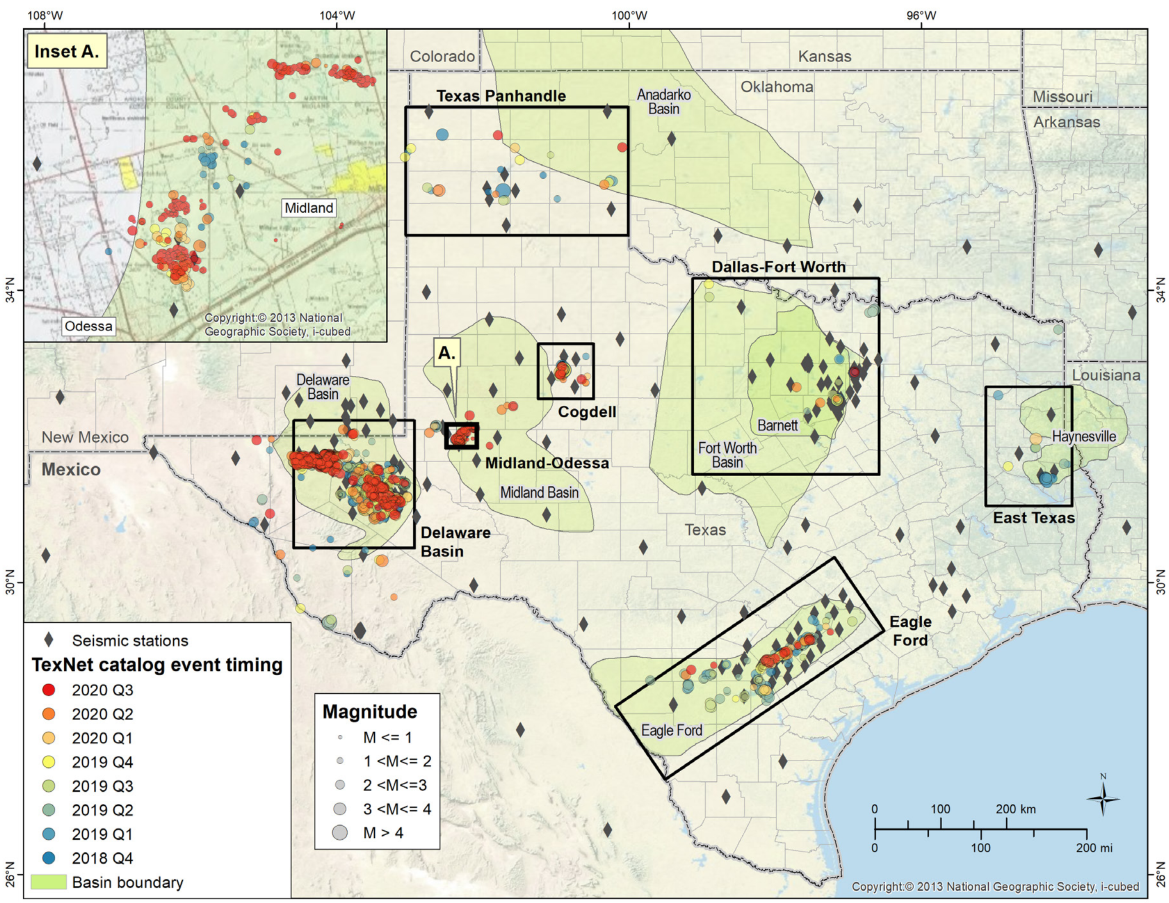


Figure 5.1. Earthquakes reported by TexNet between October 2018 and September 2020. Highest magnitude event (M_L4.9) is denoted with a yellow star. Deployed seismic stations providing real-time data for earthquake cataloging as of September 2020 are shown.

6.0 Impact of TexNet Research

During the current biennium (2020–21), following the recommendations of the TexNet TAC, we pursued research and delivered products that have significantly improved our understanding of induced (and natural?) earthquakes in Texas. Appendix A, which provides a list and brief description of the publications stemming from our work, demonstrates the breadth and depth of our progress.

Several of our projects and related publications document how TexNet is improving our ability to detect, locate, and analyze earthquakes statewide. We have honed existing techniques to catalog earthquakes promptly, and we are meeting performance metrics established by the independent TAC. We have developed and deployed new techniques to further improve location accuracy and to provide information promptly. Our work on earthquake location is on the leading edge of the science and has a high impact for our stakeholders (notably the petroleum industry and its regulators), supporting their investment and regulatory decisions that rely on accurate spatiotemporal seismicity trends.

Another category of significant advancement has been the characterization and explanation of the seismicity in different parts of the state, including highly populated areas (such as the Dallas–Fort Worth metropolitan area) and sites of increased oil and gas operations (including the Permian Basin and Eagle Ford play). Through this research, we have identified patterns and rates of seismicity, active faults (many previously unknown), and characteristics of ground motion. These research products are being used to evaluate the combination of natural factors and human influences that cause seismicity, to assess the changing seismic hazard, and to provide information to the State of Texas officials and local stakeholders who can help mitigate the associated risk. We mapped previously unknown fault zones, more fully characterizing known earthquake zones while developing a fault database that includes the susceptibility of each fault to rupture.

In areas with varying petroleum industry operations, we have created quality-controlled databases that document oil and gas operations data (e.g., hydraulic fracturing and wastewater injection). These data are being analyzed to identify the likely, and highly complex, association that these processes (hydraulic fracturing and wastewater injection) have with seismicity. By applying statistical or physics-based models, we developed new methods that identify isolated cases where seismicity is humanly induced and can hindcast earthquake hazard due to prior industry activity. In addition, we have combined geological and wastewater-injection information to provide comprehensive models that show how subsurface pore pressure has changed and thus altered the hazard due to injection.

Finally, our work on ground-motion models for earthquakes in Texas and neighboring states provides a framework to better assess the regional seismic risk and validates new ShakeMap models that are routinely used by emergency management authorities (such as the Texas Department of Emergency Management). The developed ground-motion models, complemented by assessments of the fragility of critical infrastructure components (such as bridges), has improved the evaluation of seismic risk across the state. In allocating a portion of TexNet funding to vetted and high-quality peer-reviewed research, we are providing more accurate data and analyses about the evolving earthquake hazard in Texas.

Our work is being used daily by those in the petroleum industry and its regulators to protect the well-being of the citizens, and the socioeconomic vitality, of Texas.

Appendices

Appendix A. Abstracts

TexNet: A Statewide Seismological Network in Texas

A. Savvaidis, B. Young, M. Shirley, P. Martone, J. Andrews, V. O'Sullivan, and C. Templeton

Seismological Research Letters, https://doi.org/10.1785/0220180350

Induced seismic events have been recorded recently in the southern midcontinent of the United States, including Texas. These events, associated with hydrocarbon exploration and the subsequent disposal of wastewater byproduct, have led to substantial public discussion regarding cause, public safety, and potential risks of damage to infrastructure. In an effort to better understand these events and to monitor earthquake activity in general, the 84th Texas Legislature funded creation of a statewide, seismic-monitoring program known as the Texas Seismological Network (TexNet). The goal of TexNet is to provide authenticated data to evaluate the location, frequency, and likely causes of natural and induced earthquakes, so TexNet, through October 2020, deployed almost 150 new seismic stations in the state of Texas. Of these, 25 are permanent and form, along with 18 existing broadband stations, an evenly spaced backbone, seismic network in the state. In addition to the permanent installations, portable have been deployed in six different areas of the state experiencing recent seismicity and having high-socioeconomic importance.

An earthquake-management system (SeisComp3) is being used to detect, locate, and analyze earthquake events and earthquakes measuring M_L1.5 and above have been made available through various dissemination tools by the next working day. Also, as of March 2020 we have implemented on call staffing to meet the USGS/ANSS earthquake information release time goals. Following a recent publication on updated magnitude calculation, as of October 19th, 2020, we updated our public catalog and the information we provide to USGS when we publish an earthquake event using the new M_L. The initial implementation of TexNet has reduced the magnitude of complete-ness (Mc) across Texas from 2.7 to less than 2.0 in specific areas and has played a role in a large decrease in uncertainties about earthquake-source parameters.

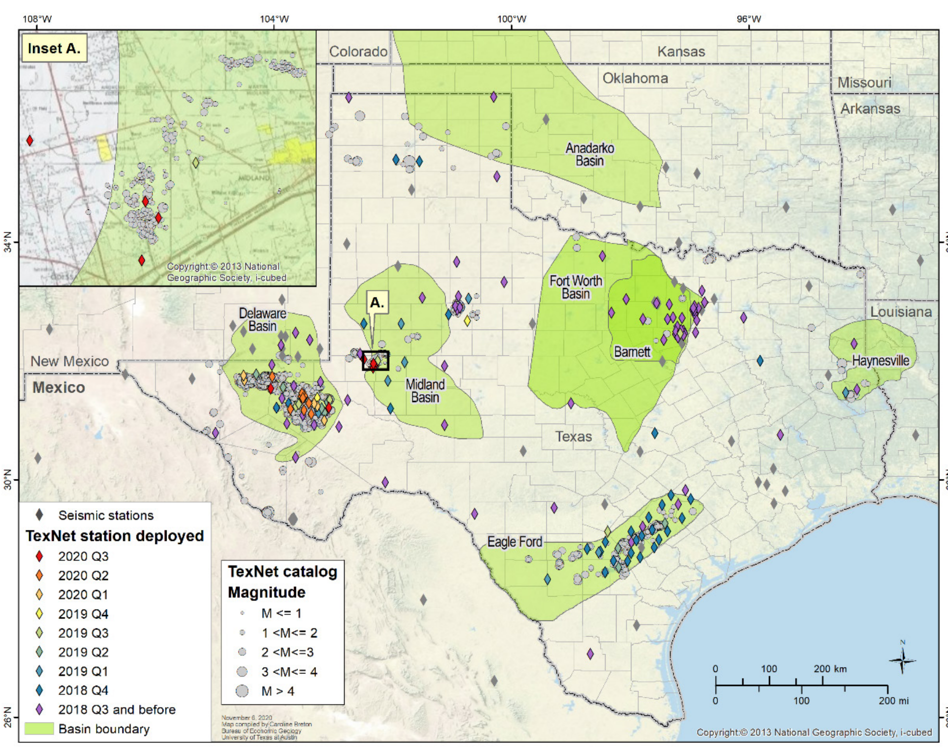


Figure 1. New regional Vs_{30} map of Texas based on geostatistical kriging incorporating a regional geologic proxy and field observations of Vs_{30}.

Determination of Local Magnitude for Earthquakes Recorded from the Texas Seismological Network (TexNet)

F. Kavoura, A. Savvaidis, and E. Rathje

Seismological Research Letters, https://doi.org/10.1785/0220180350

In this study, we present a local magnitude (M_L) relation for the earthquakes recorded from the Texas Seismological Network (TexNet) from January 1, 2017 to July 31, 2019. Using a comprehensive ground-motion data set from earthquakes in Texas, we propose a distance correction term –log A_0, which is consistent with the original definition of the Richter magnitude (Figure 1). The proposed distance correction calculation for the TexNet events accounts for the attenuation characteristics of the direct and refracted waves over different distance ranges. Regression analysis of Wood–Anderson (WA) amplitudes results in a trilinear function, which represents the attenuation attributes of the events under investigation. In parallel, to better understand the attenuation attributes in different areas in Texas, we investigate the distance correction terms and attenuation characteristics for four different areas which are well recorded: Delaware Basin, Snyder, Fort Worth Basin and Eagle Ford operating area. The derived distance correction relationship results in an accurate M_L relationship for Texas that is unbiased over a 200 km distance range.

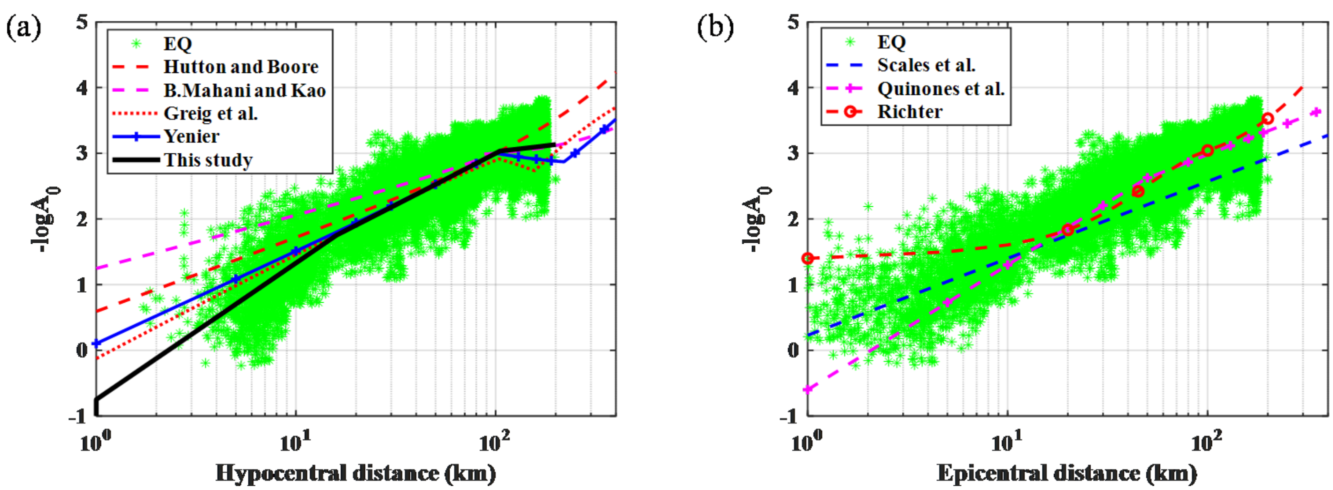


Figure 1. Distance correction term -log A_0 versus (a) hypocentral distance and (b) epicentral distance for TexNet events compared with those of local magnitude relations presented in other studies. Scatter dots (*EQ*) indicate the normalized Wood–Anderson amplitudes in the 90–110 km distance bin.

Improving Absolute Earthquake Location in West Texas Using Probabilistic, Proxy Ground-Truth Station Corrections

A. Lomax, A. Savvaidis

Journal of Geophysical Research - Solid Earth, https://doi.org/10.1029/2019JB017727

An increase in induced seismicity in the central United States since 2009 led to establishment of TexNet seismic-monitoring in Texas. Accurate, absolute seismic-event location is critical to TexNet, allowing quantitative evaluation of possible association of seismicity with human activity. For the Delaware Basin, western Texas, relocation using different velocity models in the TexNet station subset shows absolute location error up to 4–5 km. The absolute location error is increasing up to 5–7km when the earthquake source is away from a seismic station. The preferred method to reduce absolute error, ground-truth calibration, is not available in this area.

Alternatively, we used industrial well activity as proxy, ground-truth for developing probabilistic, proxy ground-truth (PPGT) station corrections for relocation. Assuming well activity causes seismicity, we defined a distance-time probability associating events and well activity. We probabilistically accumulated PPGT station corrections using event hypocenters constrained to associated fracturing-well locations. We applied this procedure within 12 km of TexNet station PB02, optimizing the procedure through comparison of rates of causal and acausal associations. Relative to the initial locations, final PPGT relocations show smaller residuals and shifts in epicenter as much as 3 km, predominantly toward the north and northwest. PPGT residuals are similar to those from relocation with standard station corrections. The initial hypocenters showed an unreasonable deepening with distance from station PB02, whereas PPGT relocations produced an overall flattening of event depths. These results are consistent with PPGT corrections giving real improvement in absolute location accuracy.

By densifying the seismic network in the Delaware basin, using improved earth models, and also performing explosion shots we expect to provide high quality ground truth sources in the area. These efforts should greatly improve epicentral accuracy and expected to reduce the absolute depth uncertainty. We expect that further development of this procedure, and application throughout the west Texas Delaware Basin study area and other TexNet priority areas, will improve our reliable association of seismic events with geographic locations of human activities.

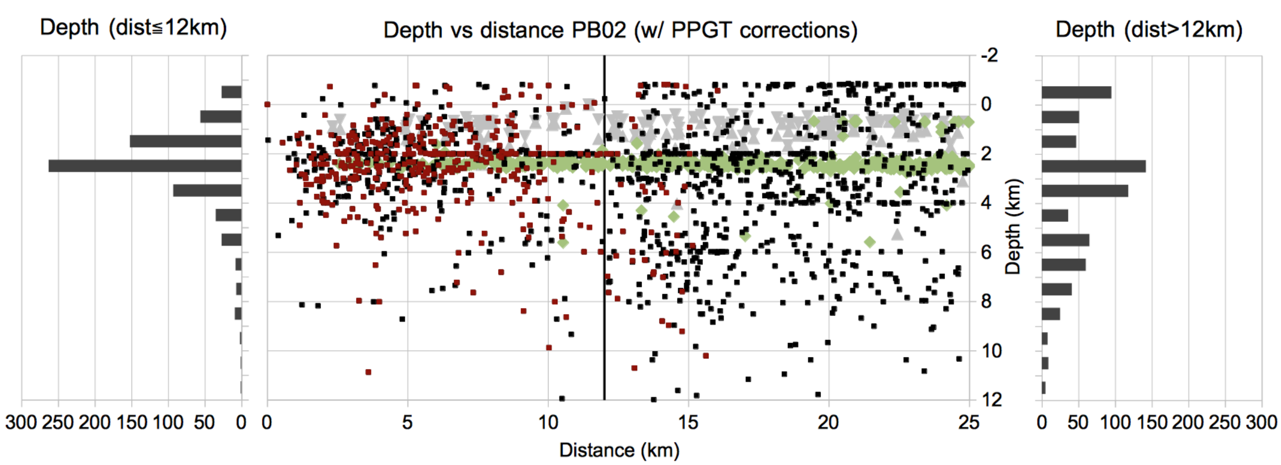


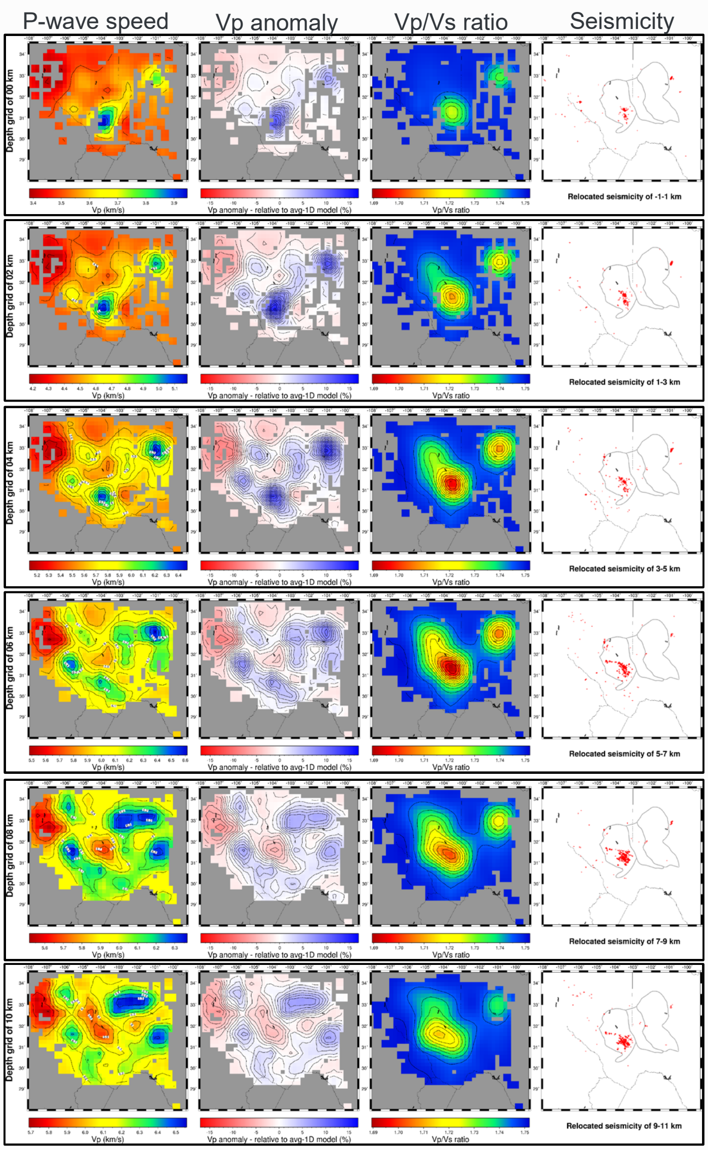
Figure 1. Section views showing (Middle) depth as a function of distance from station PB02 and corresponding depth histograms within 12-km distance from station PB02 (left) and 12-25 km distance (right) for relocations using PPGT corrections.

Mapping the 3-D Lithospheric Structure of the Greater Permian Basin in West Texas and Southeast New Mexico for Earthquake Monitoring

D. Huang, A. Savvaidis, and J. Walter

Journal of Geophysical Research – Solid Earth, 2019, https://doi.10.1029/2019JB018351

The Greater Permian Basin is not only a complex tectonic regime, but it has also been and continues to be a productive oilfield where the seismicity rate in the basin has significantly increased since 2008. Since 2015, our understanding of the seismogenesis in the basin has increased owing to the establishment of a statewide seismic network known as TexNet for monitoring earthquake activities. A crucial component of the earthquake monitoring is to improve the accuracy of the hypocentral location, which relies on an accurate velocity model that can better confirm the existing regional tectonic regime. We collected data from current TexNet operations and previously deployed seismic arrays and performed a joint local and teleseismic earthquake tomographic inversion, resulting in a 3-D tomography model for earthquake monitoring. The preferred 3-D tomography model includes a prominent feature at a depth range of 0–20 km, where distinct lower wave-speed anomalies overlap with the surface trace of the Delaware Basin. These anomalies suggest a basin-scale lithological difference from surrounding regions and corroborate basin characteristics. Findings also suggest that the Midland Basin may be more lithologically uniform than the Delaware Basin. A strong correlation exists between dense seismicity clusters and the obtained lower Vp/Vs ratios. Four significant clusters having relatively low Vp/Vs ratios were identified. Using the Vp/Vs ratio as a proxy to evaluate the state of the pore-fluid pressure, we think this spatial correlation suggests that the Greater Permian Basin currently comprises overpressurized fluid-filled host rocks. Our tomographically relocated seismicity suggest spatial correlation between the seismicity and the presence of higher pore-fluid pressure.



A crucial component in earthquake monitoring is a velocity structure that can best reflect the regional tectonic regime. We have effectively developed a tomographic velocity model for much of West Texas and southeast New Mexico for the purpose of earthquake monitoring. This research has benefited a further study on small-scaled crustal velocity in the Delaware Basin which provides a foundation for better earthquake location in West Texas.

Complex Shear-Wave Anisotropy from Induced Earthquakes in West Texas

Regan Robinson, Aibing Li, A. Savvaidis, and Hongru Hu

Bulletin of the Seismological Society of America, https://doi.org/10.1785/0120200086

We have analyzed shear-wave splitting (SWS) data from local earthquakes in the Permian basin in west Texas to understand crustal stress change and induced seismicity. Two SWS parameters, the fast polarization direction, and the delay time, are computed using a semiautomatic algorithm. Most measurements are determined in the Delaware basin and the Snyder area. In both regions, SWS fast directions are mostly consistent with local SHmax at stations that are relatively far from the earthquake clusters. Varying fast directions at one station are related to different ray paths and are probably caused by heterogeneity.

In the Snyder area, most northeast–southwest fast directions are from the events in the northern part of the cluster, whereas the northwest–southeast fast directions are mostly from the southern part. The northeast–southwest and northwest–southeast fast directions could be attributed to the northeast-trending normal faults and the northwest-trending strike-slip faults, respectively. SWS results in the Delaware basin have two unique features. First, most shallow earthquakes less than 4 km deep produce relatively large delay times. This observation implies that the upper crust of the Delaware basin is highly fractured, as indicated by the increasing number of induced earthquakes. Second, diverse fast directions are observed at the stations in the high-seismicity region, likely caused by the presence of multiple sets of cracks with different orientations. This situation is possible in the crust with high pore pressure, which is expected in the Delaware basin due to extensive wastewater injection and hydraulic fracturing. We propose that the diversity of SWS fast directions could be a typical phenomenon in regions with a high rate of induced seismicity.

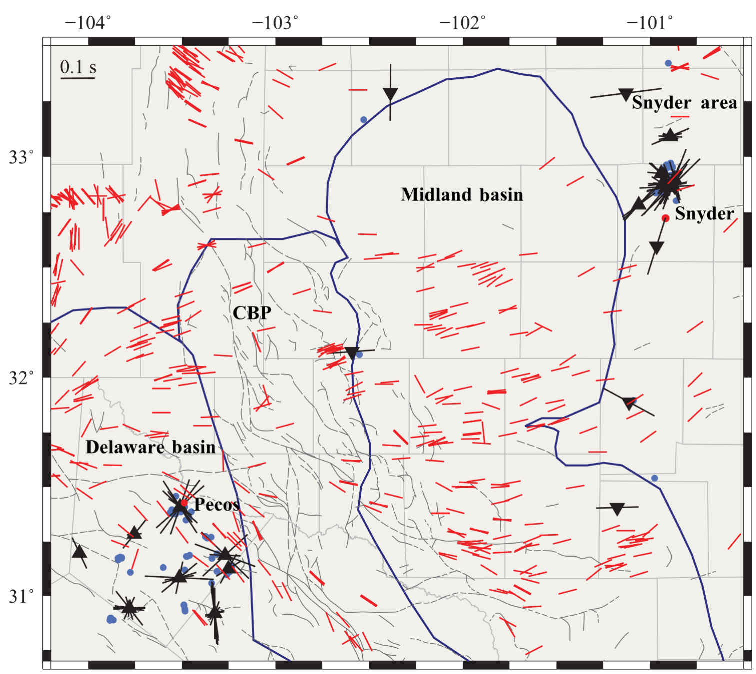


Figure 1. SWS measurements (black bars) from this study and maximum horizontal stress (red bars) in west Texas. All individual SWS measurements are plotted at the associated stations (triangles for the TexNet stations and inverse triangles for the TA stations). Blue dots are the earthquakes used for the SWS measurements. Each black bar represents one measurement. The bar orientation is parallel to the polarization direction of the fast shear wave, and the bar length is proportional to the delay time. Gray dashed lines are faults from Ewing et al. (1990). The stress data are from Lund Snee and Zoback (2020).

Cross-Correlation Relocation to Identify Active Faults in the Permian Basin

P. Li, A. Savvaidis

Submitted to Seismological Research Letters

From January 2017 to September 2020, the Texas Seismological Network (TexNet) recorded 5701 earthquakes in the Permian basin (PB), west Texas. The objective of this study is to provide a relative relocation catalog in the PB, which is critical for assessing fault structures and relating earthquakes with anthropogenic activities, by using waveform cross correlation and double-difference relocation.

The relative relocation results reveal important information of the active faults. Most of the earthquake clusters are linear distribution and suggest the active faults in the west Delaware basin (DB, west part of PB) of Texas are along almost east-west direction, then rotate clockwise to northwest-southeast direction in the south DB. The active faults in the Central Basin Platform and Midland Basin (CPB and MB, east part PB), i.e., the Odessa-Midland area, have high dip angles. The strike changes from southwest–northeast in the CBP to northwest–southeast in the MB.

We compared the earthquake relocation results with the surface deformation data from InSAR analysis in the South DB. The comparison shows that (1) the earthquake clusters in the south DB are located on the subsidence area; (2) the earthquake clusters in the Pecos area are along the boundary of a major subsidence area; and (3) the earthquake clusters in the North Pecos area are aligned with a northwest-southeast uplift zone.

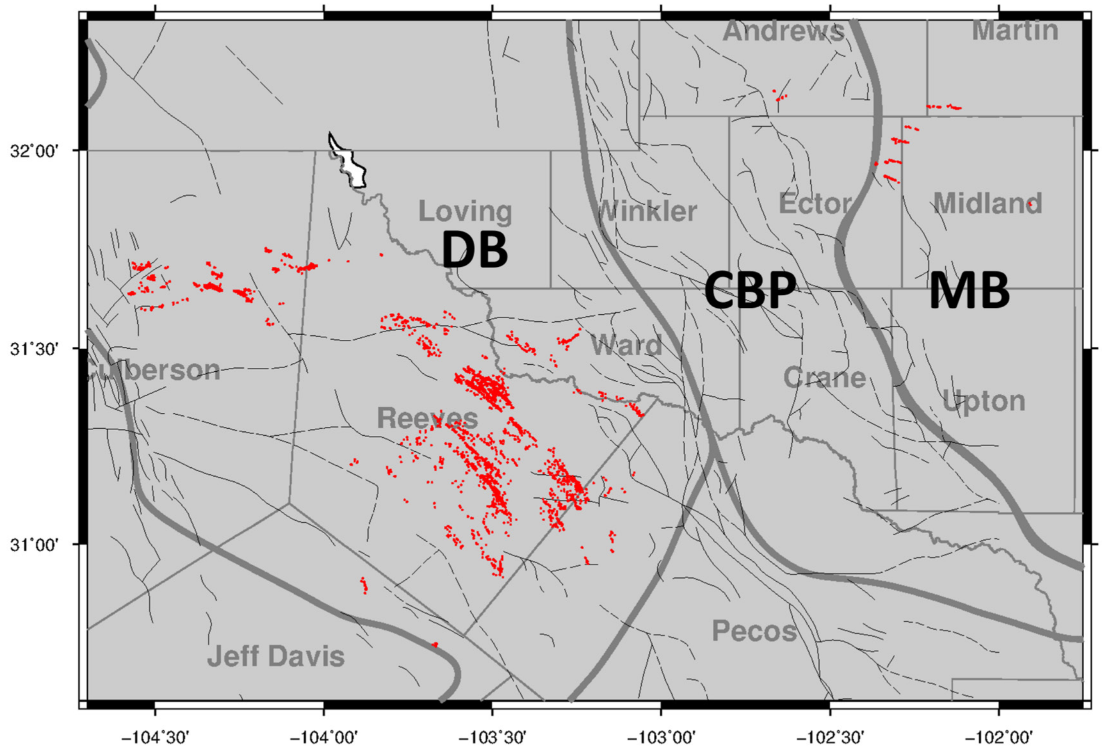


Figure 1. Map of the relocated earthquakes in the Permian Basin (PB). The PB has three geological regions: Delware Basin (DB), Central Basin Platform (CBP), and Midland Basin (MB). The red dots represent the earthquakes. The earthquake clusters in the PB shows linear features that indicate active faults. We observed a rotation of the earthquake cluster's orientation, indicating the local stress variation.

Characteristics of the Concealed Seismogenic Features in the Snyder Area, Northwest Texas, United States

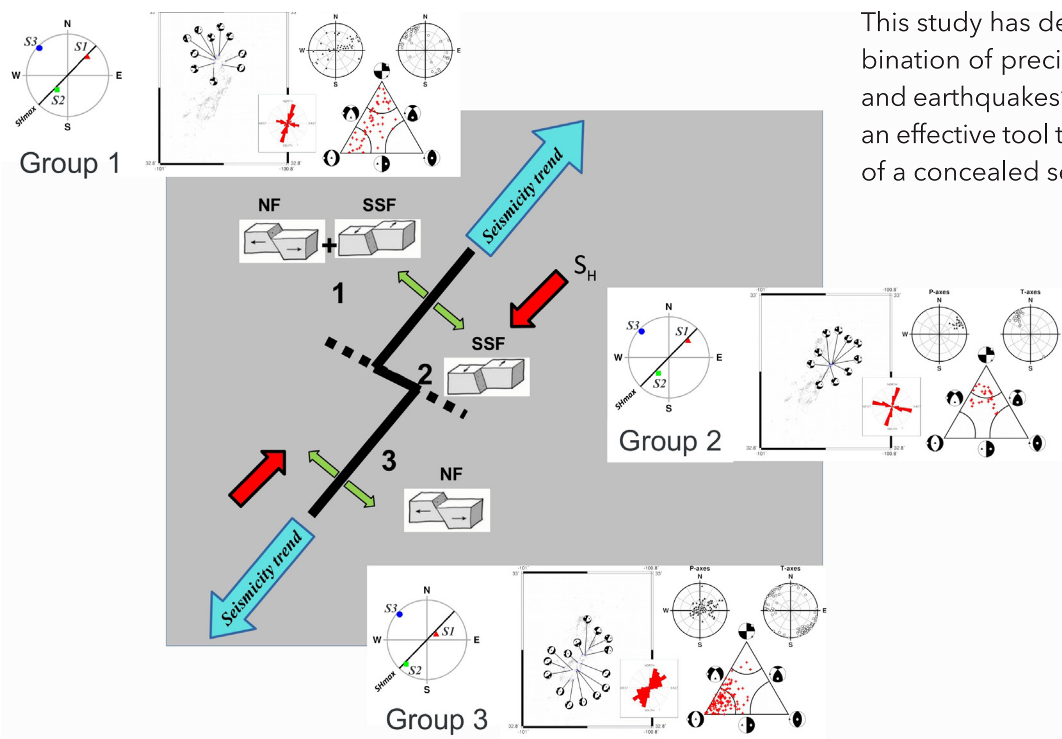
D. Huang, P. Li, F. Kavoura, and A. Savvaidis

Submitted to Seismological Research Letter, under revision

Earthquake activity in the Greater Permian Basin has significantly increased since 2008. Over time, seismic events were unevenly distributed throughout the basin and often occurred in clusters. Among these clusters, the Snyder area of northwest Texas has a significant seismicity rate, second only to that of the Delaware Basin. Although no documented fault trace in our study area can be found in the published literature, clustered earthquakes' hypocenters may help identify the buried seismotectonic structures. Determining the source mechanism can add insight into their rupture dynamics.

In this study, we investigated the concealed seismogenic structures by relocating seismicity using a recently obtained regional 3-D tomography model and performing a waveform moment tensor inversion to determine source mechanisms. Results show that the overall depth range of seismicity is between 0 and 8 km below mean sea level. The events can be geographically clustered into three subgroups, although no clear boundary between the subgroups can be drawn. The overall geometry of seismicity distribution presents an apparent northeast-to-southwest lineation. Whereas the overall pattern of source mechanisms presents a mix of strike-slip and normal faulting, the three subgroups have different rupture patterns, which indicates a transition of the stress/strain field. We further used the obtained focal mechanisms to determine the local stress field. As a result, the stress tensor is slightly rotating across the Snyder area. In addition to determining the orientation of principal stress axes, we estimated the maximum horizontal shear stress (SH_{max}) from the inverted stress tensor. Although the source mechanism pattern varies among subgroups, results show that SHmax retains a similar orientation at azimuth of 43°–44° across our study area. On the basis of our assessment of focal mechanisms, the state of stress as well as SHmax across the area, we contend that there likely have two major parallel sub-faulting systems running NNE-SSW. Although the faulting type varied across the field, the spatial occurrence of seismicity generally followed the direction of SH_{max} during TexNet's monitoring period.

This study has demonstrated that combination of precisely located seismicity and earthquakes' source mechanisms is an effective tool to identifying dynamics of a concealed seismogenic structure.



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

H. R. DeShon, C. T. Hayward, P. O. Ogwari, L. Quinones, O. Sufri, B. Stump, and M. B. Magnani

Modified from Seismological Research Letters (2019) 90 (1): 387–394

Local seismic research networks operated by Southern Methodist University (SMU) have provided basic earthquake data needed to assess seismic hazard and to address the cause of the increased seismicity rates in the Fort Worth basin (FWB) and Dallas–Fort Worth metropolitan area, an area that was aseismic until 2008. Here, we summarized the configuration, operation, and capability of the SMU FWB networks and documented how network geometries evolved in response to the onset of new earthquake sequences. The summary study provided basic information about the SMU networks to ensure that all studies with the telemetered local seismic networks are reproducible and publicly archived. SMU network design strategies focused on providing accurate hypocenter and focal mechanism information while still constrained by the realities of dense urban environment operations. This information provides fundamental data to yield insight into temporal and spatial changes in FWB earthquakes. The rich datasets contain local and regional earthquakes, anthropogenic and ambient noise, quarry blasts, and weather events. Prior publications document a causal link between earthquakes in the FWB and wastewater disposal and/or production activities associated with shale gas extraction, and the data described here allowed for breakthroughs in understanding the physical mechanisms leading to induced earthquakes.

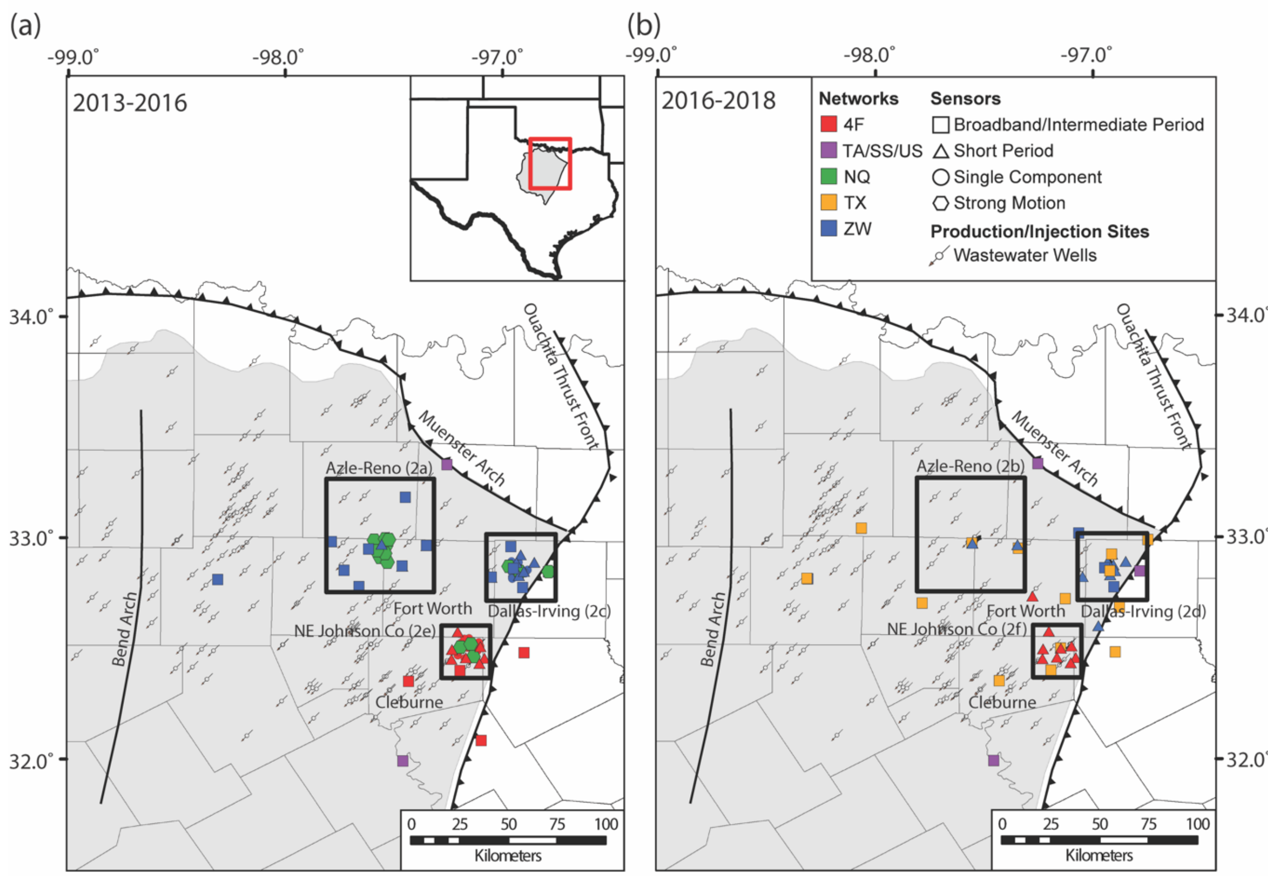


Figure 1. Map views of the Fort Worth basin (FWB) showing all stations that were active during the periods of (a) November 2013–July 2016 and (b) August 2016–August 2018. Black boxes denote areas with active seismic sequences during the study. Gray shaded area is the extent of the Barnett Shale; the basin is bounded by the Bend arch, Muenster arch, and Ouachita front in this region. (Inset) Texas and the Barnett Shale, with the box denoting study area.

Tracking Induced Seismicity in the Fort Worth Basin: A Summary of the 2008–2018 North Texas Earthquake Study Catalog

L. Quinones, H. R. DeShon, S. Jeong, P. Ogwari, O. Sufri, M. M. Holt, and K. B. Kwong

Modified from Bulletin of the Seismological Society of America (2019) 109 (4): 1203–1216

In this study, we presented an earthquake catalog for the Fort Worth Basin (FWB), TX spanning from 2008-2018, named the North Texas Earthquake Study (NTXES) catalog. This overview document occurrence of individual earthquake sequences on discrete faults that occur relatively far apart from one another (>30 km) and examined how the sequences developed over time as oil and gas development occurred. The three largest sequences (containing earthquakes with magnitudes 3.6+) were individually monitored by local stations located <15 km from the earthquakes, while regional seismicity across the basin was monitored using more distant stations. The study included the creation of new one-dimenisional seismic wavespeed models and a revised magnitude calculation specific to the FWB. The study reported that the majority of earthquakes in the basin occurred within the crystalline basement formation rocks, which lie below the primary wastefluid disposal formation (the Ellenburger formation). Overall, a correlation was found between fluid disposal activities and earthquake rate in the basin including a decrease in earthquake rate following a decrease in injection activities beginning in 2016. However, despite this basin-wide decrease in the earthquake rate, new faults have become active since 2016. Lastly, the study observed earthquakes at distances far from injection wells (>10 km) implying that far-distance stress changes associated with injection activities are important to understanding the seismic hazard of these earthquake sequences.

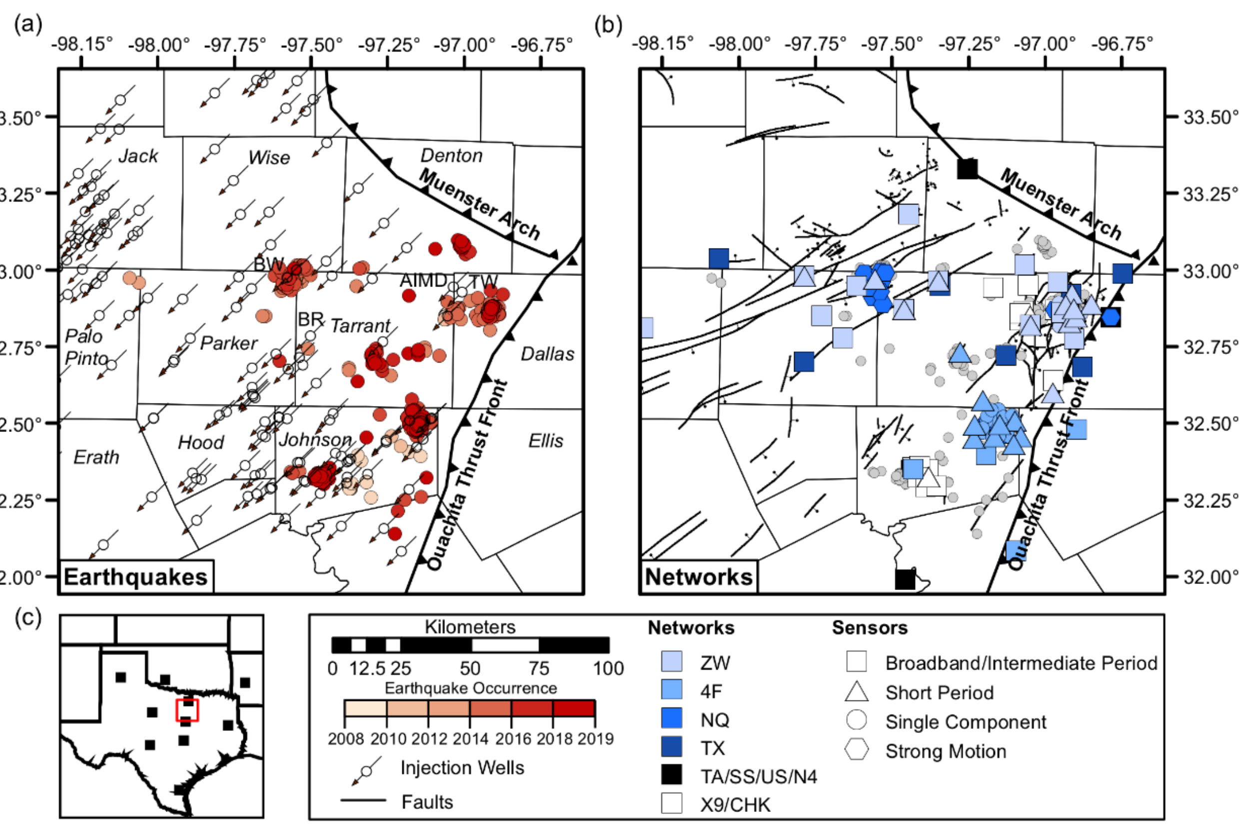


Figure 1. Map views showing the (a) locations of the NTXES earthquakes (circles) and injection wells (arrows) with important wells labeled (BR, BW, TW, A1MD), and (b) showing the locations of all stations whose symbol represents the station type. Faults on this map taken from *Hennings et al.*, 2019. (c) General map view showing the locations of regional US and TA stations along with the highlighted study area (box).

Stress Drop Estimates for Induced Seismic Events in the Fort Worth Basin, Texas

S. Jeong, B. W. Stump, H. R. DeShon, and L. Quinones

Modified from Bulletin of the Seismological Society of America (2020) (submitted, in revision)

Earthquakes in the Fort Worth Basin (FWB) have been induced by the disposal of recovered wastewater associated with extraction of unconventional gas since 2008. Four of the larger sequences (Azle-Reno, northeast Johnson county, Irving-Dallas, and Cleburne) prompted the deployment of seismic stations, and subsequent recording of seismic data that are used to estimate the kinematic source characteristics of the earthquakes. Source parameters including corner frequency, seismic moment (fault area*rock rigidity*slip distance), and stress drop (released stress during earthquake rupture, generally representing the earthquake source property) are estimated using a modified generalized inversion technique (GIT) developed for recordings on stations located in a highly-populated (noisy) sedimentary basin (no hard rock exposures) like the FWB. As an assessment of the validity of the modified GIT approach, corner frequencies and stress drops from the GIT are compared to estimates using the traditional empirical Green's function (EGF) method for 11 target events. For these events, corner frequency differences (GIT − EGF) have a mean of 0.67 Hz with a standard deviation of 0.88 Hz. We find consistent mean stress drops using the GIT and EGF methods, 9.56 MPa and 7.05 MPa, respectively. The GIT-derived mean stress drop is 5.33 MPa, similar to estimates for global, naturally occurring intraplate earthquakes. Stress drops exhibit no spatial or temporal correlations or depth dependency. In addition, there are no time or space correlations between estimated FWB stress drops and modeled pore pressure perturbations. We conclude that induced earthquakes in the FWB, occurring on pre-existing faults in the crystalline basement rocks, release pre-existing tectonic stresses, rather than releasing new energy added to the fault by the injection of wastefluids. Here, the stress drops do not directly reflect the triggering phenomenon.

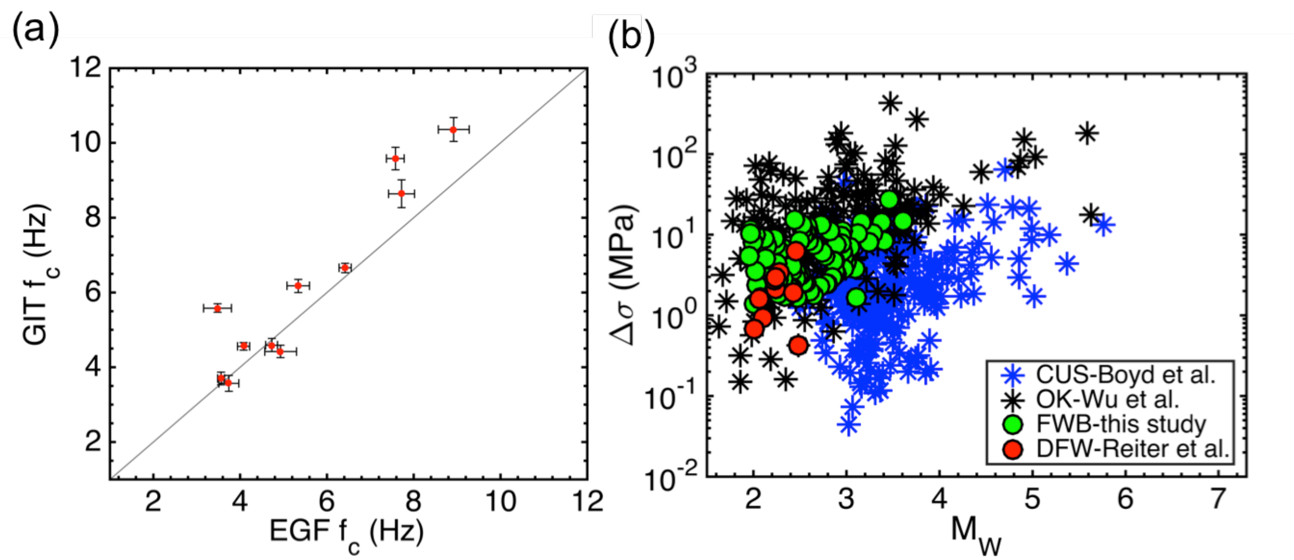


Figure 1. (a) Comparison of corner frequencies with 95% confidence intervals from GIT and EGF. Black line represent 1:1 slope. The corner frequency estimates from the GIT and EGF methods generally follow a line with a slope of 1. (b) Comparison of stress drops estimated for earthquakes in the central United States (CUS) (blue asterisks), Oklahoma (black asterisks), the FWB (this study) (green circles), and previous study of the DFW Airport sequence (red circles) as a function of moment magnitude.

Spectral Characteristics of Ground Motion from Induced Earthquakes in the Fort Worth Basin, Texas, Using the Generalized Inversion Technique

S. Jeong, B. W. Stump, and H. R. DeShon

Modified from Bulletin of the Seismological Society of America (2020) 110 (5): 2058-2076

A generalized inversion technique (GIT) was applied to local seismic data from 90 induced earthquakes (local magnitude 2.0-3.9) in the Fort Worth Basin (FWB) of north Texas. The GIT provides a numerically stable procedure to separate the effects of path (event-to-station), site (near-surface geology at recording instrument) and earthquake source characteristics, all of which ultimately help scientists improve local seismic hazard assessment. At ~30 km distance from the earthquakes, we observed a change in energy loss along the path reflecting geology of the mid-crust for the FWB. Differences in energy loss between the primary and secondary arriving seismic waves were interpreted to result from concentrations of crustal pore fluids or partial fluid-saturated material between source-to-station. Strong amplifications at some stations in the basin, by as much as 5 times on recordings of horizontal motion, reflect the thick basin sediments. Stress drops (a source parameter measuring the energetics of fault slip) range from 1.18 and 21.73 MPa, similar to values reported for tectonic (natural) intraplate events. The stress drops, strong site amplification and fluid effects on energy loss are crucial constraints on seismic hazard estimates for induced earthquakes, and especially for the highly-populated FWB.

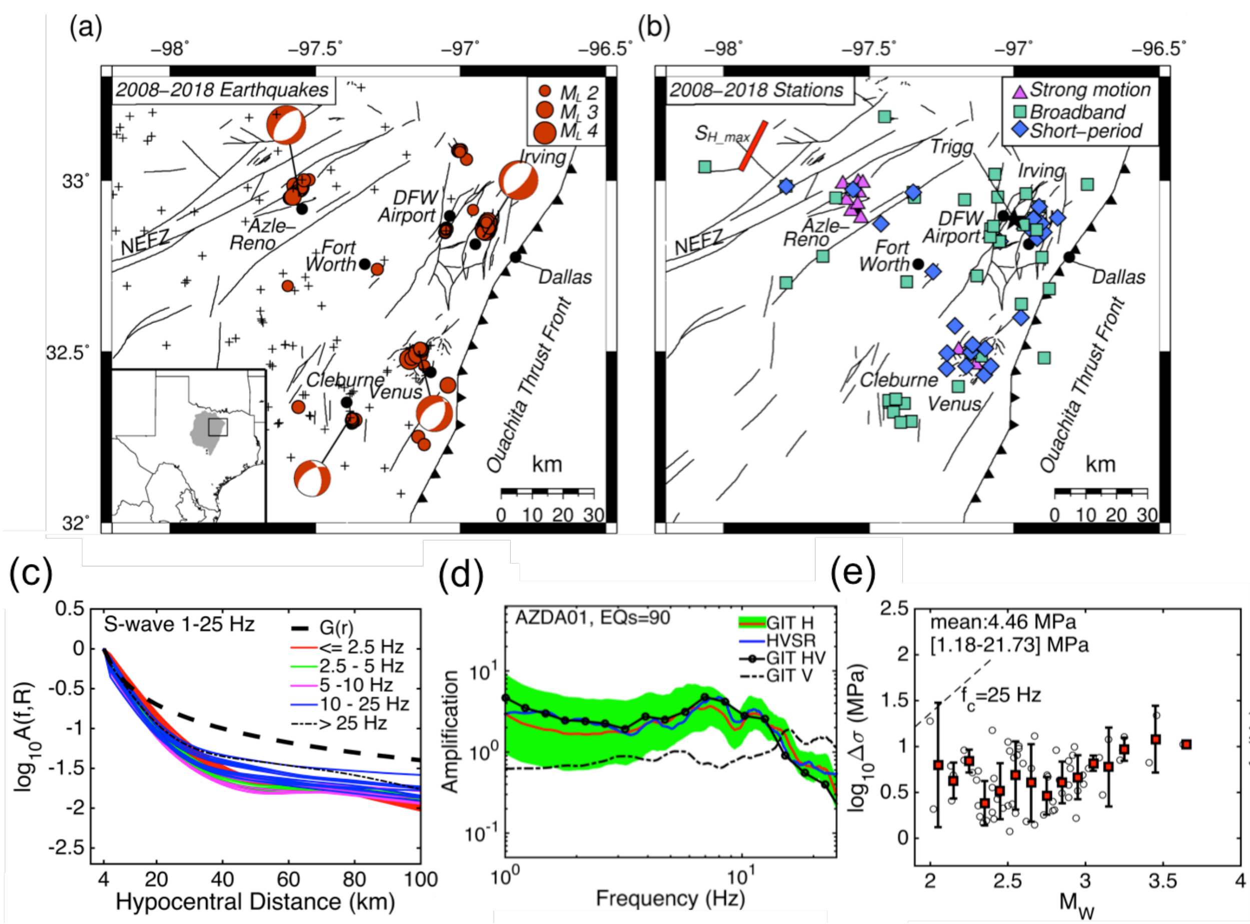


Figure 1. (a) Map illustrating the FWB earthquakes with focal mechanisms, tectonic features and regional faults [from *Hennings et al.*, 2019]. The inset illustrates the extent of the Barnett Shale (gray area). (b) Map of the seismic network used in this study (c) Energy (amplitude, A) loss decreases as a function of hypocentral distance for all selected frequencies. (d) Example site amplification for a station near Azle. (e) Stress drop versus moment magnitude, a more accurate estimate of earthquake size than local magnitude.

Stress Drop Variations of Induced Earthquakes at the Dallas-Fort Worth Airport, Texas

S. Jeong, B. W. Stump, and H. R. DeShon

Modified for Geophysical Research Letters (2021) (in preparation, submission in early 2021)

The Fort Worth Basin (FWB), which includes the Dallas-Fort Worth metropolitan area with a population in excess of seven million, has experienced multiple earthquake sequences induced by wastewater injection related to oil and gas production since 2008. We investigate how earthquake behavior changes with distance from wastewater injection activity using the earthquake parameter called stress drop, a measure of how energetic the fault slips. We show that stress drops for injection-induced earthquakes near the Dallas-Fort Worth International Airport are lower than other FWB earthquake sequences, though all events are normal faulting earthquakes occurring within the crystalline basement. The Airport stress drops increase with radial distance from the injection point, where the injector is thought to be within a few 100s of meters of a fault, but only over the first 1.5 km. For all other FWB earthquake sequences, the injection wells spatially associated with the events are >1.5 km away. The low stress drop Airport events occurred shortly after the initiation of injection. These observations suggests that stress drop can be directly and measurably affected by rapid increase in pore pressure on a fault, as theoretically predicted, and indicates that the stress release and hence ground shaking of these very near injector earthquakes may differ from other earthquakes within the same basin. Hence, stress drop could be used to explore cause, but only in very specific cases where well and fault separation is very small (<1.5 km for the FWB) and local seismic stations capture high-quality data. These results provide further guidance for safe siting and operation of waste fluid injection wells in sedimentary basins.

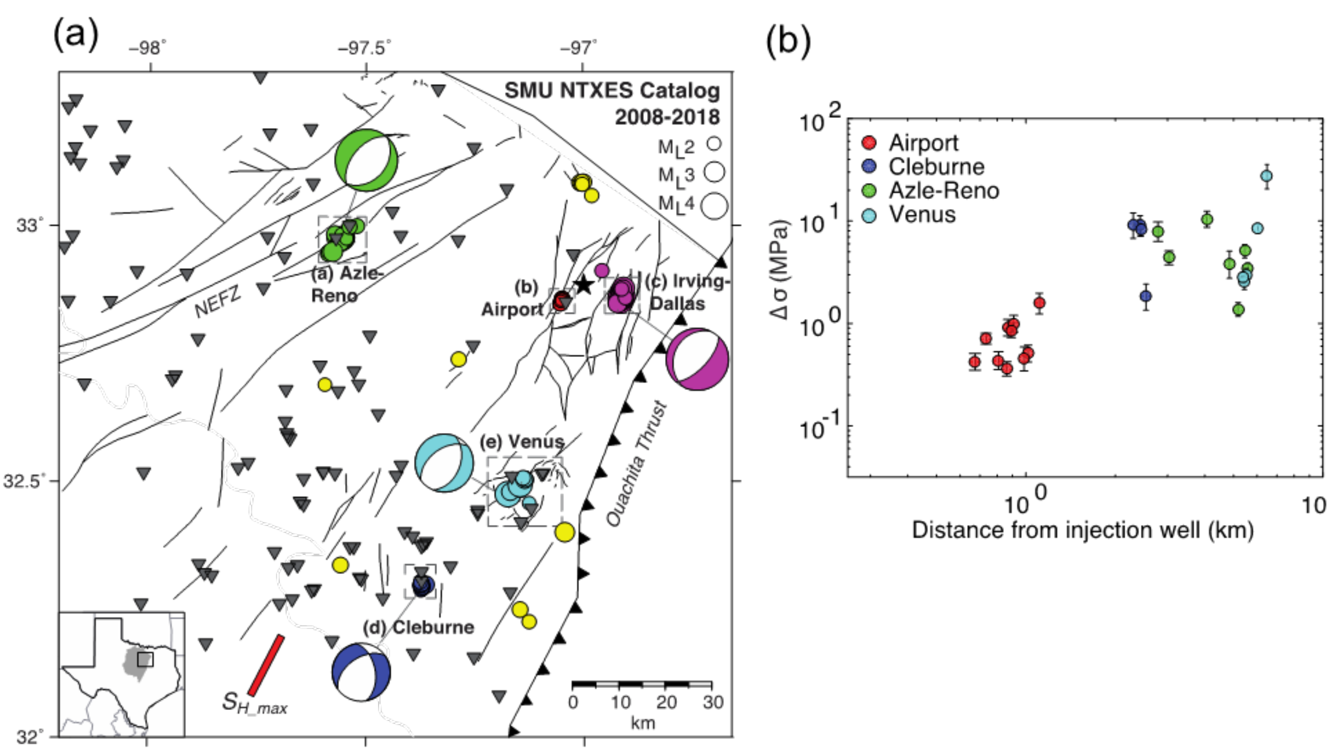


Figure 1. (a) The North Texas Earthquake catalog (colored by sequence) for the Fort Worth Basin (FWB), Texas. Focal mechanisms, regional faults (solid black lines), wastefluid injection wells (gray inverted triangles), and the maximum horizontal stress (SH_{max}) orientation (red bar) are also shown. Inset: Texas and the Barnett Shale distribution in the FWB (gray). (b) Stress drops versus distances from the nearest injection points for the Airport (red), Cleburne (blue), Azle-Reno (green), and Venus (cyan) earthquakes. The Airport earthquakes indicate an increase in stress drop with range, while stress drops from other sequences do not correlate with the distance.

Crustal Structure in Southeastern Texas from Joint Inversion of Ambient Seismic Noise and P to S Receiver Functions

R. W. Porritt, A. Savvaidis, B. Young, M. Shirley, and P. Li

The detection and classification of earthquakes in regions previously considered aseismic has led to significant advances in our understanding of anthropogenically induced earthquakes in productive basins. The Eagle Ford of southeastern Texas is one such basin that has seen an increase in earthquakes and a recent TexNet temporary network was deployed in this region to better detect and locate earthquakes. Here we present new results from a joint inversion of ambient noise derived group and phase velocity maps with P to S receiver functions for shear velocity. The first order features of this model include a clear velocity contrast parallel to the Ouachita Marathon Front and thickening of the low velocity upper crust from the northwest towards the Gulf Coast. Secondary features include NE-SW striking variations in the mid-to-upper crust, related to isolated uplifts inferred throughout the region, and variations in the presence and thickness of a high velocity lower crust. These features are anti-correlated such that the region of high velocity upper crust has little lower crust high velocity material. The Luling Uplift is identified as one of these features and we suggest the variations in lower crust structure indicate along-strike variations in the processes involved in the formation and subsequent breakup of Pangea. This model suggests the US-Gulf of Mexico margin morphology is shaped by deformation around the edges of strong blocks and that induced seismicity is focused by these structurally competent features.

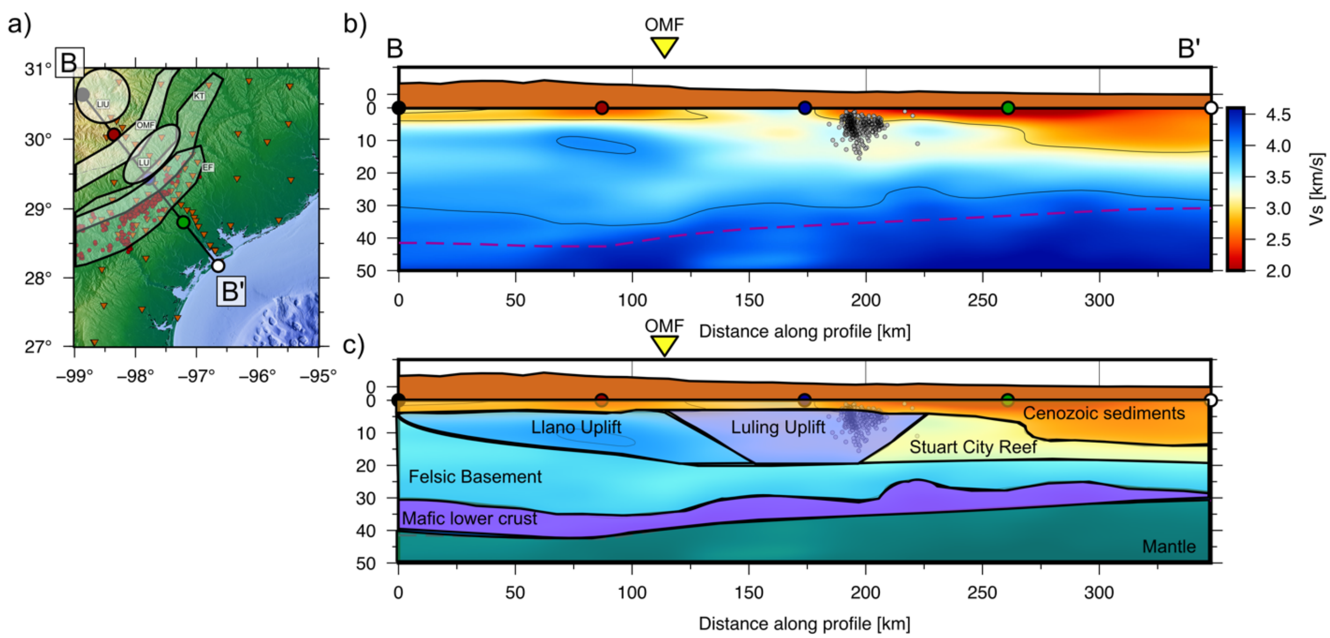


Figure 1. Cross-section perpendicular to the azimuth of major seismicity in the EF. Location of profile is plotted in panel (a) as a black line with asymmetrically colored dots which correspond to the same dots on the data cross-section B-B' in panel (b) and interpreted cartoon in panel (c). Map view (a) displays earthquakes as red circles and stations as burnt orange triangles. Cross-sections have earthquakes within 0.5° plotted as gray circles and topography on top as burnt orange starting at 0.5 km below sea level. Panel (b) displays the basement proxy as 3.0 km/s contour, 7.x proxy as 4.0 km/s contour, and CRUST 1.0 [Laske et al., 2013] as a dashed red line. Panel (c) indicates the 7.x layer as from the 4.0 km/s contour as mafic lower crust. OMF indicates approximate location of the Ouachita-Marathon Front. Highlighted features are approximate.

Characteristics of Seismicity in the Eagle Ford Shale Play Constrained by Earthquake Relocation and Centroid Moment Tensor Inversion

P. Li, G. D. Huang, A. Savvaidis, F. Kavoura, and R. W. Porritt

The analysis of earthquake locations and centroid moment tensors (CMT) is critical for assessing active fault structures and relating earthquakes with anthropogenic activities. The objective of this study is to gain insights into the active faults of the Eagle Ford shale play (EF) through relative relocation of earthquakes, assessment of CMT solutions, and investigation of the background stress field.

Using Texas Seismological Network (TexNet) data from 2017 through 2019, we were able to relocate 326 earthquakes and obtain CMT solutions for 37 M_L >=2.0 earthquakes. The earthquakes are located in the sedimentary basin and basement, with depths ranging from 2 to 10 km. The earthquake clusters in the northeastern EF are linearly distributed along the Karnes Fault Zone, whereas the southern and western clusters are spatially scattered around mapped or unmapped faults. The CMT solutions identified 32 normal fault earthquakes and 5 strike-slip earthquakes. The orientation of the fault plane of most normal fault earthquakes is southwest-northeast, while the possible fault plane of strike slip faults is largely north–south, which is roughly perpendicular to the normal faults. The normal and strike-slip faults in the EF are steep with dip angles of most faults ranging from 60° to 80°. The stress inversion results show that the major orientation of maximum horizontal stress (SH_{max}) is southwest–northeast, with minor local stress field rotations.

We further estimate earthquake energy release in the EF region using the CMT solutions. The cumulative earthquake energy release curve revealed three energy release accelerations occurred in Jan–Jul 2018, Jan–Mar, and May–Aug 2019. Whether or not these energy releases were caused by anthropogenic activities is a matter for further investigation.

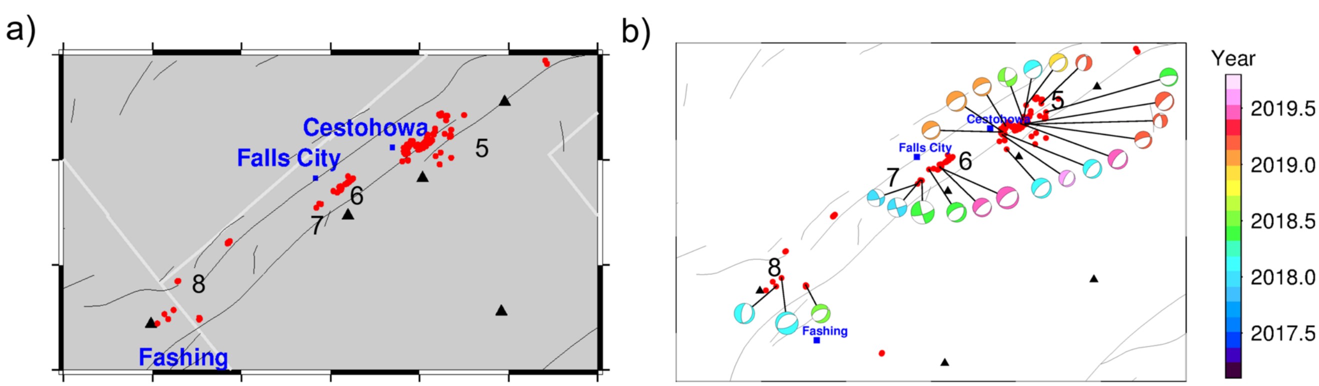


Figure 1. Maps of (a) the relocated earthquakes and (b) CMT solutions represented by beach balls of the relocated earthquakes in the Karnes Fault Zone (KFZ), central Eagle Ford shale play. The colors of the beach balls in (b) represent the origin times of the earthquakes. Most of the earthquakes in the KFZ are normal faulting earthquakes. We also observed strike earthquakes which may play a role in balancing the stress change of nearby normal faults.

Data Processing of a Local Seismological Network for West Texas Seismicity Characterization

D. Merzlikin, A. Savvaidis, S. Whittaker, and I. Bestmann

Bulletin of the Seismological Society of America, https://doi.org/10.1785/0120200086

We Propose a template-matching workflow capable of improving detection sensitivity of a seismic network and demonstrate its performance on the local seismic network comprising Texas Seismological Network installations in West Texas. We use three earthquakes from three clusters as our templates. Template matching is applied to each station independently. Then, SeisComp3 *scanloc* associator groups the obtained picks into seismic events following moveouts between stations consistent with a velocity model. In comparison to short-term over longe-term average detection workflow, the number of "new," previously undetected events more than doubles. The events detected by the template-matching workflow are registered on a set of stations, thus allowing for their absolute location. Template matching improves local network sensitivity. Among network parameters, station noise conditions appear to have the highest influence on the effectiveness of the workflow.

Our workflow discovers previously undetected earthquakes in comparison to the STA/LTA detector. Preliminary location by scanloc SeisComP3 module demonstrates that the absolute locations of the events can be restored. Template matching is currently incorporated into the TexNet workflow as an offline-processing playback.

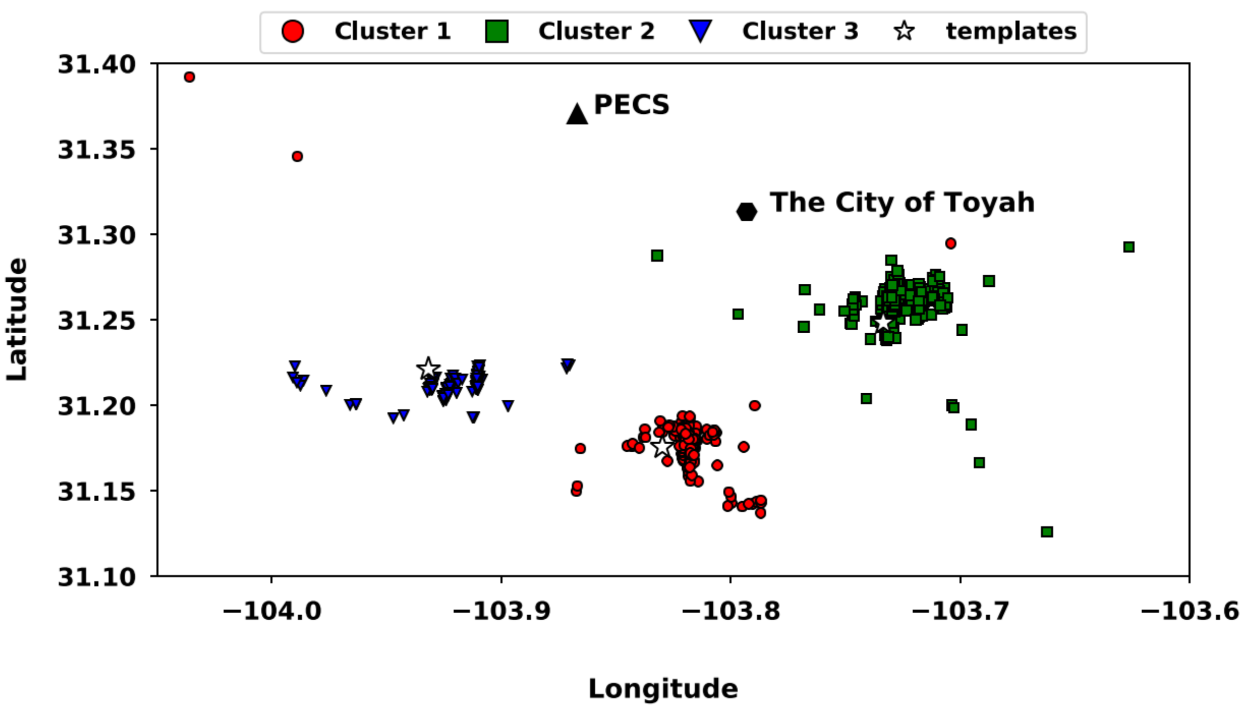


Figure 1. Map showing the epicenters of the events detected by template matching. Locations are estimated by *scanloc* SeisComP3 module as a part of the association process. High degree of clustering in the vicinity of the corresponding templates (denoted by stars) is apparent. Some location artifacts are visible. Clusters 2 and 3 have subclusters, which can represent the Earth interior, for instance, correspond to synthetic faults, or can be preliminary location artifacts.

SCALODEEP: A Highly Generalized Deep Learning Framework for Real-Time Earthquake Detection

O. M. Saad, G. Huang, Y. Chen, A. Savvaidis, S. Fomel, N. Pham, and Y. Chen

The detection of earthquake signals is fundamental in observational seismology. The detection of earthquakes is considered as a difficult task for the seismologists, therefore, a robust automatic earthquake detection algorithm is strongly demanded. Here, we develop an automatic earthquake detection framework based on a deep learning approach (SCALODEEP). It extracts high-order features embedded in the three-component seismograms by encoding time-frequency representation (scalogram) into a deep network with skip connections. The SCALODEEP is trained and validated on an open-source dataset from North California, and then employed to seismicity detection in four areas, including Arkansas, Japan, Texas, and Egypt. Despite vastly varying characteristics of regional earthquakes (e.g., mechanism, duration and noise level), SCALODEEP successfully detects seismic signals over a broad range of magnitudes (as low as -1.3 M_L) and outperforms conventional algorithms such as STA/LTA, FAST, template matching, and CRED. In summary, SCALODEEP demonstrates a great generalization ability and offers a promising new tool to improve the existing earthquake detection system, such as the TexNet.

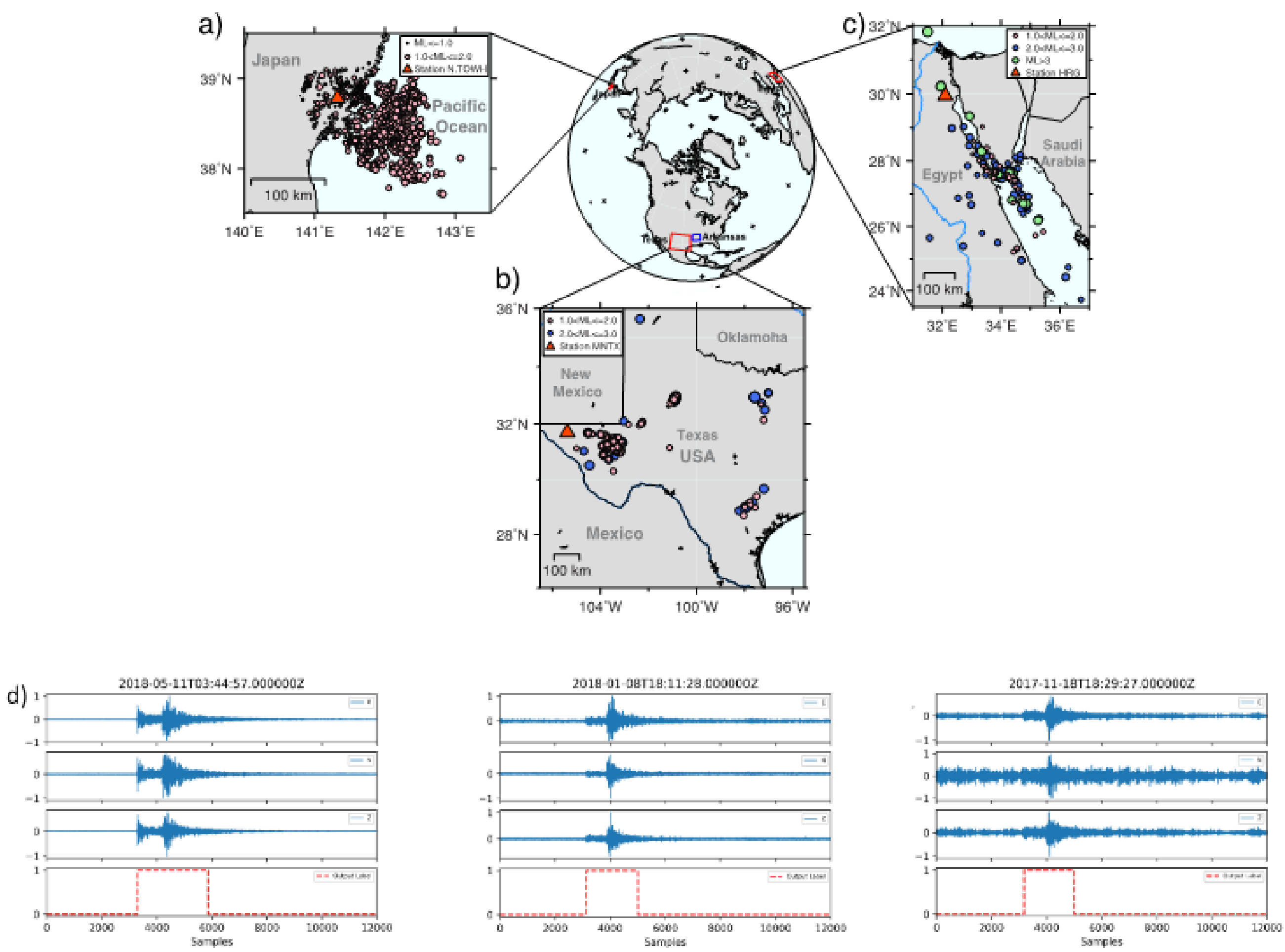


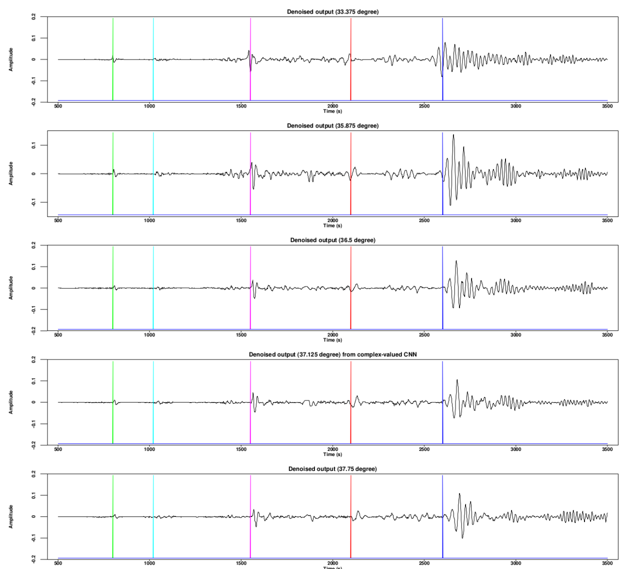
Figure 1. The generalization ability of the SCALODEEP network has been tested via (a) Japanese network, (b) TexNet, and (c) Egyptian network. (d) Automatic earthquake detection results for the MNTX station of the TexNet.

Passive Seismic Signal Denoising Using Convolutional Neural Network

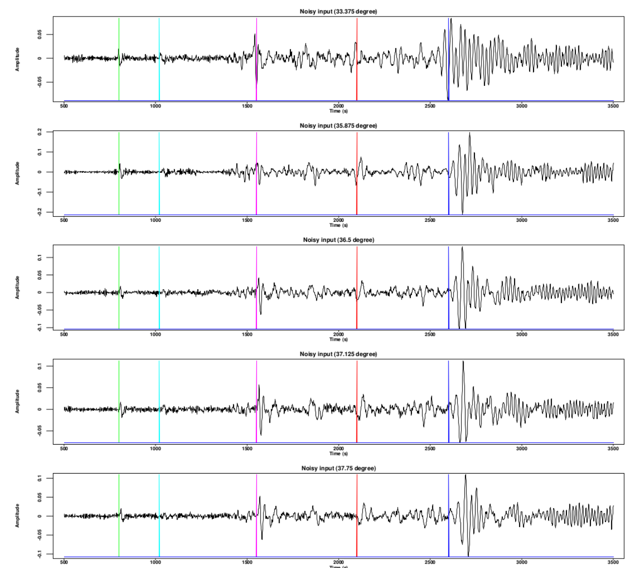
N. Pham, D. Merzlikin, S. Fomel, and Y. Chen

Published in the SEG Technical Program Expanded Abstract 2020, DOI: https://doi.org/10.1190/segam2020-3427266.1

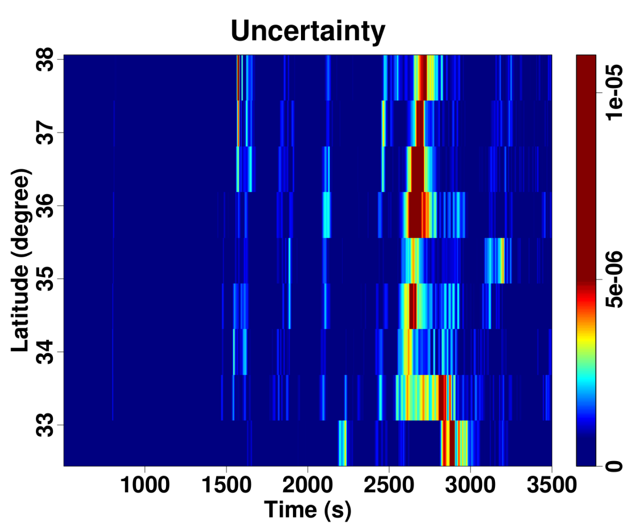
We propose a method for earthquake denoising using complex-valued convolutional neural network. We use UNet architecture with complex inputs from local time-frequency transform (LTFT). We use a modified LTFT which applies a smoothing operator along the frequency axis to obtain a higher temporal resolution. We add drop-out layers to quantify the model uncertainty. We train the network on synthetic earthquakes and then apply it to field data. Applying the model parameters trained on synthetic data to real earthquakes can efficiently recover signals of different phases. Model uncertainties are related to waveform complexities of different arrivals.



Noisy data



Denoised output



Model Uncertainty

Earthquake Detection Using PhaseNet Near Pecos, TX in the Delaware Basin

J. Faith, D. Merzlikin, M. Karplus, D. Doser, S. Veitch, A. Savvaidis, W. Ellsworth, W. Zhu, G. Beroza, and S. M. Mousavi

Since 2009, there has been a notable increase in seismicity in the Pecos, Texas region of the Delaware Basin. From January 2017 to August 2020, TexNet (Texas Seismological Network) reported 6 M3.0+ earthquakes and ~276 M2.0–2.9 earthquakes within a 50 km radius of Pecos, TX. To better constrain earthquake locations and depth, The University of Texas at El Paso and TexNet collaborated to design and deploy a network of 25 3-Component Magseis Fairfield Z-land 5-Hz geophones in the Pecos, Texas region from November 2018 to January 2020.

Due to increasing volumes of seismic data in West Texas, we apply PhaseNet, a deep-neural-network based seismic arrival time picking method, to automatically determine onsets of both P- and S- phases for five months of our data. We compare the P- and S- picks from PhaseNet to picks from a short-term average/long term average (STA/LTA) automatic phase picker used by TexNet that are manually checked by TexNet analysts.

We further compare an earthquake catalog derived from the PhaseNet picks with TexNet catalogs using analyst manual picks to examine how location and depths change with these different workflows. We discuss the performance of PhaseNet for this application and find that PhaseNet is an efficient and robust method for automating earthquake catalog creation for West Texas.

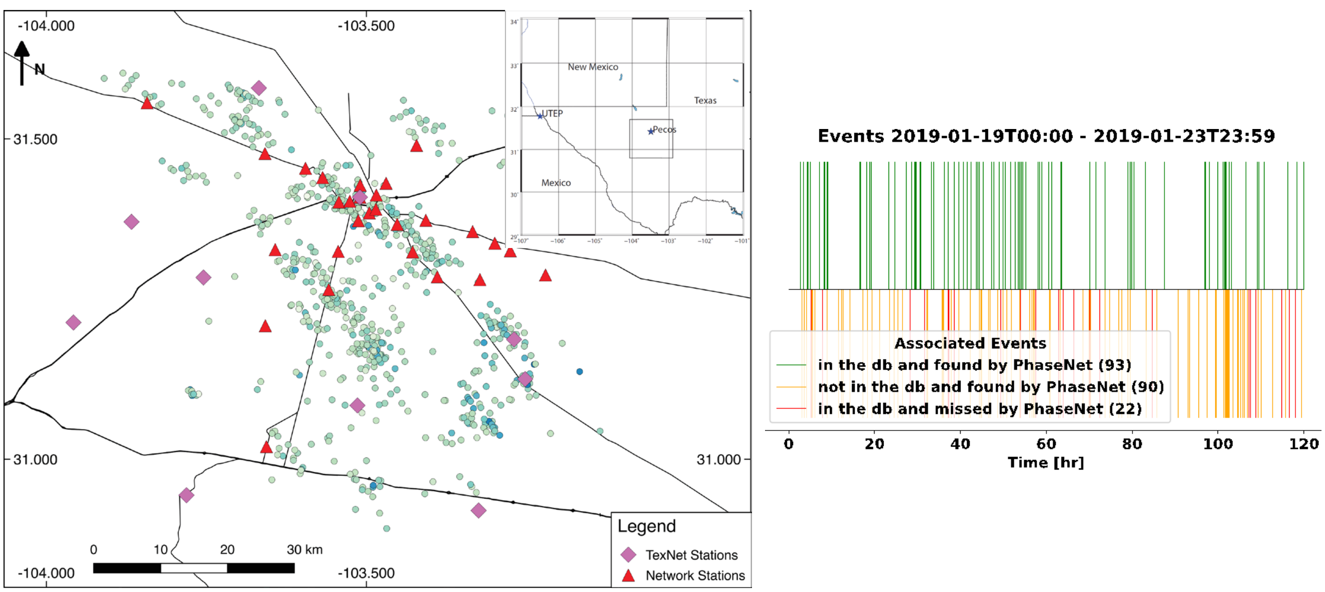


Figure 1. (left) Map of Pecos Array study area in the Delaware Basin showing TexNet stations (pink diamonds), Pecos Array stations (red triangles), and TexNet catalog earthquakes from Nov. 2018 to March 2019 (blue/ green circles). Inset shows location within West Texas. (right) Plot of associated events from Jan 19–23, 2019. Lines indicate earthquake events detected using the standard TexNet database method (STA/ LTA plus analyst review) compared to using the PhaseNet automatic picking method. Green lines indicate events found by both methods. Orange lines indicate events found by PhaseNet only, and red lines indicate events found by the TexNet database method only.

Spatiotemporal and Stratigraphic Trends in Saltwater Disposal Practices of the Permian Basin, Texas and New Mexico, U.S.

C. R. Lemons, G. McDaid, K. M. Smye, J. P. Acevedo, P. H. Hennings, D. A. Banerji, and B. R. Scanlon

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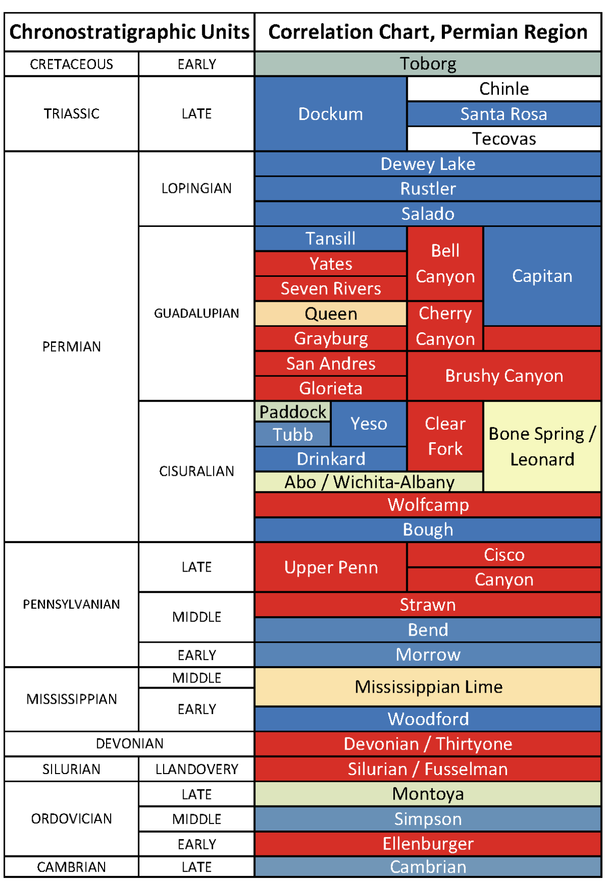
Subsurface disposal of saltwater co-produced with oil and gas has become a critical issue in the U.S. due to linkages with induced seismicity, as seen in Oklahoma and North-Central Texas. Here we assess the spatiotemporal and stratigraphic variations of saltwater disposal (SWD) volumes in the Permian Basin. The results of this analysis provide critical input into integrated assessments needed for handling of produced water and for emerging concerns, such as induced seismicity.

Wellbore architecture, permits, and disposal volumes were compiled, interpreted for disposal intervals and geologic targets, and summarized at formation, subregion, 100 mi^2 (260 km^2) area, and monthly volumes for the year 1978-2016. Geologic targets were interpreted by intersecting the disposal intervals with gridded stratigraphic horizons and by reviewing well logs where available.

A total of 30 billion (B) barrels (~5 trillion Liters) were disposed into 73 geologic units within 6 subregions via 8,201 active SWD wells for 39 years. Most disposal occurred in the Midland Basin and Central Basin Platform (CBP) over the first 34 years but shifted from the CBP to the Delaware Basin over the last 5 years (2011–2016) with the expansion of unconventional oil and gas production. About half of the saltwater is disposed above the major unconventional reservoirs into Guadalupian-aged formations, raising concerns of overpressuring and interference with production. Operators are exploring deeper SWD targets; however, proximity to crystalline basement poses concerns for high drilling costs and the potential for induced seismicity by reactivation of deep-seated faults.



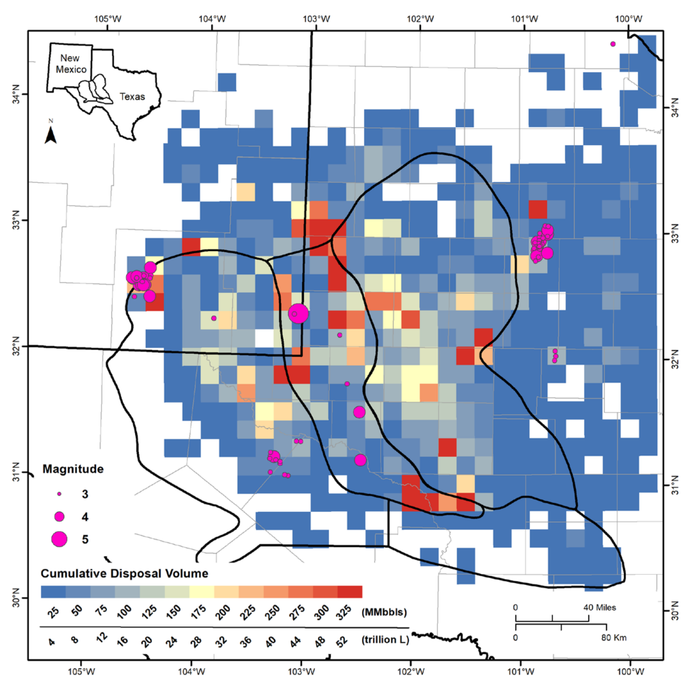


Figure 1. Geographic, geologic, and temporal variation in SWD activity for the Permian Region, Texas from 1983 to 2016. (left) Cumulative disposal volumes (1983–2016) are differentiated into 40 major geologic targets using the cumulative disposal volumes color scale, for which blue indicates the lowest volume and red indicates highest volumes. (right) Cumulative SWD volumes are mapped in 100 mi^2 (161 km^2) block grids using the same color scale.

Stratigraphic Architecture and Petrophysical Characterization of Formations for Deep Disposal in the Fort Worth Basin, TX

K. M. Smye, C. R. Lemons, R. Eastwood, G. McDaid, and P. Hennings

Published in Interpretation, Nov. 2019, https://doi.org/10.1190/INT-2018-0195.1

Disposal of hydraulic fracturing flowback and produced water into Ordovician and Cambrian formations of the Fort Worth Basin (FWB), coupled with an increase in observed seismicity in the Dallas–Fort Worth area, necessitates an understanding of the geologic character of these disposal targets. More than two billion barrels (Bbbls) of wastewater have been disposed into the Ordovician Ellenburger Group of the Fort Worth Basin over the past 35 years. Since the implementation of the TexNet Earthquake Catalog (Jan 1, 2017), more than 20 earthquakes of local magnitude M_L2.0 or greater have been detected in the area, with depths ranging from 2–10 km (~6500–33,000 ft). The cited mechanism for inducement of these earthquakes is reactivation of basement faults due to pore pressure changes, either directly related to proximal disposal or due to disposal volume build-up over time. Here we present a stratigraphic and petrophysical analysis of Fort Worth Basin disposal targets and their relation to basement rocks to serve as a framework in which to test pore pressure changes over time with saltwater disposal. We show that the Ellenburger consists of alternating layers of limestone and dolomite, with minor siliclastics above basement toward the Llano Uplift. The disposal zone pore volume is estimated from thickness and porosity maps, and ranges from <0.1 to >0.60 billion barrels per square mile.

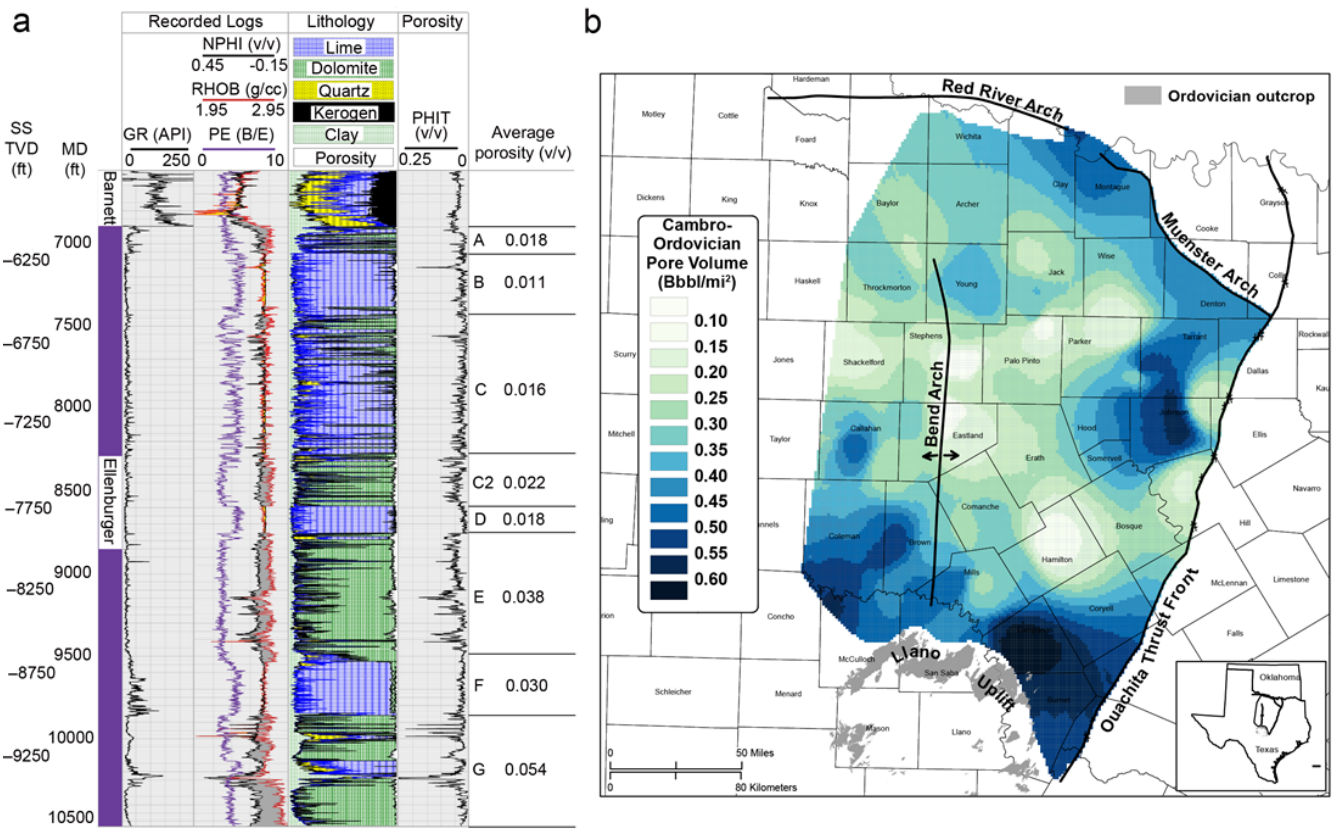


Figure 1. Ellenburger disposal interval geologic characterization. (a) Interpretation of lithology and porosity for different stratigraphic layers of the Ellenburger. (b) Ellenburger and Cambrian regional pore volume (porosity * thickness).

Injection-Induced Seismicity and Fault-Slip Potential in the Fort Worth Basin, Texas

P. H. Hennings, J.-E. Lund Snee, J. L. Osmond, H. R. DeShon, R. Dommisse, E. Horne, C. Lemons, and M. D. Zoback

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The rate of seismicity in the hydrocarbon-producing Fort Worth Basin of north-central Texas, which underlies the Dallas–Fort Worth metropolitan area, increased markedly from 2008 through 2015, coinciding spatiotemporally with injection of 2 billion barrels of wastewater into deep aquifers. Although the rate of seismicity has declined with injection rates, some earthquake sequences remained active in 2018 and new clusters have developed. Most of this seismicity occurred away from regionally mapped faults, challenging efforts to constrain the continuing hazards of injection-induced seismicity in the basin. We present detailed new models of potentially seismogenic faults and the stress field, which we use to build a probabi-listic assessment of fault-slip potential. Our new fault map, based on reflection seismic data, tens of thousands of well logs, and outcrop characterization, includes 251 basement-rooted normal faults that strike dominantly north-northeast, several of which extend under populated areas. The updated stress map indicates a relatively consistent north-northeast–south-southwest azimuth of the maximum horizontal principal stress over seismically active parts of the basin, with a transition from strike-slip faulting in the north to normal faulting in the southeast. Based on these new data, our probabi-listic analysis shows that a majority of the total trace length of the mapped faults have slip potential that is equal to or higher than that of the faults that have already hosted injection-induced earthquake sequences. We conclude that most faults in the system are highly sensitive to reactivation, and we postulate that many faults are still unidentified. Ongoing injection operations in the region should be conducted with these understandings in mind.

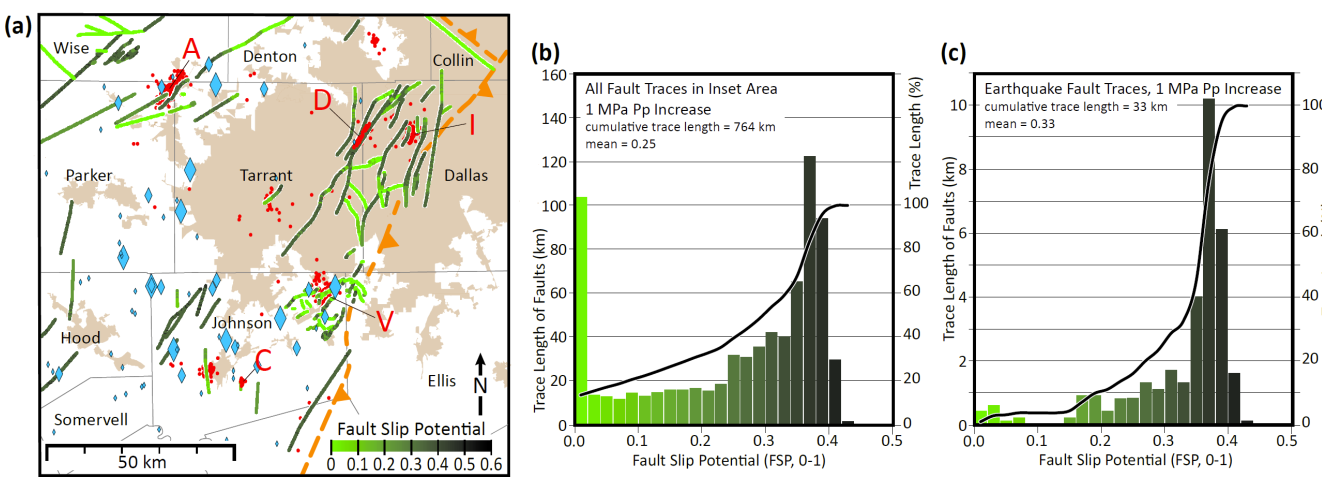


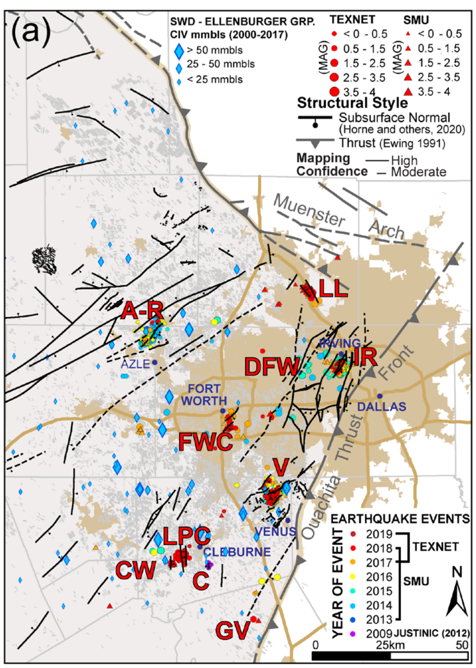
Figure 1. Fault Slip Potential map and distributions for the Dallas-Fort Worth areas of the Fort Worth Basin including the areas with largest cumulative injection volumes, earthquake sequences, and higher-confidence fault interpretation. (a) FSP map for the case of 1 MPa increase in pore pressure. (b) FSP distribution for the fault segments in (a). (f) FSP distribution for the fault segments in (a) that have hosted earthquakes. The possible range of FSP is 0-1.0.

Structural Characterization of Potentially Seismogenic Faults in the Fort Worth Basin

E. A. Horne, P. H. Hennings, J. L. Osmond, and H. R. DeShon

Published in the SEG Journal of Interpretation: https://doi.org/10.1190/INT-2019-0188.1

From 2006 through mid-2018 there have been 125 Mw ≥ 2.5 recorded earthquakes within the Fort Worth Basin and the Dallas-Fort Worth metropolitan area. There is general scientific consensus that this increase in seismicity has been induced by increases in pore fluid pressure from waste water injection and from cross-fault pore pressure imbalance due to injection and production. Previous fault stress analyses show that many of the faults are critically stressed, therefore careful consideration should be taken when injecting in close proximity to these structures. Understanding the structural characteristics that control geomechanical aspects of these earthquake-prone faults is vital to characterizing this known hazard. To improve the understanding of faults in the system we provide a characterization using a new basin-wide fault interpretation and database that has been assembled through the integration of published data, 2D and 3D seismic surveys, outcrop mapping, earthquakes, and interpretations provided by operators resulting in a 3D structural framework of basement-rooting faults. Our results show that a primary fault system trends NE–SW, with architectures that range from isolated faults to linked and cross-cutting relay systems. Seismogenic faults are generally less than 10 km long, trend towards the northeast, and exhibit over 50 meters of normal displacement. The intensity of faulting decreases to the west away from the Ouachita structural front. Fault attribute interrelationship analyses enable a more complete characterization of faults in the basin which can be used to mitigate the seismic hazard. Finally, we show that a significant percentage of the total population of faults may be susceptible to reactivation and seismicity as those that have slipped recently.



(b)

EQ SEQUENCE NAME	ABBREV.	2008	2009	2013	2014	2015	2016	2017	2018	2019
Azle - Reno	AR					m 3.6				
Cleburne - Justinic 2012	C									
Cleburne - West	CW									
Dallas Fort Worth Airport	DFW					m 3.6				
Fort Worth City	FWC									
Grandview	GV									
Irving	IR					m 3.5				
Lake Lewisville	LL									
Lake Paul Cleburne	LPC									
Venus	V					m 4.0				

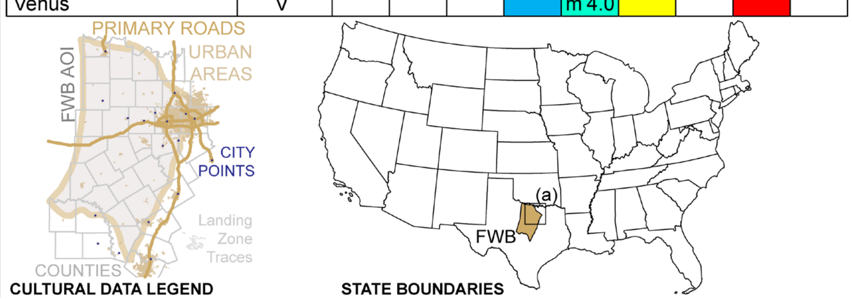


Figure 1. Fault map and spatiotemporal distribution of earthquake events within the greater FWB. (a) Fault map of basement-rooted faults for the FWB, and discrete earthquake sequences, hypocenter colors reflect the year of event, and sized according to magnitude. (b) Earthquake hypocentral events for discrete sequences grouped by year, significant events occurred in 2015 for several sequences, the magnitudes for these events are annotated.

A Comprehensive Hydrogeologic Model of Pore Pressure Change in the Ellenburger Group, Fort Worth Basin, North-Central Texas

R. Gao, J.-P. Nicot, P. Hennings and others

Submitted to AAPG Bulletin

Produced water generated by hydrocarbon production from the Barnett Shale has been injected into geologically-complex carbonates of the Ellenburger Group for 20 years. It consists of karstic platform carbonates with locally high injection potential, and that commonly directly overlies the Precambrian crystalline basement at 4500-15,000 ft depths. Its thickness varies from >4000 ft to <2000 ft. The basin has experienced anomalous seismicity in the crystalline basement very likely induced by the associated pore pressure increase. The BEG developed a thorough and highly detailed numerical fluid flow model of the Ellenburger Group covering ~30 counties with the goal of estimating pore pressure evolution through space and time in order to understand the anomalous seismic events and for management of the disposal resource.

Stratigraphic information and flow parameters were extracted from available logs of conventional wells (1200+ wells) and petrophysical analyses (47 wells). Data from operations of a few SWD wells anchored the model input parameters. Limited well tests allowed for quantification of the impact of faults and fractures. Faults and fractures form important features of these structurally- and diagenetically-complex formations and data sources include outcrops, 3D seismic, and well logs. Fault and fracture permeability and porosity were estimated through a Discrete Fracture Network modeling approach. Major faults are implemented deterministically whereas fractures and minor faults, which considerably enhance the permeability of the carbonate system, are implemented stochastically and history-match the pressure data. A total of 127 saltwater disposal (SWD) wells injected a cumulative volume of 2.23 billion barrels from ~2003 to 2018.

The model is upscaled into 10+ layers and calibrated using the CMG-STARS software with the help of injection pressure constraints while honoring injection volume history. Very little pressure monitoring data is available; model is calibrated by converting surface injection pressures to bottom-hole pressures. Investigating selected areas distributed across the model (Figure 1), the minimum pressure increase in the strata immediately above crystalline basement is ~20 psi (0.14 MPa) and the maximum increase is ~210 psi (1.4 MPa). Although the rates of SWD have decreased from the system peak in 2011, the pore pressure at all of the sampling areas of the model show either continued increases or a plateau. The system-wide hydrogeologic connectedness of the EBG allows pore pressure increases from SWD to dissipate broadly at the regional scale and therefore, understanding the impact of SWD needs to be conducted at the regional scale.

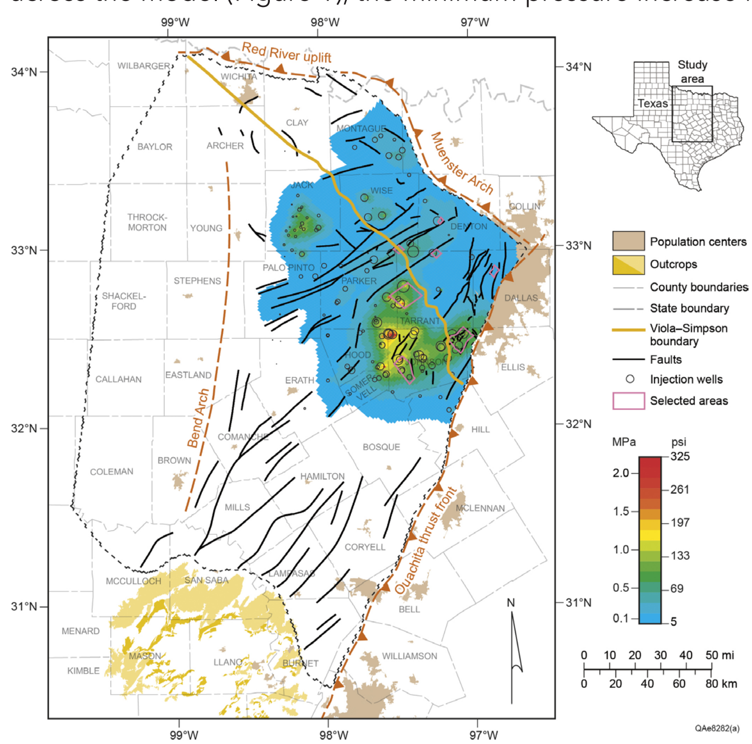


Figure 1. Map of pressure increase in the basal sediment layer. Cumulative injection volumes at the well locations are shown by variable-size circles (Scale is non linear and cumulative injection volumes vary from 84 million bbl to 37 thousand bbl (median is 10.7 million bbl and average is 17.6 million bbl).

Pore Pressure Threshold and Fault Slip Potential for Induced Earthquakes in the Dallas-Fort Worth Area of North Central Texas

P. H. Hennings, J. P. Nicot, R. S. Gao, H. R. DeShon, J-E. Lund Snee, A. P. Morris, M. R. Brudzinski, E. A. Horne, and C. Breton

Presented at the Society of Exploration Geophysicists Annual 2020 Annual Conference and submitted to the Geophysical Research Letters.

Earthquakes were induced in the Fort Worth Basin from 2008 through 2019 by changes in pore pressure from injection of oilfield wastewater (SWD). In this region and elsewhere, a missing link in understanding the mechanics of causation has been a lack of comprehensive models of pore pressure evolution (ΔPp) from SWD. We integrate detailed earthquake catalogs, ΔPp, and probabilistic fault slip potential (FSP) and find that faults near large-scale SWD became unstable early, when ΔPp reached ~0.26 MPa and FSP reached 0.22. Faults farther from SWD became unstable later, when FSP reached 0.14 and at much smaller ΔPp. Earthquake sequences reactivated with ΔPp of ~0.05 MPa. There is strong variability in the response of faults, with many remaining stable at higher ΔPp and few that became seismogenic at smaller changes. As ΔPp spread regionally, an ever increasing number of faults were impacted and the most sensitive became unstable.

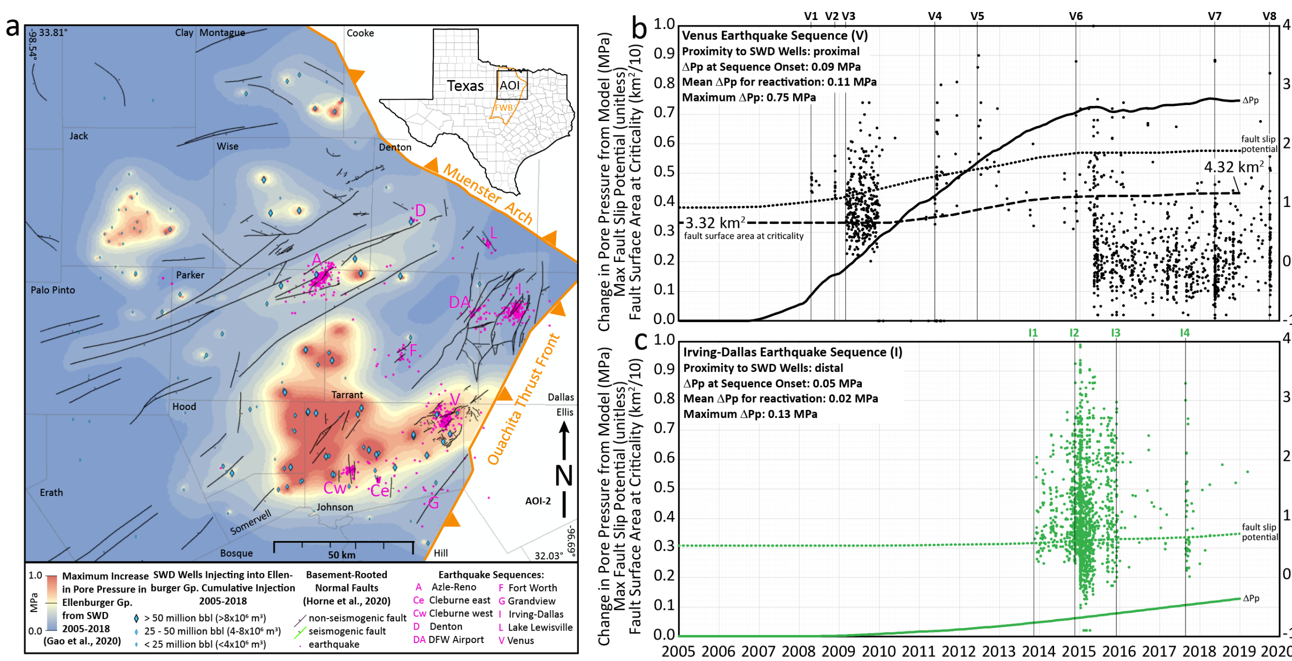


Figure 1. (a) Map of the area of interest in the FWB (AOI) showing SWD wells and cumulative injected volumes, the earthquake sequences that we study here, traces of basement-rooted faults from Horne et al. (2020), and the distribution of the maximum ΔPp at the basement-sediment interface from the Gao et al. (submitted) hydrogeologic model. (b and c) Temporal evolution of factors at the Venus and Irving-Dallas earthquake sequence (ES) areas showing earthquake history (dots), interpreted ES onset and reactivation, local ΔPp from the hydrogeologic model (solid curve), deterministic estimate of the surface area of the seismogenic faults that was critically stressed (dashed curve, b only), and slip potential (FSP) of the seismogenic faults (dotted curve).

Facies and Reservoir Properties of the Delaware Mountain Group of the Delaware Basin and Implications for Saltwater Disposal

K. M. Smye, D. A. Banerji, R. Eastwood, G. McDaid, and P. Hennings

In revision at the Journal of Sedimentary Research, Oct. 2020

Deepwater siliciclastic deposits of the Delaware Mountain Group (DMG) in the Delaware Basin are the primary interval targeted for disposal of wastewater (SWD) from unconventional oil production in the Delaware Basin. Water can be up five times the volume of oil produced, and needs to be safely disposed or recycled. In some areas of the basin, especially in southeastern Reeves Co., there appears to be a relationship between increases in SWD into the DMG and the shallowest of recent earthquakes as cataloged by TexNet. Concerns about storage capacity and induced seismicity necessitate geologic characterization of the disposal intervals to understand how reservoir properties might impact the flow of injected fluid.

Formations of the DMG are comprised primarily of sandstones deposited in a deepwater environment. Here we present a basin-wide geologic characterization of the DMG of the Delaware Basin. The stratigraphic architecture, lithology, facies, and flow properties including porosity, permeability, amalgamation ratios and bedding trends, are interpreted and mapped. This geologic characterization can be used to assess the regional injection disposal resource of the DMG, which is a critical step in mitigating potential risks such as induced seismicity, water encroachment on production, and drilling hazards, particularly with likely development scenarios in the basin and the associated produced water volumes that will need to be managed.

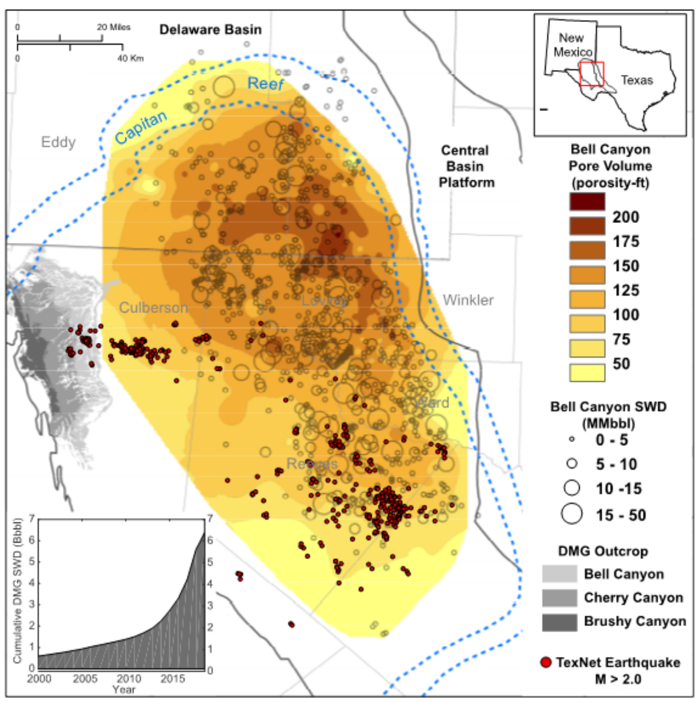


Figure 1. Pore volume (porosity * thickness) for the Bell Canyon Formation of the Delaware Mountain Group with saltwater disposal well volumes and TexNet earthquakes $M_L > 2.0$. Inset plot shows cumulative Delaware Mountain Group disposal volume from 2000 through 2018.

Variations in Vertical Stress in the Permian Basin Region

K. M. Smye, P. H. Hennings, and E. A. Horne

In revision at the American Association of Petroleum Geologists Bulletin, Oct. 2020

Constraining the magnitude of vertical stress (S_V), or overburden pressure, is key in determining a region's stress state, and has implications for reservoir geomechanics and the potential for induced seismicity. Of the principal stress orientations (S_V, and minimum and maximum horizontal stresses S_{Hmin}, S_{Hmax}), S_V is the most straightforward to constrain using wireline log data because it is the integration of density with depth. The magnitude of S_V varies with rock type and degree of compaction, potentially causing local changes in the *in situ* stress field. Previous studies on the state of stress in the Permian Basin use a constant S_V and yield an interpretation that the faulting regime transitions from normal faulting in the west to normal/strike-slip faulting in the east. Here we present an interpretation of the spatial and depth variability in vertical stress trends in the Permian Basin based on density log integration. Where density measurements are absent, values are calculated from compressional velocity logs using a transform that is fit to local data. Notable variations include higher S_V gradients on carbonate platforms and shelves, where high-density carbonates are thicker and are found at shallower depths than in the basins. Within the basins, the magnitude of S_V gradient is as low as 1.06 psi/ft (0.024 MPa/m) at depth. This work shows the potential for regional interpretations of S_V to gain insight into the effect of variations in S_V on state of stress

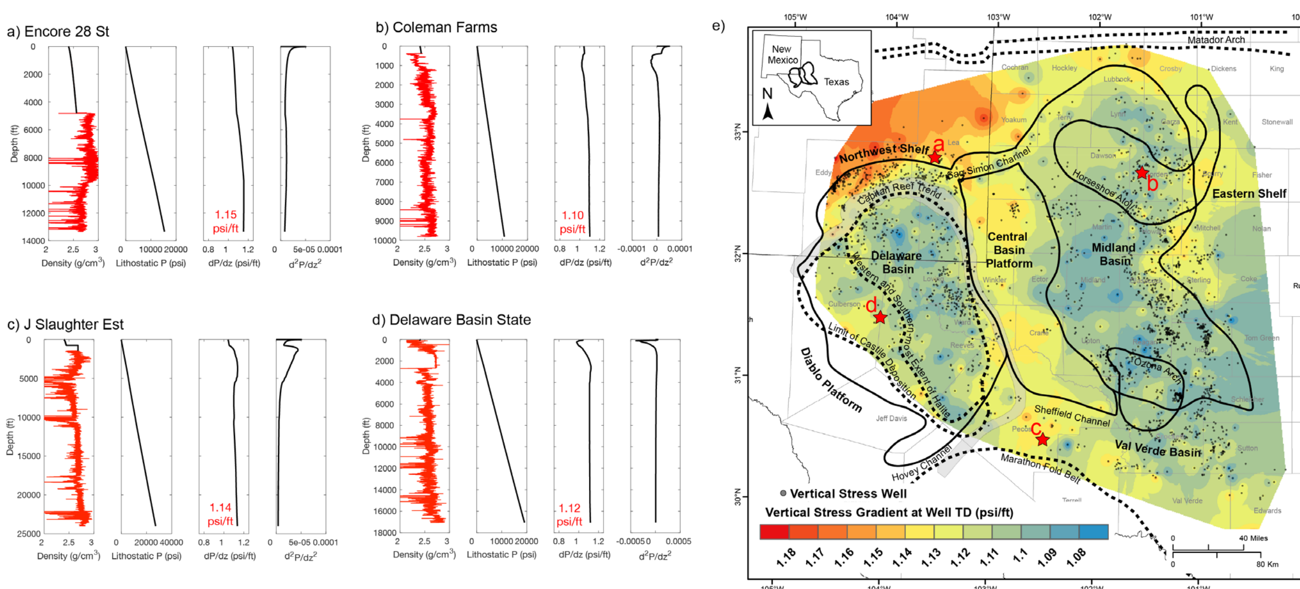


Figure 1. Interpretation of vertical stress by well and regionally. Density log (red line) and shallow density approximation (black line), lithostatic pressure or vertical stress, pressure gradient, and second derivative of pressure with depth for wells located in (a) Northwest Shelf, (b) Midland Basin, (c) Val Verde Basin, and (d) Delaware Basin. (e) Vertical stress variations at well total depth throughout the Permian Basin region.

Hydrogeological Modeling and Pore Pressure Characterization of the Delaware Basin Delaware Mountain Group, West Texas

J. Ge, J.-P. Nicot, and P. Hennings

Submitted to Paper Presented at GSA 2020

The Permian-age Delaware Mountain Group (DMG) of the Delaware Basin in west Texas and southeastern New Mexico is the major target for produced water disposal and has taken up a large fraction of the overall water volume produced in the Basin from unconventional operations. Seismic activity in the Delaware Basin has recently increased starting in 2010 and is possibly related to injection operations, which have been increasing in the same time of period. The goal of the study is to determine the historical, current, and future pore pressure in the DMG using a numerical flow model (CMG-STARS software).

To better understand the relationship between seismicity, pore pressure evolution, and produced water disposal, a 3D hydrogeological model of the DMG was constructed with all available static data: well log data, stratigraphic data, petrophysical analysis, and core data. The model was upscaled into 18 layers composing the three major formations of the DMG (Bell Canyon, Cherry Canyon, and Brushy Canyon). Input data for the simulations are the monthly injection rates of 974 saltwater disposal (SWD) wells. The model permeability field was updated with dynamic injectivity information based on surface injection pressures and rates of the SWD wells. Model calibration was achieved comparing model pressures at well locations to bottom-hole pressures computed from field flowing wellhead pressures. Pressure projections (to 2025) were simulated using injection rates based on the average rate of last 6 months of each SWD well. Preliminary simulation results suggest pressure will keep growing at an increased rate. The basin-wide hydrogeological model provides a preliminary view on the pore pressure evolution of the DMG and is of great interest to help in implementing safe SWD management practices in the area.

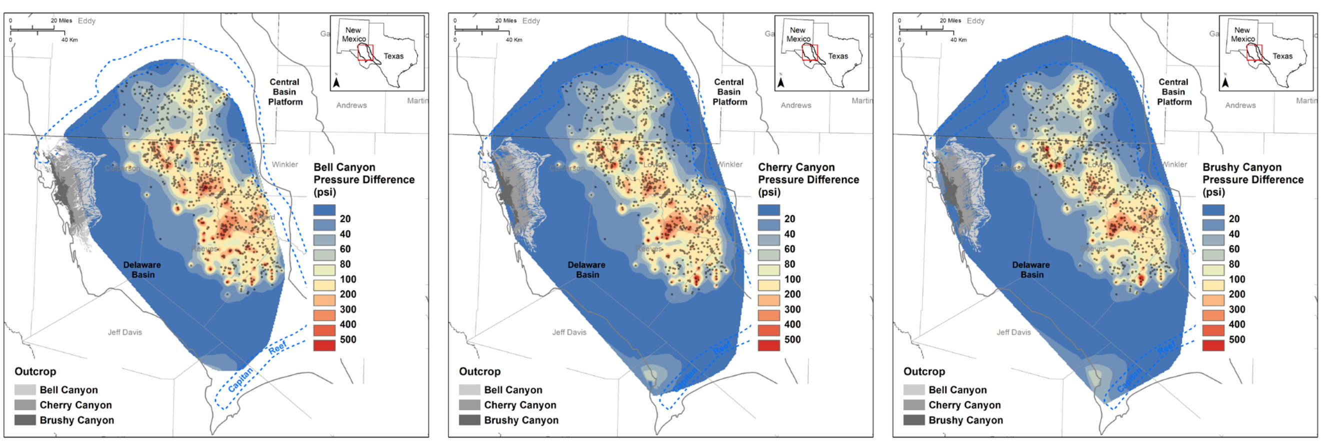


Figure 1. Pressure buildup due to injection from 1982-2018 in the formations of DMG.

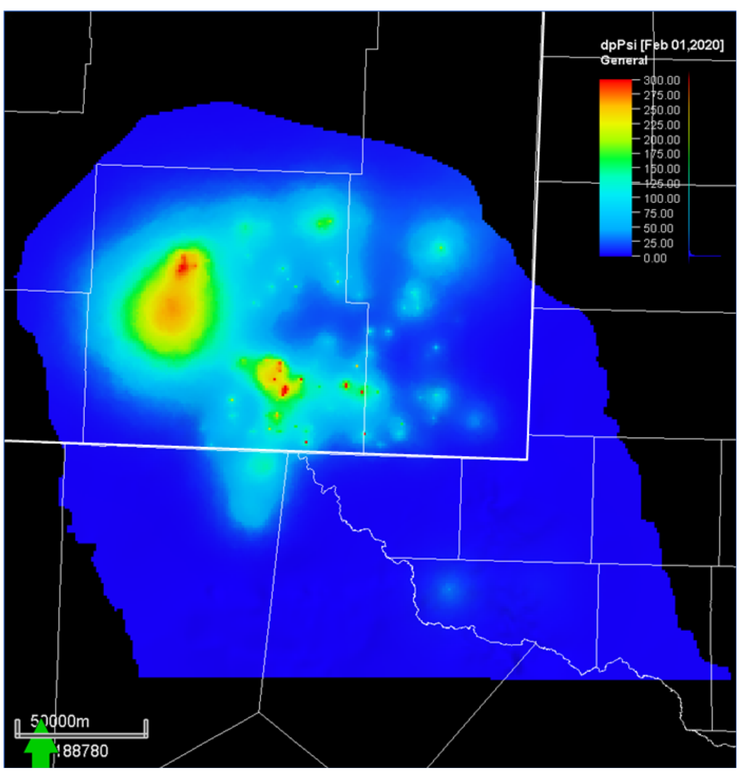
Preliminary Hydrogeological Modeling of Produced Water Deep Injection in the Delaware Basin for Pore Pressure Characterization

R. Gao, J.-P. Nicot, P. Hennings and others

Paper Presented at GSA 2020

Over the last decade the Delaware Basin of west Texas and southeast New Mexico has become a top hydrocarbon producing province; the region has also experienced a significant increase in the rate of seismicity, some events attributed to salt water disposal (SWD). Most of the water volume produced in the Delaware Basin from operational operations is injected into the Delaware Mountain Group (DMG), a clastic package with relatively high permeability overlying the Permian-age producing strata. However, a significant fraction is received by formations older than Permian, in particular in New Mexico (Figure 1). A preliminary assessment of the pore pressure buildup in these formations (Cambrian to Pennsylvanian but, in particular, porous carbonates of Silurian to Devonian age) was conducted by the BEG. It followed the approach already established in the FWB and for the overlying DMG but in a simplified fashion. With limited characterization data available, the objective is to conduct a screening-level hydrogeological model that spans the injection formations and approximately characterize the pore pressure evolution.

The geomodel is built in Petrel and properties upscaled to a fluid flow model to be run in CMG-STARS. The model is divided into 5 layers as determined by the well log analysis and other information from published documents. Each layer is divided into 3 sublayers to accommodate the vertical location of the injection intervals of the 189 SWD wells of the model. Grid cells are 1 km across. Porosity and permeability fields honor the geostatistical characteristics used in the Fort Worth Basin Ellenburger disposal formation in Central Texas as an analog and permeability values are anchored thanks to injectivity estimates (well head pressure vs. injection rate). No fault and no hydrocarbon production are included. The model is calibrated using a total of 37 injection wells, the ones with accurate data, for which wellhead injection pressure was approximately converted into the more useful bottom hole pressure



Simulation results show local pore pressure increases up to 300 psi (2 MPa) (Figure 1). The increase is particularly steep during the recent years and is focused in New Mexico where most of the injection is taking place. This scoping-level geologic and hydrogeologic model suggests that pore pressure in the deep strata will increase sharply regionally and that updates to the model are needed, in particular, through a detailed geological framework and petrophysical characterization.

Figure 1. Pore pressure buildup in the Devonian-Silurian strata from June 1989 to January 2020. New Mexico–Texas state line in thick white line.

InSAR Reveals Complex Surface Deformation Patterns Over an 80,000 Square Kilometer Oil-Producing Region in the Permian Basin

S. Staniewicz, J. Chen, H. Lee, J. Olson, A. Savvaidis, R. Reedy, C. Breton, E. Rathje, and P. Hennings

Geophysical Research Letters, https://doi.org/10.1029/2020GL090151

Over the past decade, breakthroughs in horizontal drilling and hydraulic fracturing have made the Permian Basin one of the most productive oil fields in the world. Using spaceborne Interferometric Synthetic Aperture Radar (InSAR), we mapped how the Permian Basin's land surface has deformed from oil and gas production activities. We developed a new processing technique to mitigate tropospheric noise associated with turbulent variations, which allows us measure ground changes with millimeter-level accuracy. We observed numerous subsidence and uplift features near active production and disposal wells. The observed deformation rate is the highest in 2018 when the largest volume of oil and gas was produced in the basin. The InSAR-observed subsidence patterns over the Pecos area can be modeled as dip-slip over multiple normal faults and discretized cylindrical reservoir compaction. The implication for the scientific community, as well as a broader sector of stakeholders, is that the increase in high quality satellite-based data now allows us to monitor vast areas for subsurface stress and pore pressure changes in oil-producing regions.

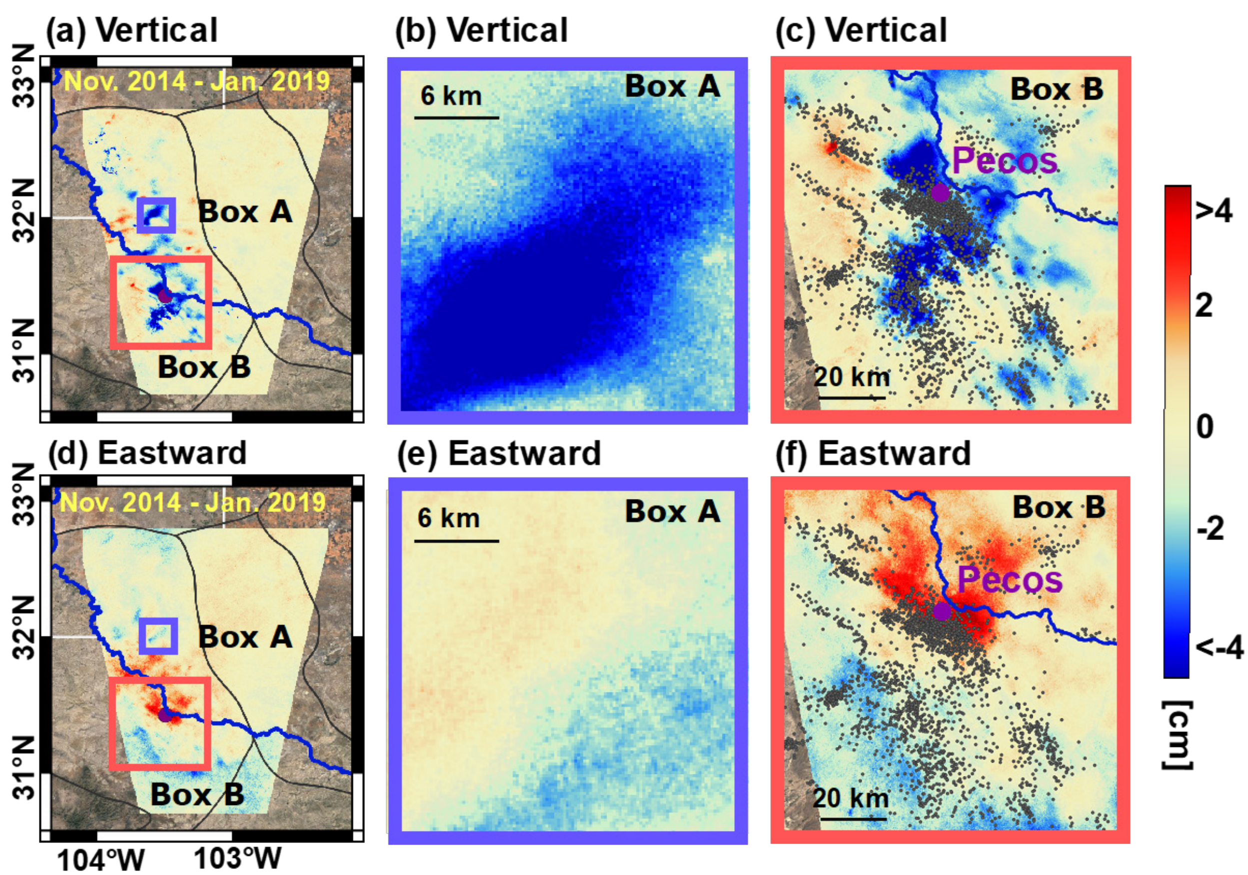


Figure 1. (a) Cumulative vertical deformation between Nov. 2014 and Jan. 2019 over the region where Sentinel-1 path 78 and path 85 overlap. A zoomed-in view of Box A in the northern Delaware Basin and Box B in the southern Delaware Basin are shown in panel (b) and (c) respectively. (d) Cumulative eastward deformation between Nov. 2014 and Jan. 2019 over the region where Sentinel-1 path 78 and path 85 overlap. A zoomed-in view of Box A in the northern Delaware Basin and Box B in the southern Delaware Basin are shown in panel (e) and (f) respectively. In the southern Delaware Basin, the observed vertical and eastward deformation (panel (c) and (f)) show linear patterns along with earthquake hypocenters (gray dots) detected by TexNet in 2018.

Basement-Rooted Faults of the Delaware Basin and Central Basin Platform, Permian Basin, West Texas and Southeastern New Mexico

E. A. Horne, P. H. Hennings, and C. Zahm

In press for publication as a chapter within a forthcoming BEG Report of Investigations

The Permian Basin of Texas and New Mexico is an important petroleum province that has been shaped by several divergent and convergent events since the Proterozoic. These events have generated a complex network of regional faults that have compartmentalized the Permian Basin spatially and impact the present-day stress state. This work provides a new interpretation of >650 basement-rooted faults in the Delaware Basin and surrounding structural flanks. Of the faults mapped, 48% of segments strike NNE-SSW, 40% strike WNW-ESE/ENE-WSW and 12% strike NNE-SSW. These faults were classified according to structural style, morphology (length, offset), and mapping confidence (high and moderate). These analyses provided grounds to develop a qualitative kinematic interpretation. NNW-SSE striking primary faults initiated first, in response to Ancestral Rocky Mountain convergence. WNW-ESE/ENE-WSW striking secondary fault zones formed under the combined stresses from the Ancestral Rocky Mountain and Ouachita-Marathon convergent fronts, which compartmentalized the region, and NNE-SSW striking subordinate faults are attributed to local realignment of stresses from interacting primary and secondary fault systems. The results of this work can be used to understand controls on neotectonic stress state, reservoir productivity and production characteristics, and seismicity, both natural and induced.

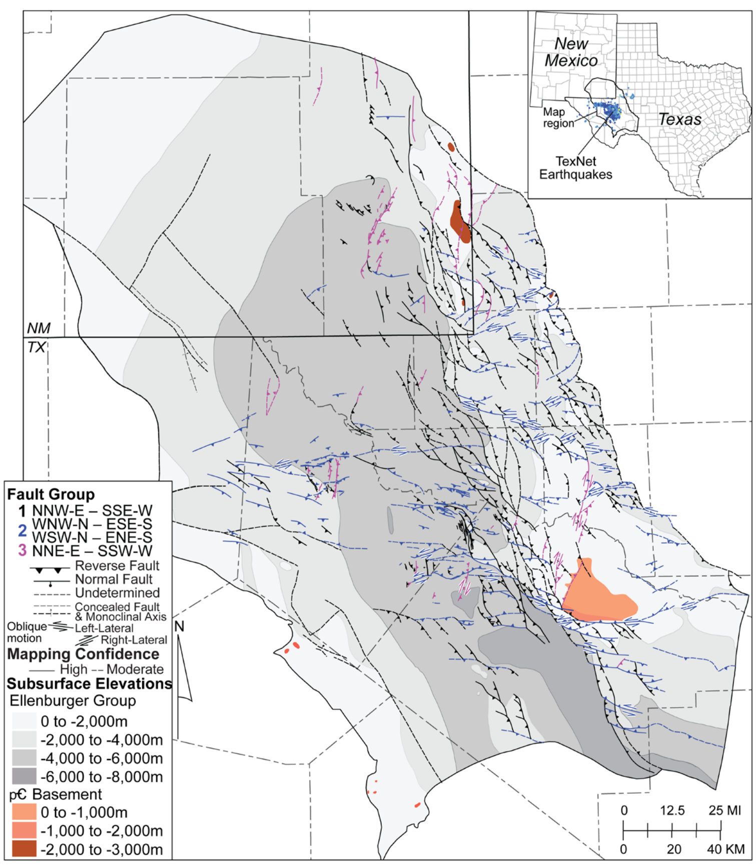


Figure 1. Basement-rooted fault map of the Delaware Basin and surrounding structural flanks. Fault segment interpretations are compiled from regional, sparse and local, high-resolution datasets. Fault colors represent the respective orientation-based fault group. Interpreted zones of oblique or minor strike-slip motion are annotated. These interpretations of strike-slip motion remain subjective. TexNet-located earthquake hypocentral data is highlighted in inset map.

Wastewater Injection and Slip Triggering: Results from a 3D coupled Reservoir/Rate-and-State Model (SPE-191670-MS)

M. Babazadeh, J. Olson

Seismicity induced by fluid injection is controlled by several groups of parameters including injection, reservoir, and frictional. A fundamental understanding of which factors are the most important in triggering slip in areas of active wastewater injection/disposal have been hampered by interrelationships between the various parameters, leading to suggestions of injection volume, rate, or pressure being the most important. However, the reservoir characteristics, such as size, permeability, etc. must also be considered. Additionally, rupture nucleation on faults near a region of injection depends on rate-and-state and related physics.

We present results from a combined model that brings together injection physics, reservoir dynamics, and fault physics to better explain the primary controls on induced seismicity. We created a 3D fluid flow simulator with embedded discrete fracture technique, coupled with a 3D displacement discontinuity geomechanics model that uses rate and state friction to model stable or unstable rupture events. The model incorporates reservoir properties including vertical and horizontal extent; stratification including top-seal, reservoir, and basement; multiple permeability and porosity. Injection parameters include rate and pressure. Fault properties include size, 2D permeability, and frictional properties. Several suites of simulations were run to evaluate the relative importance of each of the factors from all three parameter groups.

We find that the injection parameters interact with the reservoir parameters in the context of the fault physics. For a given reservoir and fault properties, injection rate increases magnitude and frequency of earthquakes, and volume is unimportant. For a different reservoir, these relations may change, leading to the need to specify/examine the injection parameters only within the context of a particular faulted reservoir. Both injection and reservoir properties can interact with the fault properties to trigger or impede slip, so that the magnitudes of induced earthquakes depend on all three groups of parameters. For example, the fault permeability structure is a key factor in inducing earthquakes in basement in many reservoir scenarios. In some cases, the main component in inducing seismicity include the pressure on the fault and its rate of change, which affect how big of a fault area is being affected, and therefore initial earthquake size. By implication, selecting reservoirs for wastewater disposal may involve prioritizing those reservoirs with lower permeability as it takes longer for fluid pressure to increase and trigger large unstable rupture events on nearby faults.

Basement Fault Reactivation by Fluid Injection into Sedimentary Reservoirs: Poroelastic Effects

Zhiqiang Fan, P. Eichhubl, and P. Newell

To investigate mechanisms of seismic fault reactivation in crystalline basement in response to fluid injection in overlying sedimentary reservoirs we conducted three-dimensional finite element simulations to assess the effects of direct pore pressure communication and indirect poroelastic stress transfer on the change in Coulomb failure stress of favorably oriented faults of varying permeability structure in normal, strike-slip, and reverse faulting stress regimes. We demonstrate that the direct pore pressure effect transmitted along a hydraulically conductive fault exceeds the indirect poroelastic effect but alone is insufficient for fault reactivation in the basement. The poroelastic effect on the Coulomb failure stress results from induced normal tractions and, to a lesser extent, from induced shear tractions that relate to the flexing of the fault as the reservoir expands poroelastically with fluid injection. Assuming a higher Biot coefficient for reservoir over basement rock as previously reported, the combined direct pore pressure and indirect poroelastic effects result in reactivation of hydraulically conductive faults in the basement in normal and strike-slip faulting stress regimes, and in the reservoir in reverse faulting regimes (Figure 1). Sealing normal faults that are not preferentially conductive also preferentially reactivate in the reservoir. These findings apply to injection in either hanging or footwall of normal and reverse faults. Reducing the contrast in Biot coefficient between reservoir and basement favors fault reactivation in the reservoir for injection in the footwall in normal faulting stress regimes. These simulations demonstrate that geomechanical models without coupled poroelasticity underestimate the potential of fault reactivation in crystalline basement.

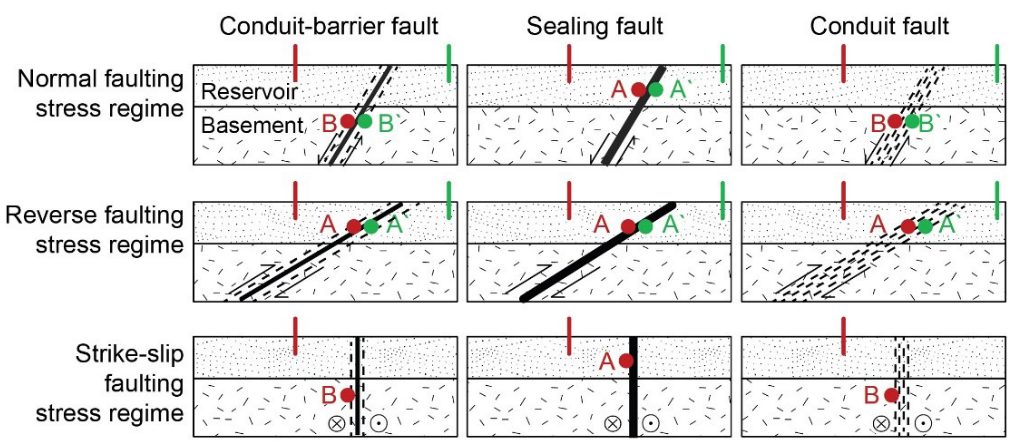


Figure 1. Location of fault reactivation relative to position of injector for an optimally oriented fault in normal, reverse, and strike-slip stress regimes and for a conduit-barrier, conduit, and sealing fault permeability structure. Fault reactivation location indicated with letter A or A´ for the reservoir and B or B´ for the basement section of the fault.

Poroelastic Models for Fault Reactivation in Response to Concurrent Injection and Production in Stacked Reservoirs

M. Haddad, P. Eichhubl

Published in the Journal of Geomechanics for Energy and the Environment, DOI: 10.1016/j.gete.2020.100181

Concurrent production and injection in stacked reservoirs as commonly conducted in unconventional resource exploitation potentially influences reactivation of nearby faults. Using three-dimensional, fully-coupled poroelastic finite-element simulations, we assessed the potential for reactivation of a barrier normal fault in a normal-faulting stress regime for twelve generic injection-production scenarios that differ in the depth of injection and production, and in the position and distance relative to the dipping fault plane. The simulations display significant variation in the Coulomb failure stress (CFS) with depth along the fault plane for these scenarios, reflecting differences in pore pressure distribution and associated poroelastic changes in normal and shear stress across the fault. Based on the CFS trends with depth we find that 1.) concurrent production and injection reduces or increases the fault reactivation potential in the injection reservoir depending on the lateral position and the distance of the wellbores relative to the fault plane; 2.) the fault is most prone to reactivation with stacked wellbores and injection into the upper reservoir within the hanging wall or the lower reservoir within the footwall, and 3.) the fault is least prone to injection-induced reactivation for stacked wellbores and injection into the lower reservoir within the hanging wall at wellbore-to-fault distances ten times the reservoir thickness. With decreasing wellbore-to-fault distance, induced poroelastic shear stresses and thus CFS increase, making injection only into the lower reservoir, without concurrent production, the most stable configuration at close distance (Figure). These simulations demonstrate the importance of the coupled poroelastic effects and of the three-dimensional arrangement of injection and production wellbores on fault reactivation. Our results are intended to provide general guidance for further detailed site-specific geomechanical evaluations needed for induced seismic hazard assessment.

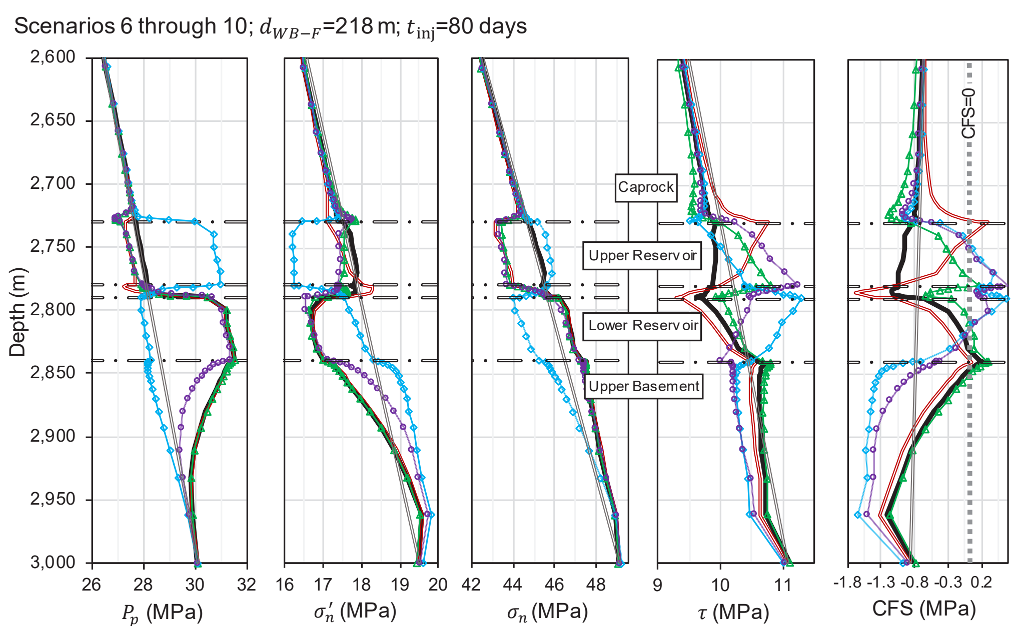


Figure 1. Depth profiles of various field variables along the fault symmetry axis in the dip direction, for scenarios 6 through 10 (out of 10 scenarios discussed in the article) at the well-to-fault distance of 218 m, after 80 days of combined injection and production, preceded by 60 days of production only. Scenario 6 is injection only. Both positive and negative pore pressure changes due to injection and production and the consequent poroelastic stress changes over the fault core can be observed in all scenarios.

Induced Seismicity in the Delaware Basin, West Texas, is Caused by Hydraulic Fracturing and Wastewater Disposal

A. Savvaidis, A. Lomax, and C. Breton

Bulletin of the Seismological Society of America, https://doi.org/10.1785/0120200087

Most current seismicity in the southern U.S. midcontinent is related to oil and gas operations (O&G Ops). In Texas, although recorded earthquakes are of low-to-moderate magnitude, the rate of seismicity has been increasing since 2009. Because of the newly developed Texas Seismological Network, in most parts of Texas, recent seismicity is reported on a daily basis with a magnitude of completeness of M_L 1.5. Also, funded research has allowed the collection of O&G Op information that can be associated with seismicity. Although in the Dallas-Fort Worth area, recent seismicity has been associated mostly with saltwater disposal (SWD), in the South Delaware Basin, West Texas, both hydraulic fracturing (HF) and SWD have been found to be causal factors. We have begun to establish an O&G OP database using four different resources-HIS, FracFocus, B3 and the Railroad Commission of Texas-with which we can associate recent seismicity to HF and SWD. Our approach is based on time and epicentral location of seismic events and time, location of HF, and SWD. Most seismicity occurs in areas of dense HF and SWD-well activity overlapping in time, making association of seismicity with a specific well type impossible. However, through examination of clustered seismicity in space and time, along with isolated clusters of spatiotemporal association between seismicity and O&G Ops, we are able to show that a causation between HF and seismicity may be favored over causation with SWD wells in areas of spatially isolated earthquake clusters (Toyah South, Reeves West, Jeff Davis Northeast, and Jeff Davis East). Causality between SWD and seismicity may be inferred for isolated cases in Reeves South and Grisham West.

By developing two methods we managed to deduce causality of seismicity from its space–time clustering and probabilistic association with O&G Ops. Applying our methods, we can identify earthquakes induced by hydraulic fracturing versus by wastewater disposal. When use both approaches, we can help mitigate seismicity in near real time if Oil and Gas Operations data are also available.

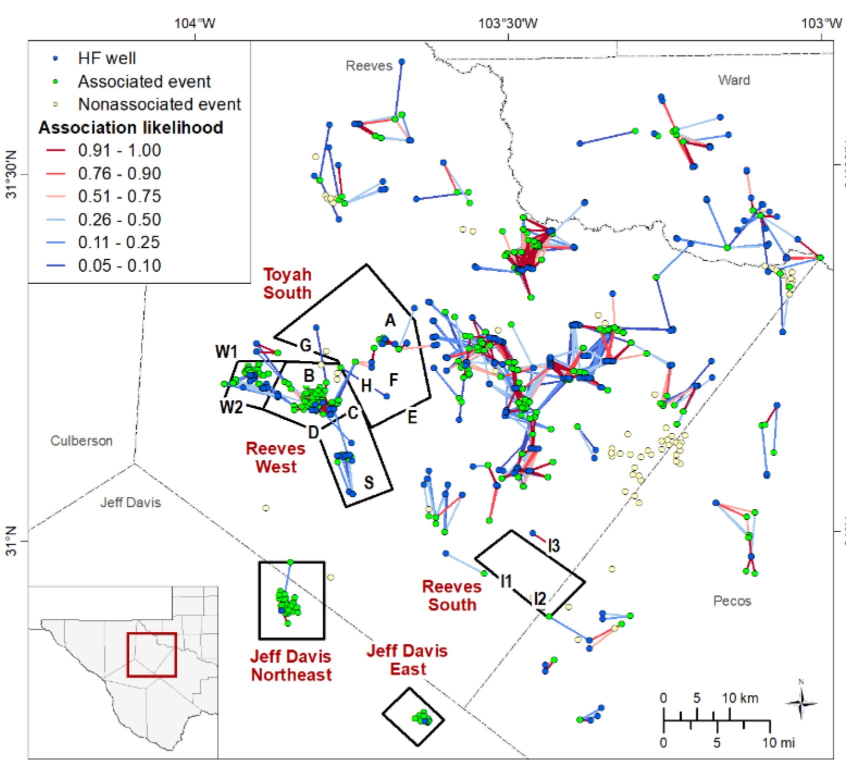


Figure 1. Probabilistic association of reference events, with HF jobs excluding event associated with SWD to clearly emphasize spatial clusters with likely HF cause, for (top) Reeves, Pecos, and Jeff Davis Counties and (bottom) Culberson County. Shown are midpoint HF toe to heel location (blue dots), associated reference events (green dots), unassociated events (light yellow with black outline dots) and event-well activity associations (lines set in proportion to association probability L_A). Polygons indicate areas of seismicity most likely associated with hydraulic fracturing and /or saltwater disposal. Letters indicate isolated well-event clusters used to examine association of seismicity with FH and SWD activity. Inset maps show area of study, with west Texas and south New Mexico state and Texas county lines.

Onset and Cause of Increased Seismic Activity Near Pecos, West Texas, United States, From Observations at the Lajitas TXAR Seismic Array

Cliff Frohlich, Chris Hayward, Julia Rosenblit, Chastity Aiken, Peter Hennings, A. Savvaidis, Casee Lemons, Elizabeth Horne, Jacob I. Walter, and Heather R. DeShon

Journal of Geophysical Research - Solid Earth, https://doi.org/10.1029/2019JB017737

In recent years, numerous small earthquakes have occurred near the town of Pecos in West Texas; however, when this activity began and whether it was caused by increased petroleum industry activity has been uncertain because prior to 2017 there were few permanent seismograph stations in the region. We identify and locate earthquakes using data recorded since 2000 at TXAR, a sensitive 10-station seismic array situated about 240 km south of Pecos. We thus show that in 2007, one earthquake occurred near Pecos, in 2009 several more occurred (Figure 1), and subsequently, activity has increased considerably, with more than 2000 events identified in 2017. A time-of-day and year-by-year analysis identifies geographic areas in West Texas where events are likely to be natural earthquakes and quarry blasts. However, for the Pecos events, annual seismicity rates increase along with annual volumes of petroleum production and fluid waste disposal, suggesting a causal link. Analysis of seismograms collected by the EarthScope Transportable Array indicates that the 2009 earthquakes had focal depths of 4.0–5.2 km below sea level, within or just below strata where petroleum is produced and/or wastewater is injected. The largest earthquake to end of 2017 had magnitude M_L3.7, but the recent high activity rates suggest that greater magnitudes may be possible. For the years 2000–2017, we provide a catalog of 10,753 epicenters (Figure 1) of seismic events recorded at TXAR.

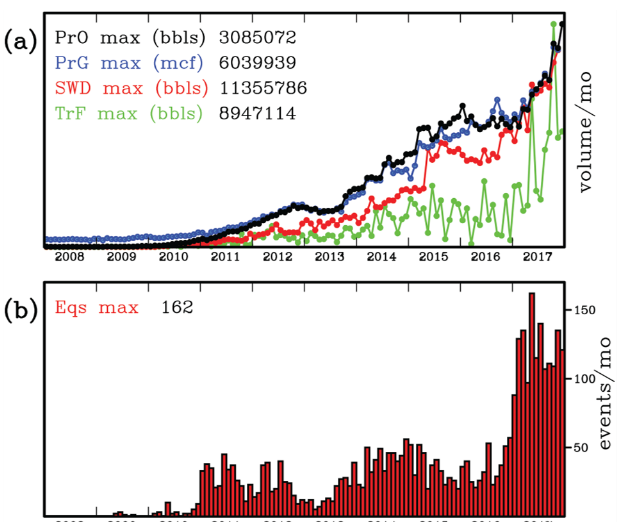


Figure 1. Petroleum-production operations and seismicity in 10 km around Pecos City. (a) Monthly volumes for produced oil (PrO), produced gas (PrG), wastewater disposal (SWD), and hydraulic fracturing treatment fluid (TrF). Plotted values on vertical axes are normalized to maximum monthly values, given at upper left. (b) Monthly earthquake numbers in TXAR catalog.

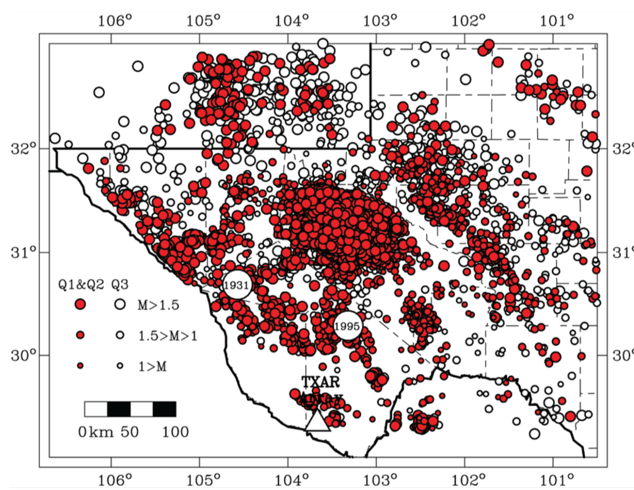


Figure 2. Map of epicenters (2000–2017) determined in this study from the analysis of TXAR data. Symbol size and color indicates magnitude MTXAR and quality Q1 (better) to Q3 (worse) assigned by analyst to P and S time picks

Earthquakes Induced by Wastewater Injection, Part I: Model Development and Hindcasting

I. Grigoratos, E. Rathje, P. Bazzurro and A. Savvaidis

Bulletin of the Seismological Society of America, https://doi.org/10.1785/0120200078

Over the last 20 years, new pioneering techniques in hydraulic fracturing enabled the extraction of natural gas and oil from previously unproductive tight shale formations. These techniques, however, lead to massive quantities of coproduced flowback fluids (wastewater) being pumped up together with the crude oil and being disposed several kilometers underground through injection into high-permeability aquifers. Following an increase in these wastewater volumes, Oklahoma experienced unprecedented levels of seismicity over the last decade, about 100 times higher than the historical average. In this article, we present a semi-empirical model to hindcast the observed seismicity given the injection time-history. Our proposed recurrence model is a modified version of the Gutenberg–Richter relation, building upon the seismogenic index model, which predicts a linear relationship between the number of induced events and the injected volume.

Overall, the simulated seismicity rates from our model are in very good agreement with the observed seismicity both regionally and locally, even though the proposed methodology accounts only for the first-order effects of the underlying phenomenon and has essentially only two free parameters for calibration. We should note the great variability in the modeling approaches found in the literature, which often disagree on fundamental principles behind the parameterization of the wastewater-induced seismicity. Further research is required to establish a scientific consensus around the source of the apparent time lag in the response of the seismicity rates and for the development of a new declustering algorithm, tailored for this type of seismicity. The developed model is applied here to Oklahoma but is generic enough to be potentially applicable to any region affected by wastewater disposal and could potentially be applied also in areas affected by hydraulic fracturing.

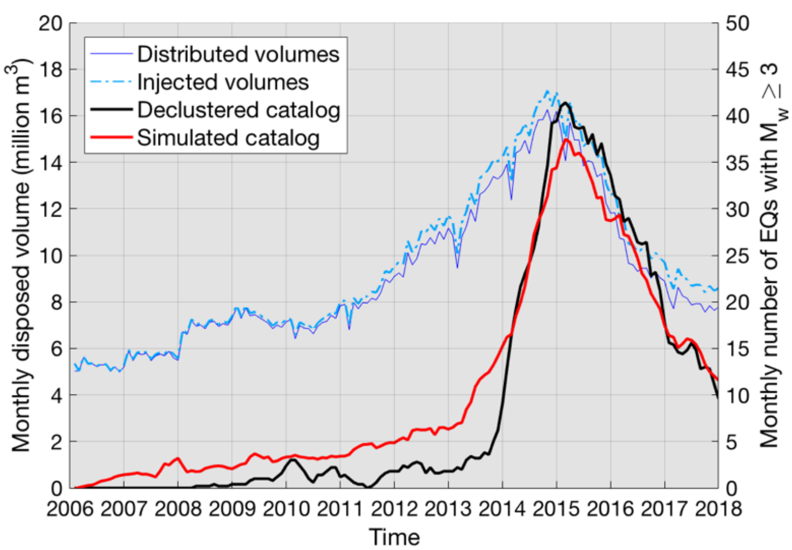


Figure 1. Simulated (red) and observed (black) monthly seismicity rates for the Oklahoma study area. The blue lines represent the monthly wastewater disposal rates.

Earthquakes Induced by Wastewater Injection, Part II: Statistical Evaluation of Causal Factors and Seismicity Rate Forecasting

I. Grigoratos, E. Rathje, P. Bazzurro and A. Savvaidis

Bulletin of the Seismological Society of America, https://doi.org/10.1785/0120200079

Wastewater disposal has been reported as the main cause of the recent surge in seismicity rates in several parts of central United States, including Oklahoma. In this article, we employ the semi-empirical model of the companion article first to test the statistical significance of this prevailing hypothesis and then to forecast seismicity rates in Oklahoma given future injection scenarios.

The results show that the vast majority (76%) of the seismically active blocks in Oklahoma can be associated with wastewater disposal at a 95% confidence level. These blocks experienced 84% of the felt seismicity in Oklahoma after 2006, including the four largest earthquakes. In terms of forecasting power, the model is able to predict the evolution of the seismicity burst starting in 2014, both in terms of timing and magnitude, even when only using seismicity data through 2011 to calibrate the model. Under the current disposal rates, the seismicity is expected to reach the pre-2009 levels after 2025, whereas the probability of a potentially damaging earthquake with magnitude Mw ≥ 5.5 between 2018 and 2026 remains substantial at around 45%.

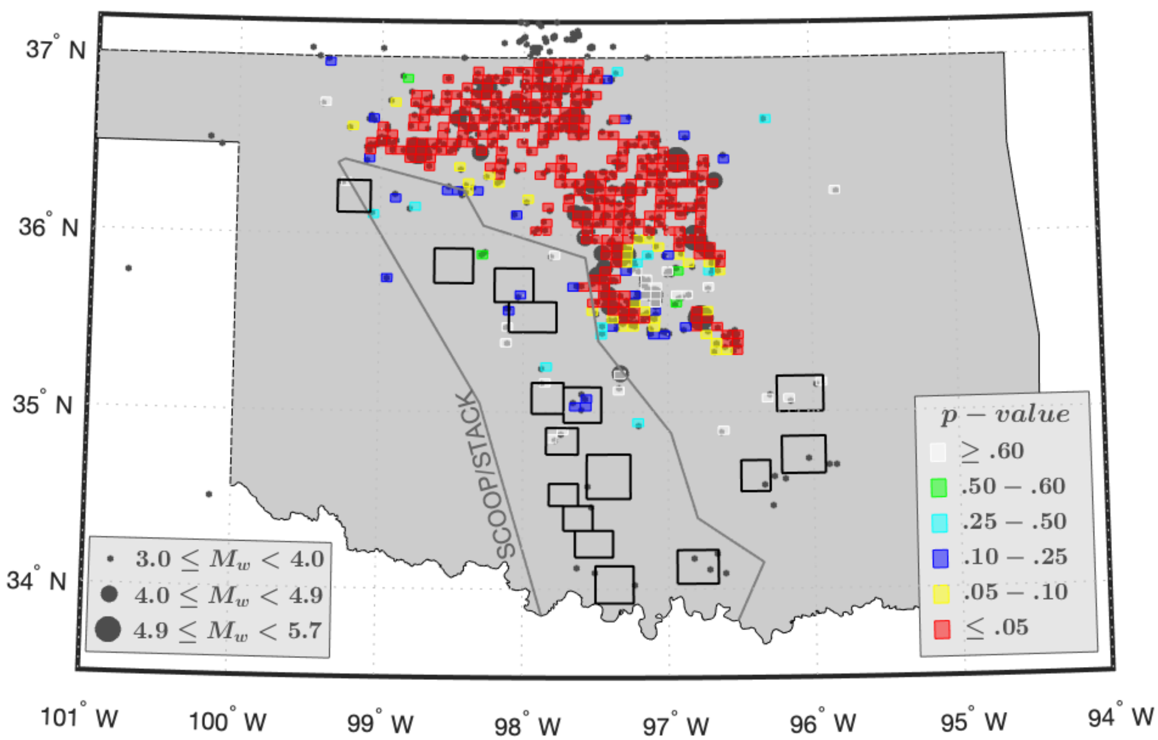


Figure 1. Low p-values on this map (red and yellow colors) indicate that the seismicity there is most likely caused by wastewater disposal, a common oil and gas acitvity. The black rectangles represent zones with seismicity predominantly related to hydraulic fracturing, as identified by a different study.

Analysis of Wastewater Injection and Prospect Regions for Induced Seismicity in the Texas Panhandle, USA

J. P. Acevedo, C. R. Lemons, G. McDaid, M. H. Young, and B. R. Scanlon

Submitted to American Association of Petroleum Geologists Bulletin of Environmental Geology

Saltwater disposal and enhanced oil recovery through underground injection control (UIC) wells in the Texas Panhandle were analyzed from 1983-2018. During this same period, a total of 64 earthquakes of M ≥ 2.5 were recorded. The average earthquake rate increased from 1.21 events per year (1983-2007) to 3.50 events per year (2008-2018). A total of 1,926 active UIC wells in the Texas Panhandle were identified from the Railroad Commission of Texas database during the study period. We identified 54 geologic stratigraphic formations present in the region and focused on 34 target formations into which wastewater was injected. Cumulative volumes were found to be localized by geographic region and geologic formations, where a total of 2.26 billion barrels (Bbbls, where 1 barrel = 159 liters) of wastewater were injected. Approximately 87% of the total disposal volume (1.96 Bbbls) was injected into seven geologic formations, including the igneous Precambrian basement; another 27 formations received less than 100 million barrels (MMbbls) each (Figure). Monthly injection rates fluctuated in time, similar to overall O&G industry activity. From this analysis, we determined that 61% of earthquake events are possibly or probably induced by a combination of UIC and production practices. Additionally, we identified regions at risk of potentially hosting future earthquakes induced by current injection or production operations. Understanding how and where these operations are affecting seismicity rates in the State of Texas can lead to strategies to reduce or mitigate negative externalities such as induced seismicity.

(a) (b)

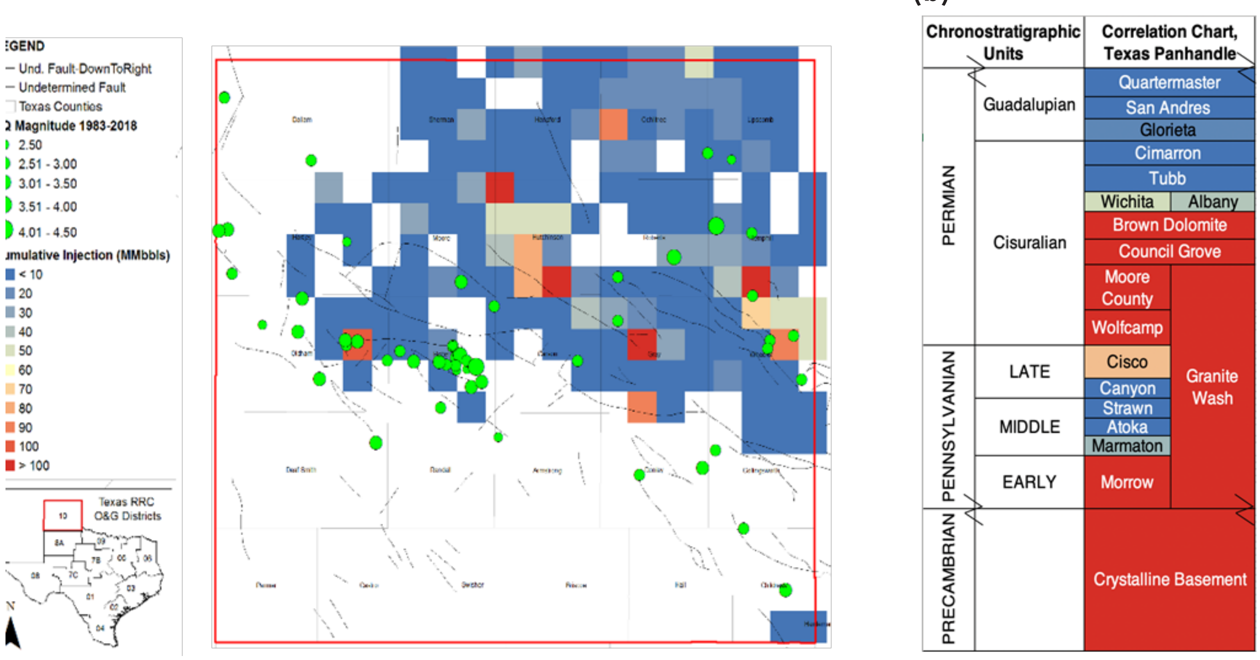


Figure 1. (a) Geographic distribution of cumulative wastewater injection in the Texas Panhandle in 259 km^2 (100 mi^2) block grids following the same color scale as Figure b. Dashed lines depict basement-rooted faults with undetermined geometry. (b): Heat-mapped stratigraphic correlation chart of the major disposal targets of the Texas Panhandle.

Time-Dependent Seismic Hazard and Risk Due to Wastewater Injection in Oklahoma

I. Grigoratos, P. Bazzurro, E. Rathje and A. Savvaidis

Accepted for publication Earthquake Spectra

In the past decade, Oklahoma has experienced unprecedented seismicity rates, following an increase in the volumes of wastewater that are being disposed underground. In this paper, we perform a probabilistic assessment of the time-dependent seismic hazard in Oklahoma and incorporate these results into an integrated seismic risk model to assess the evolution of the state-wide economic losses, including a conservative forecast through 2030. Our risk model employs an injection-driven earthquake rate model, a region-specific ground motion model, a recent Vs30 map, HAZUS exposure data and updated vulnerability curves for both structural and non-structural elements, and contents.

The resulting seismic hazard maps illustrate the incompatibility of the regional seismic provisions with the current seismicity. In 2015 in particular, the induced seismic hazard in several places in Oklahoma (Figure 1) was higher than across the San Andreas fault. During the peak of seismicity in 2015, the seismic risk was 275 times higher than the background level, with the vast majority of losses originating from damages to non-structural elements and contents. Our direct economic loss estimates are in rea Basement Fault Reactivation by Fluid sonable agreement with the paid insurance claims, but show significant sensitivity to the ground motion model selection. The proposed risk model (Figure 2), with possible regular updates on the seismicity rate forecast, can help stakeholders define acceptable production levels.

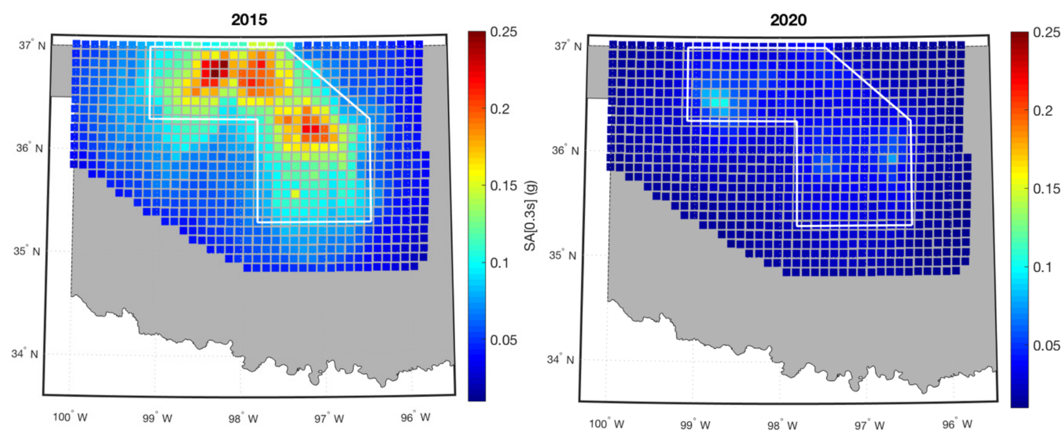


Figure 1. Hazard maps in terms of Spectral Acceleration at 0.3s at 10% annual probability of exceedance, for the year 2015 and 2020. The white polygon indicates the Area of Interest for wastewater disposal.

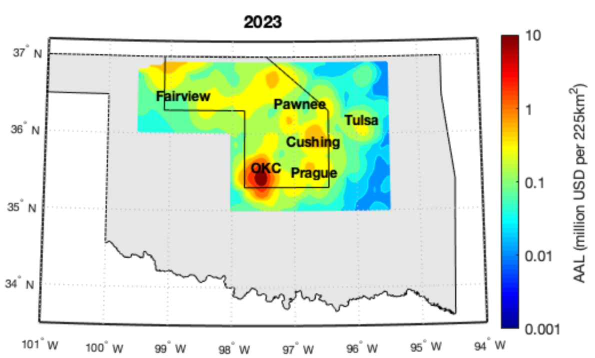


Figure 2. Spatial distribution of the forecasted average annual direct economic losses (AAL) for the year 2023. The labels indicate the epicenters of the four largest earthquakes since 2006 and the two biggest cities, i.e. Tulsa and Oklahoma City (OKC). The black polygon indicates the Area of Interest for wastewater disposal.earthquakes since 2006 and the two biggest cities, i.e. Tulsa and Oklahoma City (OKC). The black polygon indicates the Area of Interest for wastewater disposal.

A Regional Vs_{30} Map for Texas Incorporating Geology and Vs_{30} Observations

M. Li, E. Rathje, B. Cox, and M. Yust

A regional Vs_{30} map is developed for Texas that uses geostatistical kriging integrated with a regional geologic proxy, field measurements of Vs_{30} and P-wave seismogram estimates of Vs_{30}. The regionally-based geologic proxy is used first to predict Vs_{30} from the surface geologic conditions across the state, and then geostatistical kriging with an external drift is used to incorporate the local Vs_{30} measurements/estimates into the map. Compared with the Vs_{30} map of Texas developed from a topographic slope proxy, the regional Vs_{30} map predicts larger Vs_{30} values across much of Texas, except for the Gulf Coast region where the values are similar. The utilization of kriging brings the regional Vs_{30} map into better agreement with the in-situ measurements and estimates of Vs_{30}. The sensitivity of predicted ground motions by ShakeMap to changes in Vs_{30} values is evaluated with a scenario earthquake in the Dallas-Fort Worth area. The results suggest smaller predicted ground motions due to the generally larger values of Vs_{30} in the regional Vs_{30} map as compared to the Vs_{30} from the topographic proxy. The new regional Vs_{30} map of Texas developed in this study is attached here.

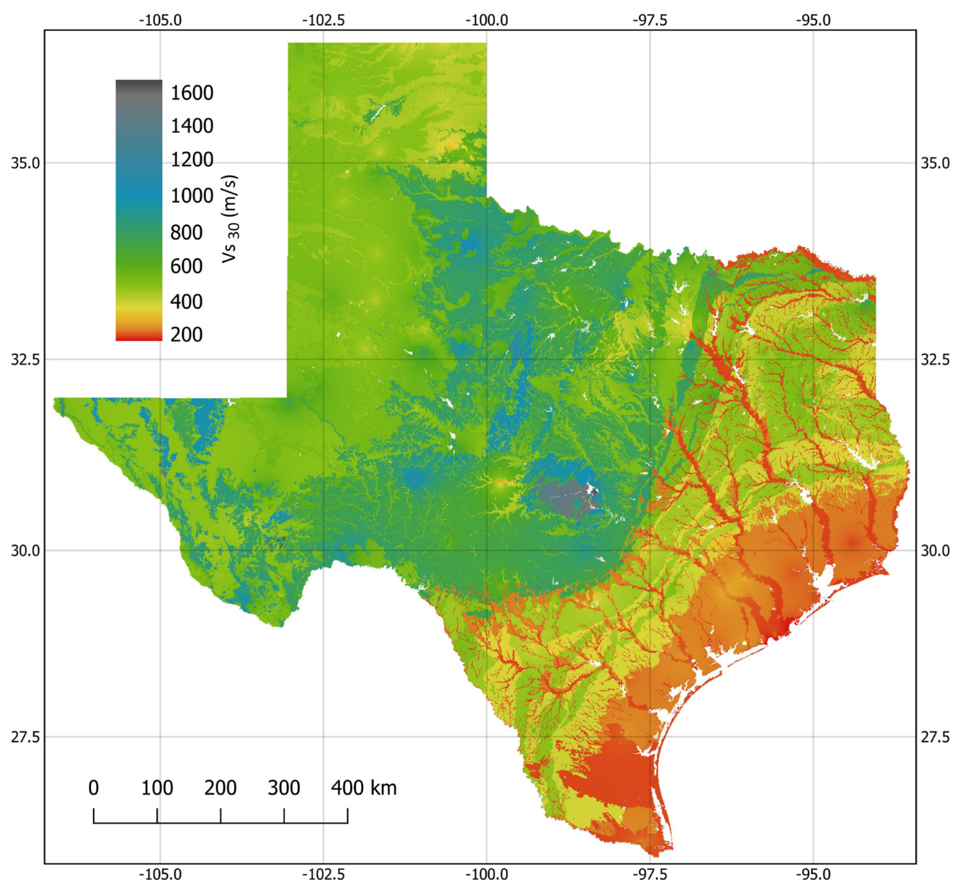


Figure 1. New regional Vs_{30} map of Texas based on geostatistical kriging incorporating a regional geologic proxy and field observations of Vs_{30}.

Artificial Neural Network Based Frameworkfor Developing Ground Motion Models for Natural and Induced Earthquakes in Texas, Oklahoma, and Kansas

F. Khosravikia, J. Kurkowski, and P. Clayton

Submitted to Journal of Building Engineering, 28: 101100

This article puts forward an artificial neural network (ANN) framework to develop ground-motion models (GMMs) for natural and induced earthquakes in Oklahoma, Kansas, and Texas. The developed GMMs are mathematical equations that predict peak ground acceleration, peak ground velocity, and spectral accelerations at different frequencies given earthquake magnitude, hypocentral distance, and site condition. The motivation of this research stems from the recent increase in the seismicity rate of this particular region, which is mainly believed to be the result of the human activities related to petroleum production and wastewater disposal. Literature has shown that such events generally have shallow depths, leading to large-amplitude shaking, especially at short hypocentral distances. Thus, there is a pressing need to develop site-specific GMMs for this region. This study proposes an ANN-based framework to develop GMMs using a selected database of 4528 ground motions, including 376 seismic events with magnitudes of 3 to 5.8, recorded over the 4- to 500-km hypocentral distance range in these three states since 2005. The results show that the proposed GMMs lead to accurate estimations and have generalization capability for ground motions with a range of seismic characteristics similar to those considered in the database. The sensitivity of the equations to predictive parameters is also presented. Finally, the attenuation of ground motions in this particular region is compared with those in other areas of North America.

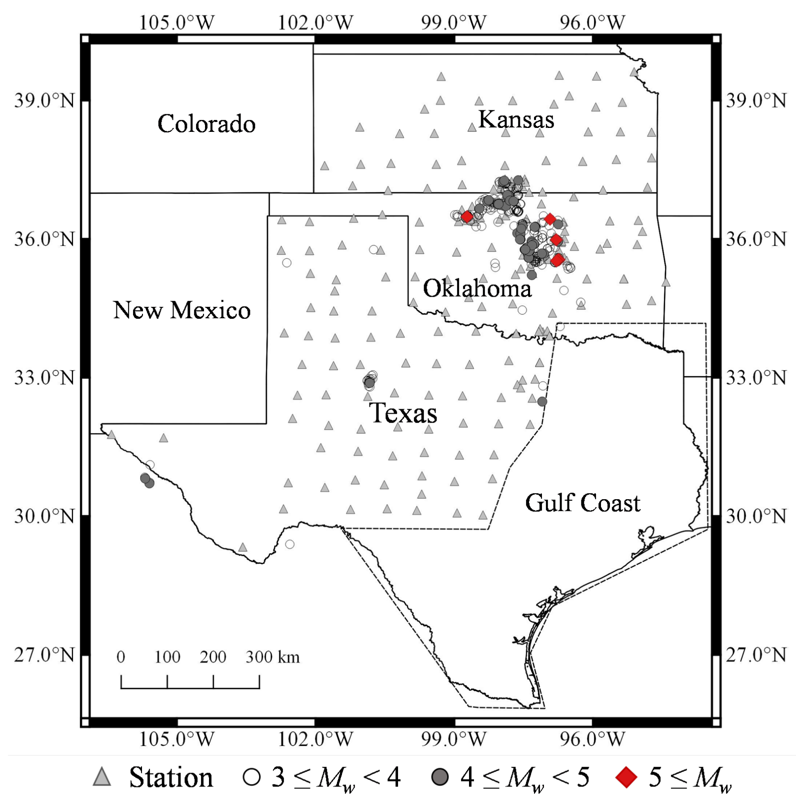


Figure 1. Geographic distribution of the events and stations considered in this study.

Updated Evaluation Metrics for Optimal Intensity Measure Selection in Probabilistic Seismic Demand Models

F. Khosravikia, P. Clayton

Submitted to Engineering Structures, 202: 109899

This study proposes an update on the criteria that are typically used to select the optimal intensity measures (IMs) for development of probabilistic seismic demand models (PSDMs), which relate the input seismic hazard and structural responses. Employing an optimal IM contributes to decreasing the uncertainty in the PSDMs, which, in turn, increases the reliability of the PSDMs used in performance-based earthquake engineering analyses. In the literature, the optimality of the IMs is generally evaluated by the following metrics: efficiency; practicality; proficiency, which is the composite of efficiency and practicality; sufficiency; and hazard computability. The present study shows that the current criteria for evaluating the practicality and proficiency features may mislead the selection of the optimal IM when IMs with different ranges and magnitudes are investigated. Moreover, the efficiency metric can provide biased results when comparing IMs for predicting demands of different structural components or types of systems. As a result, alternative solutions are proposed to investigate the efficiency, practicality, and proficiency features of the IMs. The suggested metrics are employed in a case study to evaluate the IMs used to develop PSDMs for multi-span continuous steel girder bridges in Texas subjected to human-induced seismic hazard. The results show that for this bridge system, the velocity-related IM (i.e. PGV) leads to more accurate estimates of the structural responses, while literature shows that the acceleration-related IM (i.e. PGA) is the most proficient IM for similar bridge systems in other areas of the Central United States.

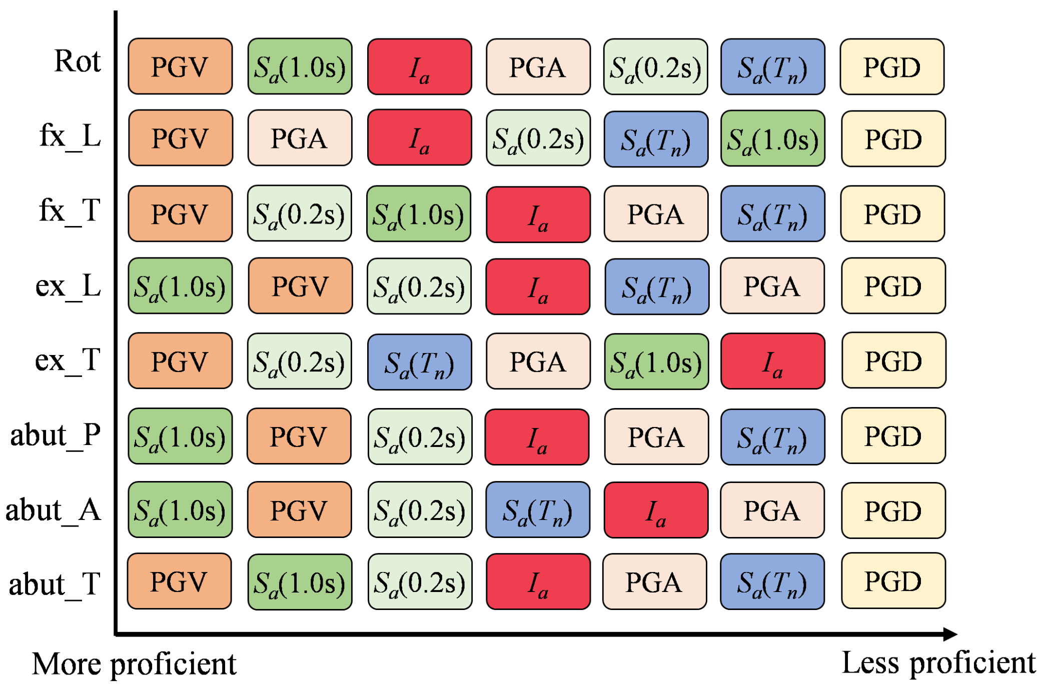


Figure 1. Proficiency evaluation of considered IMs for different demand parameters of steel girder bridges in Texas.

Fragility of Masonry Veneers to Human-Induced Central U.S. Earthquakes Using Neural Network Models

F. Khosravikia, J. Kurkowski, and P. Clayton

Submitted to Journal of Building Engineering, 28: 101100

Since 2008, an increase in human-induced seismic activity related to natural gas production and petroleum activities has resulted in millions of dollars of damage in the Central United States, primarily to residential buildings including chimneys and masonry veneers. This study aims to better understand and evaluate the impacts of such seismic hazards on masonry veneers. To do so, a probabilistic framework is proposed in which fragility curves representing the probability of cracking and collapse damage states for masonry veneers are developed. In the proposed framework, Artificial Neural Networks are adopted to develop probabilistic seismic demand models from experimentally-validated finite element analyses of non-seismically detailed masonry veneers. The framework utilizes a suite of 200 ground motions largely believed to be from human-induced earthquakes with magnitudes of 3.6–5.8 recorded in the Central U.S. since 2008. Fragility curves are produced for masonry veneers with code compliant corrugated brick ties and those with thinner brick ties that are commonly employed in residential construction in the Central U.S. Additionally, the proposed fragilities developed for human-induced earthquakes are compared to those from the literature, which were developed for the New Madrid seismic hazard and are commonly used for seismic vulnerability assessments of infrastructure in the Central U.S. The results indicate that for a given PGA level, induced earthquakes may be more likely to produce damage compared to earthquakes representing the New Madrid hazard. Finally, the regional extents of damage from a recent induced seismic event are estimated using the newly developed and existing fragility functions to evaluate the implications of using these models for regional vulnerability assessments.

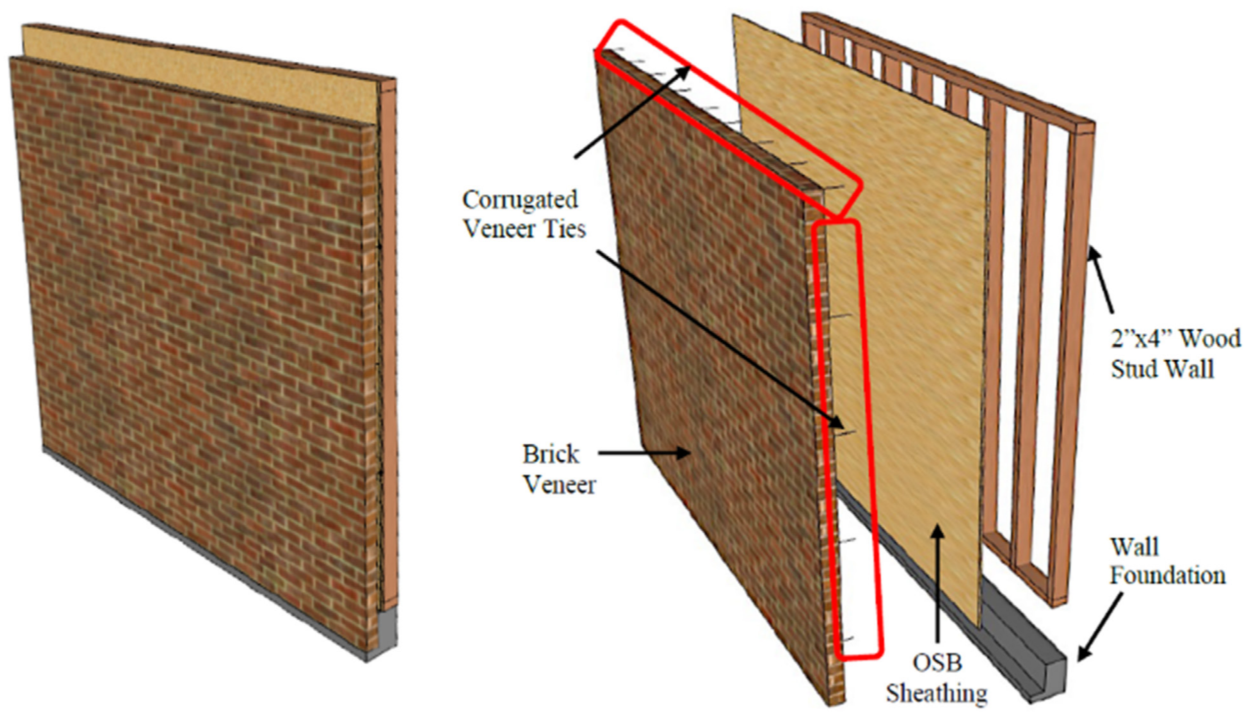


Figure 1. Renderings of brick veneer wall: (a) Actual wall panel as constructed, (b) Actual wall with individual elements labeled.

Appendix B. TexNet Research Budget

Theme	Project Title	Institution/ Unit	Personnel	Materials & Services	Sub-Contracts	Computer Charges	Tuition	Travel	Special Equipment	Fiscal Yr 20/21 Project Total
Seismology	T2.1: Seismicity Characterization in Texas	UT-BEG	$ 287,196.00	$ 38,023.00		$ 11,411.00		$ 12,213.00		$ 348,843.00
	T2.1: Ft. Worth Basin Seismicity Studies	SMU			$ 77,756.00					$ 77,756.00
	T2.1: Texas Seismicity Prior to TexNet in the Delaware Basin	SMU			$ 36,467.00					$ 36,467.00
	T2.1: TexNet Calibration Shots	UTEP			$ 220,000.00					$ 220,000.00
	T2.2: Machine Learning in Seismology	UT-BEG	$ 178,380.00	$ 51,923.00		$ 2,212.00	$ 4,834.00	$ 3,243.00		$ 240,592.00
	T6: Seismicity Trends and Operations Impact	UT-BEG	$ 190,085.00	$ 69,397.00		$ 9,700.00		$ 5,889.00		$ 275,071.00
Geologic Characterization	T4: Geologic Characterization and Analysis	UT-BEG	$ 280,740.00	$ 19,259.00		$ 10,250.00		$ 8,753.00		$ 319,002.00
Fluid Flow and Geomechanics	T5.1: FW Basin Poroelastic Modeling	SMU			$ 50,575.00					$ 50,575.00
	T5.2: General Geomechanical Modeling	UT-BEG	$ 11,623.00	$ 26,611.00						$ 38,234.00
Seismic Hazard and Risk Assessment	T7.1: Seismic Risk Assessment in DFW	UT-BEG	$ 65,967.00				$ 18,025.00	$ 1,200.00		$ 85,192.00
	T7.2: Shear Wave Velocity Characterization in SA/EF	UT-BEG	$ 54,180.00	$ 4,940.00			$ 22,513.00	$ 3,000.00		$ 84,633.00
	T7.3: Assessment of Dam Fragility Relationships for Texas	UT-BEG	$ 11,517.00				$ 10,677.00	$ 1,441.00		$ 23,635.00
Operational Data and Info Distribution	T3: QC Geodatabase	UT-BEG	$ 189,716.00	$ 1,157.00		$ 6,535.00		$ 2,592.00		$ 200,000.00
Total:										**$ 2,000,000.00**

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