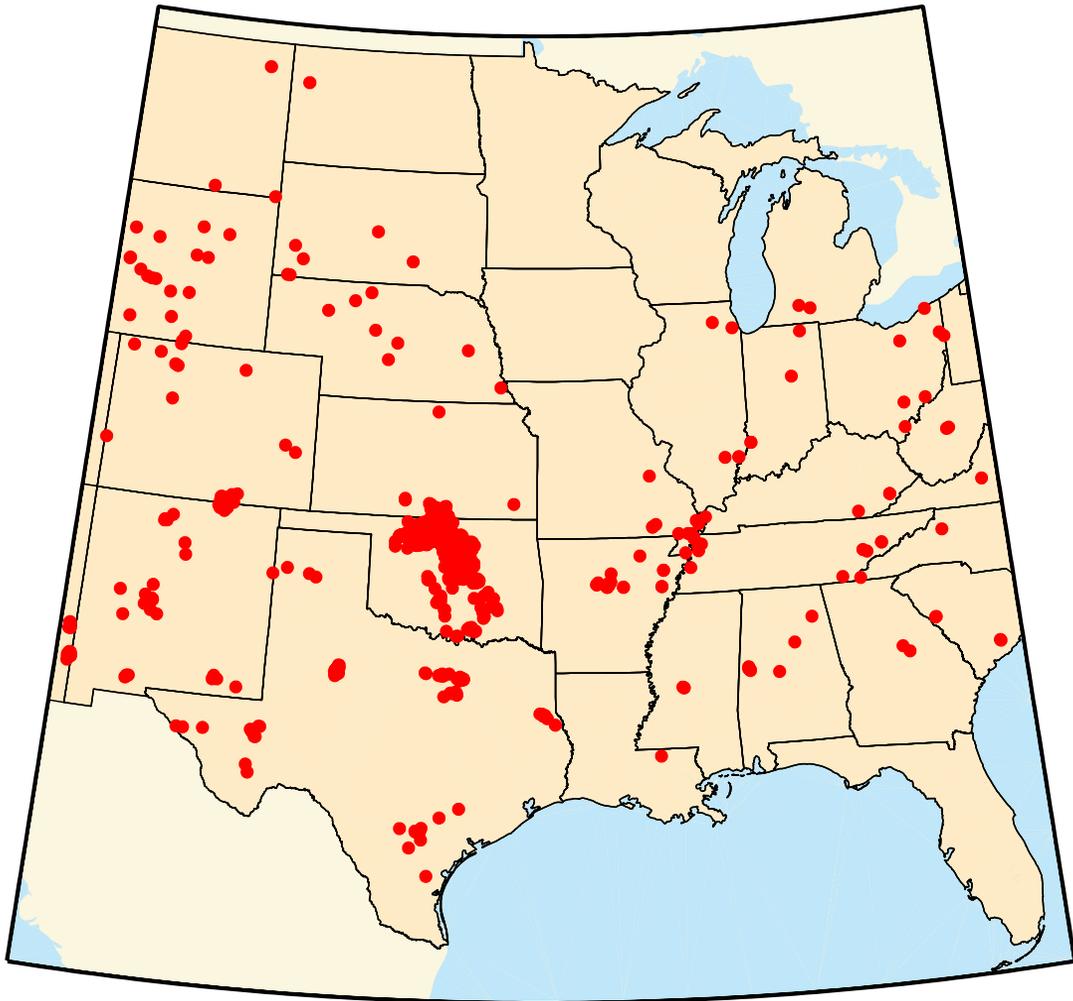


Stanford | Stanford Center for Induced
and Triggered Seismicity

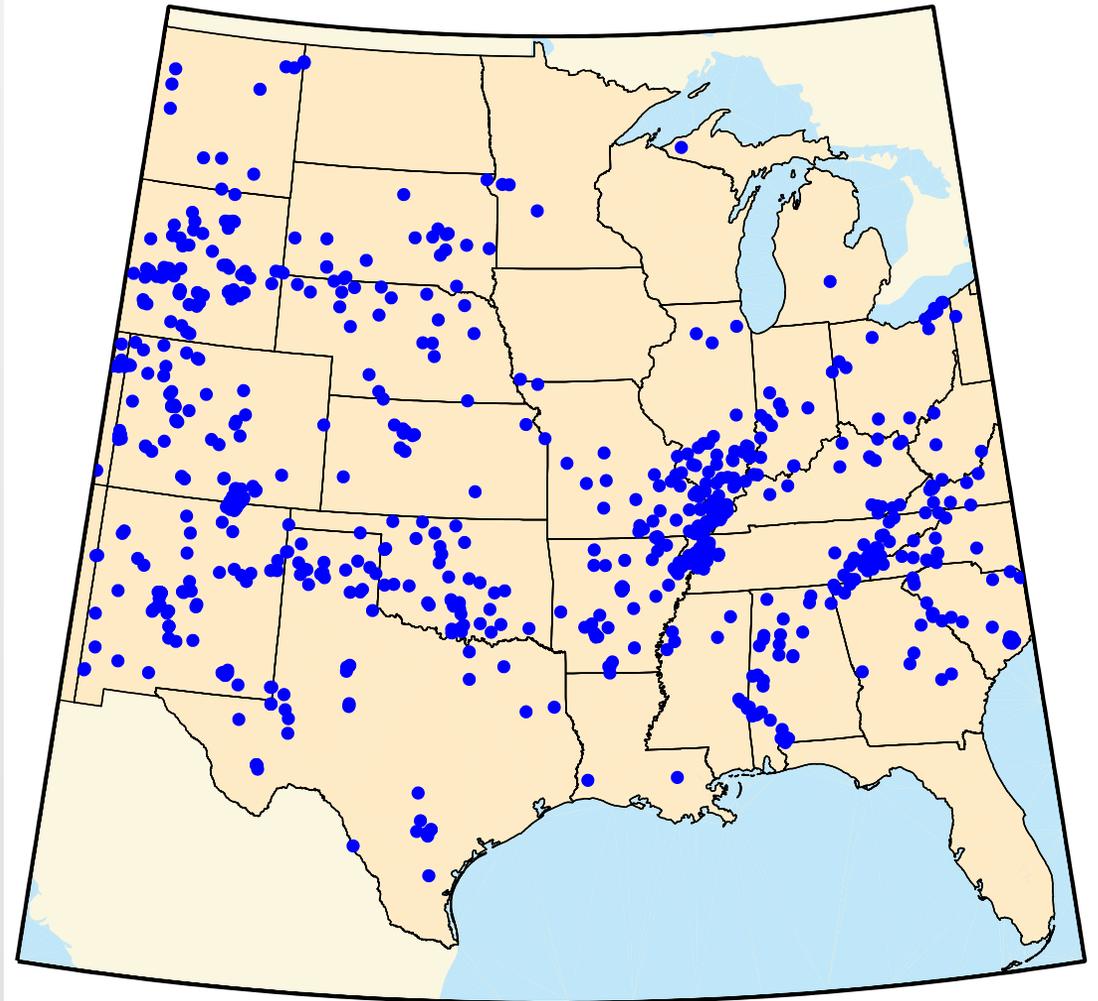
Bill Ellsworth, Jens Jund Snee,
Karissa Pepin and Miao Zhang

Induced Seismicity in the Permian Basin, USA
Basin overview, deformation, seismicity, open questions

2009 - 2015
391 M \geq 3/year



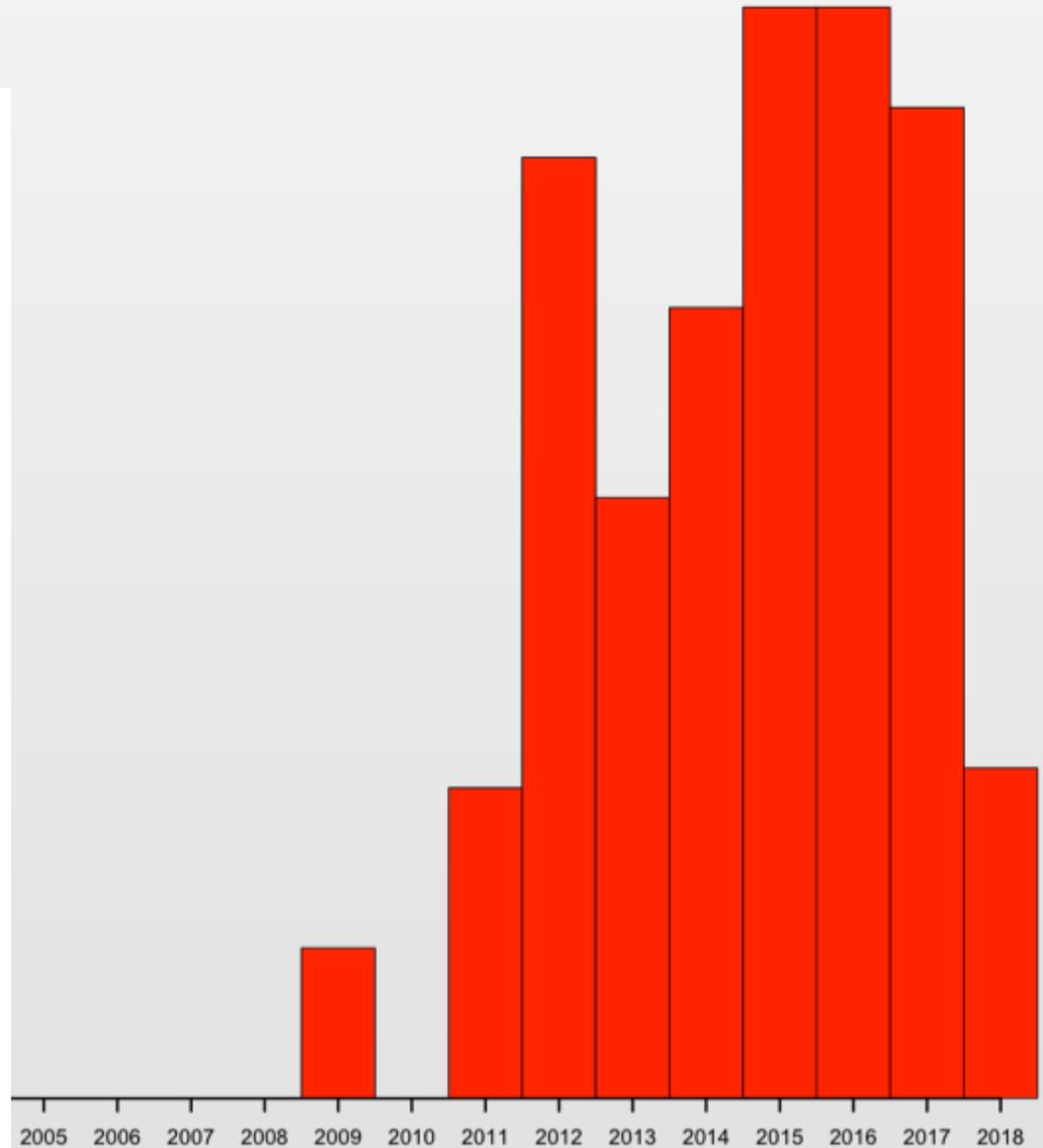
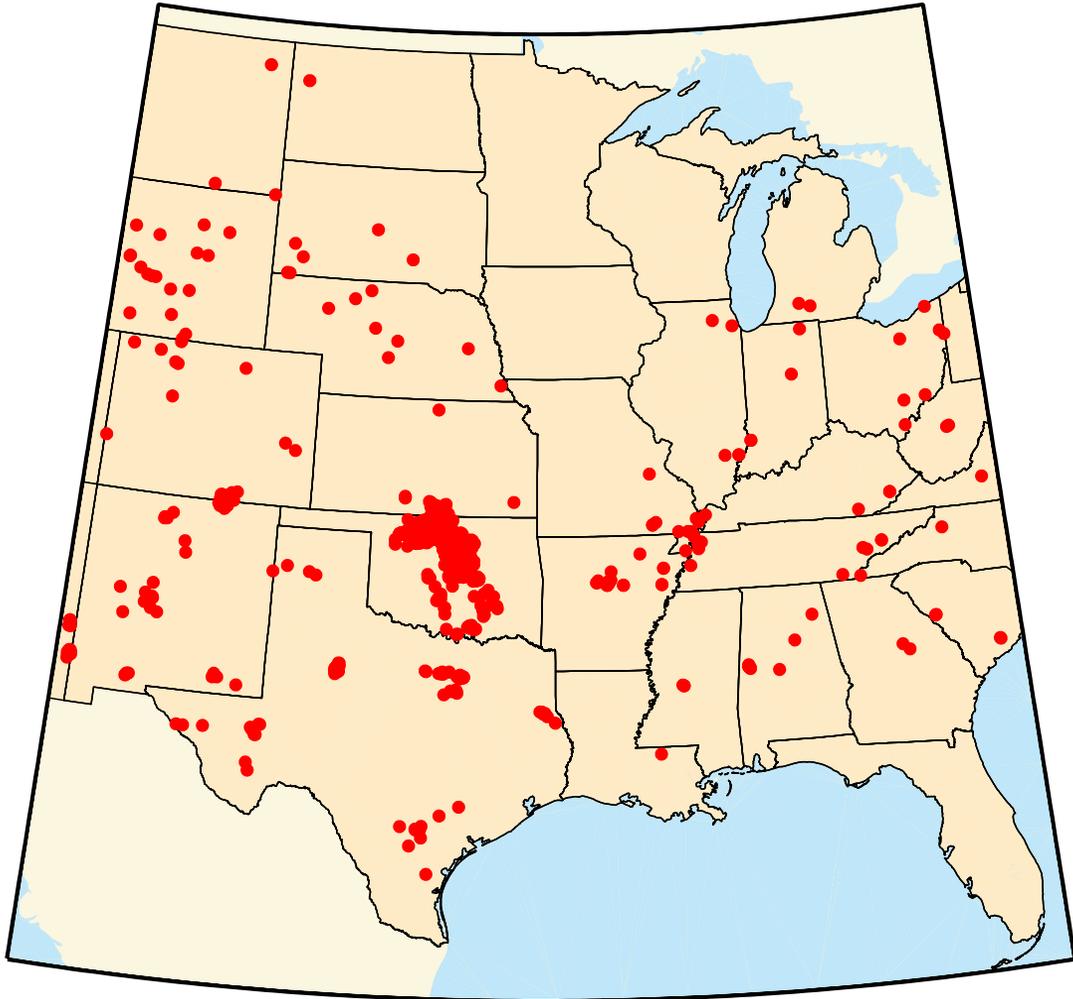
1973 - 2008
24 M \geq 3/year

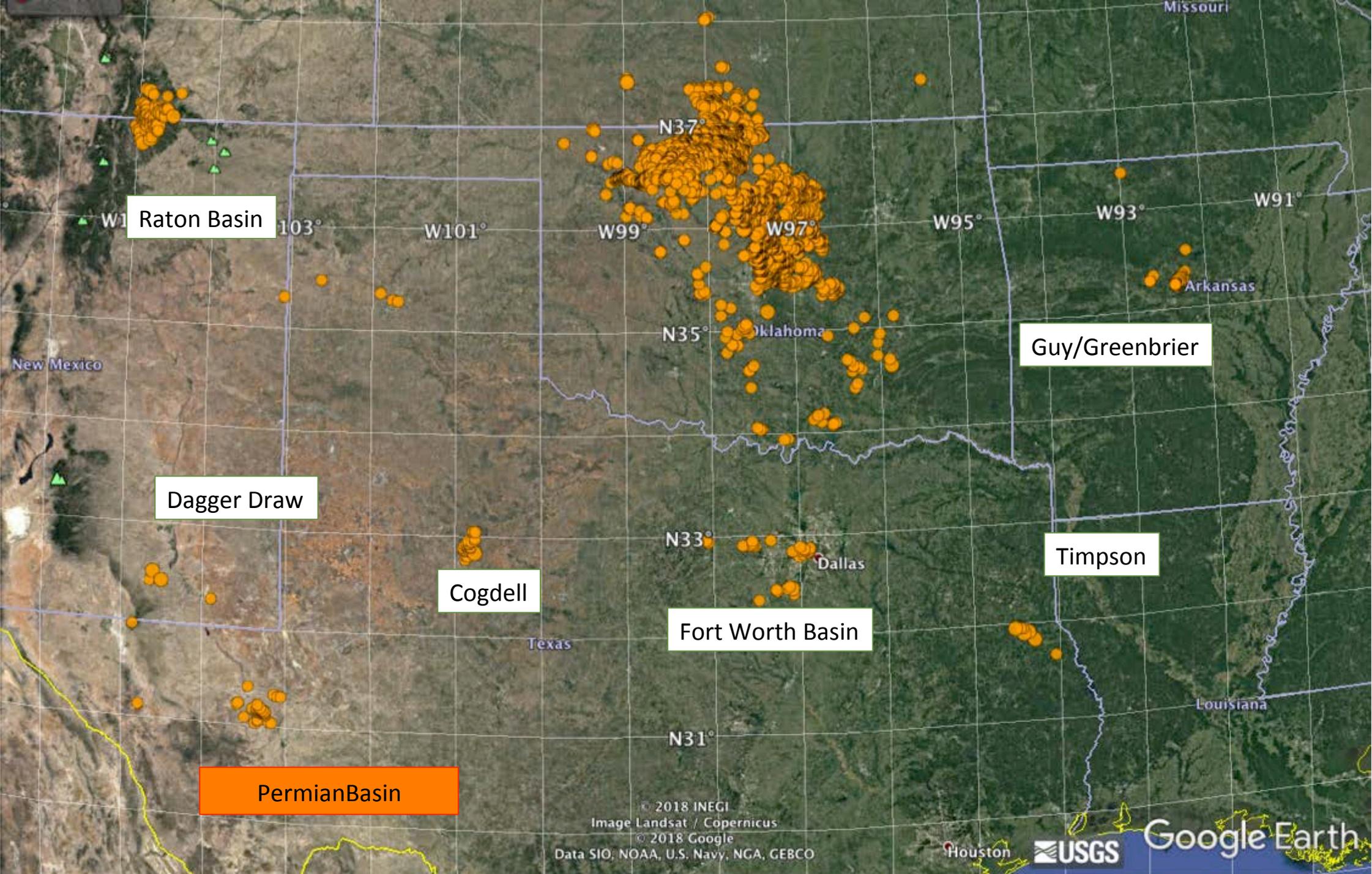


2009 – 2015

Fall AGU presentations on induced seismicity

391 $M \geq 3$ /year





Raton Basin

Dagger Draw

Cogdell

Fort Worth Basin

Guy/Greenbrier

Timpson

PermianBasin

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Image Landsat / Copernicus
© 2018 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

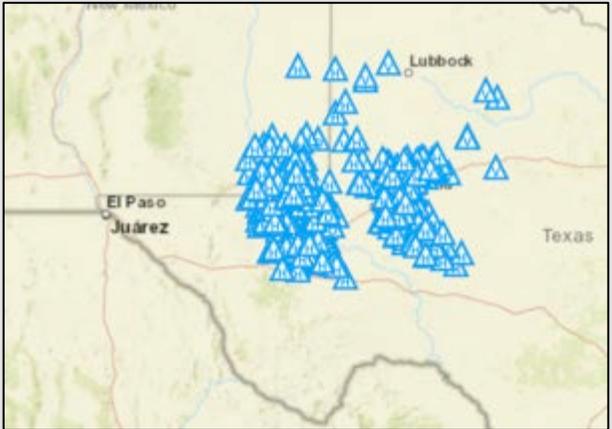
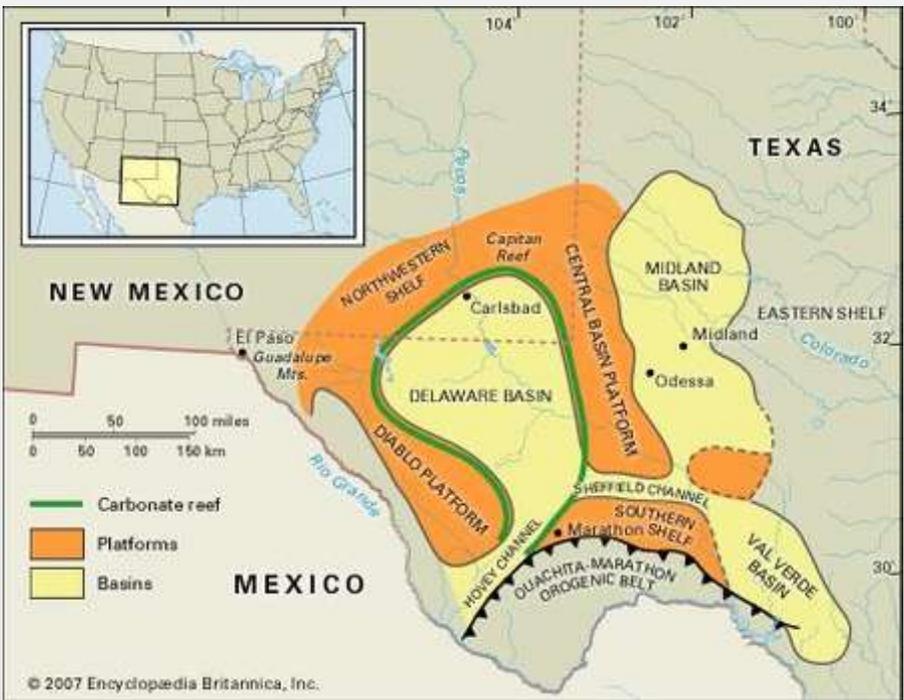
Houston



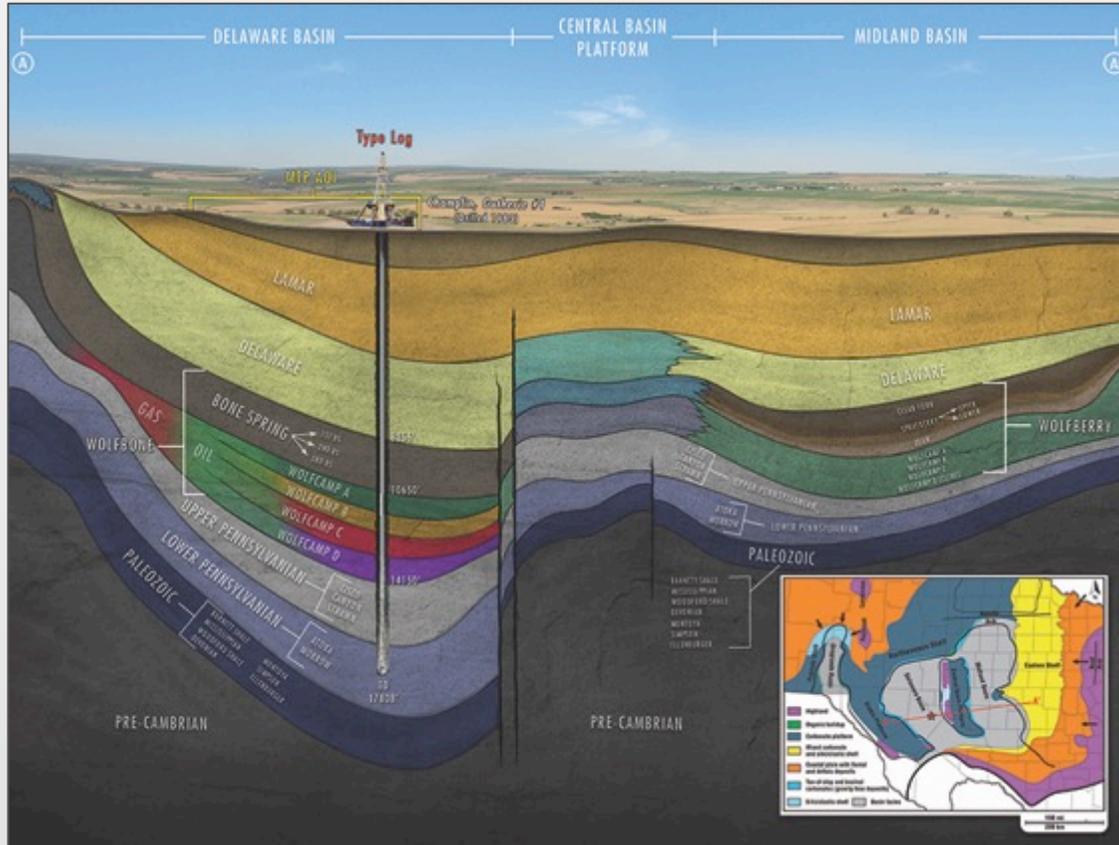
Google Earth

Permian Basin: giant oil field of west Texas

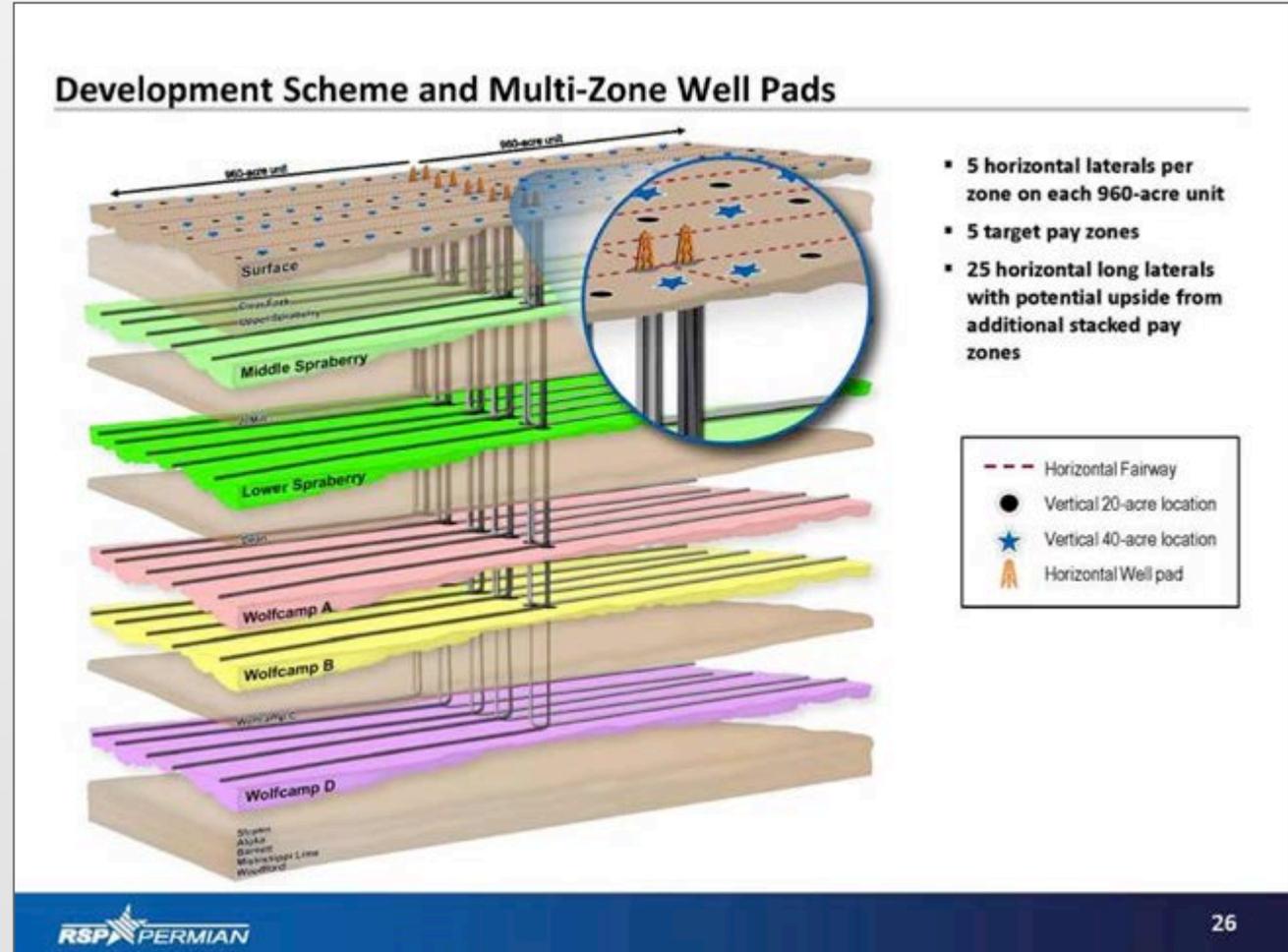
- Producing for nearly 100 years
- Shale drilling boom since 2009; accelerating since 2017
- Recoverable reserves *far* in excess of past produced volumes (≥ 500 BBOE (has been called "permanent resource"))
- 20% of all active drill rigs globally are currently in the Permian Basin



Many productive intervals ("stacked pay")



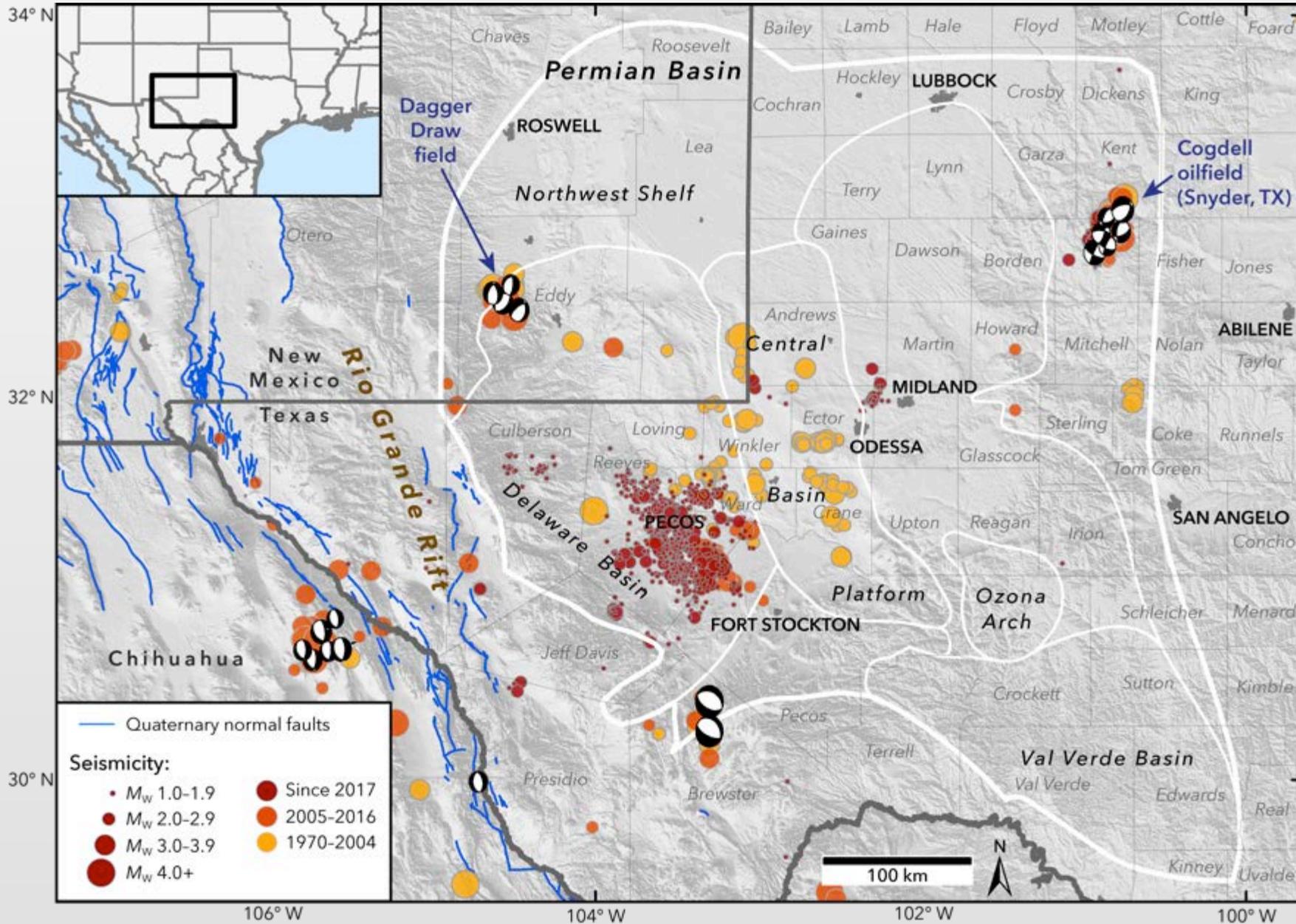
Manti Exploration & Production



- Oil
- ★ Gas
- ★ Oil / Gas
- Plugged Oil
- ★ Plugged Gas
- ◇ Canceled / Abandoned Location
- ★ Plugged Oil / Gas
- ◇ Injection / Disposal
- ◇ Core Test
- ◇ Sulfur Test
- Storage from Oil
- ★ Storage from Gas
- Shut-In Oil
- ★ Shut-In Gas
- Injection / Disposal from Oil
- ★ Injection / Disposal from Gas
- ★ Injection / Disposal from Oil / Gas
- ◇ Geothermal
- ◇ Brine Mining
- ◇ Water Supply
- Water Supply from Oil
- ★ Water Supply from Gas
- ★ Water Supply from Oil / Gas
- ◇ Observation
- Observation from Oil
- ★ Observation from Gas
- ★ Observation from Oil / Gas
- ◇ Storage
- ◇ Service
- Service from Oil
- ★ Service from Gas
- ★ Service from Oil / Gas
- ★ Storage from Oil / Gas
- ◇ Injection / Disposal from Storage
- Injection / Disposal from Storage / Oil
- ★ Injection / Disposal from Storage / Gas
- ★ Injection / Disposal from Storage / Oil / Gas
- ◇ Observation from Storage
- Observation from Storage / Oil



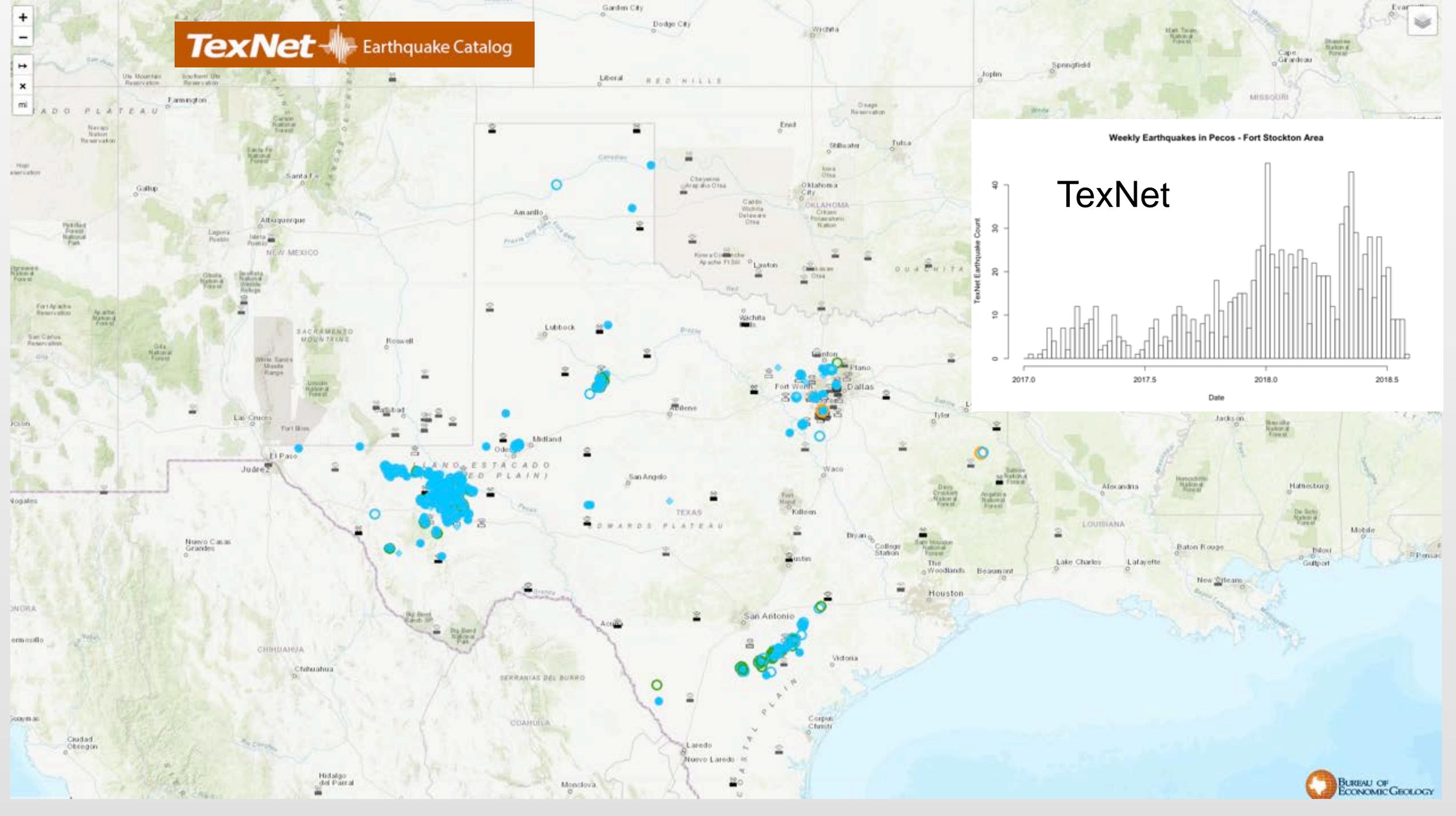
Decades of potentially induced seismicity



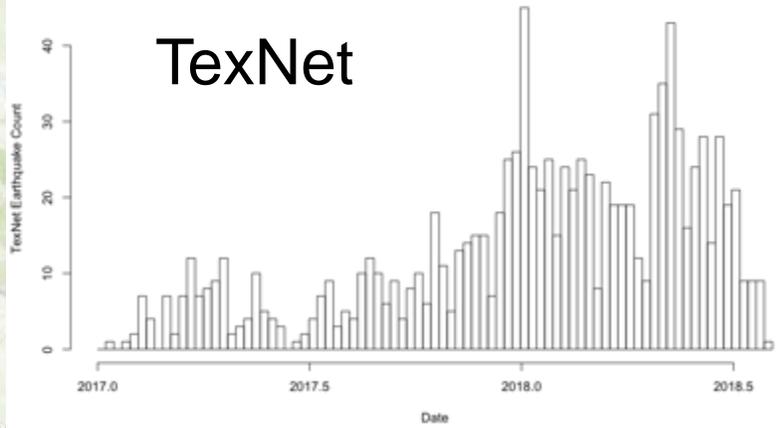
Earthquakes from U.S. Geological Survey (NEIC), TexNet Seismological Network, Doser et al. (1991, *BSSA*; 1991, *WTGS*; 1992, *PAGEOPH*) and Gan & Frohlich (2013, *PNAS*)

Focal mechanisms from Saint Louis University (Herrmann et al., 2011)

TexNet Earthquake Catalog



Weekly Earthquakes in Pecos - Fort Stockton Area



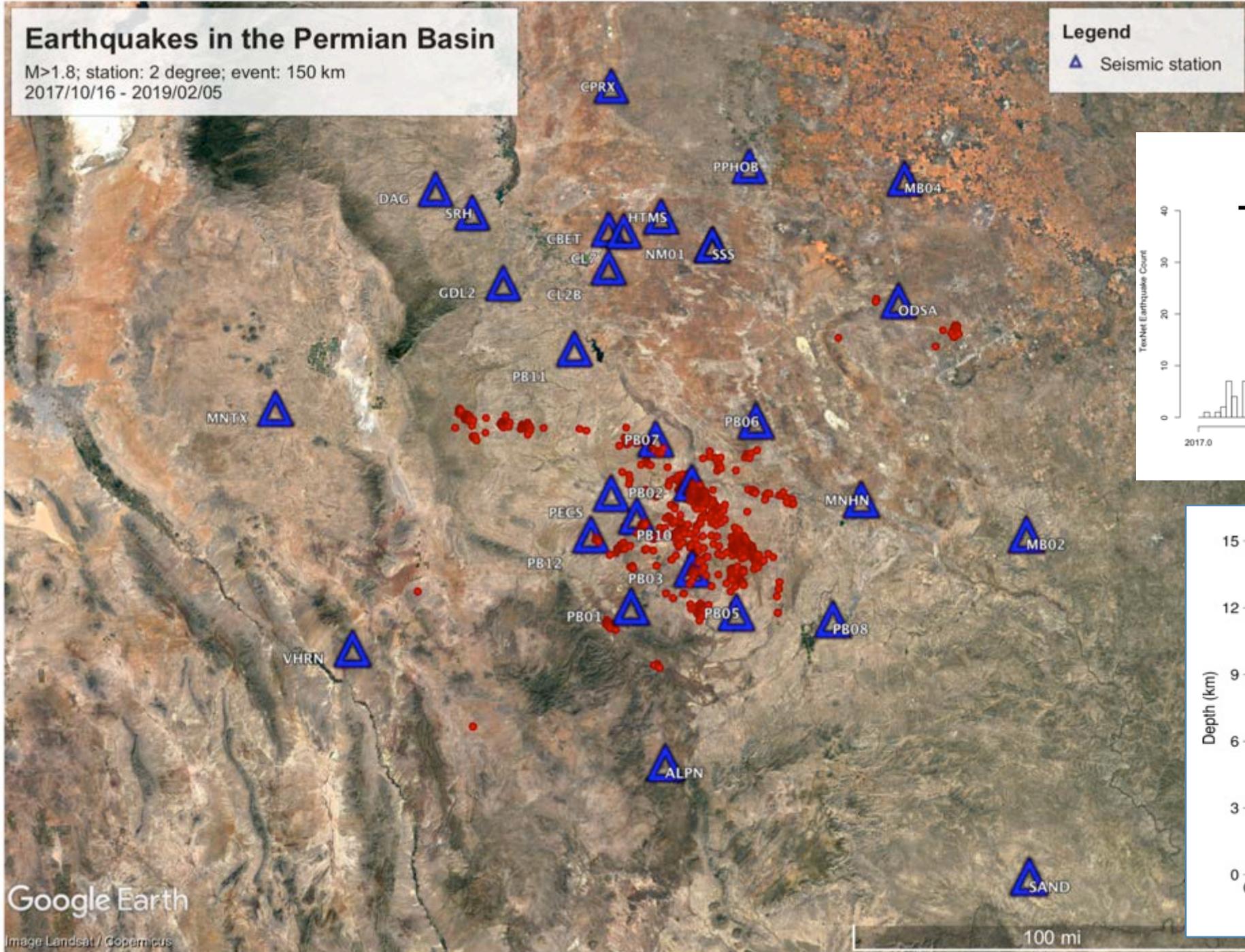
TexNet

Earthquakes in the Permian Basin

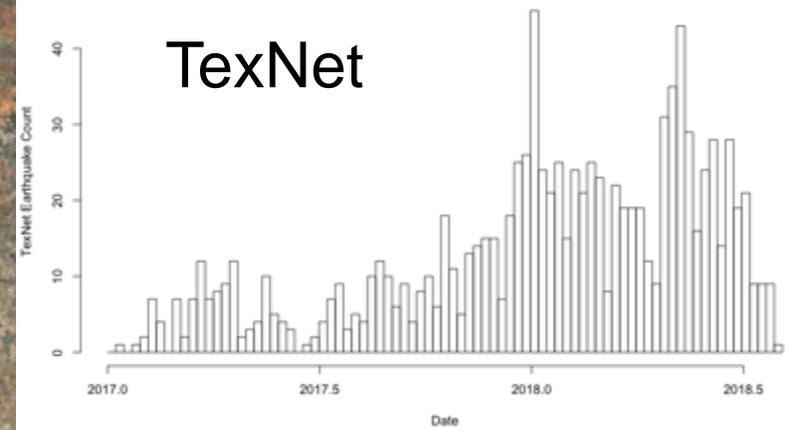
M>1.8; station: 2 degree; event: 150 km
2017/10/16 - 2019/02/05

Legend

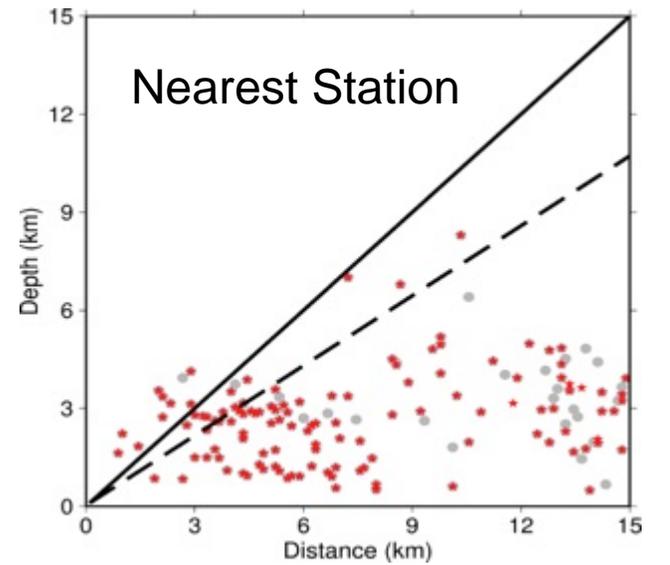
▲ Seismic station



Weekly Earthquakes in Pecos - Fort Stockton Area

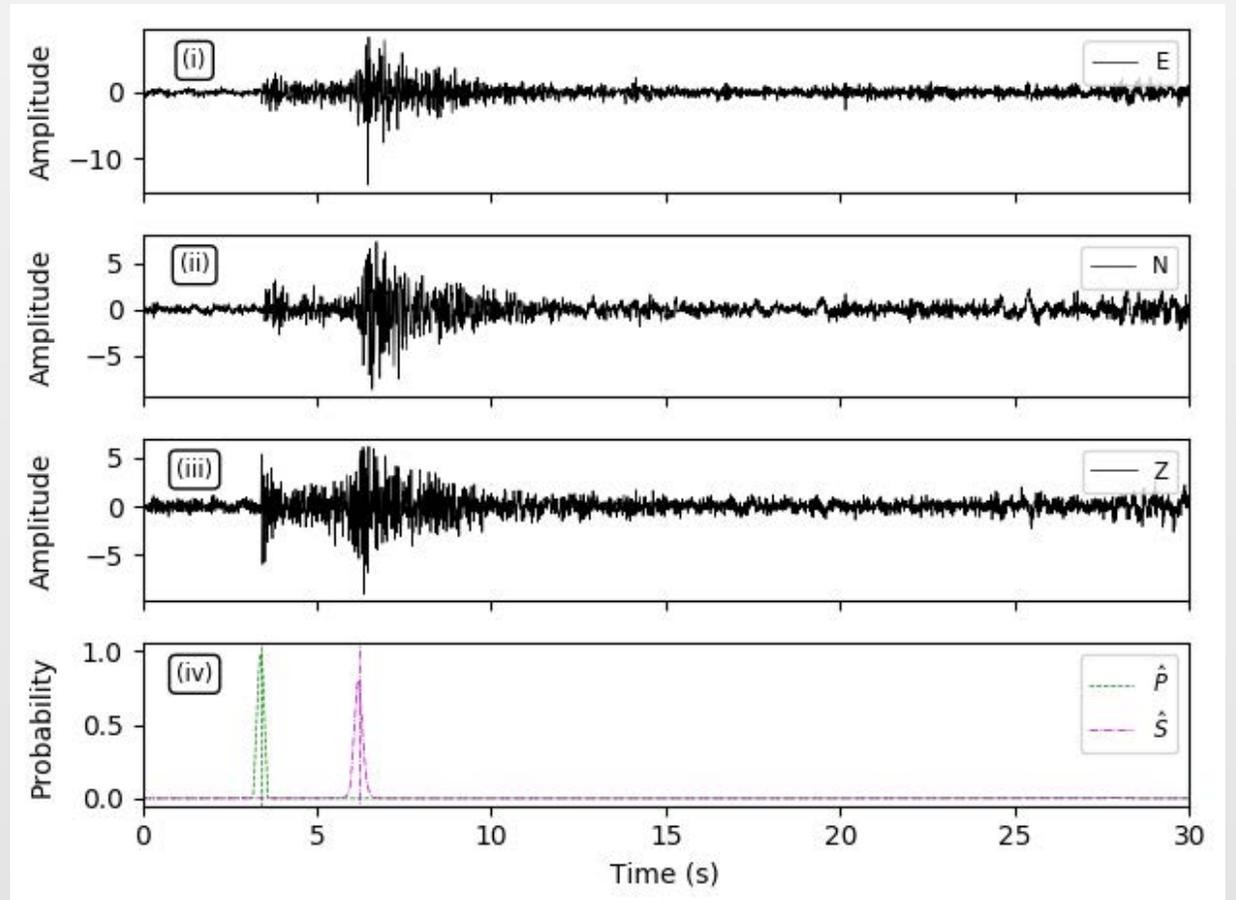
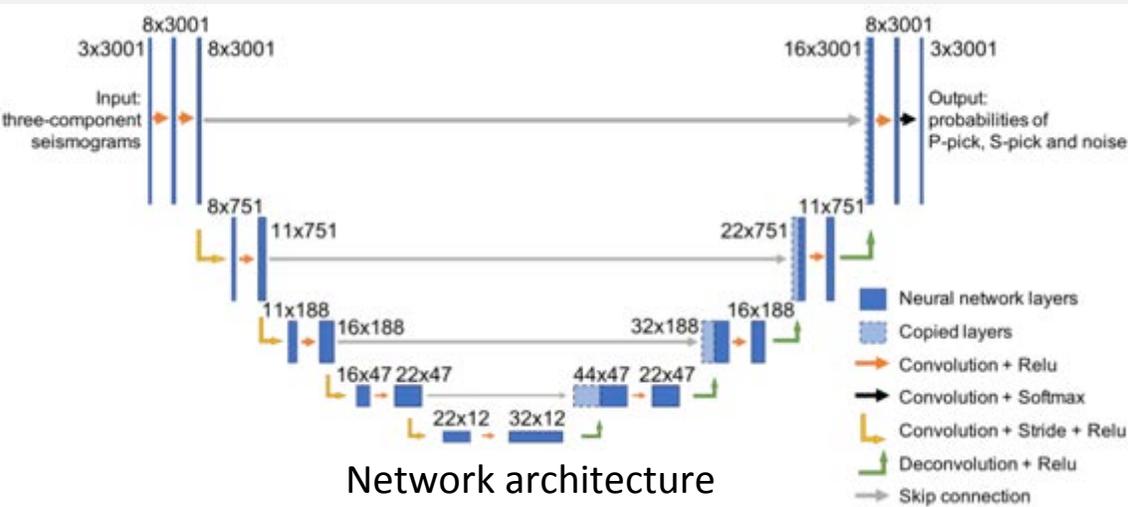


TexNet

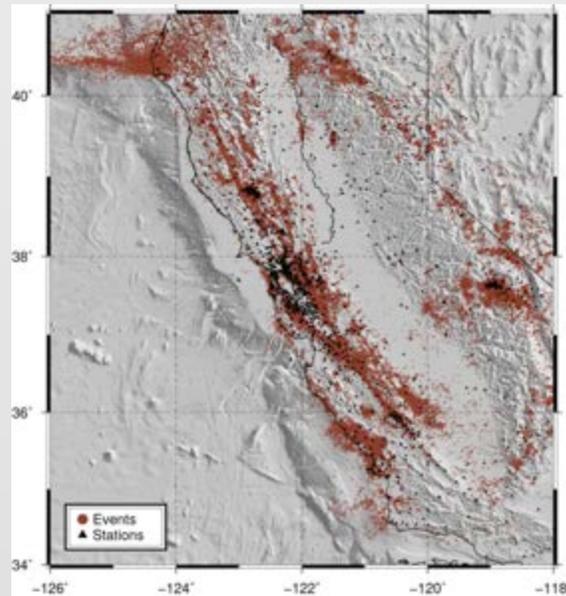


PhaseNet: deep-learning picker

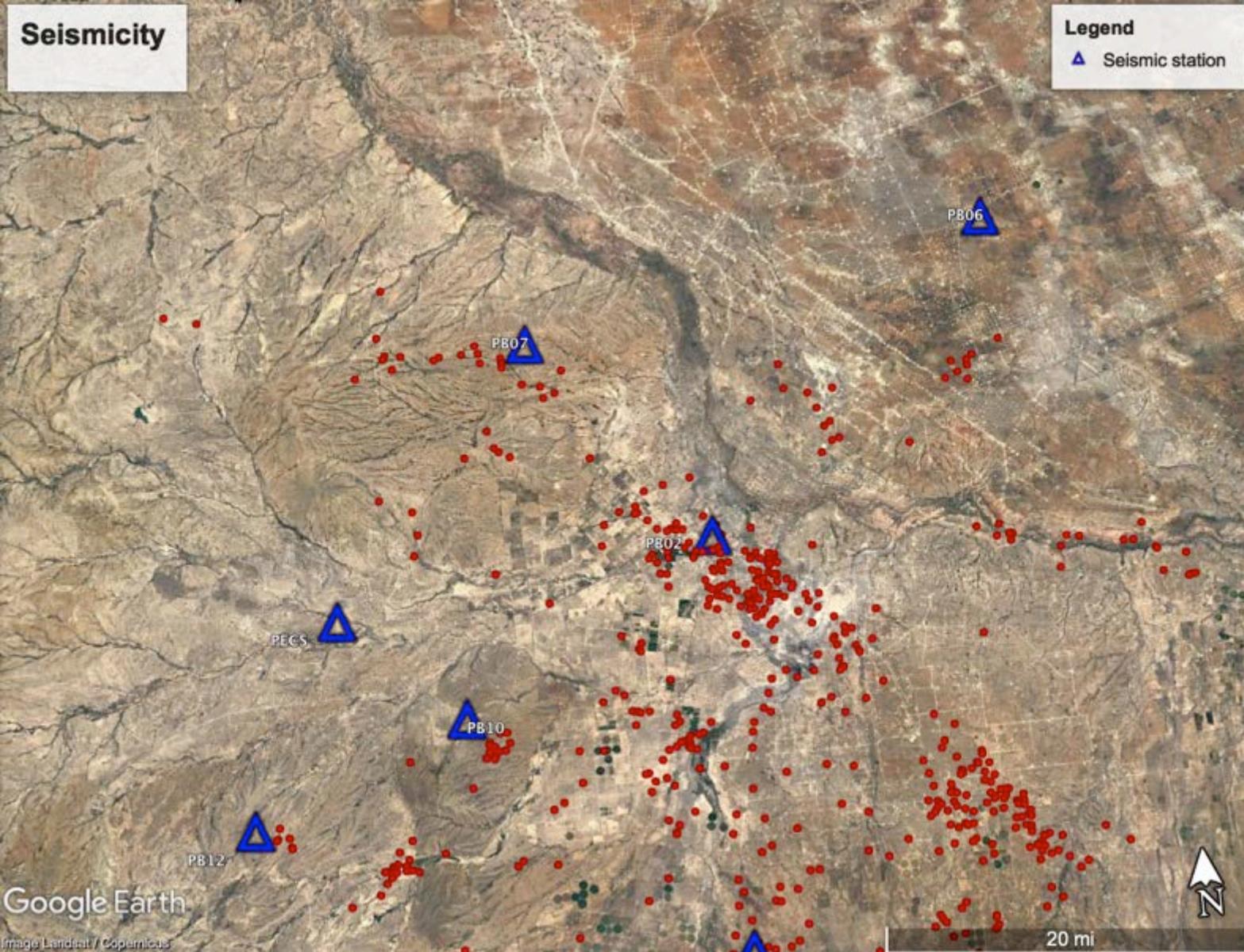
Zhu and Beroza, GJI, 2019



Training dataset (NCSN catalog)



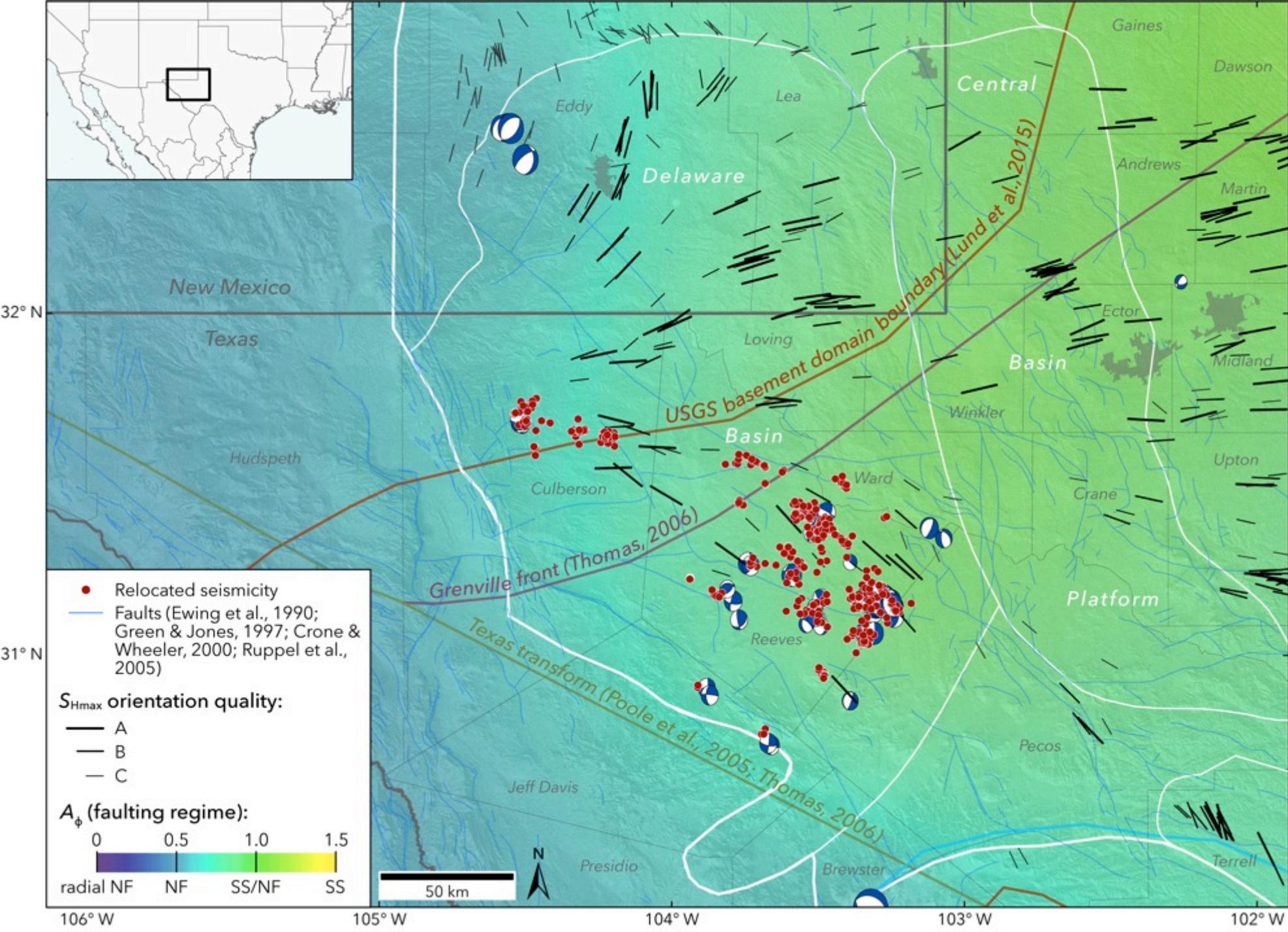
Independent probability distributions for P-pick, S-picks and no-pick (noise)



Initial Results

- Depths are shallow (< 5 km)
- Depth range matches depths of both horizontal wells and disposal wells
- Some of the events are frac related
- Not sure about %
- Efforts underway to improve seismic network

32 km

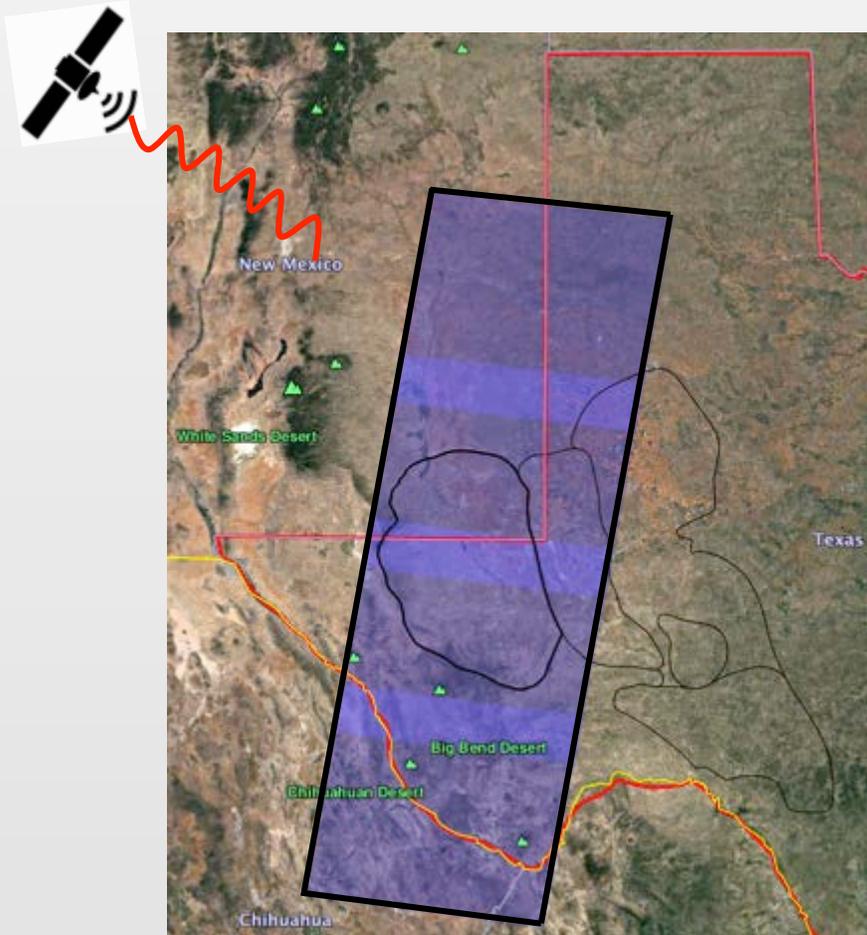


Normal faulting to strike slip faulting stress state.

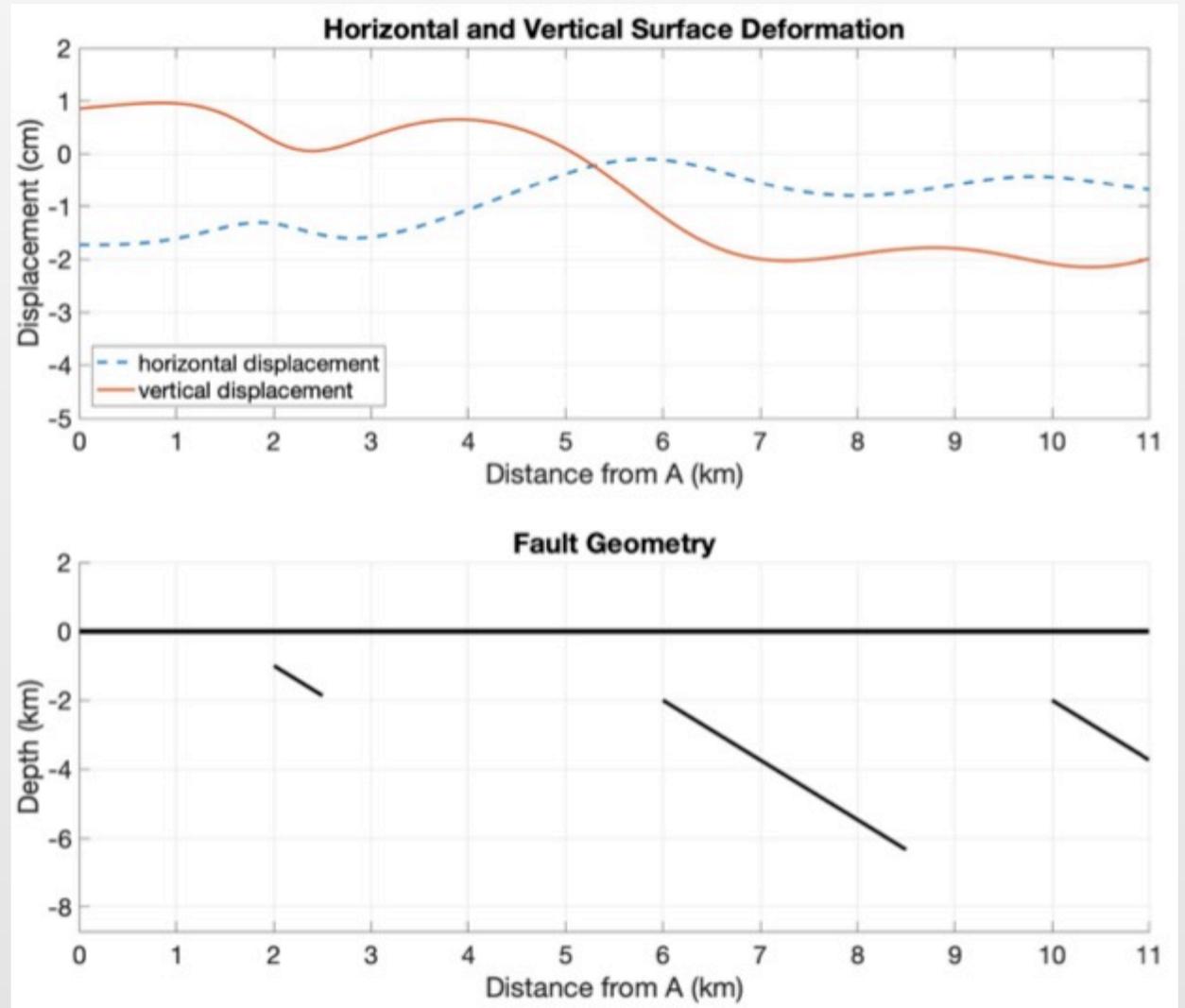
Focal mechanism quality still poor.

Seismicity hints at structures on a large scale.

Sentinel 1A/1B coverage over the Delaware Basin



Descending Orbit

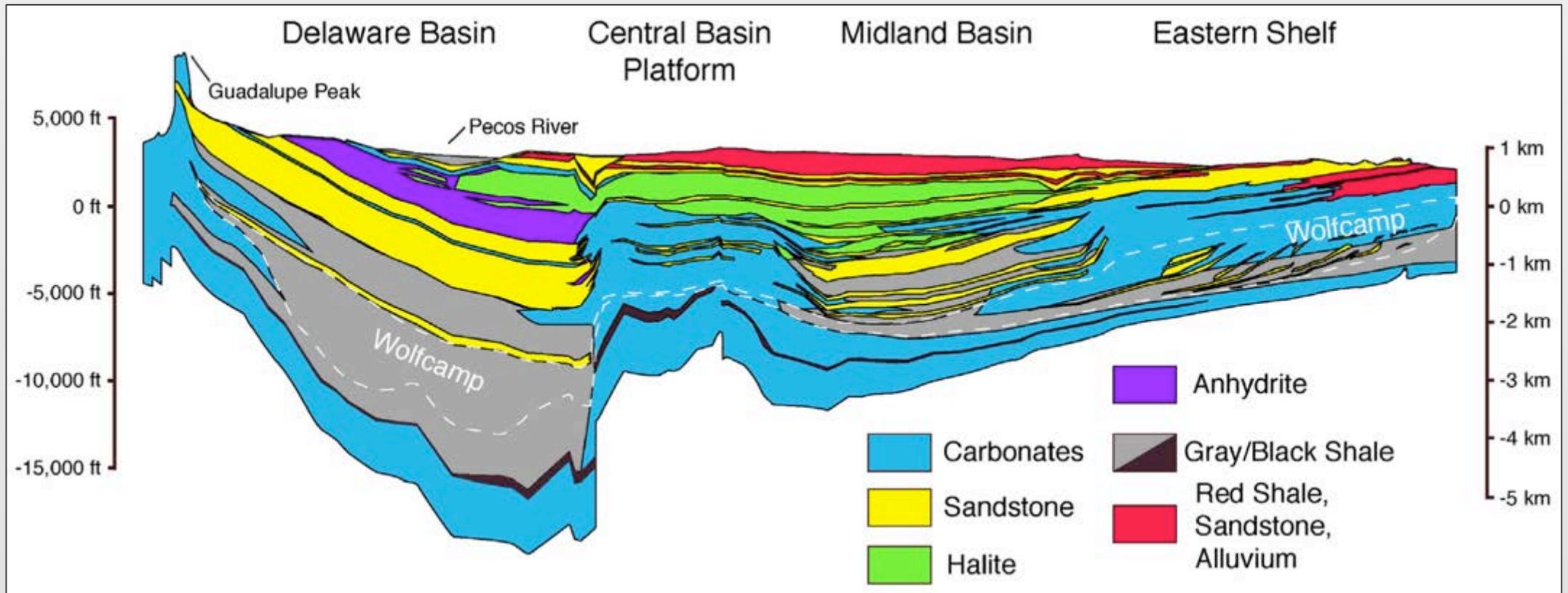


Normal slip of several centimeters on optimally oriented normal faults might account for the deformation

Seismicity is too feeble to explain deformation – largest to date Mw 3.4

Open question if most earthquakes are caused by fracking, production or disposal

Saltwater disposal growing problem with shallow zones rapidly filling to capacity



Questions

