[PS]Hydraulic Fracture Injection Strategy Influences the Probability of Earthquakes in the Eagle Ford Shale Play of South Texas*

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Abstract

Southern Texas has a history of active oil and gas production, hydraulic fracturing (HF), wastewater disposal, and seismicity, with some areas of pervasive faulting. Previous studies of this region have attributed cases of seismicity to increases in production of oil/water and a few cases to wastewater disposal. With the advancements in horizontal drilling and HF, the Upper Cretaceous Eagle Ford Shale has become a focus of shale-gas development since 2008, and we sought to investigate how HF may have contributed to a recent seismicity rate that is 75 times higher than background levels. We used times and locations of HF from the FracFocus catalog and enhanced the TexNet catalog of earthquakes from January 2017 to December 2018 by employing single-station template matching back to March 2014 when continuous recording began. We identified over 2000 earthquakes (84%) that were closely related in time and space to 200 HF wells mostly in Karnes, Atascosa, and Gonzales counties, representing the first documented cases of HF-induced seismicity in Texas. Much of the HF-induced seismicity occurred in a 15 x 15 km area just north of Karnes City where 33% of the HF wells correlated with seismicity. We found that "zipper" wells stimulating synchronously with another nearby lateral were more than twice as likely to produce seismicity than asynchronous wells. The magnitude of HF-induced seismicity and low b-value support the idea that these events represent slip on pre-existing faults and not the process of fracturing the target formation. Furthermore, TexNet fault plane solutions for HF-induced earthquakes are in agreement with the orientation of SH_{max} and previously mapped faults. A M_w 4.0 earthquake on May 1, 2018 would be the largest reported HF-induced earthquake in the US, occurring ~10 km from a M_w 4.8 earthquake in 2011 attributed to fluid extraction. This represents the most critical findings in our study: faults in this area are capable of producing felt and potentially damaging earthquakes due to ongoing operational activities.

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Hydraulic Fracture Injection Strategy In uences the Probability of Earthquakes in the Eagle Ford Shale Play of South Texas

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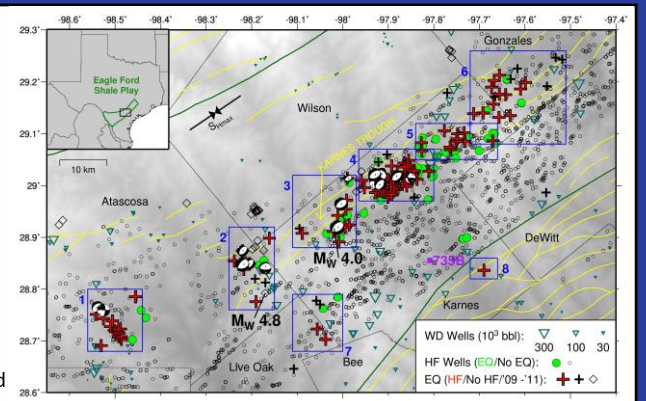
Introduction

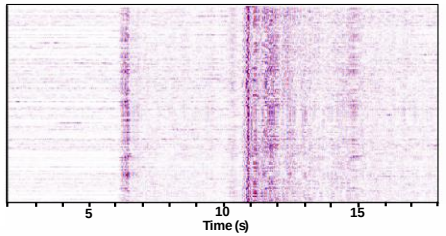
- Increased occurence of earthquakes (M_L > 3) in Central and Eastern U.S. has mostly been attributed to wastewater disposal (WD)
- Hydraulic-fracture (HF)-induced seismicity has become more common
- The largest magnitude HF-induced events have increased to include a M_W 5.3 in China, approaching the largest (M_W 5.8) WD-induced earthquake in OK
- Seismicity rate of M ≥ 3.0 earthquakes in the Eagle Ford shale play grew to 33 times the background rate in 2018
- This study investigates seismicity since 2014 by examining how HF and WD may have contributed to the rate increase



Earthquakes analyzed with template matching are shown with crosses. HF wells in this study are indicated by black circles. Correlated earthquakes and HF wells are red and green, respectively. White diamonds show earthquakes identi ed during 2009-2011 as due to extraction or WD. The purple square shows the seismic station used for template matching. WD wells are teal triangles sized by median monthly volumes. Faults are in yellow.

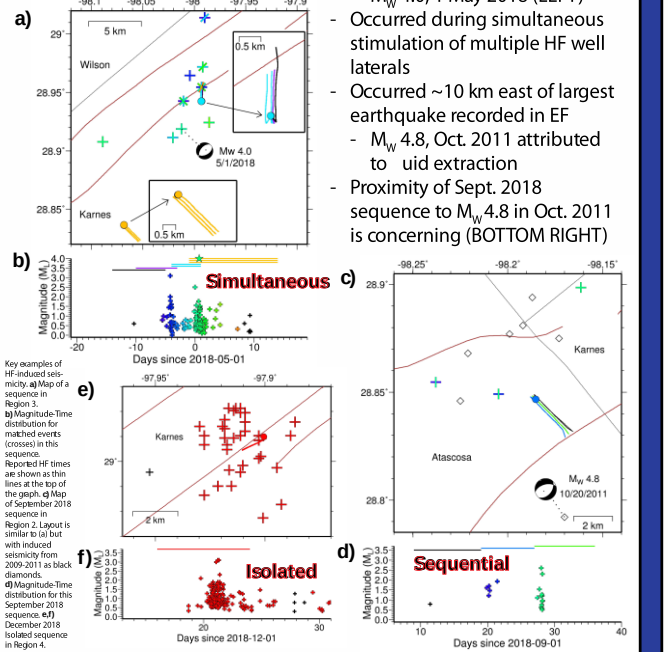
Methods

- Waveform cross-correlation using nearest seismic station (N4 735B) and TexNet catalog for earthquake templates to detect more seismicity and estimate magnitudes of smaller events
- FracFocus times and locations of HF wells
- Seismicity divided into 8 regions ~20km wide for comparison with operations
- HF correlations: Seismicity <10 km and 7 days of HF wells with > 5 earthquakes during stimulations



Gridded waveform plot of matched events from N4 735B from the most active template to show similarity of waveforms.

HF-Seismicity: Examples

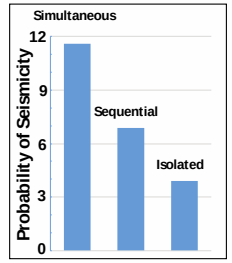


Key examples of HF-induced seismicity. **a)** Map of a sequence in Region 3. **b)** Magnitude-Time distribution for matched events (crosses) in this sequence. Reported HF times are shown as thin lines at the top of the graph. **c)** Map of September 2018 sequence in Region 2. Layout is similar to (a) but with induced seismicity from 2009-2011 as black diamonds. **d)** Magnitude-Time distribution for this September 2018 sequence. **e,f)** December 2018 Isolated sequence in Region 4.

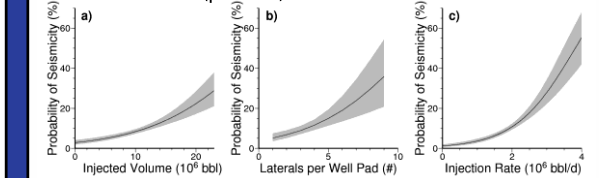
- Largest HF-induced earthquake
  - M_W 4.0, 1 May 2018 (LEFT)
- Occurred during simultaneous stimulation of multiple HF well laterals
- Occurred ~10 km east of largest earthquake recorded in EF
  - M_W 4.8, Oct. 2011 attributed to uid extraction
- Proximity of Sept. 2018 sequence to M_W 4.8 in Oct. 2011 is concerning (BOTTOM RIGHT)

Stimulation Strategies and Probability of Seismicity

- Formal odds ratio calculated for relative probabilities of binary factors and p-value test for signi cance
- Simultaneous laterals 3.2x more likely to produce seismicity than laterals Isolated in time (p = 0.0002)
- Simultaneous laterals 1.8x more likely to produce seismicity than Sequential laterals (p = 0.005)
- Sequential laterals were 1.8x more likely to produce seismicity than Isolated laterals (p = 0.06)



Probabilities of induced seismicity for di erent HF operational strategies.



Predicted probability of seismicity from logistic regression for a) injected volume, b) number of laterals per well pad, and c) injection rate. Line shows best t and shading shows 95% con dence interval.

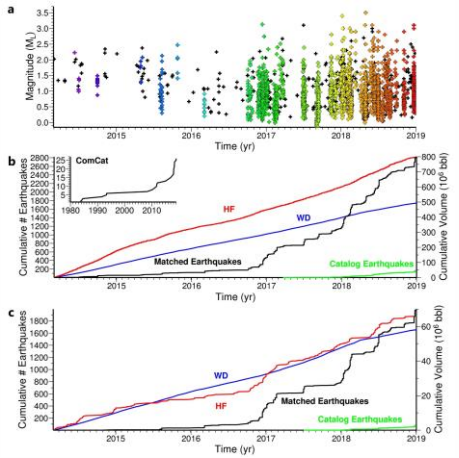
- Logistic regression produced a probability curve that best ts input data and calculates p-value for probability the factor does not in uence seismicity
- Several other factors in uence probability of seismicity including injection rate, volume, number of laterals

Spatial, Temporal, and Magnitude Distribution

- Earthquakes mainly occurred along mapped normal faults that trend NE/SW
- Enhanced catalog shows short-lived, spatio-temporally clustered events
- Seismicity rate increased over time, with a few M_L > 3.0 earthquakes per year in 2018

	Earthquakes Correlated with HF	HF Wells Correlated with Seismicity	HF Pads Correlated with Seismicity
M ≥ 1.5	291 (68%)	178 (61%)	70 (60%)
M ≥ 2.0	94 (76%)	128 (69%)	54 (63%)
M ≥ 2.5	29 (83%)	69 (77%)	30 (73%)
M ≥ 3.0	10 (90%)	12 (92%)	8 (88%)
M ≥ 3.5	1 (100%)	5 (100%)	2 (100%)

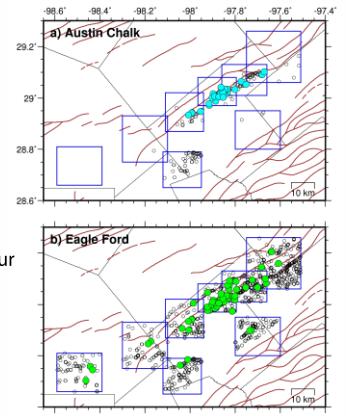
Number of HF-induced earthquakes and associated HF well laterals and well pads since March 2014 for di erent magnitude thresholds common in ta c light protocols. Percentage in parentheses is the fraction of earthquakes or wells that occurred in 2018



Number of earthquakes, HF wells,WD injected volume over time. **a)** Magnitude vs. time for all unique matched events with a correlation above 17*MAD. Colored crosses represent earthquakes that met the criteria for HF-induced seismicity while black crosses did not. **b)** Comparison of the cumulative number of HF wells stimulated, WD cumulative injected volume, total matched earthquakes and catalog template earthquakes for the entire study region. Inset shows cumulative number of earthquakes M ≥ 3.0 from the Advanced National Seismic System comprehensive catalog (ComCat) since January 1980. **c)** Same as (b) but for Region 4 only.

Correlations Between HF and Seismicity

- No correlation found between temporal distribution of seismicity over whole study region and HF or WD injected volume
- Several smaller regions show correlation with HF
  - Region 4 (70% of seismicity):
    - Correlation between uctuations in seismicity rate and HF injected volume
- 50% to 100% of earthquakes correlated with HF in our focus regions
  - Similar in Appalachian Basin and Oklahoma
- Higher percentages of HF wells with seismicity in Regions 5 (13%) and 4 (32%)
- ~10% of HF wells in 8 focus regions targeted Austin Chalk Formation compared to 90% Eagle Ford
  - Higher percentage of AC wells correlating with seismicity (19.2% vs 7.1%)
  - Related to greater proximity to susceptible faults



Map of **a)** Austin Chalk and **b)** Eagle Ford wells. HF wells (circles: FracFocus) that correlated with seismicity are colored; otherwise they are black. Blue boxes label regions analyzed for in uence of wells that target the Austin Chalk and Eagle Ford.

- Precise locations will help interpretation

Conclusions and Implications on Operations

- Hydraulic fracturing induced ~90 earthquakes larger than magnitude 2.0 in the Eagle Ford shale play of south Texas from 2014-2018
- One of the largest earthquakes induced by hydraulic fracturing in the US occurred near the largest recorded earthquake in south Texas
- Hydraulic fracturing of multiple well laterals simultaneously increases the probability of earthquakes relative to wells in isolation
- Faults in this area are capable of producing felt and potentially damaging earthquakes due to ongoing operational activities.

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