TexNet CISR

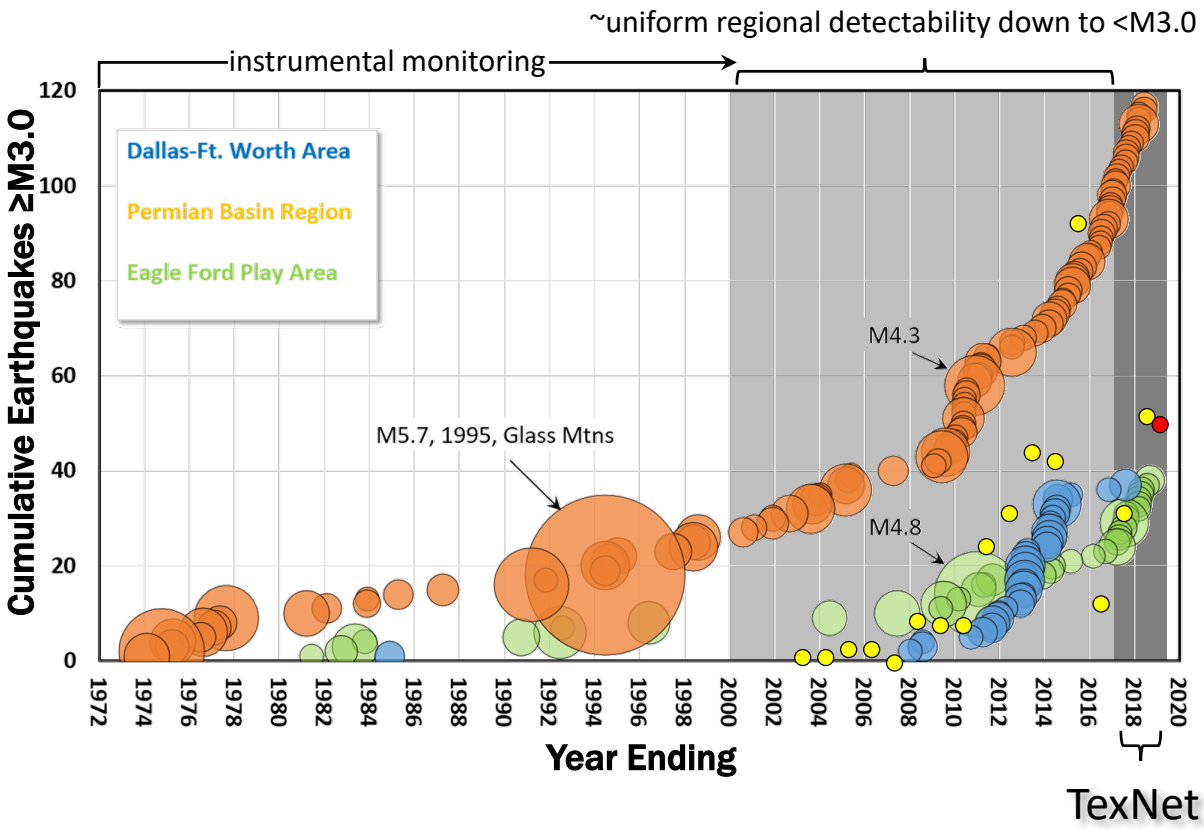
Earthquake Hazard Characterization of the Fort Worth Basin

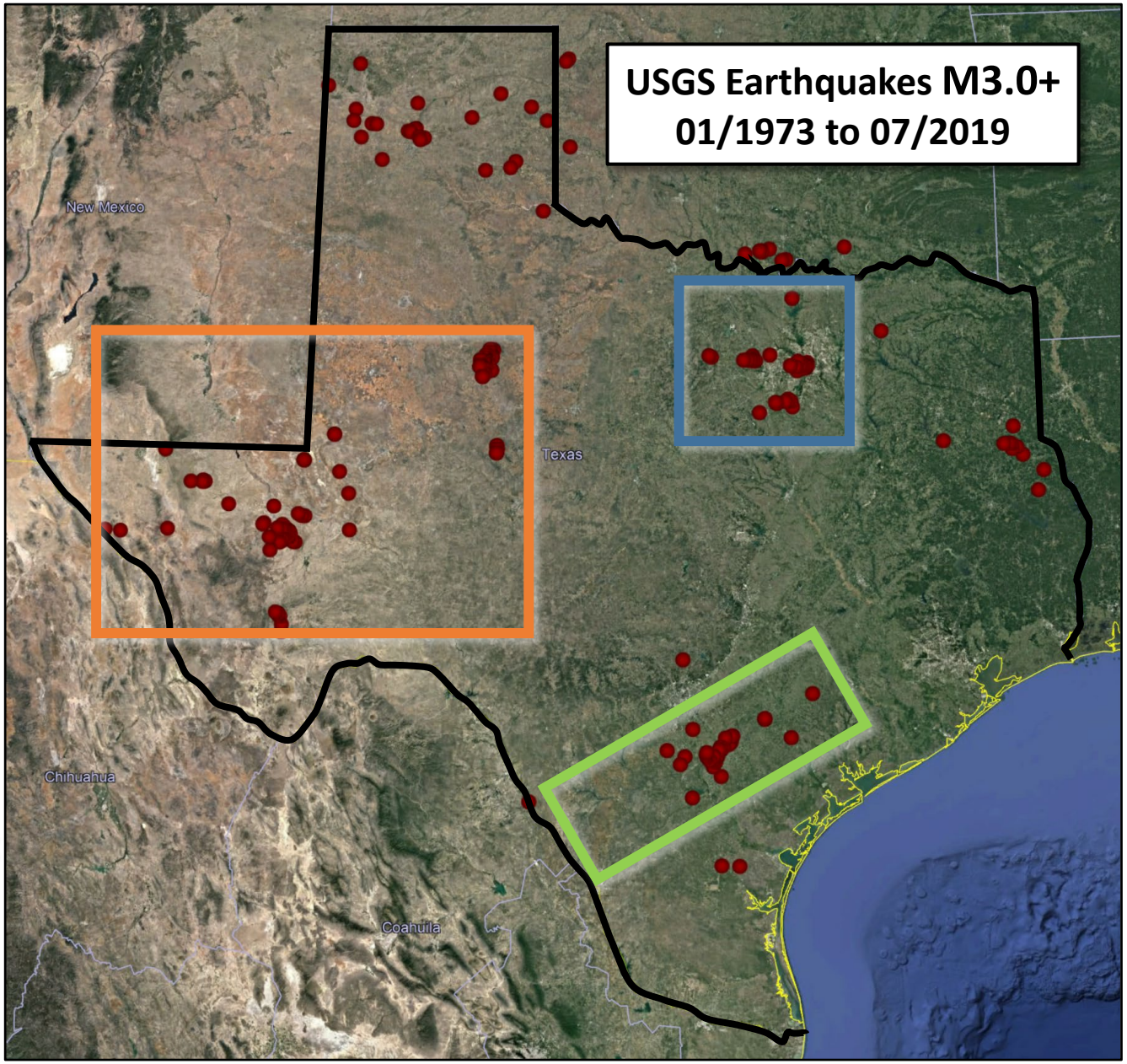
Bureau of Economic Geology

Today's Presentation

- Background on seismicity in Texas and the TexNet-CISR Program
- Synopsis of prior seismicity research in the Fort Worth Basin
- Review of the BEG's recently completed and current research in the FWB
- Future research plans in the FWB
- Closing remarks

M3.0+ Historical Seismicity in Texas





- Annual number of USGS Did You Feel It? earthquakes (all Texas)
- 2019 YTD USGS Did You Feel It? earthquakes (all Texas)

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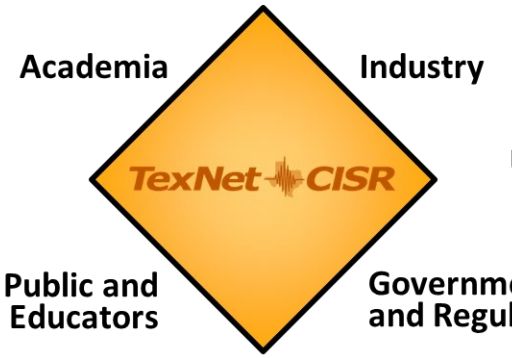
TexNet-CISR Program - 2 Parts of a Whole

TexNet

Using funding from the State of Texas, the Bureau and its partners monitor, catalog, and analyze earthquakes employing a *backbone* seismic network for State-wide coverage, and *temporary* stations for local studies. Quality-controlled earthquake data is provided to the public. A comprehensive program of research is conducted on earthquake characteristics and causes for application to improvements in practice and for hazard mitigation.

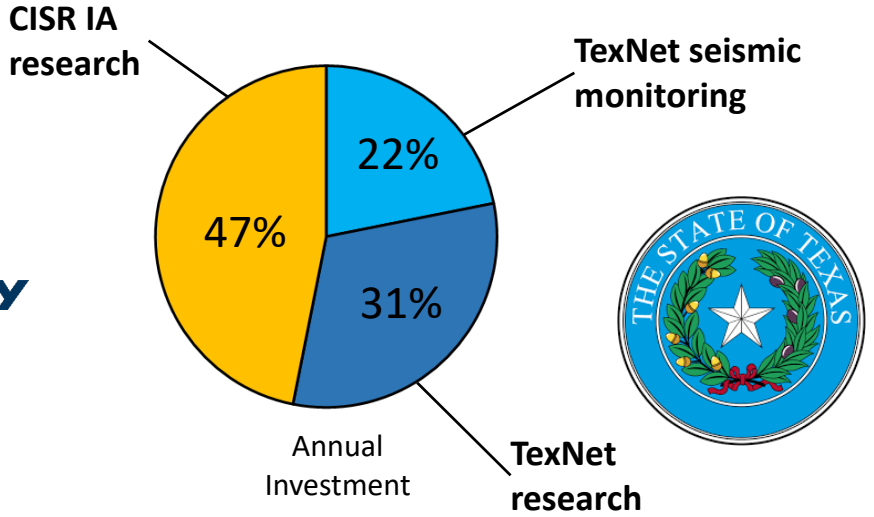
Center for Integrated Seismicity Research

Industry partnership leverages and extends TexNet monitoring and research to more thoroughly study earthquake occurrences, trends, and causes to deepen the understanding of induced earthquakes and to develop appropriate mitigation strategies.



Collaborators

UT Bureau of Economic Geology
UT Institute for Geophysics
UT Petroleum Geosystems and Engineering
UT Civil, Arch, and Environmental Engineering
UT Aerospace Engineering
Texas A&M Petroleum Engineering
SMU Geosciences
University of Houston Seismology
University of Texas at Dallas Seismology
University of Texas at El Paso Seismology
Stanford University SCITS
Lomax Consulting
Morris Consulting
gempa GmbH



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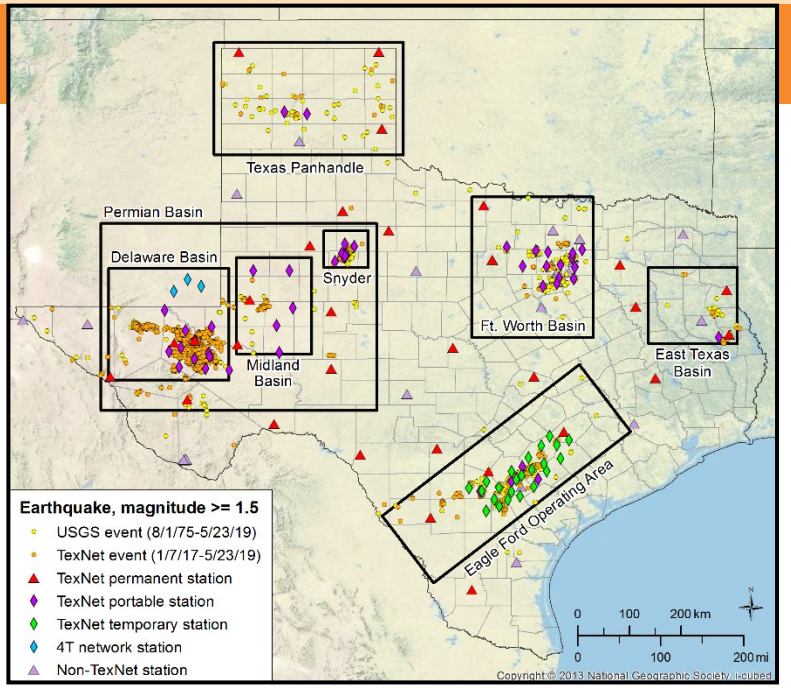
TexNet-CISR Operations and Research Timeline

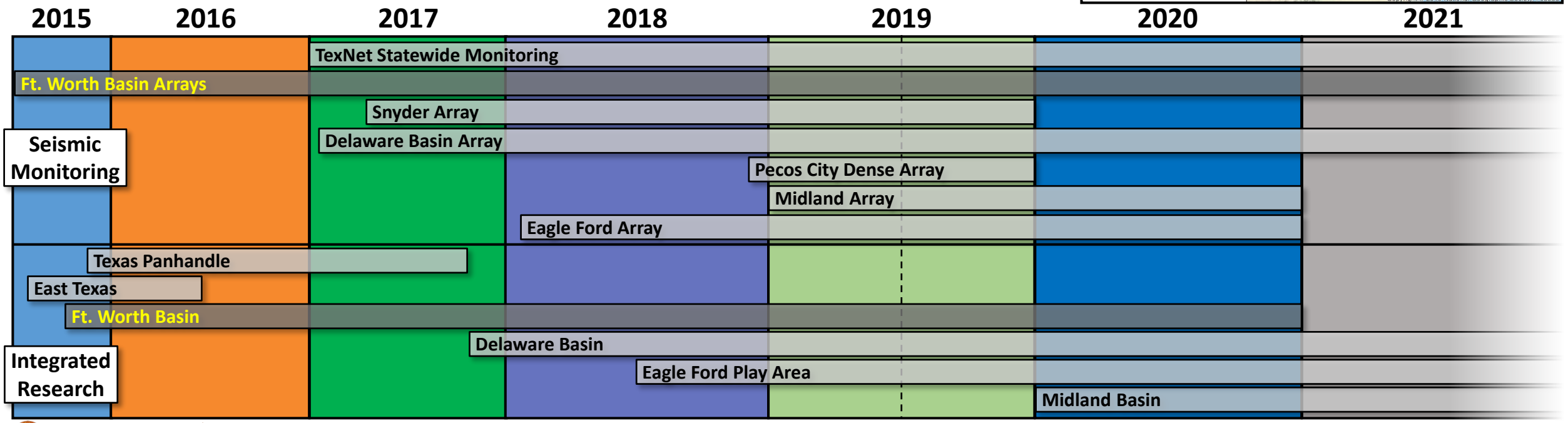
Research Goals:

- Understand Earthquake Activity
- Understand Causal Factors
- Understand Impacts
- Enable Mitigation

Geographic Project Areas:



Monitoring and Research Timeline of Geographic Emphases:



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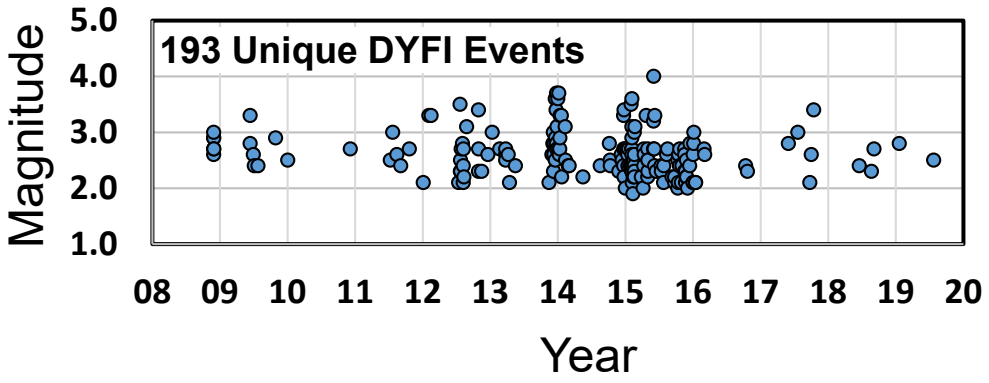
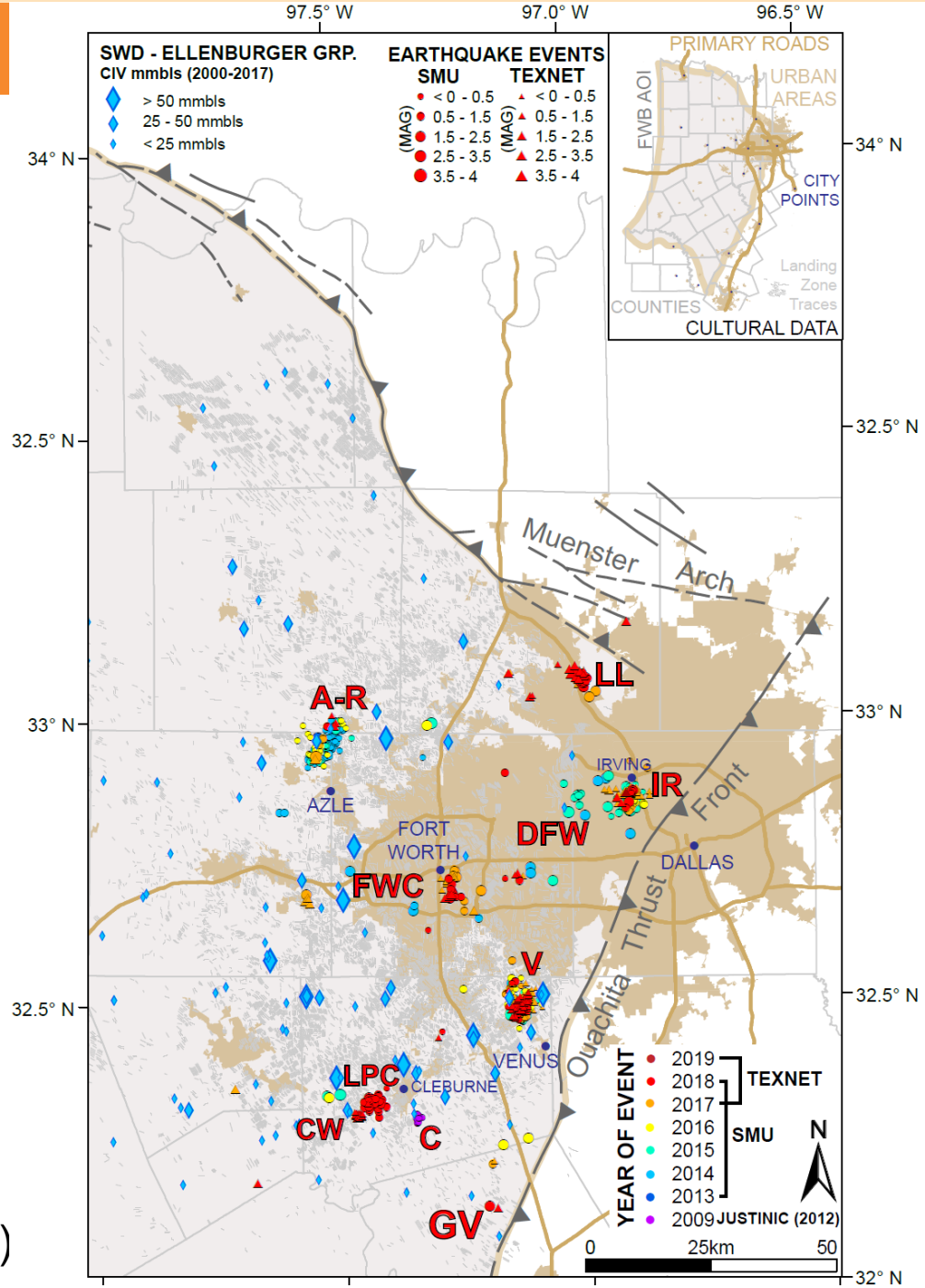
Seismicity in the Fort Worth Basin

All Catalogued Earthquakes

EQ SEQUENCE - FAULT	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				





Horne et al. (*in prep*)

Synopsis of prior seismicity research in the Fort Worth Basin

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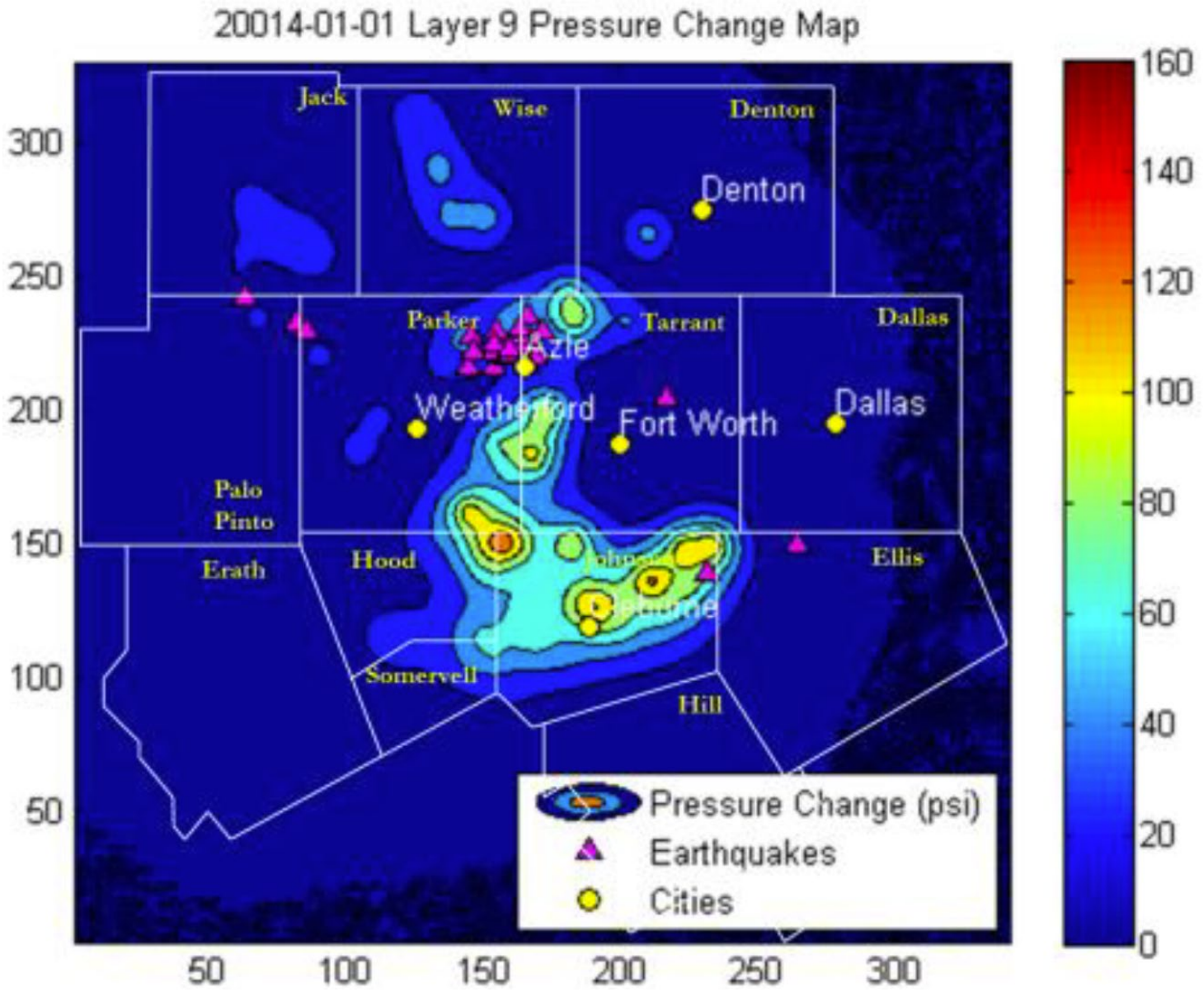

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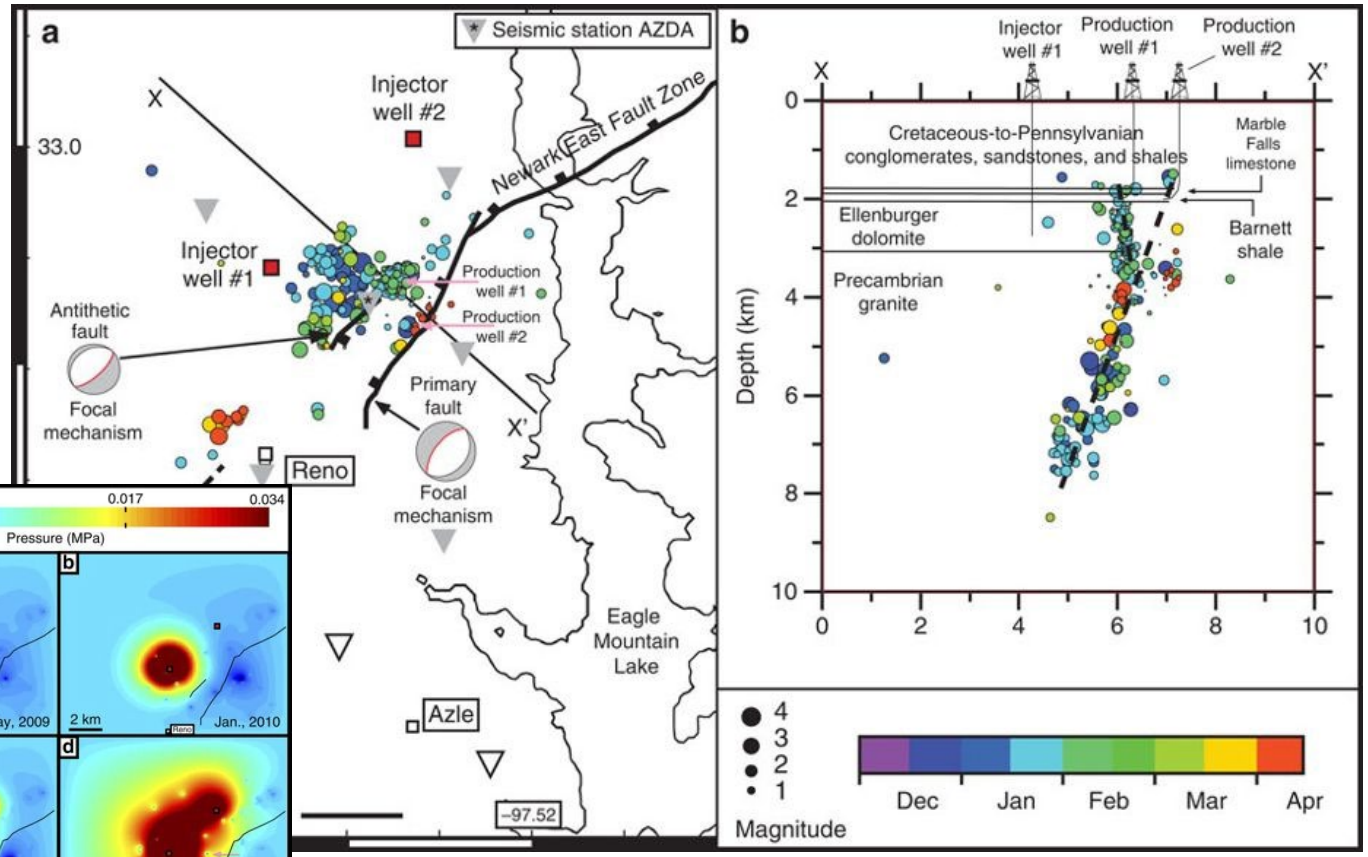

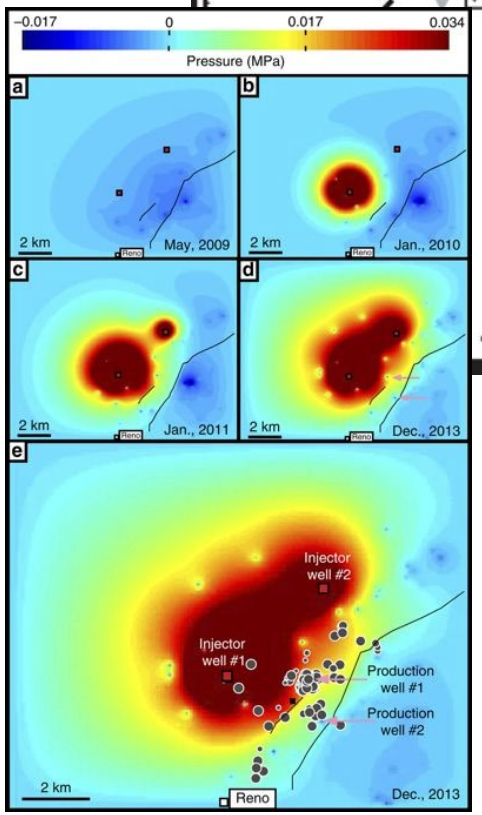

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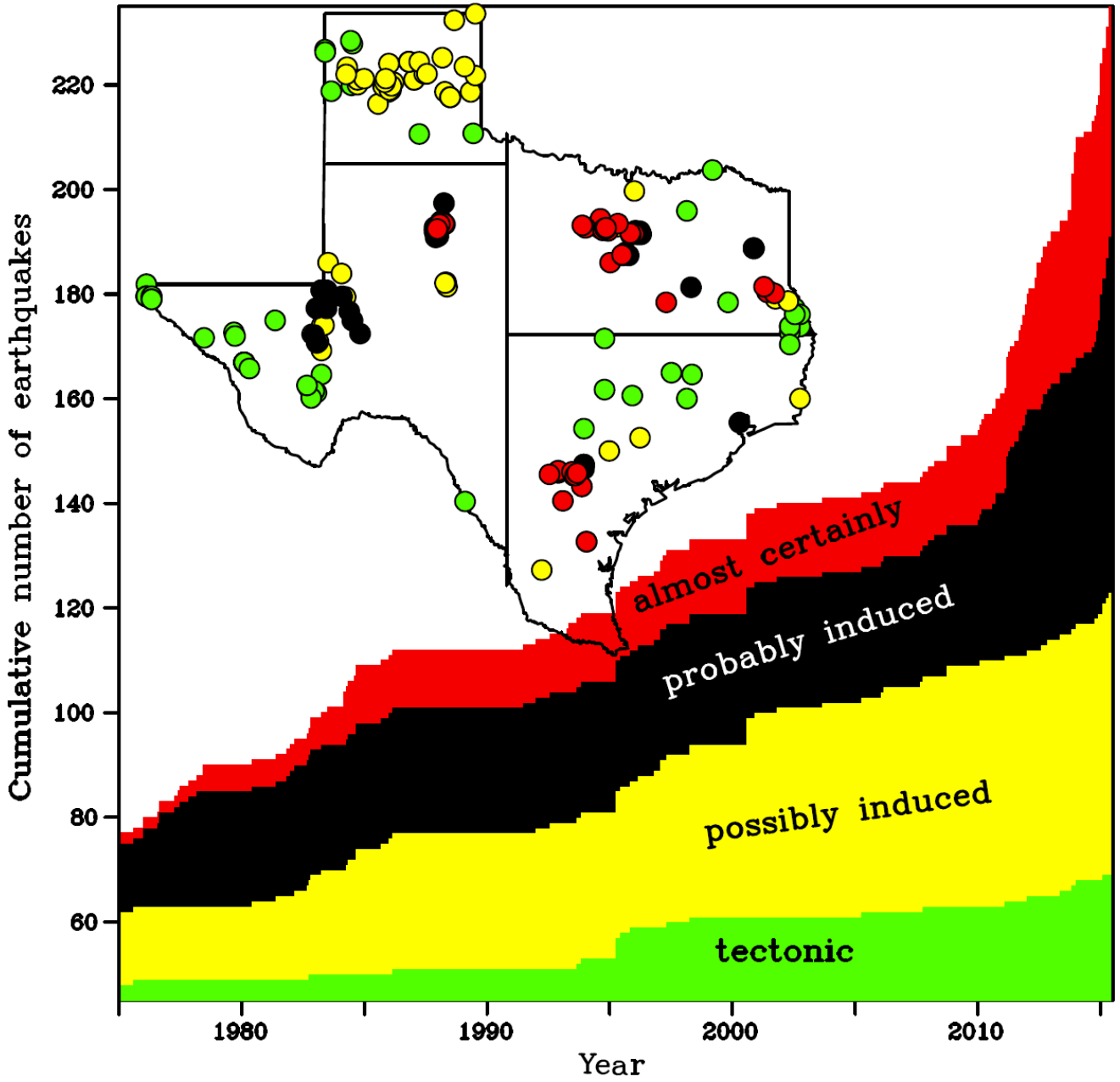

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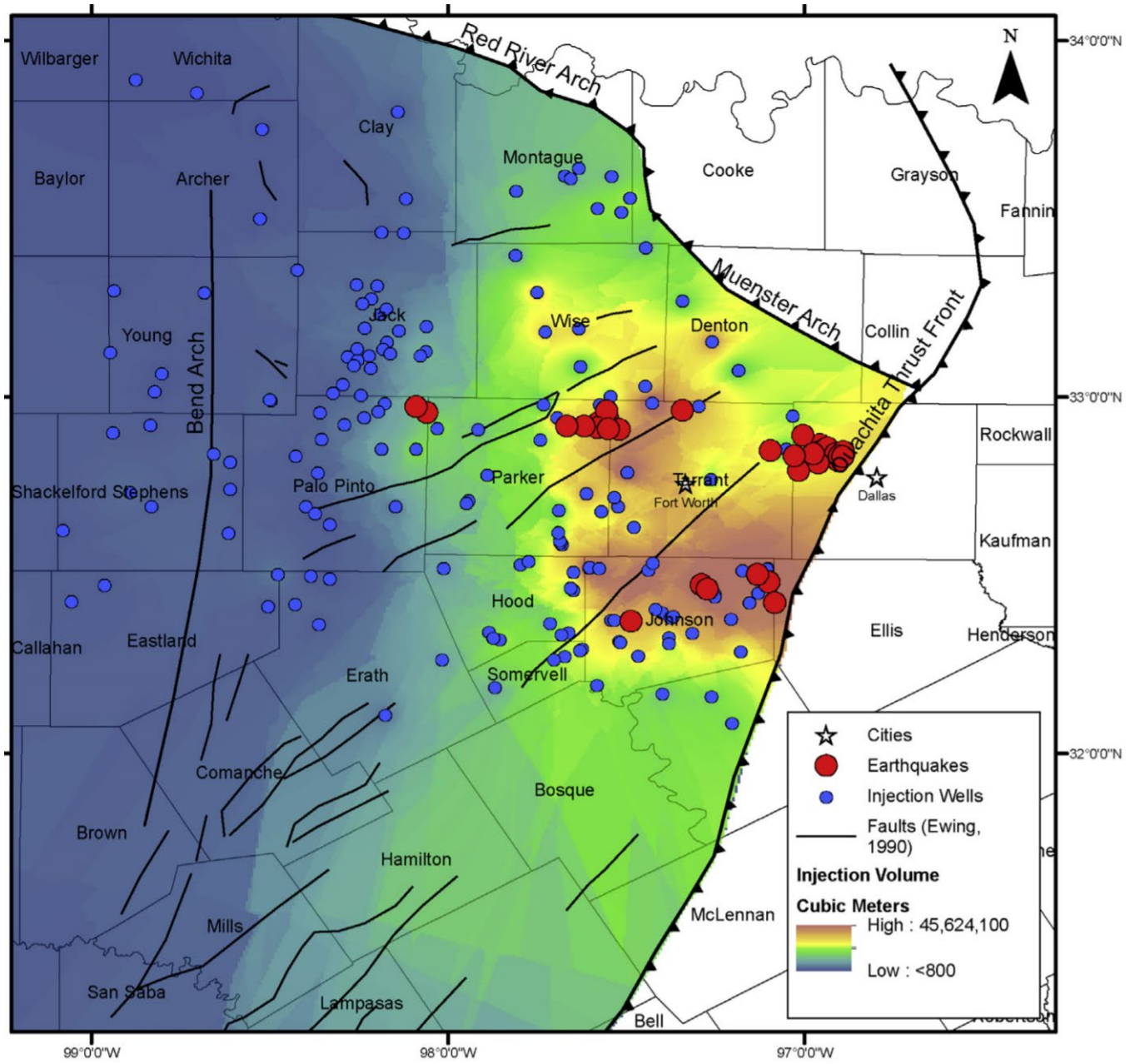

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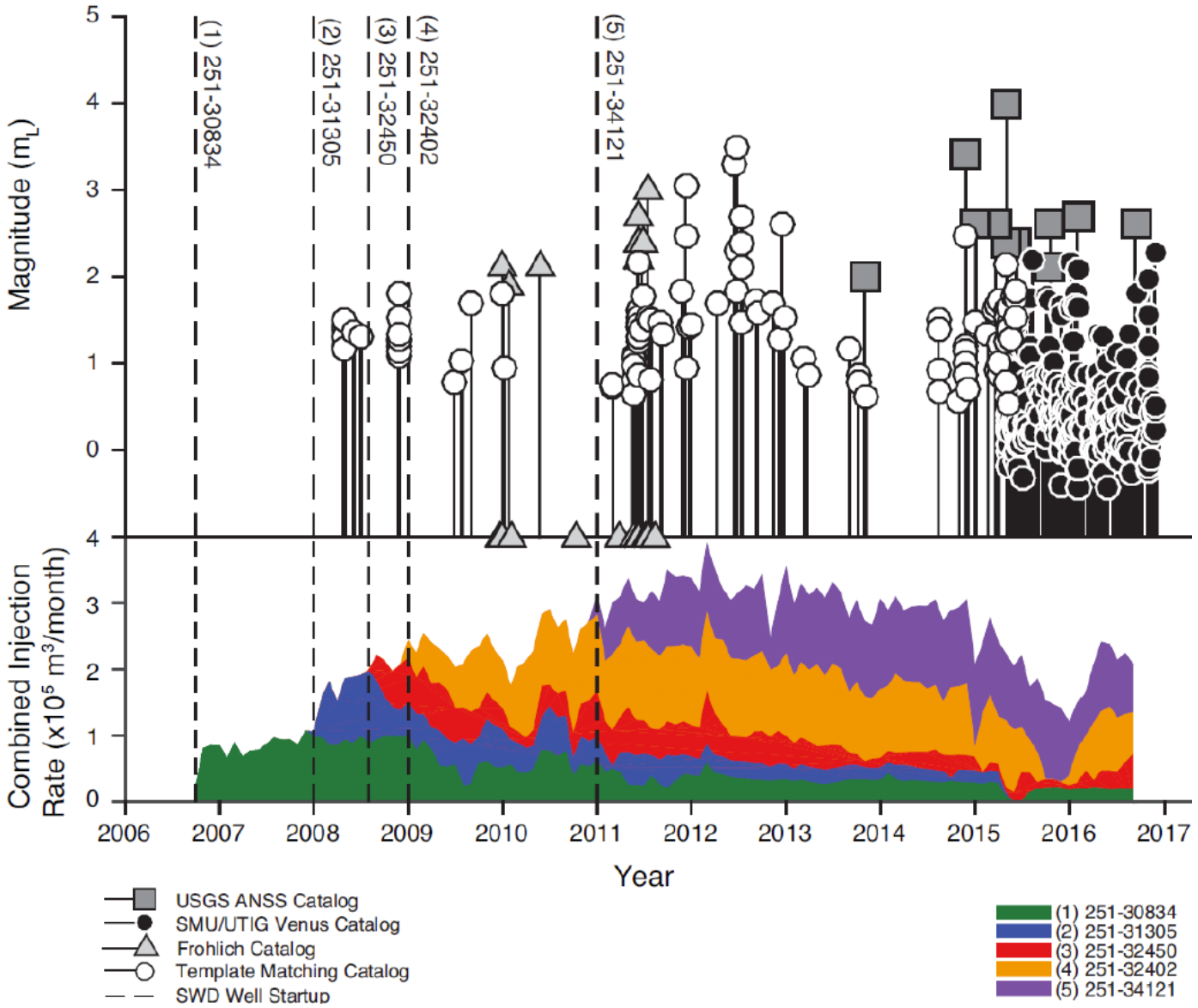

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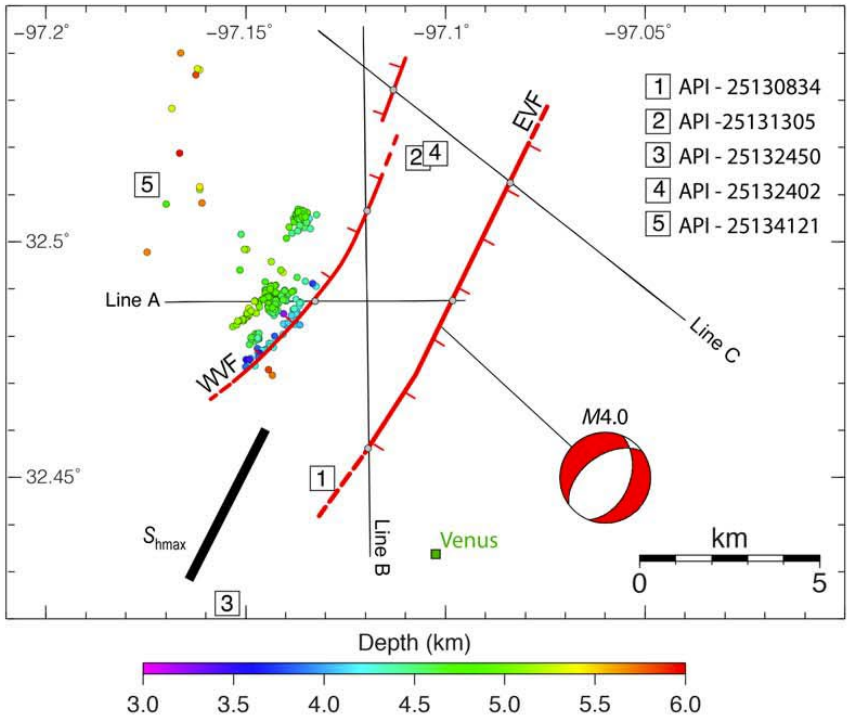

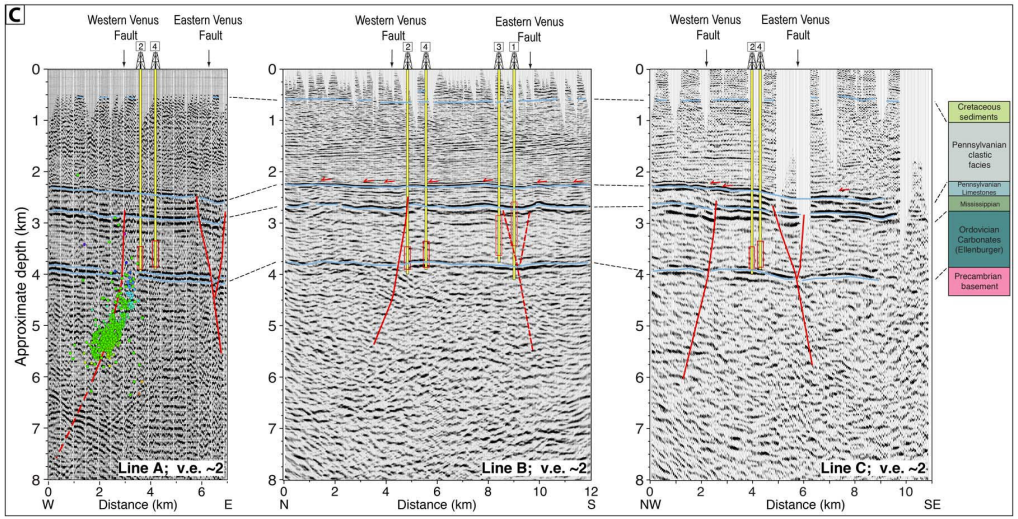

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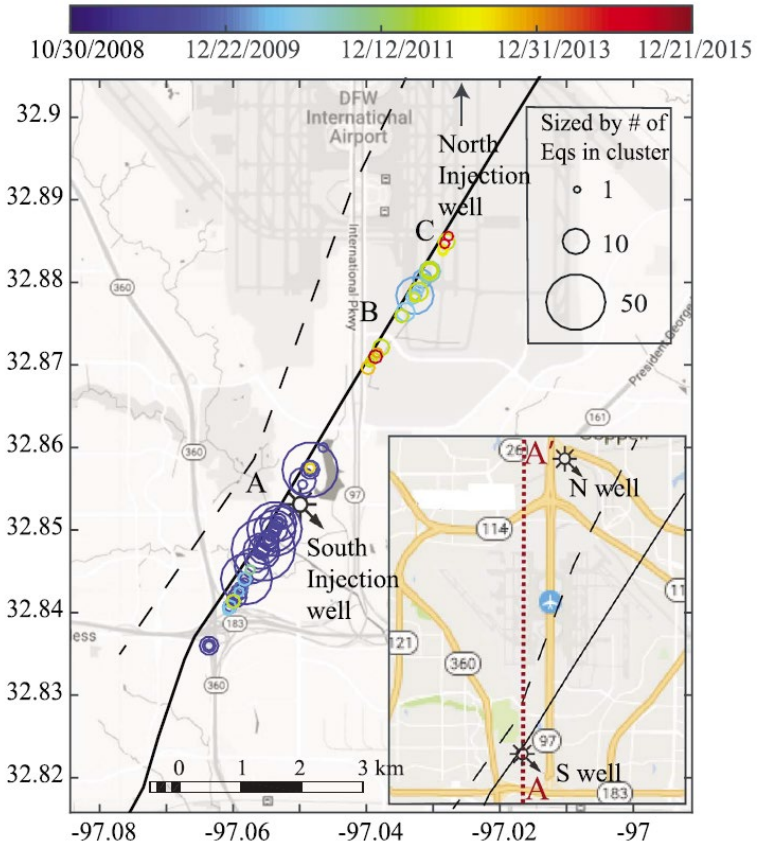

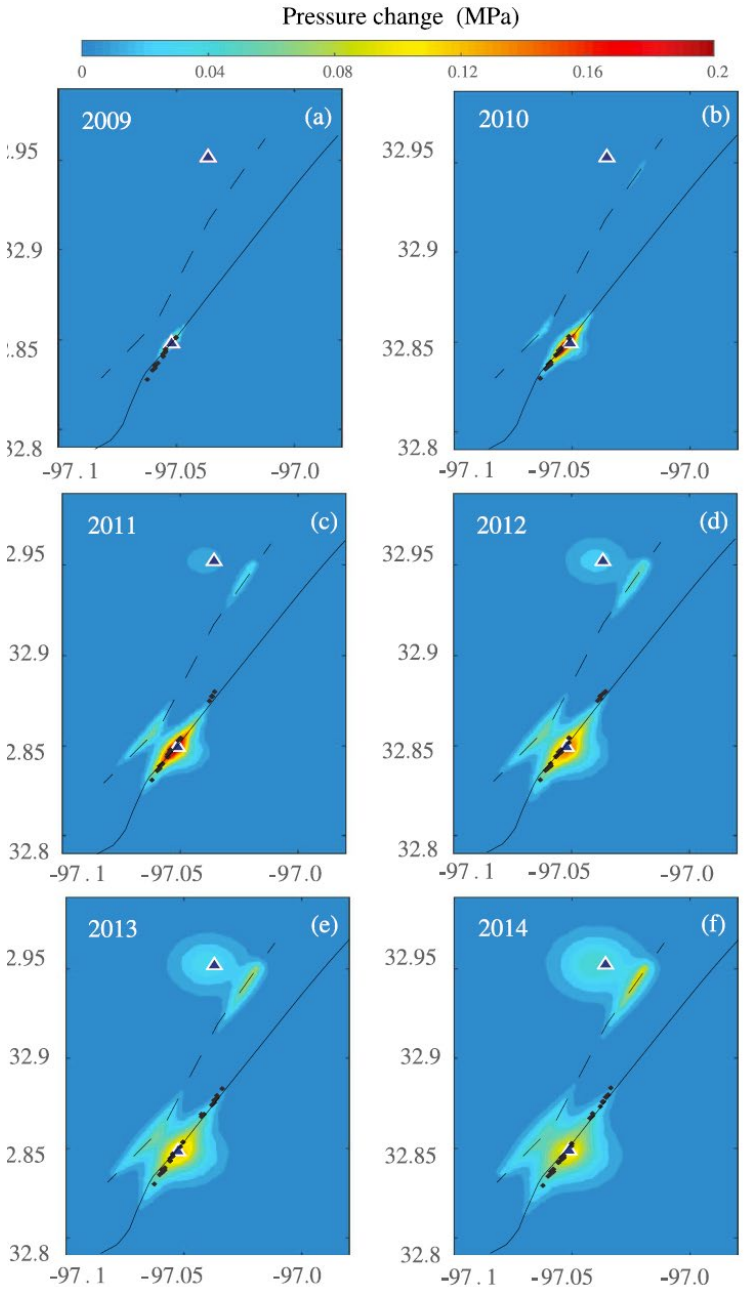

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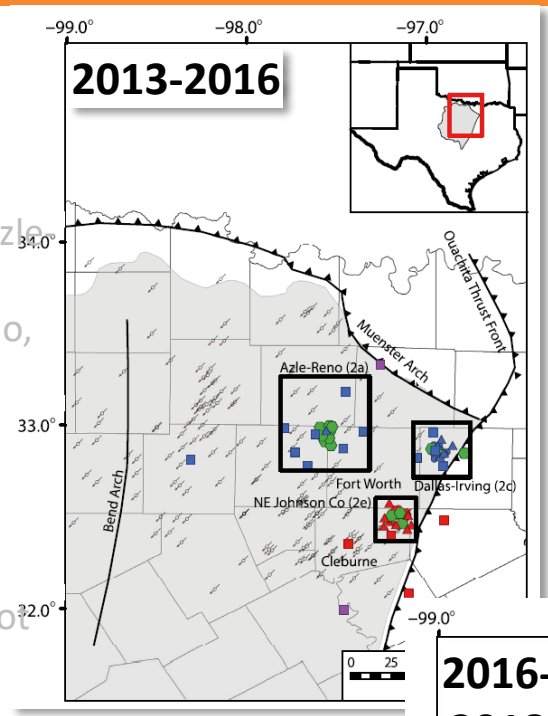

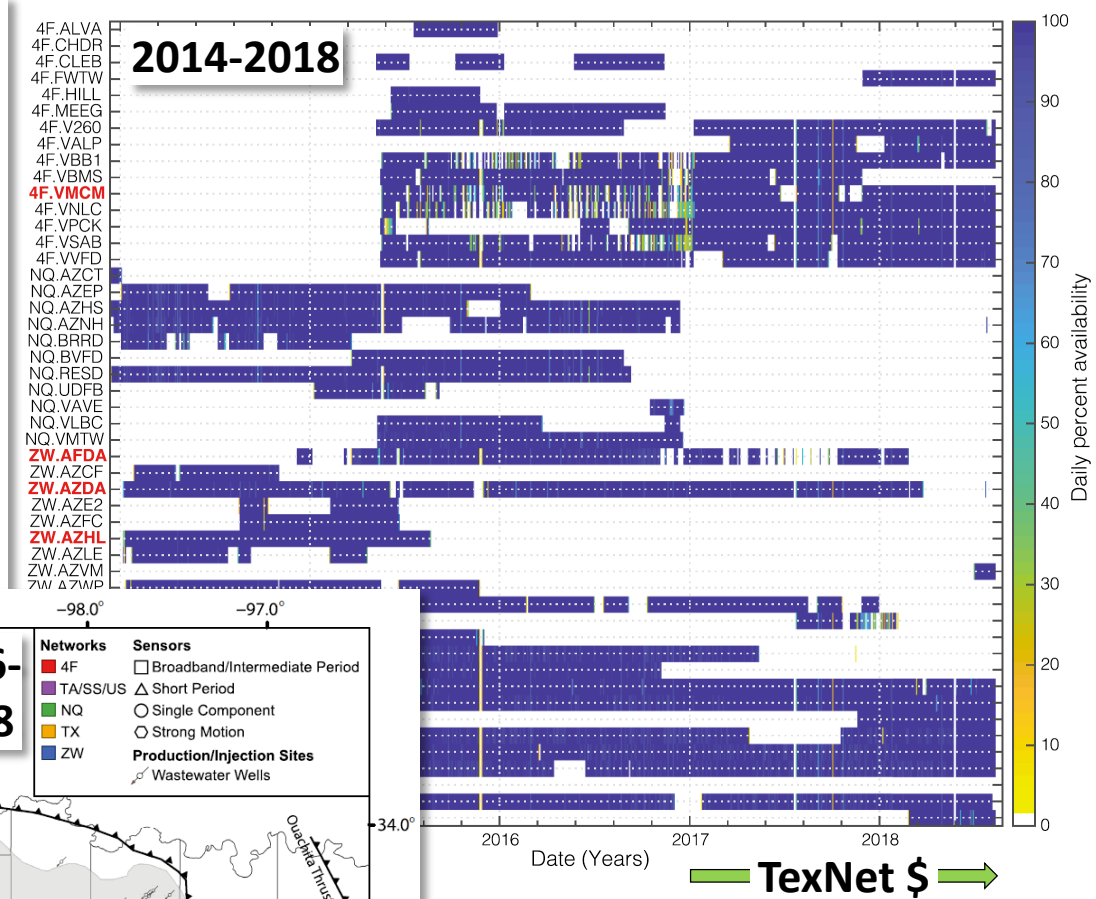

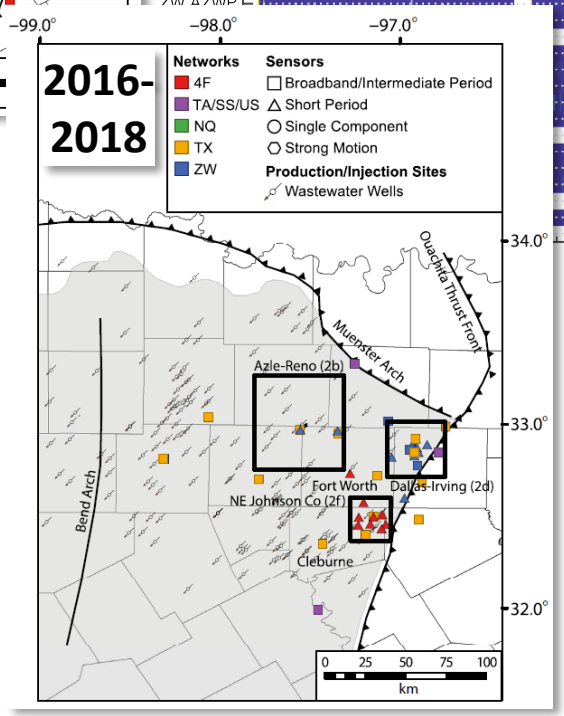

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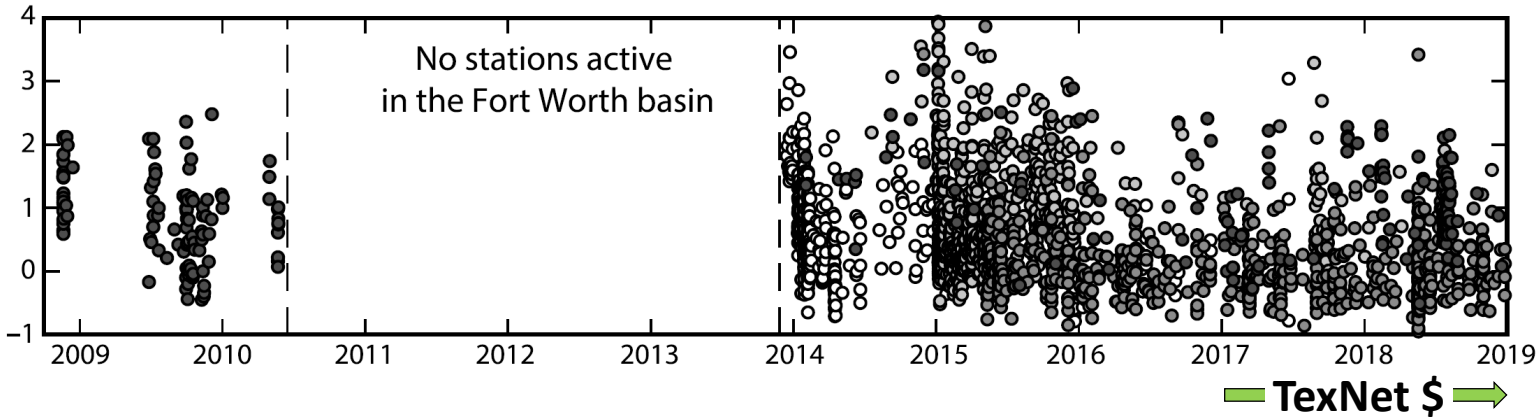

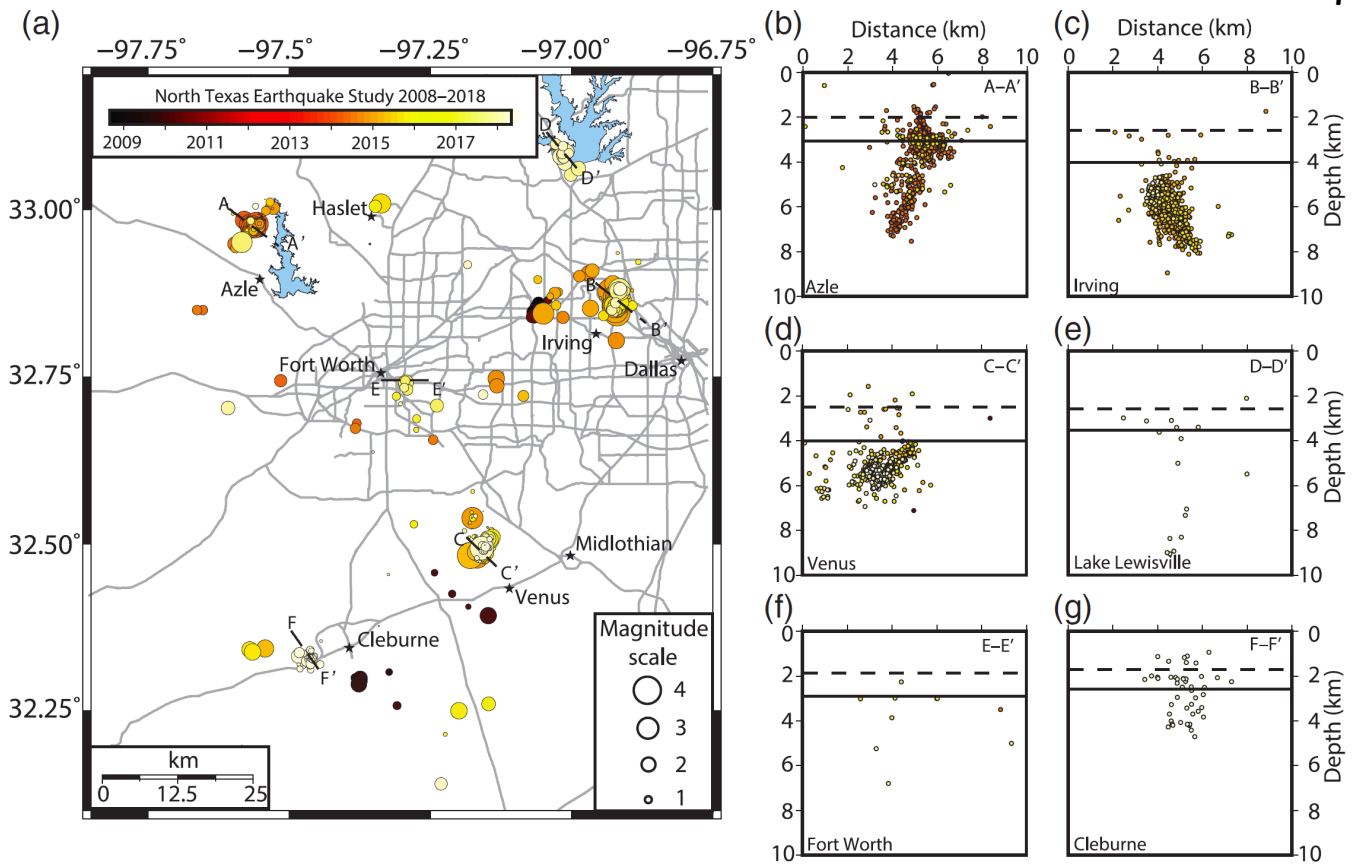

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- **Future research plans in the FWB**
- **Closing remarks**

Questions We've Pursued

- **What is the deterministic nature of the seismicity hazard, the geology of it?**
  - mapped faults and stress and analyzed the earthquake sequences
- **How has the hazard changed?**
  - performed fault slip potential analysis
- **What specific operational influences caused the hazard to change?**
  - detailed characterization of SWD data
  - developed a world-class basin-scale reservoir model
  - performed hydrogeologic modeling
- **What now and what's next?**
  - Time-sequence fault slip potential using hydrogeologic model
  - Develop a realistic and calibrated physics-based earthquake rate forecast
  - Additional site-specific, fully-coupled reservoir models (BEG, TAMU, SMU)

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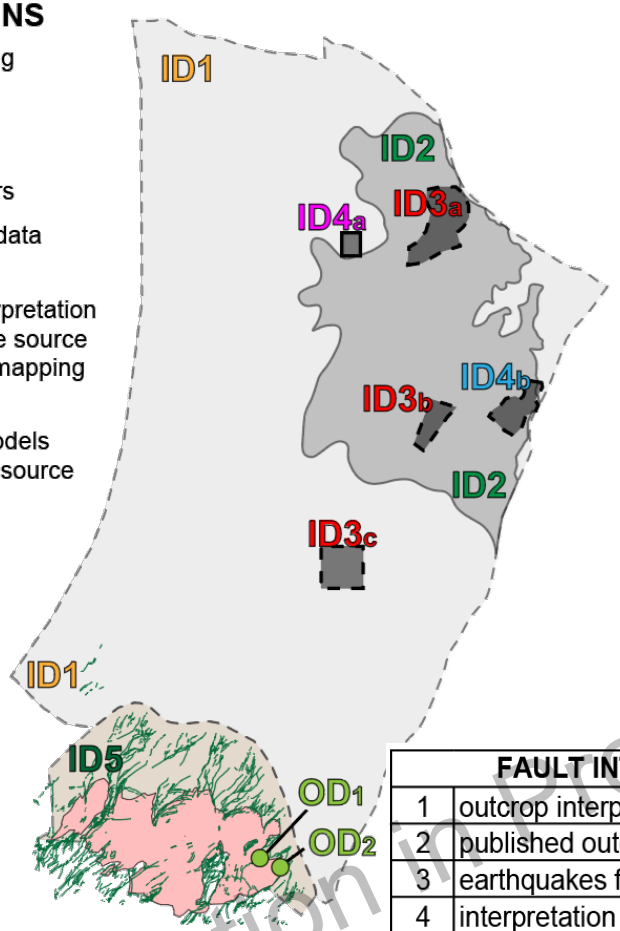
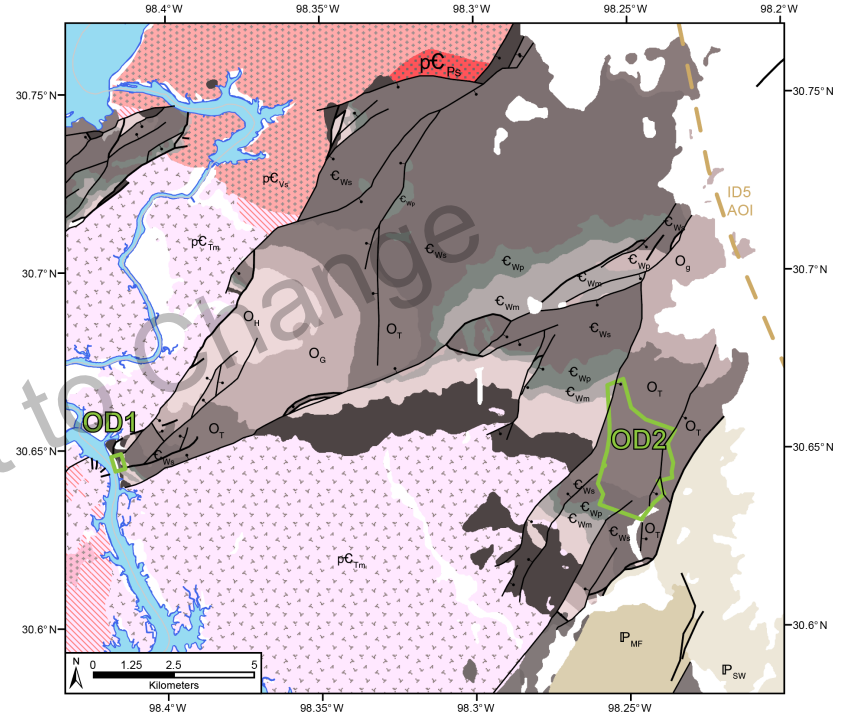
Fort Worth Basin Fault Interpretation

INTERPRETATION DOMAINS

- ID1 — published info, 2D mapping (subsurface)
- ID2 — analysis of horizontal well landing intervals, earthquake hypocenters
- ID3 — 3D seismic interpretation data - x indicates source
- ID4 — first-hand 3D seismic interpretation - x & colors indicate source
- ID5 — published info, 2D mapping (outcrop)
- OD — outcrop fault models - x indicates source



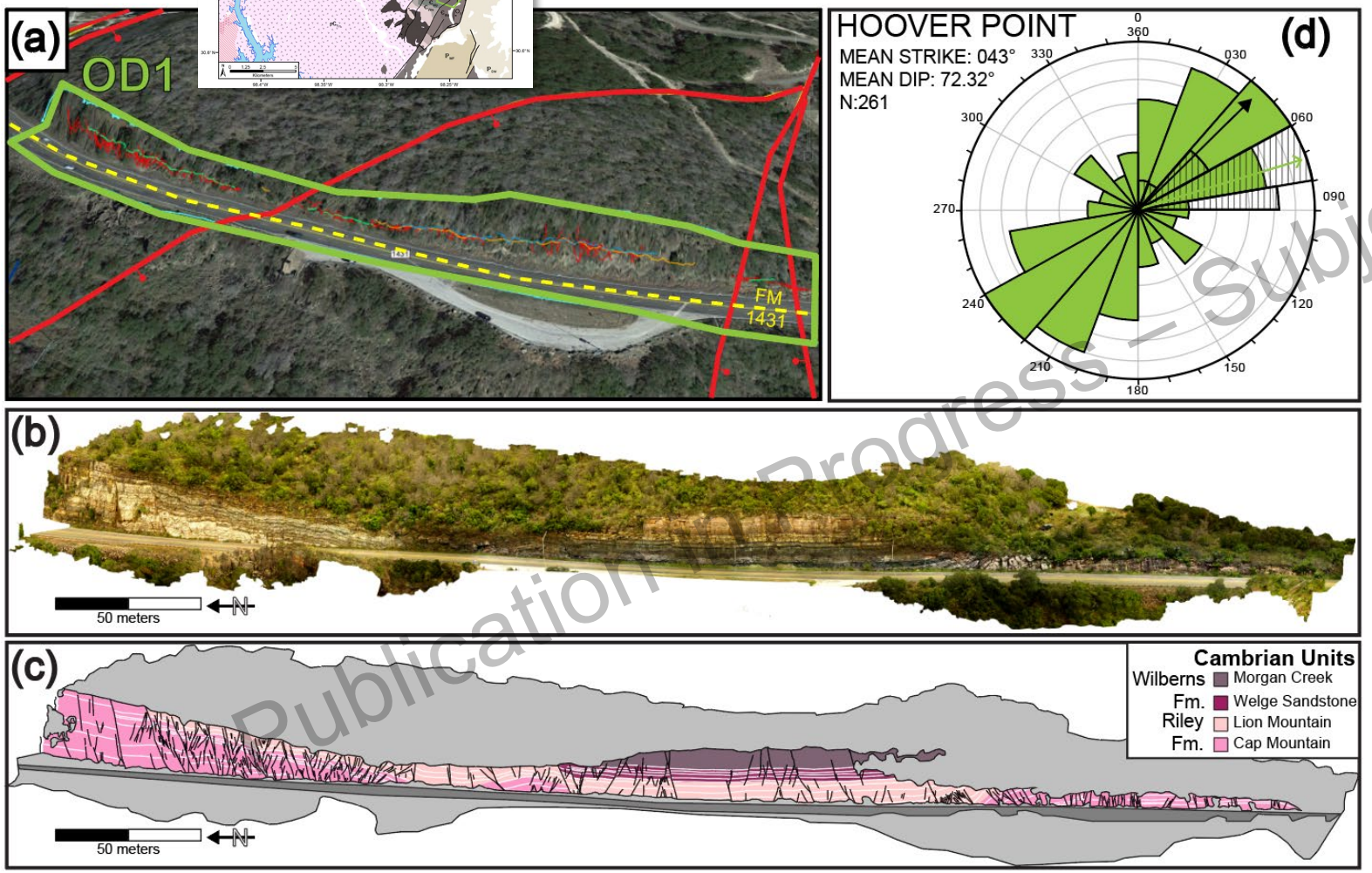


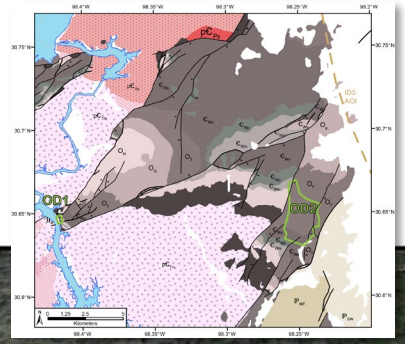
	FAULT INTERPRETATION DATA AND METHODOLOGY	ID's	CONFIDENCE	FAULT FAMILY COLORS & NAMES
1	outcrop interpretation by the authors	OD	SUBSURFACE FAULTS WITH HIGH CONFIDENCE N:271	3D FROM OUTCROP (LLANO UPLIFT)
2	published outcrop interpretation	ID5		2D FROM PUB (LLANO UPLIFT)
3	earthquakes from dense monitoring arrays & detailed velocity models	ID2		3D FROM PUB, LZ AND EQ
4	interpretation of 3D seismic data completed by the authors	ID4		3D FROM SEISMIC (BOONSVILLE)
5	data from 3D seismic interpretation verified by the authors	ID3		3D FROM SEISMIC (VENUS)
6	published 3D seismic data interpretation using trusted methods	ID3		3D FROM SEISMIC (OTHER)
7	first-hand 3D mapping of 21,000+ horizontal wells	ID2		3D FROM PUB, LZ AND EQ
8	published 2D seismic data interpretation verified by the authors	ID2	SUBSURFACE FAULTS WITH MODERATE CONFIDENCE N:72	3D FROM PUB, LZ AND EQ
9	published 2D seismic data interpretation using trusted methods	ID2		3D FROM PUB, LZ AND EQ
10	fault maps submitted to the TX-RRC developed using trusted methods	ID2		3D FROM PUB, LZ AND EQ
11	mapping of 1,286 vertical wells correlated by the authors	ID1		2D FROM PUB (FORT WORTH BASIN)
12	published mapping of vertical wells verified by the authors	ID1		2D FROM PUB (FORT WORTH BASIN)

Bureau of Economic Geology TexNet CISR

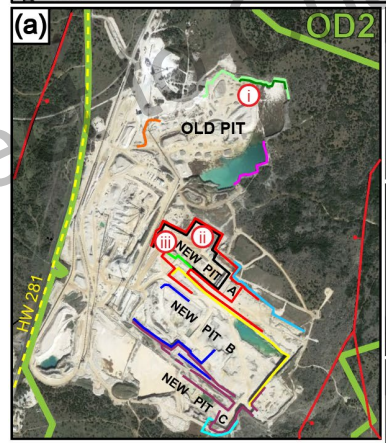
Hennings et al., 2019; Horne et al., in prep

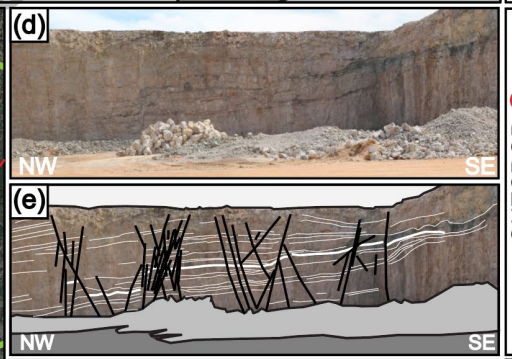
Fort Worth Basin Fault Interpretation – Outcrop Data





OUTCROP (i)





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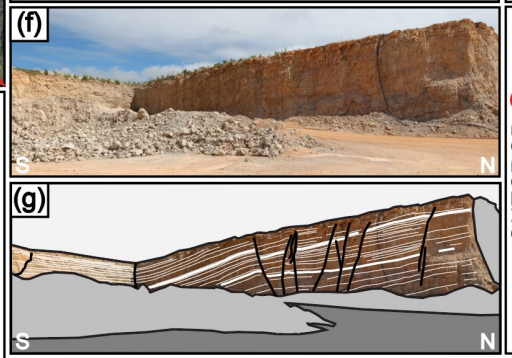

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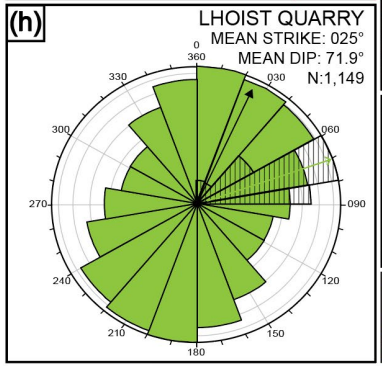
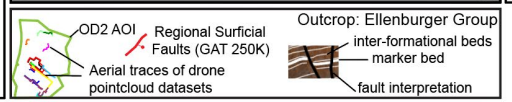
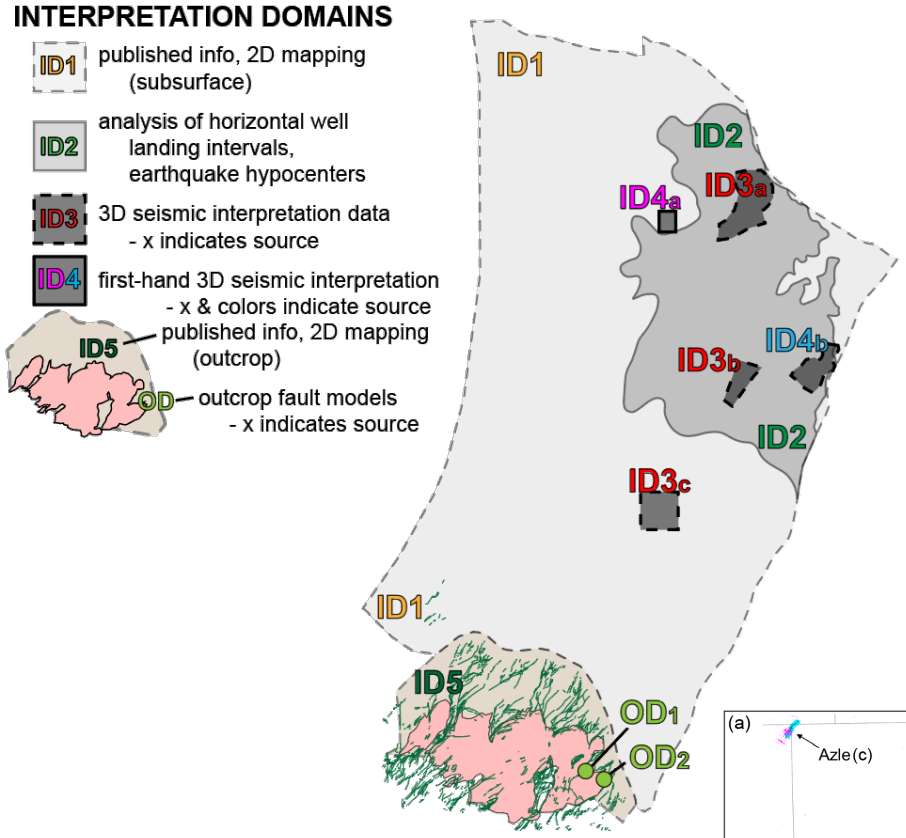
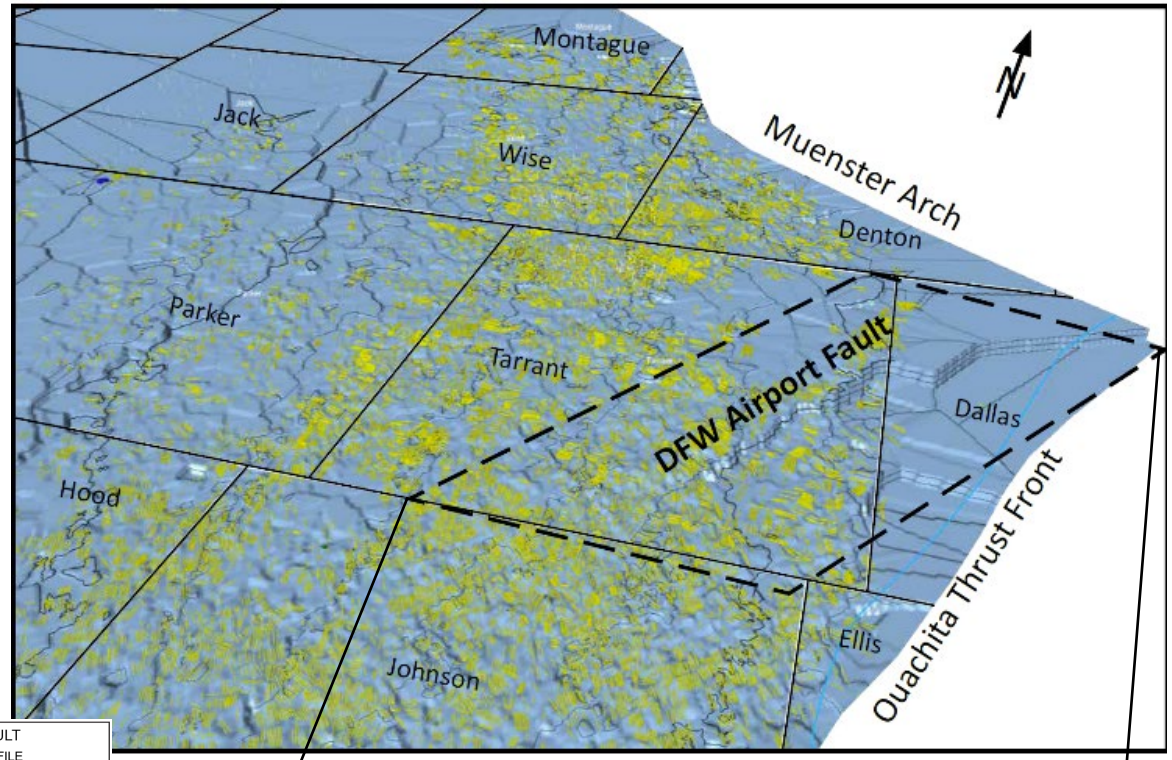


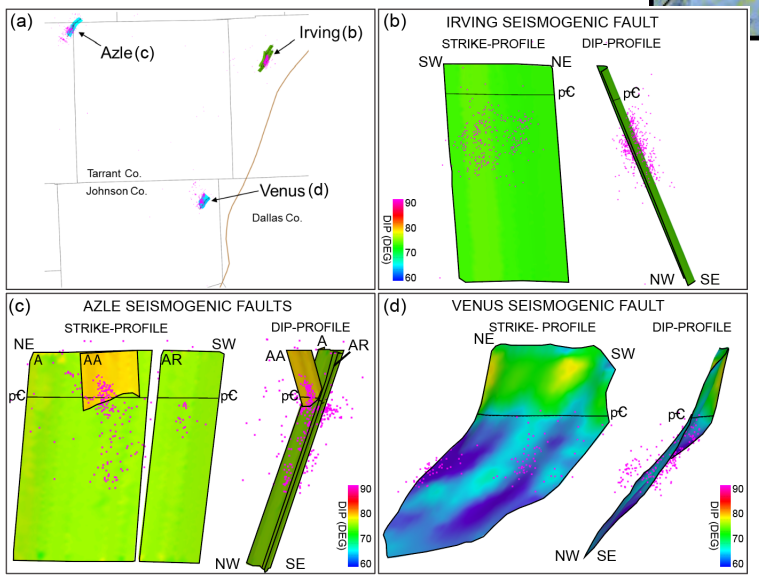


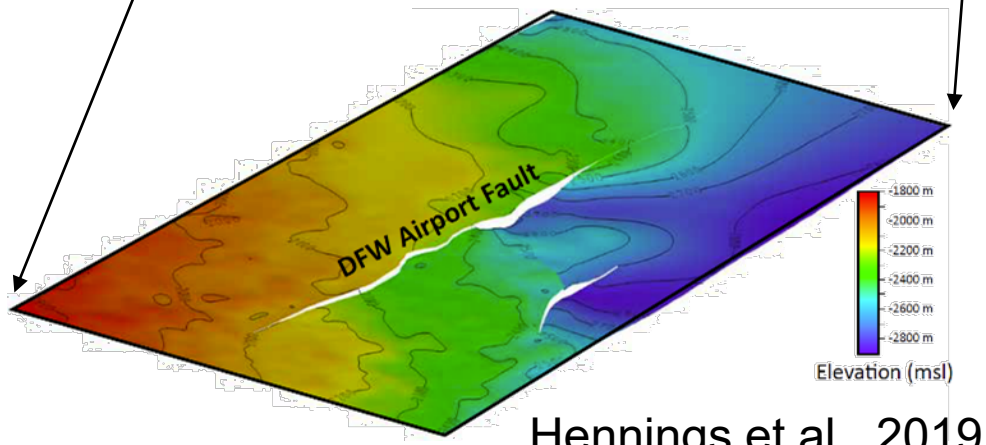
Horne et al., in prep

Fort Worth Basin Fault Interpretation – Well and EQ Mapping









Hennings et al., 2019
Horne et al., in prep

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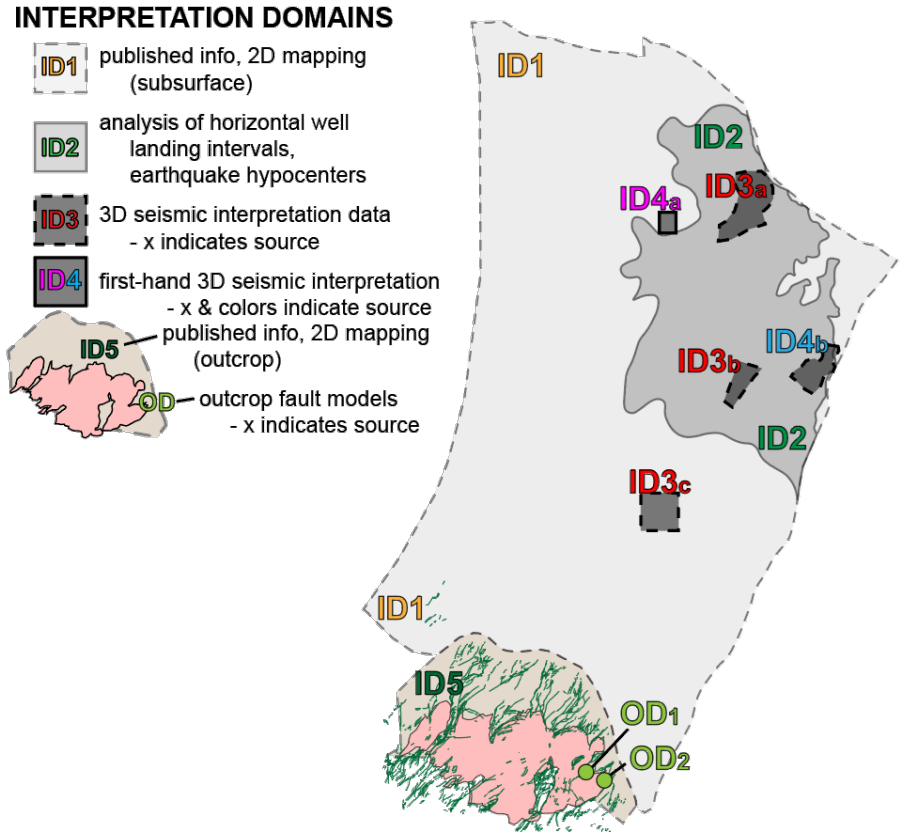
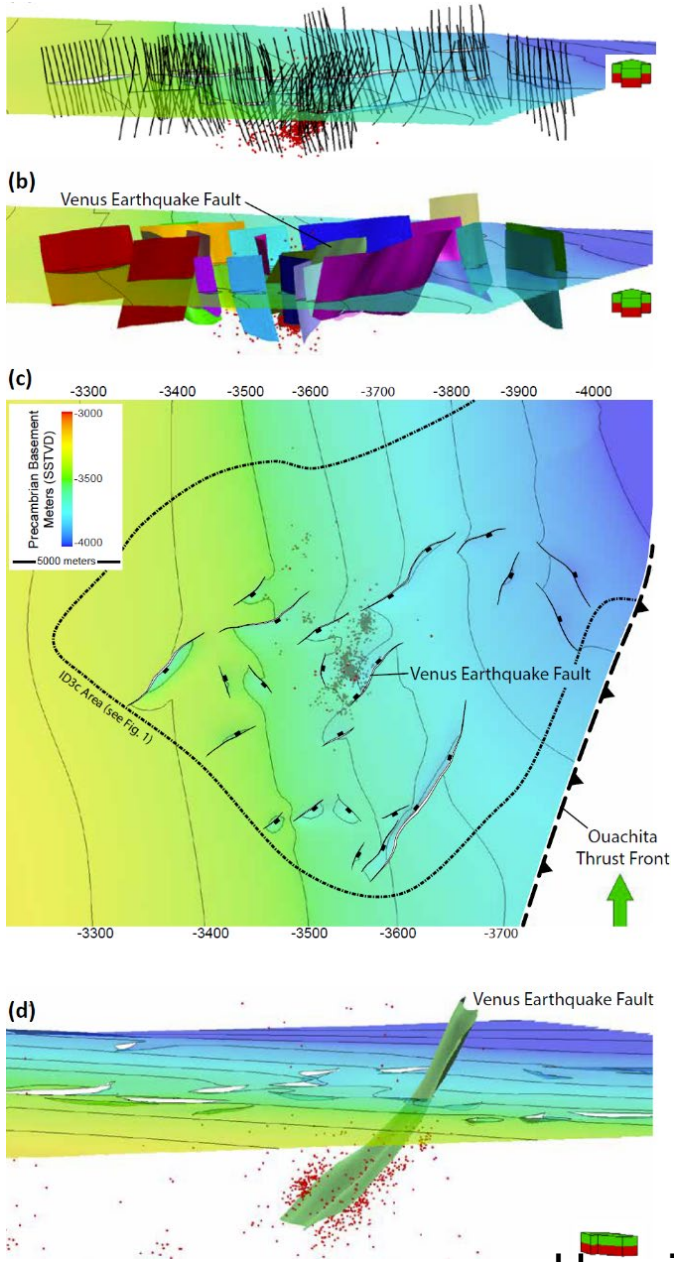
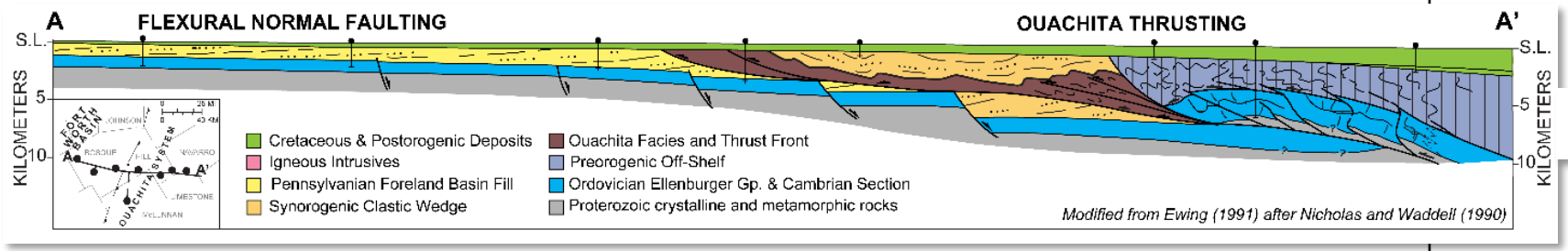
Fort Worth Basin Fault Interpretation – 3D Seismic Data and Interps

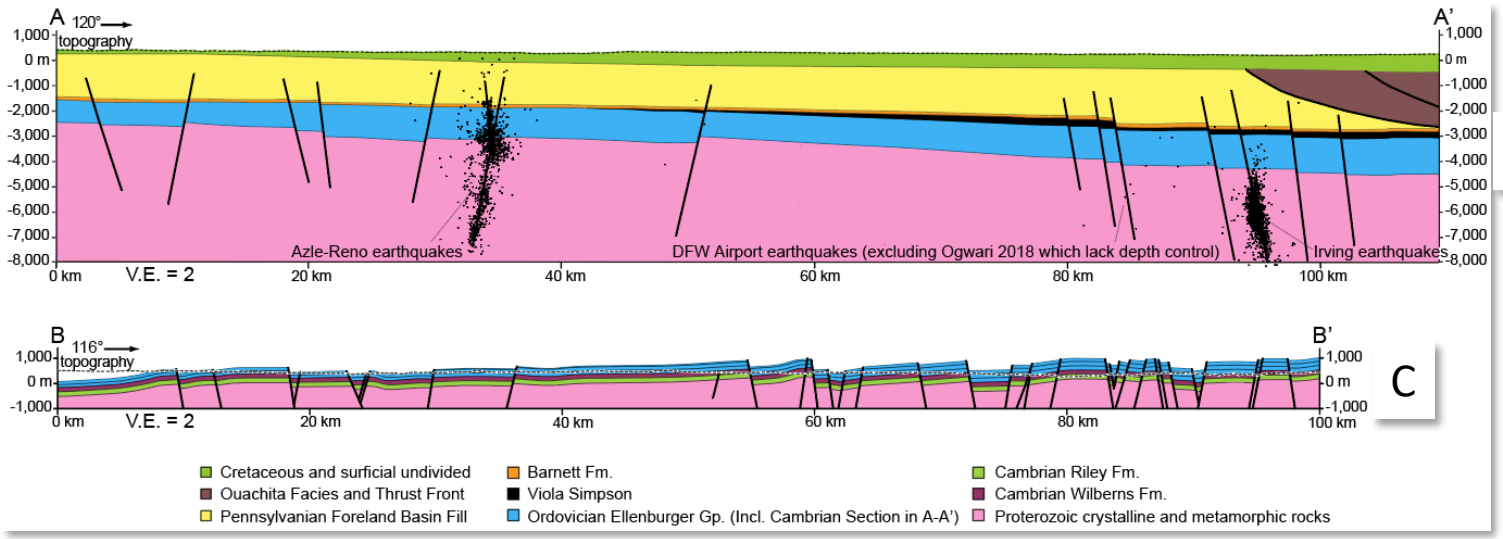


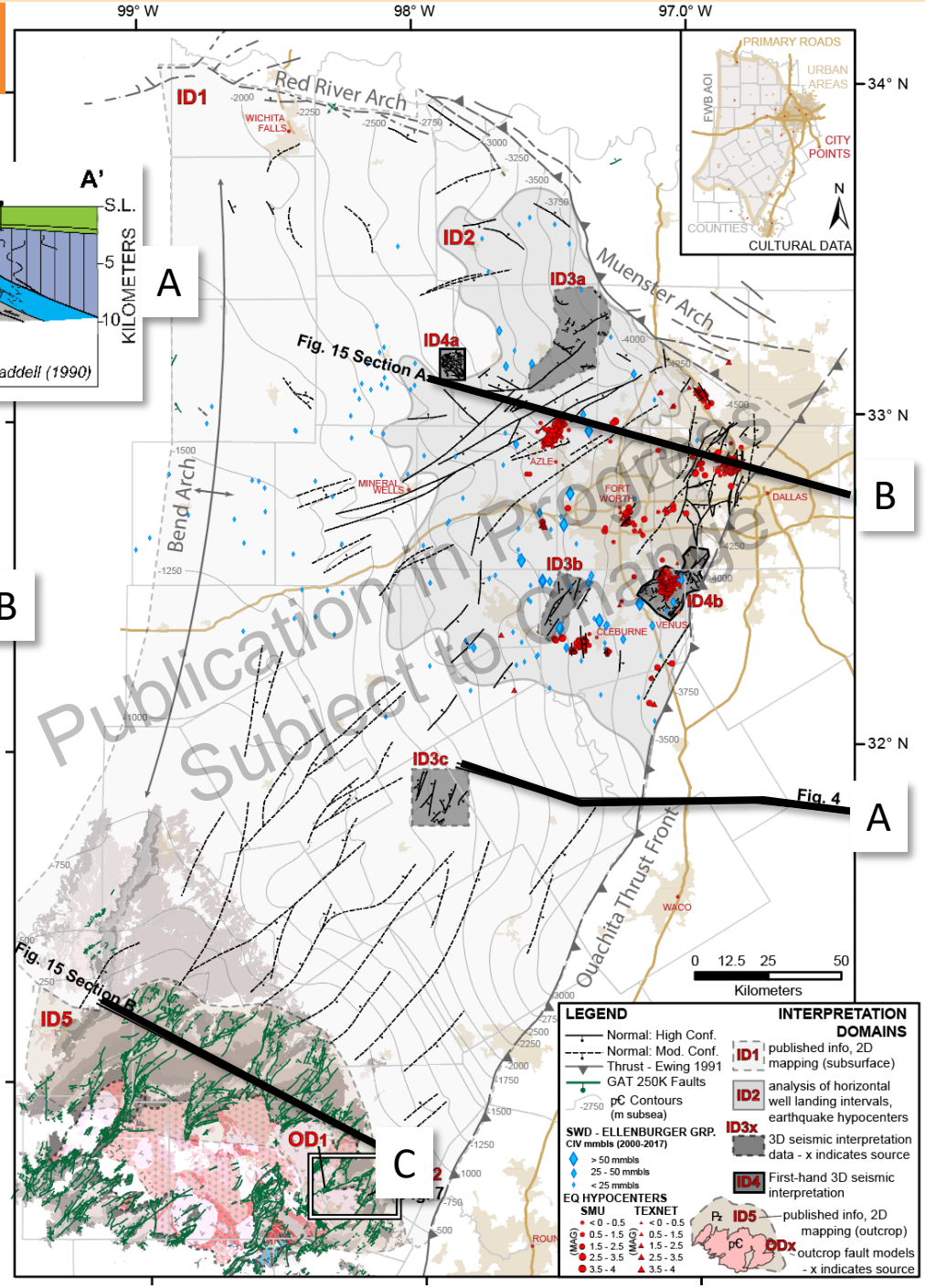


Hennings et al., 2019

New Fort Worth Basin Fault Map

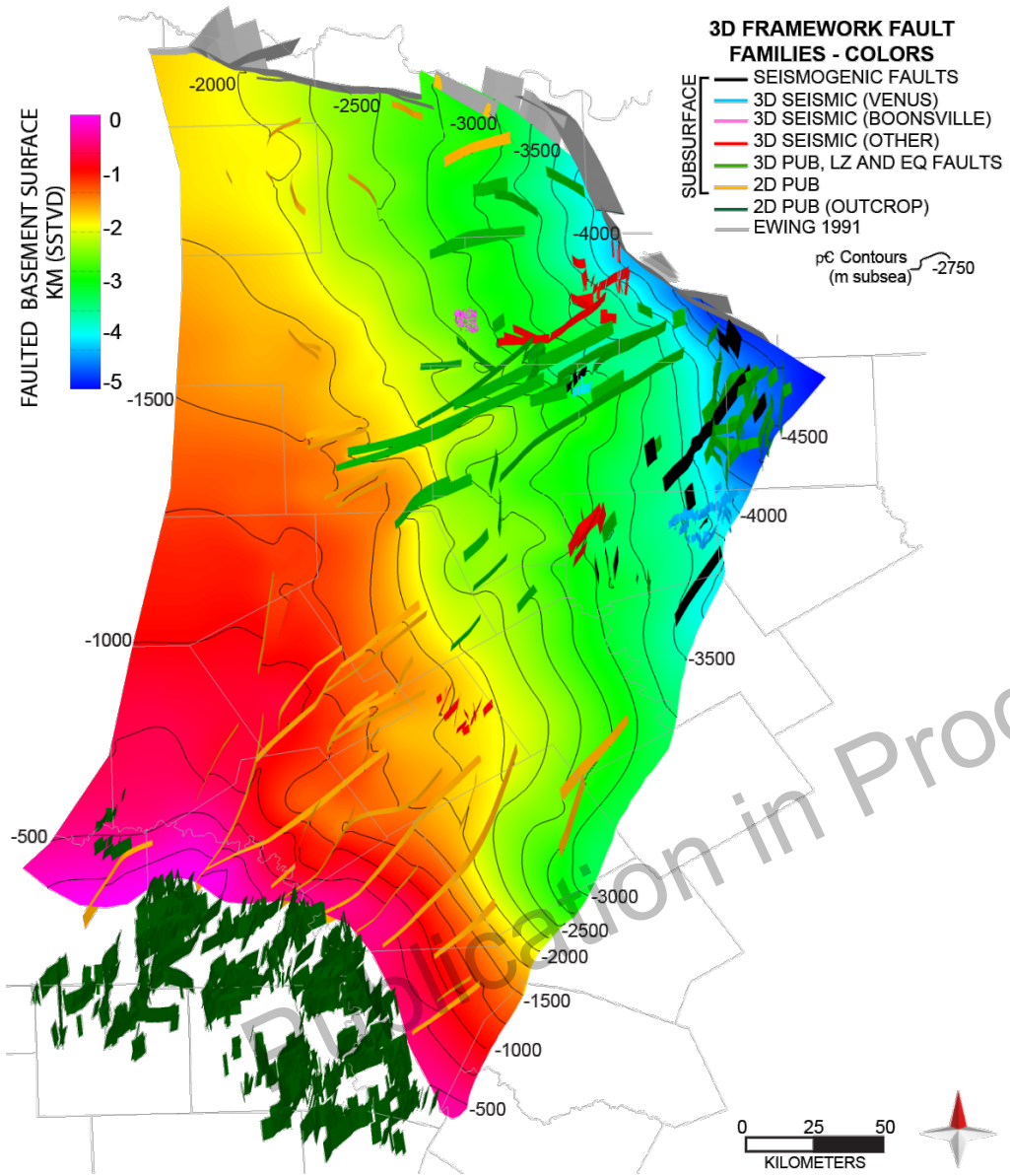


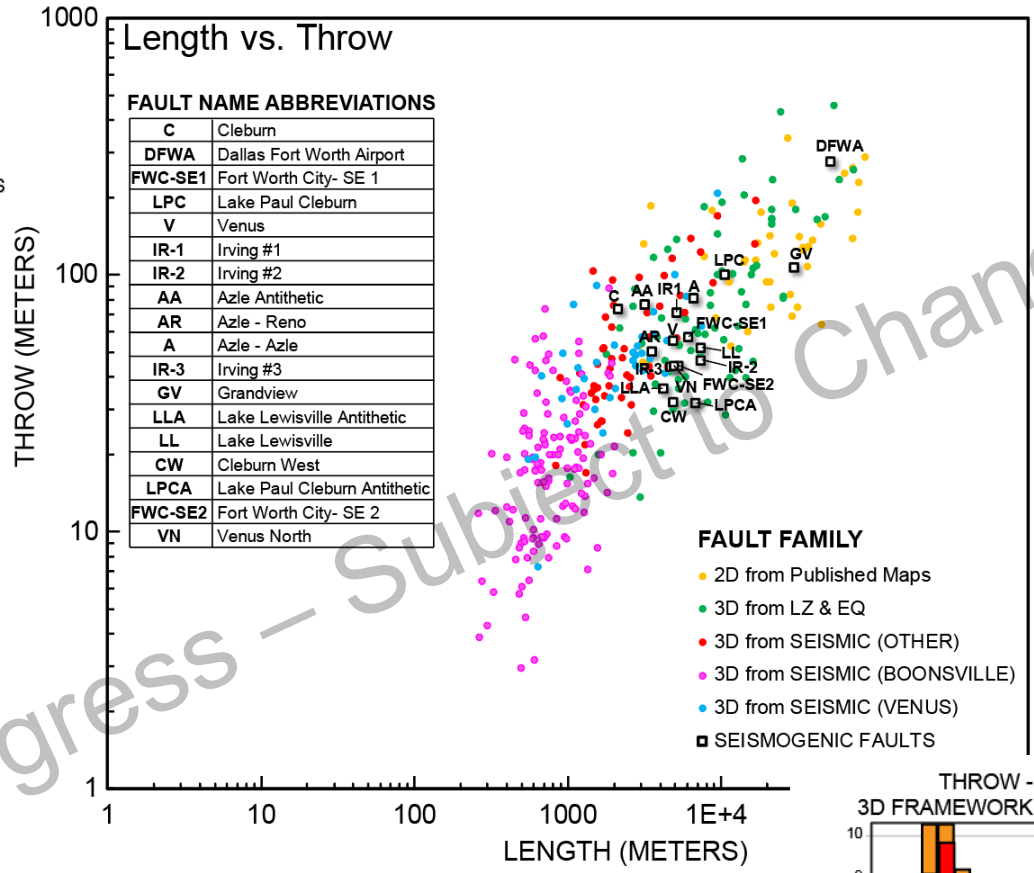


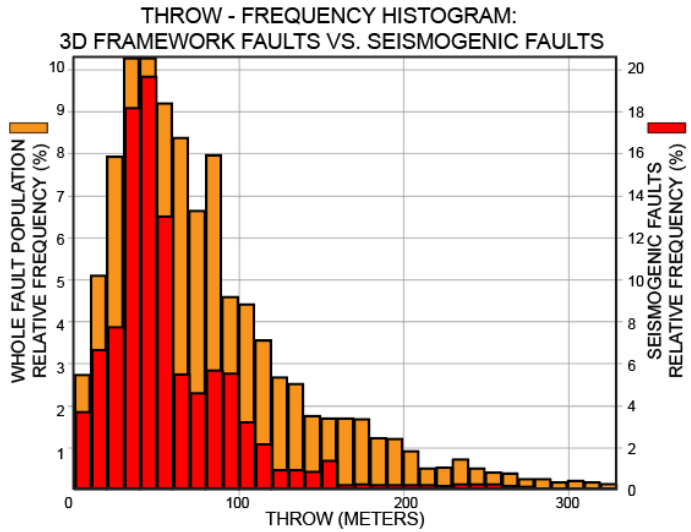


Hennings et al. (2019)
Horne et al. (in prep)

Fort Worth Basin Fault Characterization



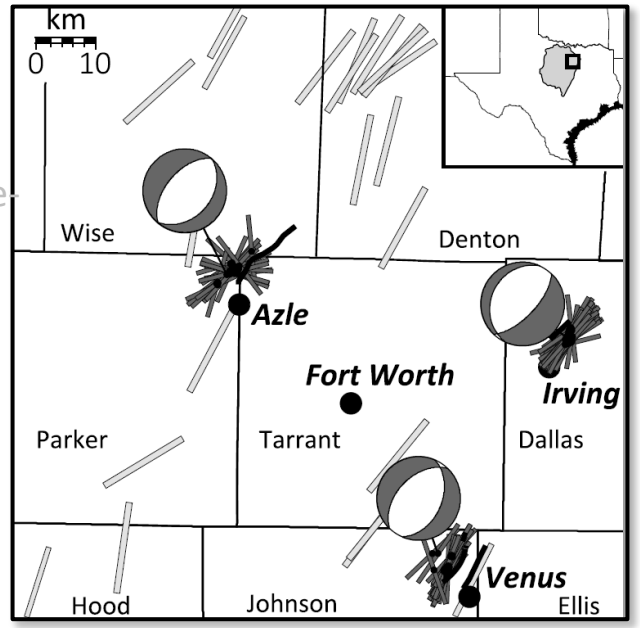


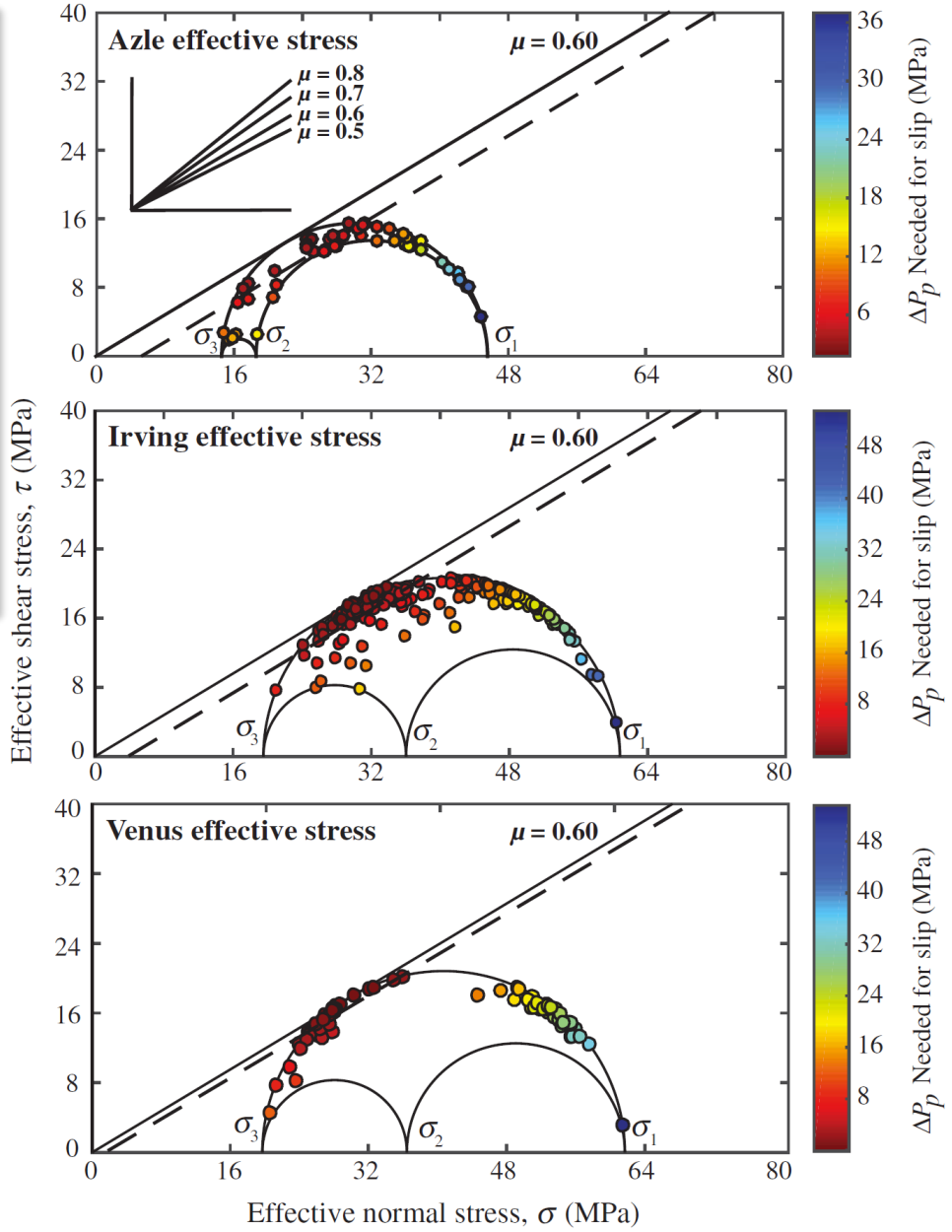


Horne et al. (in prep)

Synopsis of prior seismicity research in the Fort Worth Basin

- **Justinic et al. (2013)**: analyzed the Cleburne earthquakes and were inconclusive on cause
- **Gono et al. (2015)**: related SWD Pp increase to sequences and proposed faults as conduits
- **Hornback et al. (2016)**: assessed causation for the Azle-Reno sequence, concluded that it's SWD
- **Frohlich et al. (2016)**: found that Cleburne, Azle-Reno, DFW sequences were "almost certainly induced"
- **Hornback et al. (2017)**: related SWD volumes to sequences & proposed long range inducement
- **Scales et al. (2017)**: Venus sequence was caused by SWD and has lasted 10 yrs
- **Magnani et al. (2017)**: FWB earthquake faults had not moved in millions of years
- **Ogwari et al. (2018)**: DFW sequence was active for many years following SWD
- **Quinones et al. (2018)**: moment solutions to propose an in situ stress model variation
- **Chen et al. (2018)**: pressure imbalance from SWD and production important for Azle-Reno
- **Zhai & Shirzaei (2018)**: Poroelastic effect is ~10% of stress change regionally, stress-seismicity rate model
- **DeShon et al. (2018)**: summarized monitoring of FWB seismicity by NTXES
- **Quinones et al. (2019)**: summarized the history & characteristics of FWB seismicity





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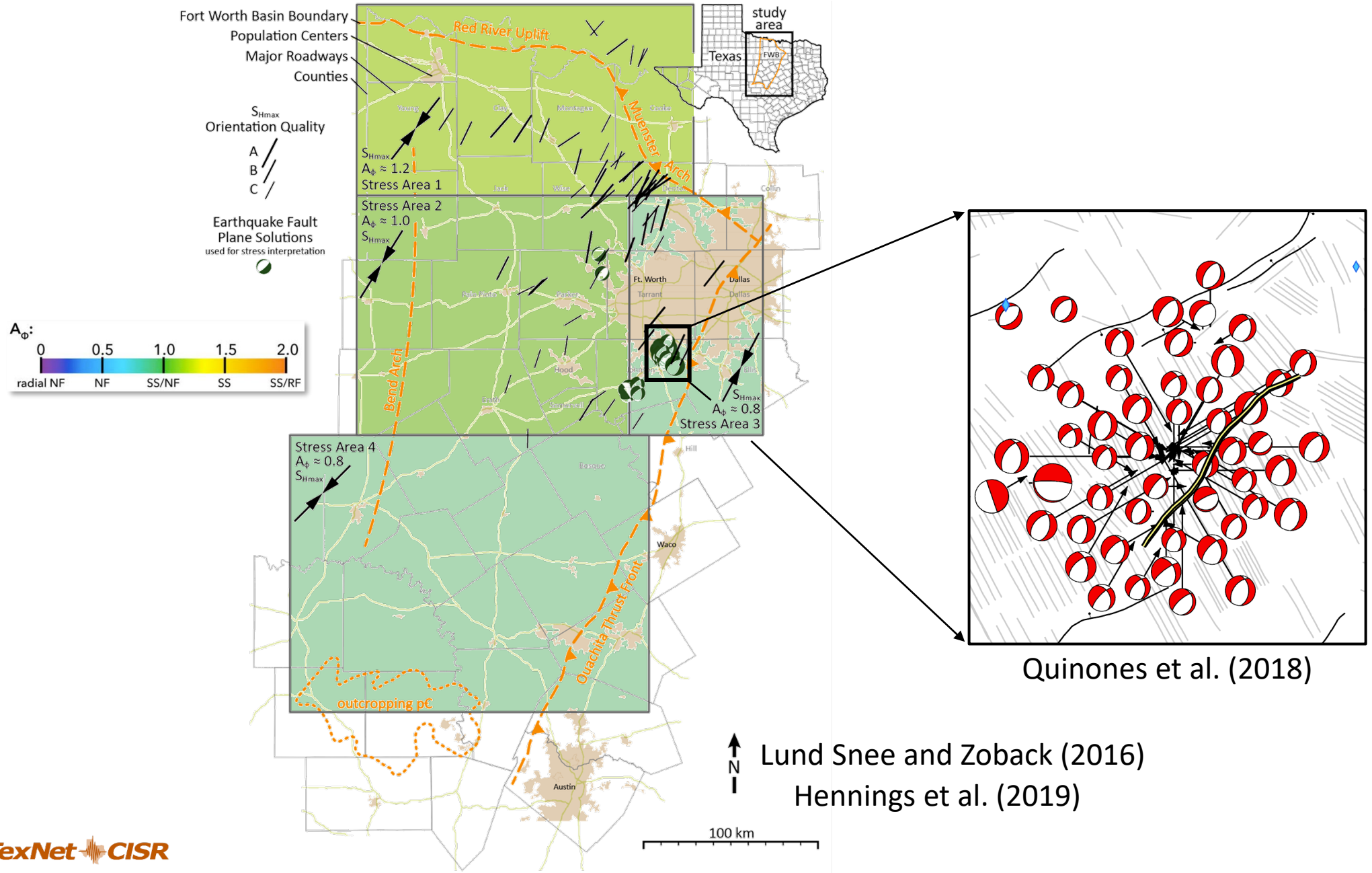
Revised Fort Worth Basin Stress State



Quinones et al. (2018)

Lund Snee and Zoback (2016)

Hennings et al. (2019)

Questions We've Pursued

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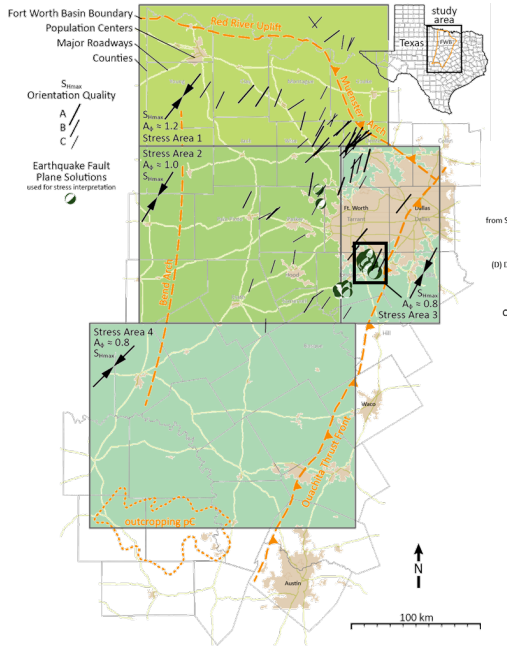
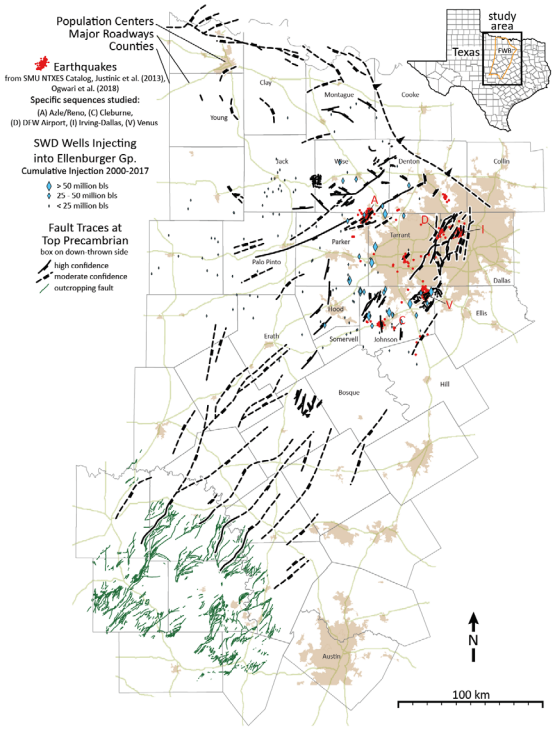
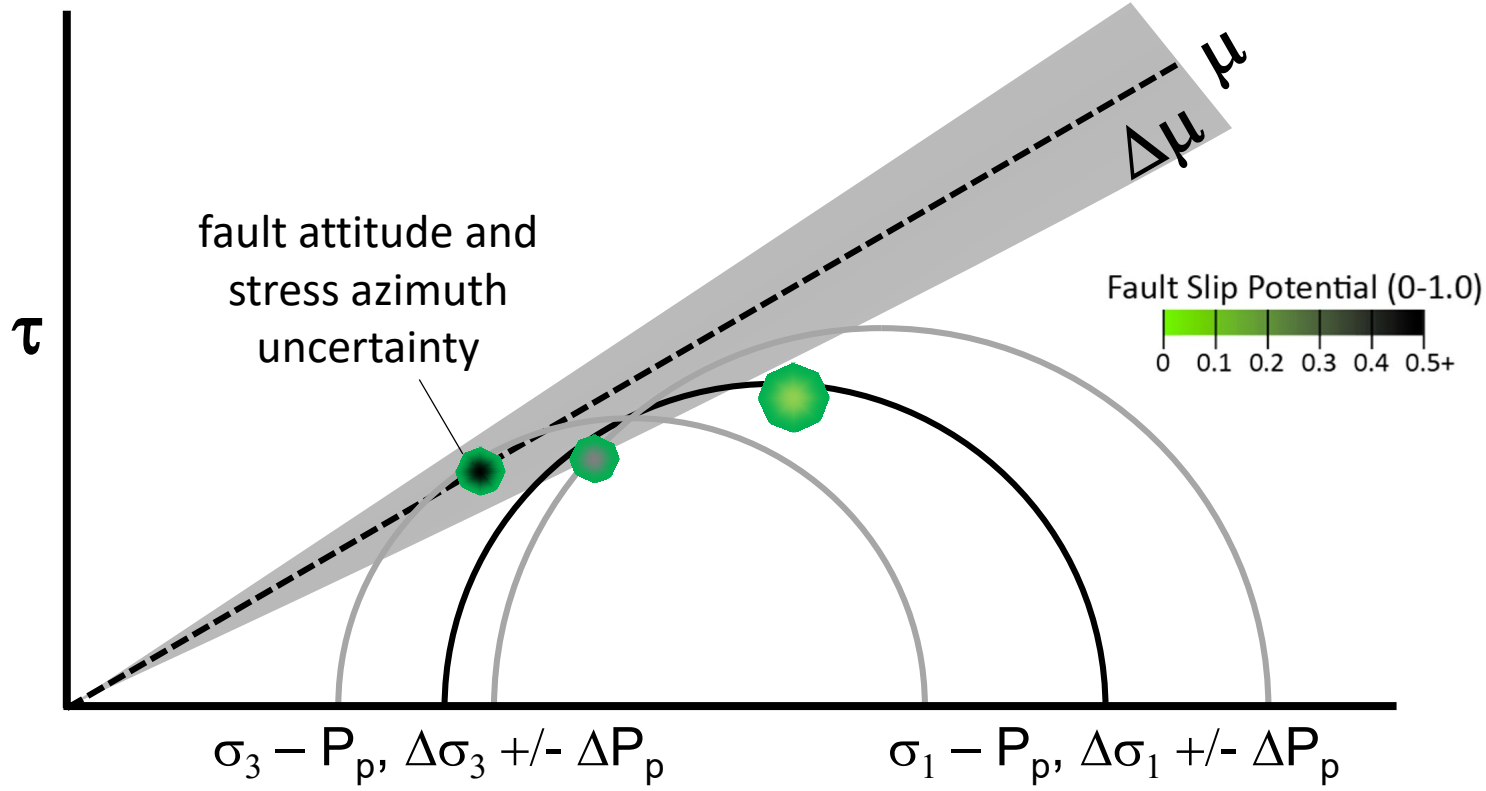
Fault Slip Potential Uncertainty Parameter Space



Stress Interpretation

Fault Interpretation





FSP Inputs																			Stress Gradients		
Stress Area	NW Lat (deg)	NW Lon (deg)	SE Lat (deg)	SE Lon (deg)	S_{Hmax} Az (deg)	S_{Hmax} Az unc (deg)	Aϕ	Aϕ unc	Cohe-sion	Fault μ	Fault μ unc	Reference Depth (m)	Initial P_p (psi/ft)	Initial P_p unc (psi/ft)	P_p inc (psi)	S_v (psi/ft)	S_v unc (psi/ft)	Fault strike unc (deg)	Fault dip unc (deg)	S_V (MPa/km)	S_{hmax} (MPa/km)	S_{hmin} (MPa/km)
1	34.20	-99.00	33.25	-97.00	38	20	1.18	0.30	0	0.7	0.05	3300	0.493	0.05	0, 145	1.15	0.05	5	10	26.01	28.46	14.86
2	33.25	-98.80	32.10	-97.40	32	16	1.00	0.22	0	0.7	0.05	2900	0.471	0.05	0, 145	1.15	0.05	5	10	26.01	26.01	14.20
3	33.25	-97.40	32.10	-96.40	25	15	0.80	0.21	0	0.7	0.05	3900	0.466	0.05	0, 145	1.15	0.05	5	10	26.01	23.65	14.20
4	32.10	-99.40	30.70	-97.20	45	20	0.82	0.15	0	0.7	0.05	2000	0.433	0.05	0, 145	1.15	0.05	5	10	26.01	23.89	14.20

Fort Worth Basin Fault Slip Potential

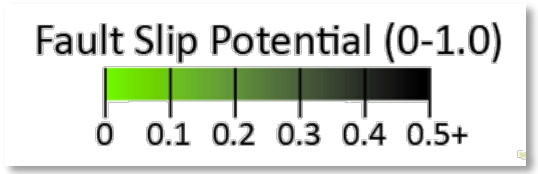
Fault Slip Potential (FSP):
The cumulative probability of a known fault exceeding Mohr-Coulomb slip criteria from fluid pressure increase.

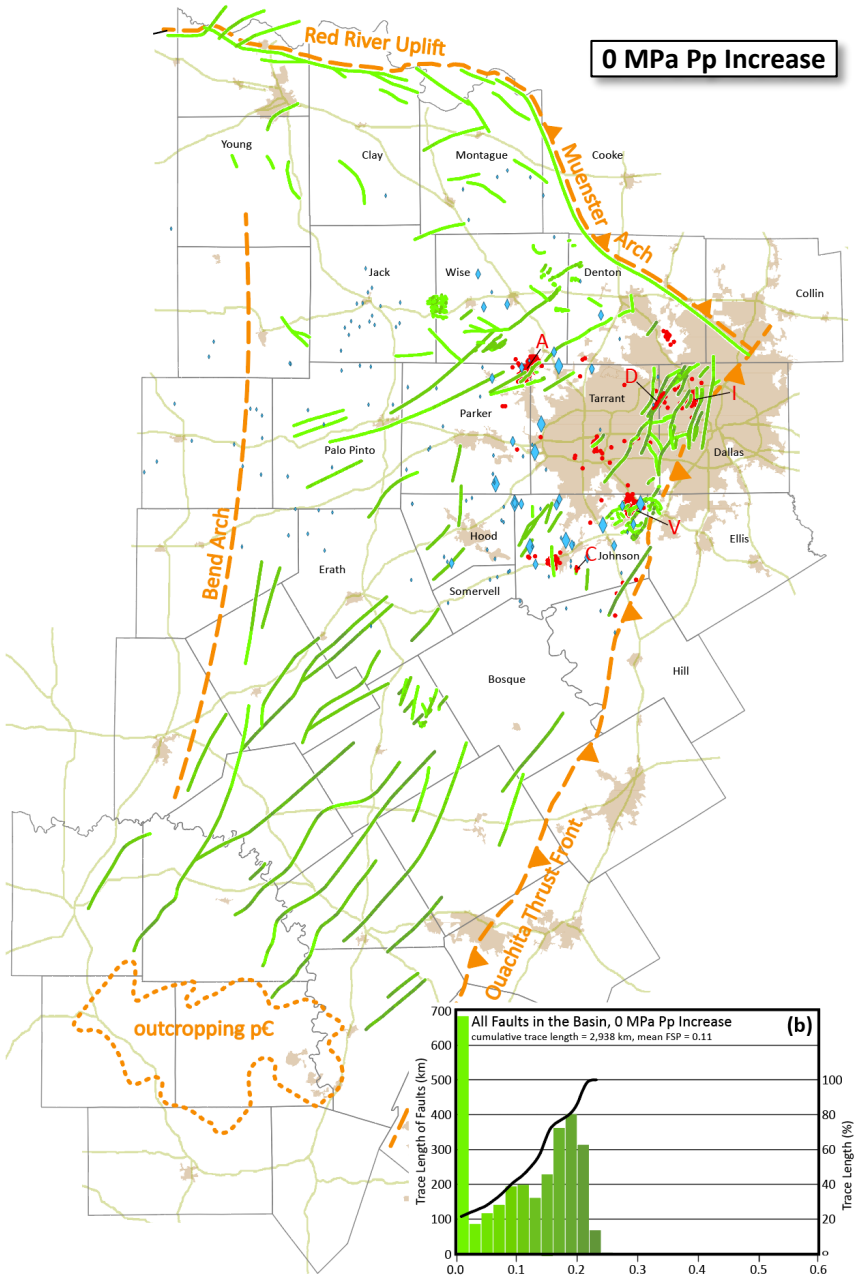
The FSP comes from a Monte-Carlo simulation of the deterministically-seeded PDF of key input parameters.

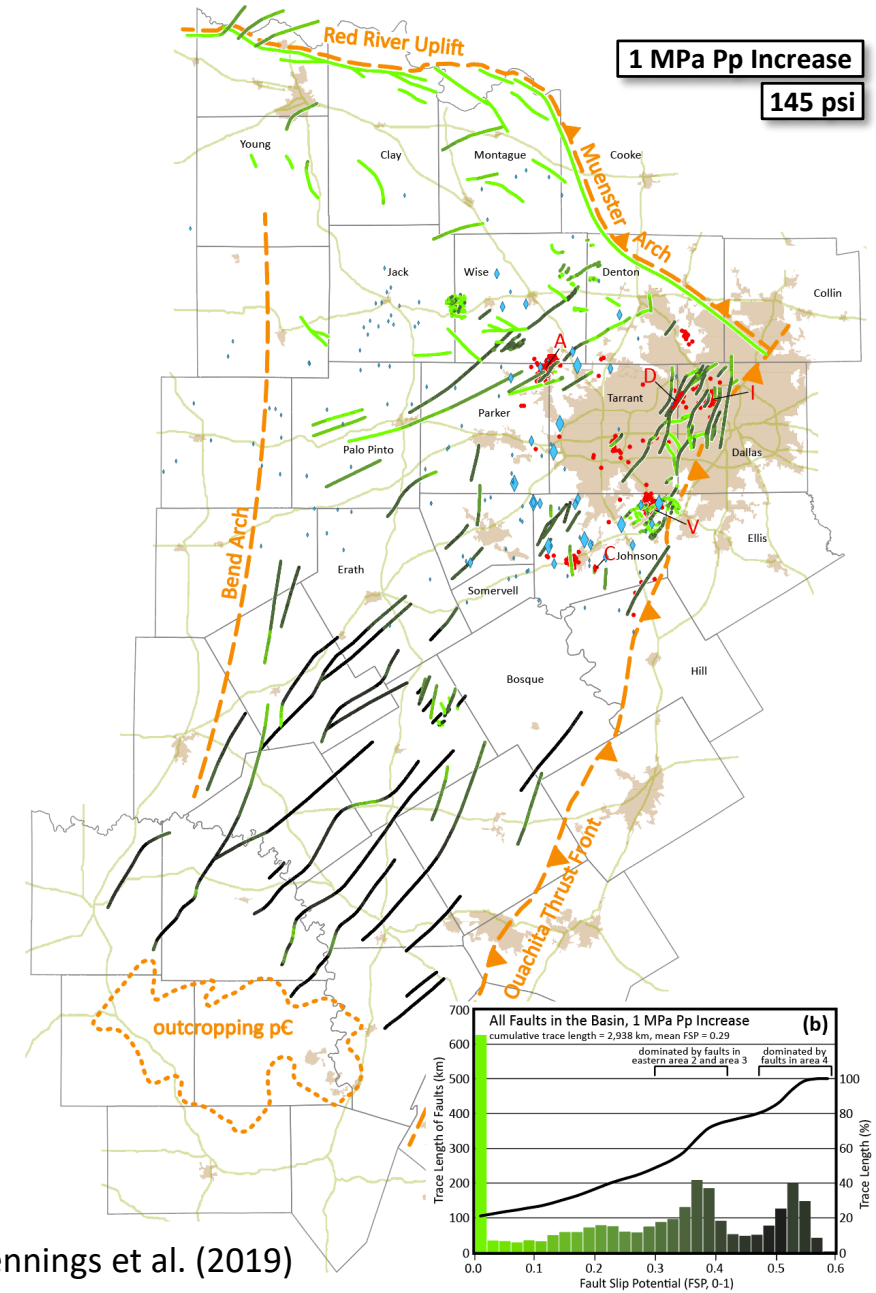
FSP doesn't predict earthquakes, and it doesn't address whether a fault might have already slipped in recent geologic history, releasing existing stress.

Nor does FSP does not assess risk, which is the product of hazard, exposure, and vulnerability at a particular location, and is used to describe the probabilities of adverse consequences.

see Walsh and Zoback (2016)



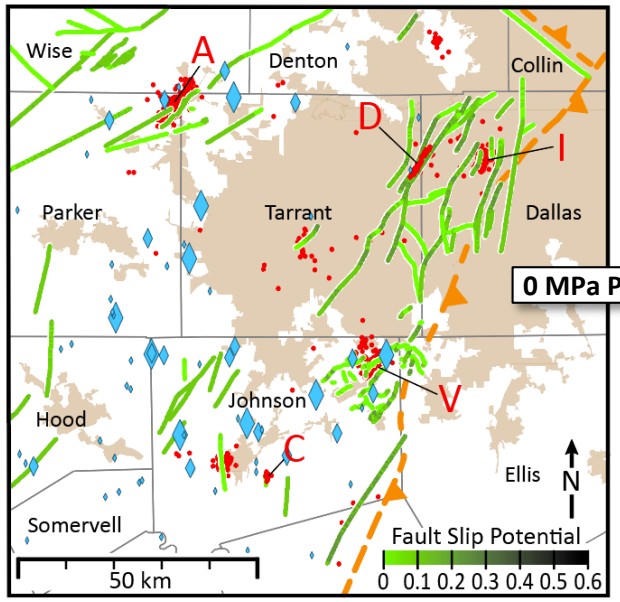




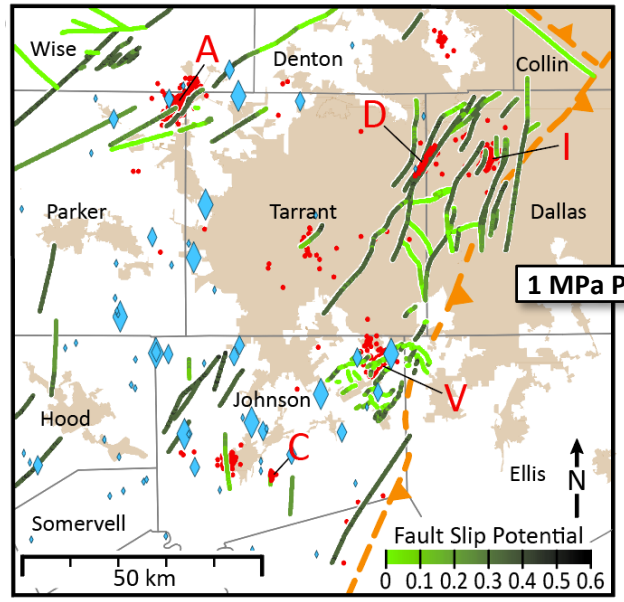
Hennings et al. (2019)

Bureau of Economic Geology TexNet CISR

Fort Worth Basin FSP Evolution Assuming ΔPp 0 & 145 psi (1 MPa)

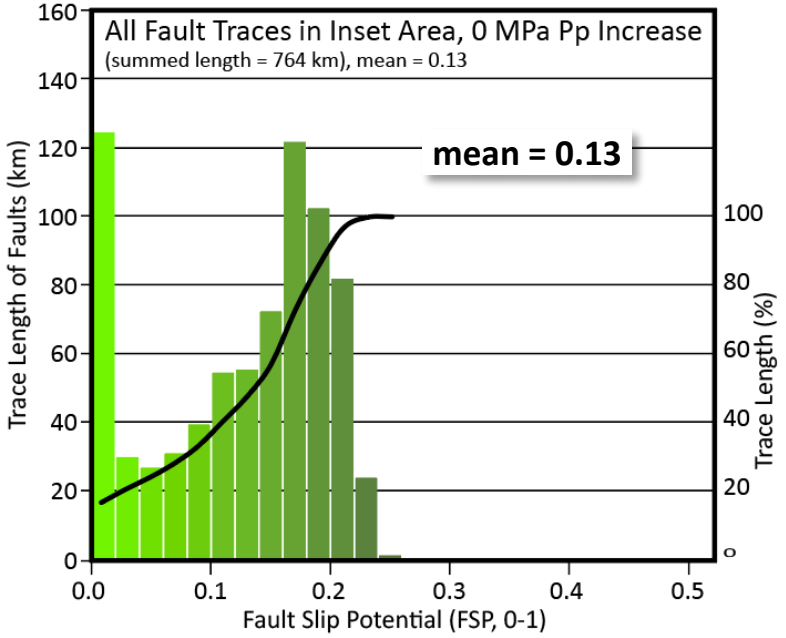


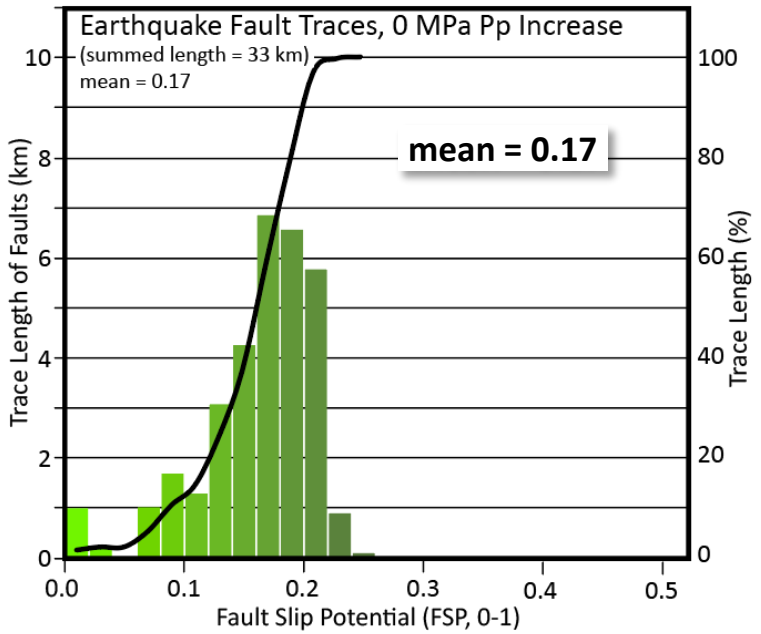
0 MPa Pp Increase

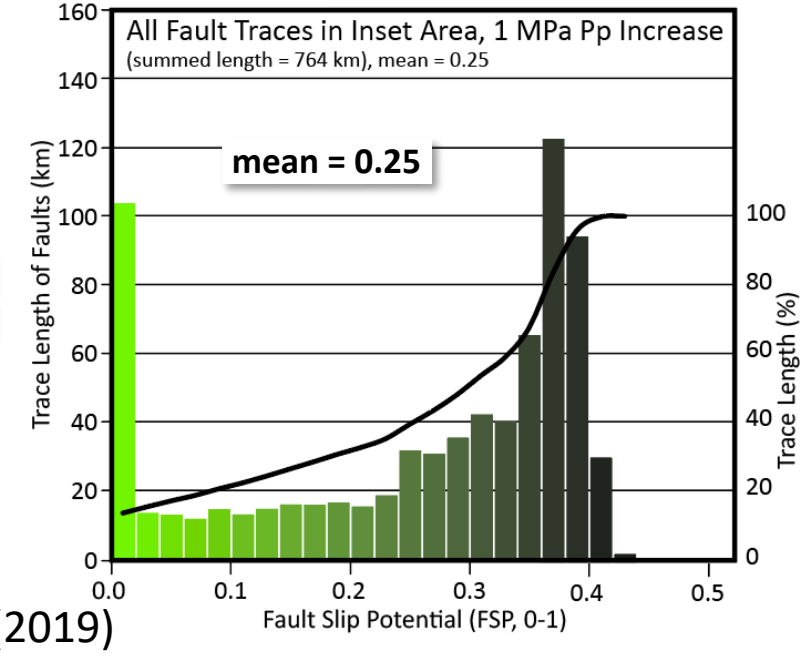


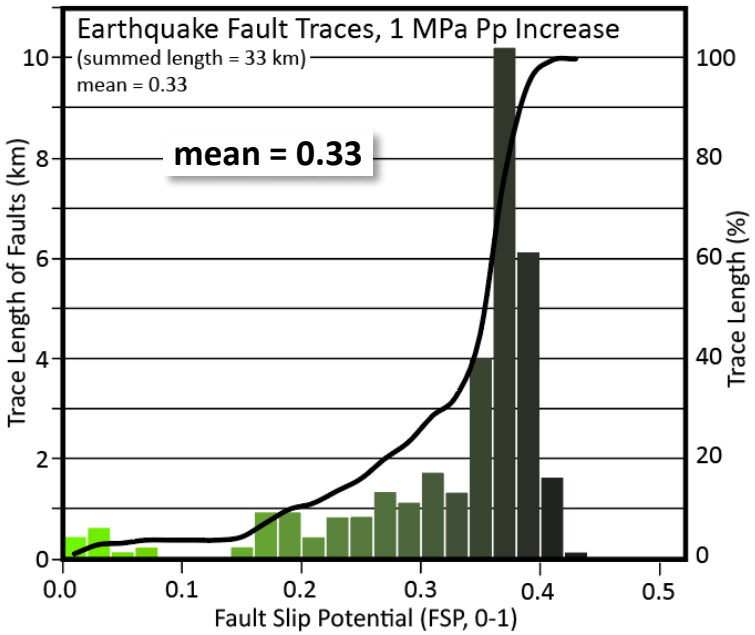
1 MPa Pp Increase

145 psi









Bureau of Economic Geology TexNet CISR

Hennings et al. (2019)

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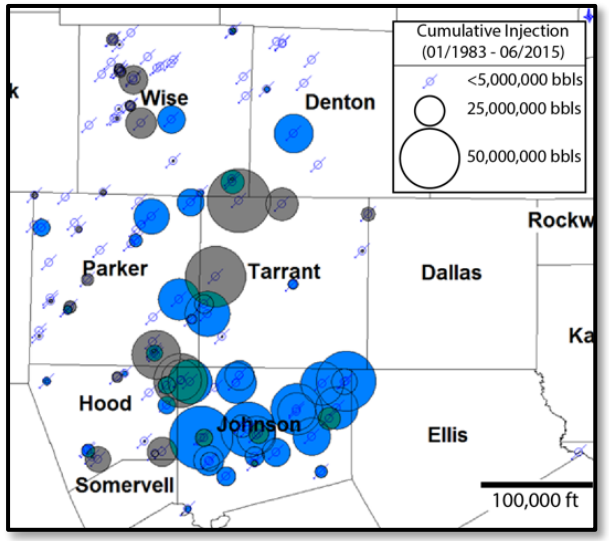
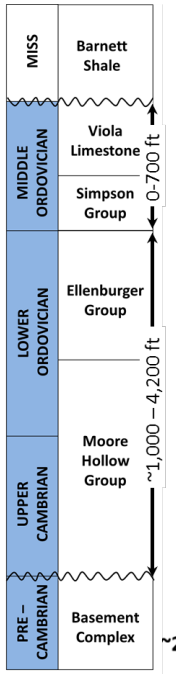
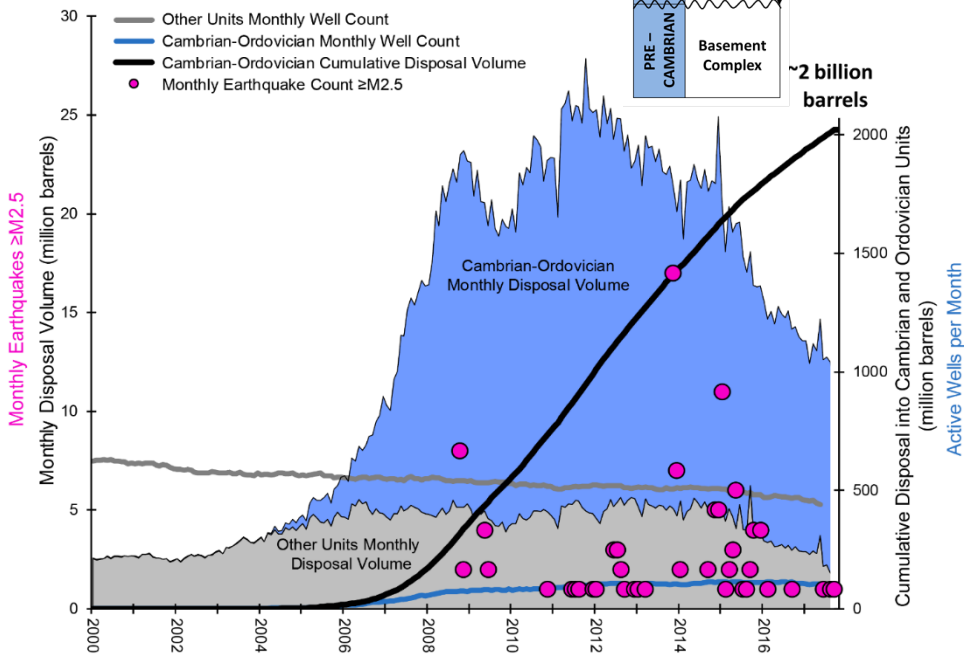
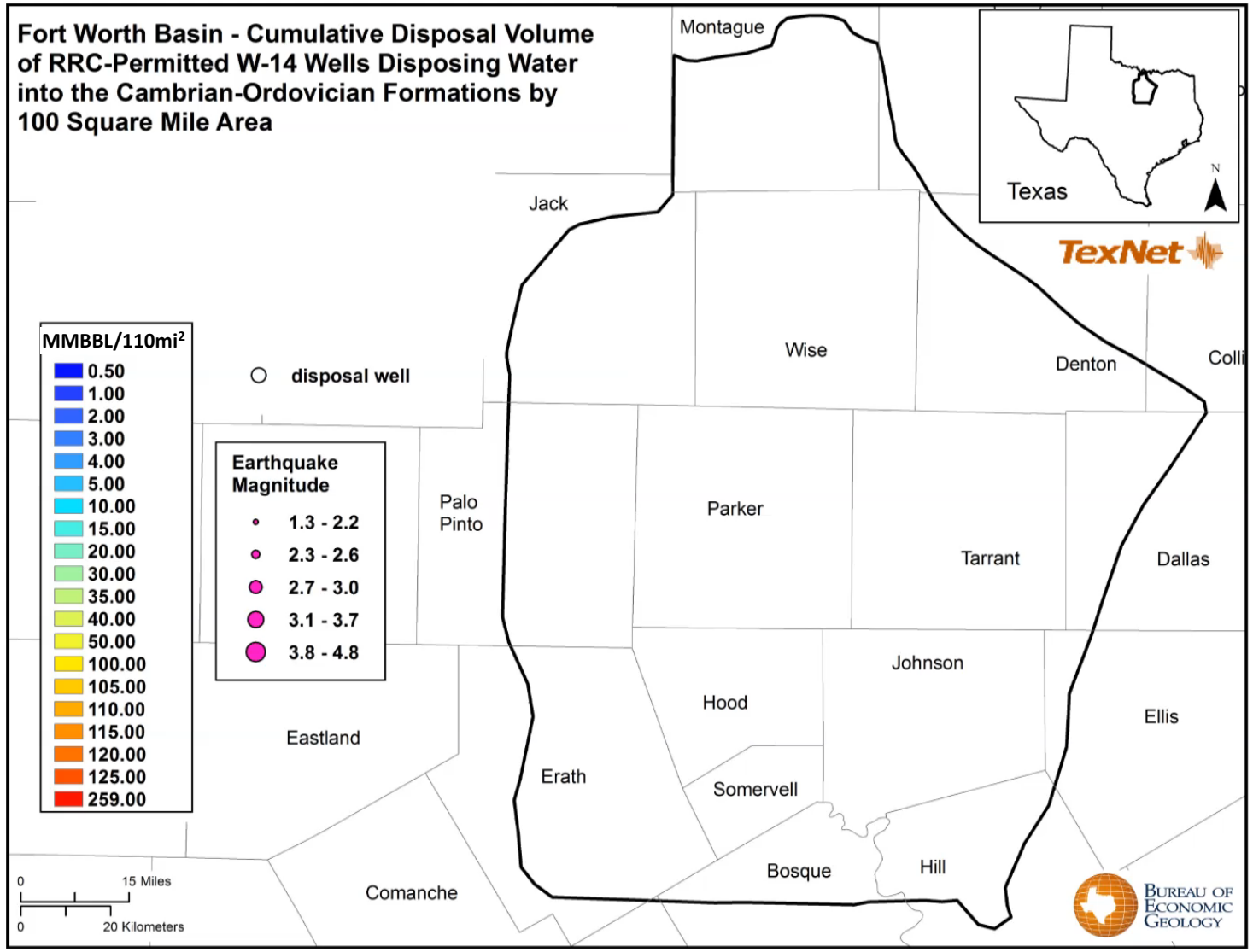
Fort Worth Basin database of SWD volumes and history





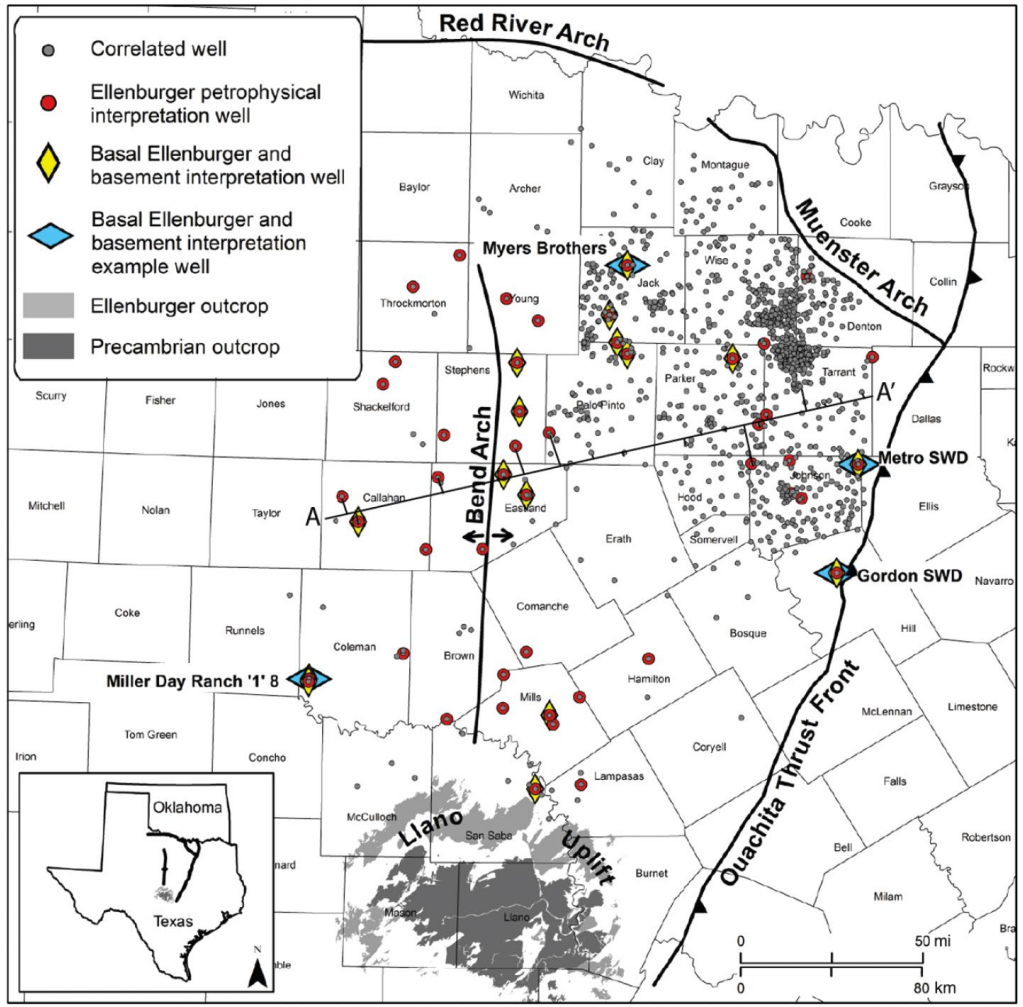


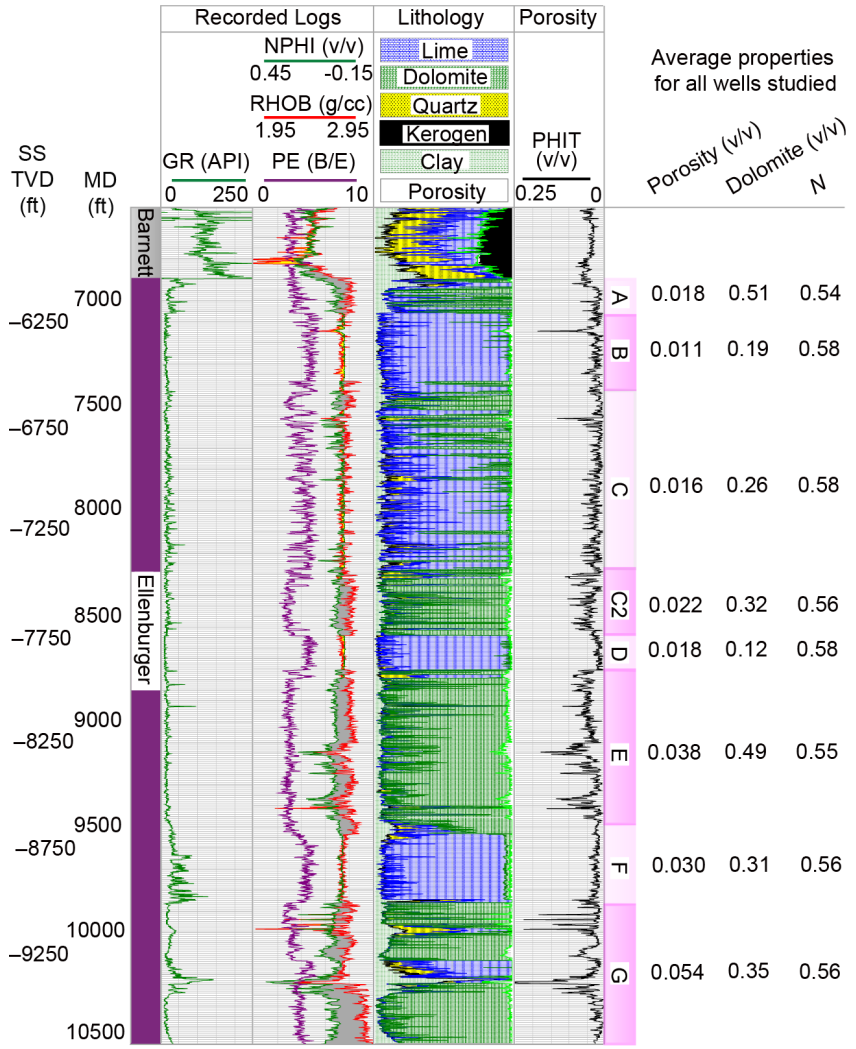


Lemons et al. (in prep)

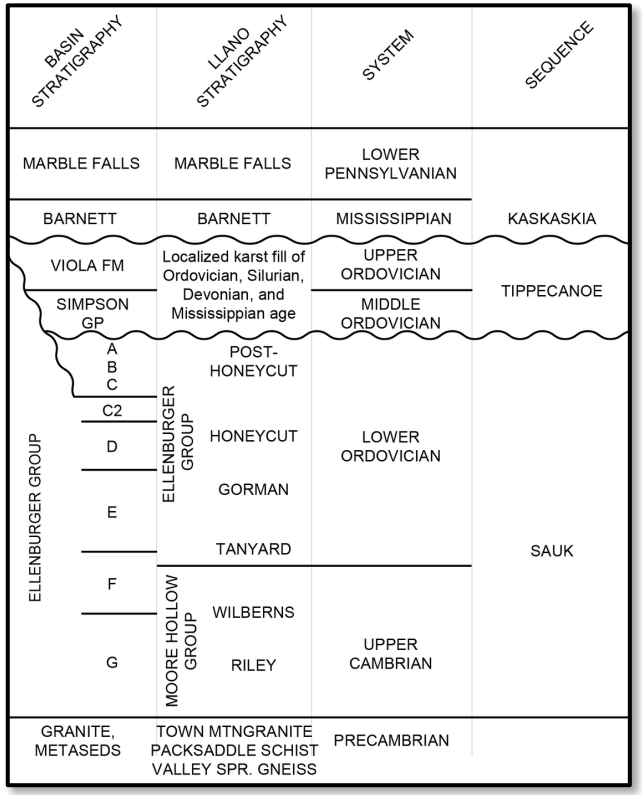
Bureau of Economic Geology TexNet CISR

Development of the Injection Geological Model

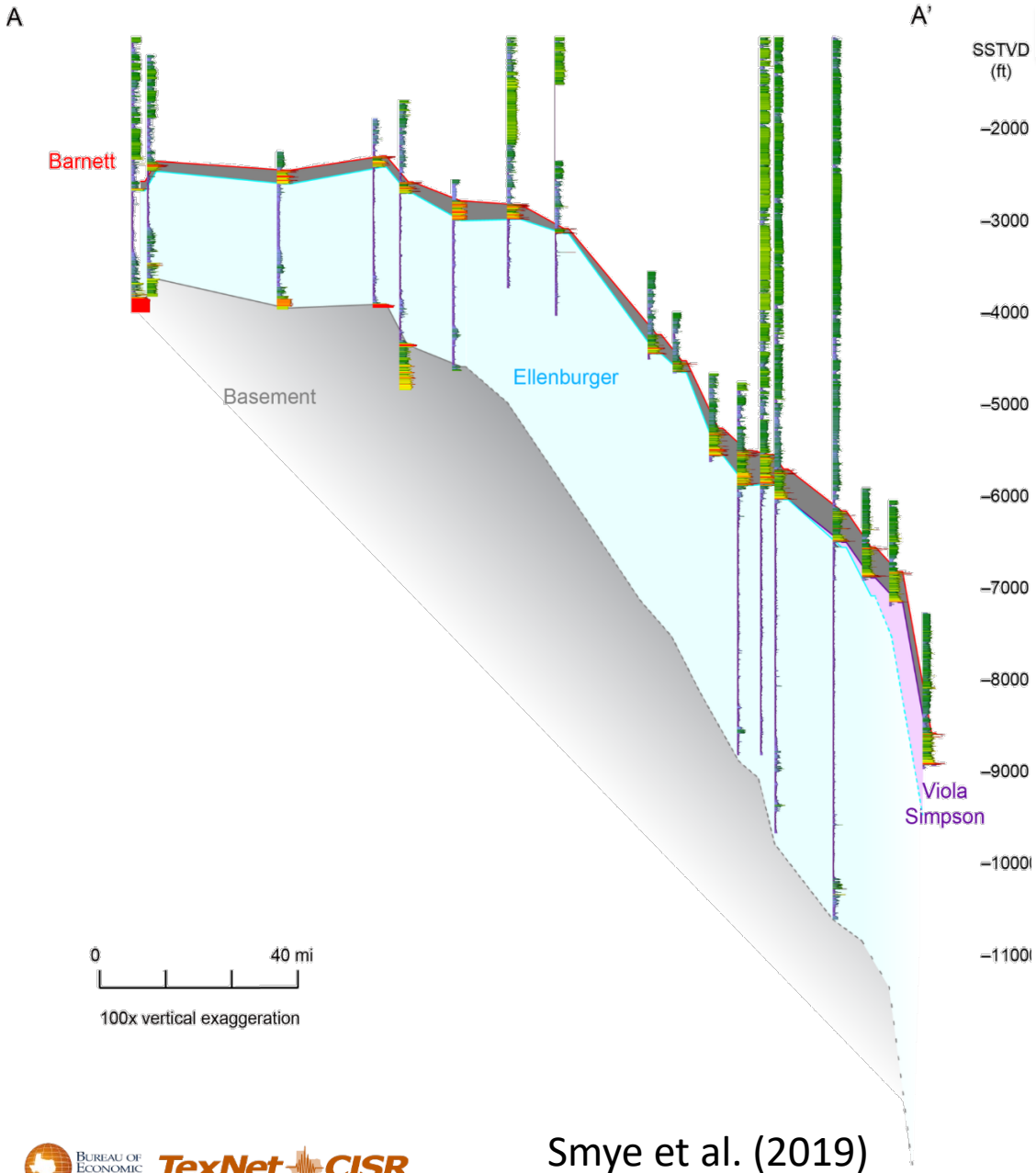




Smye et al. (2019)

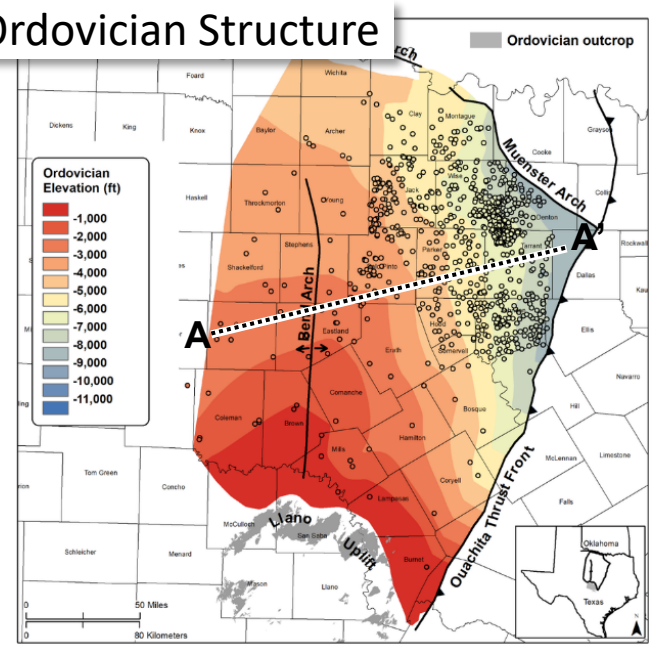


Development of the Injection Geological Model

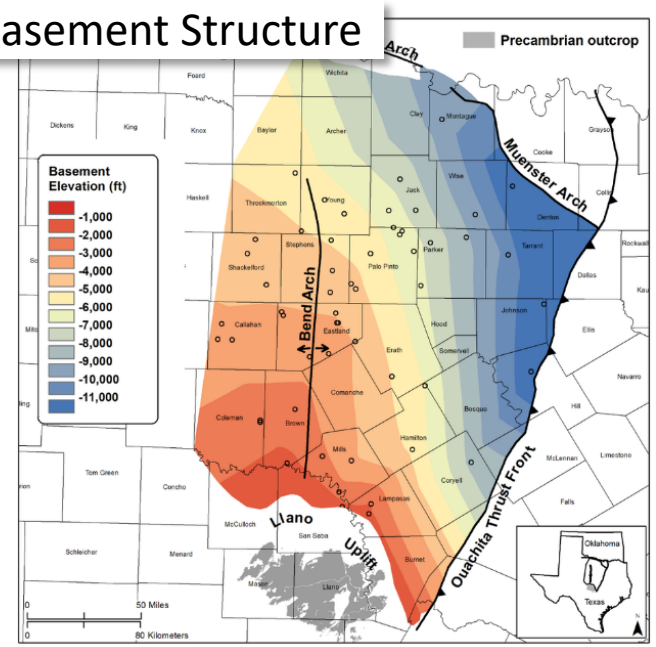


Smye et al. (2019)

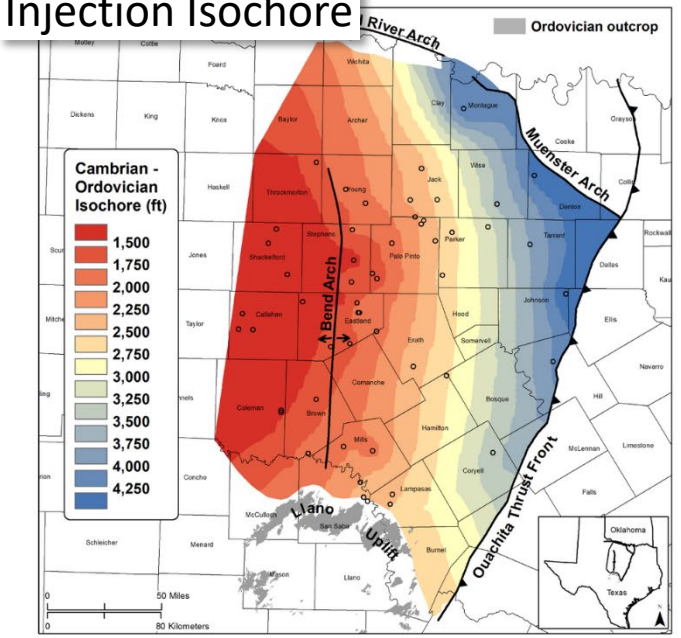
Ordovician Structure



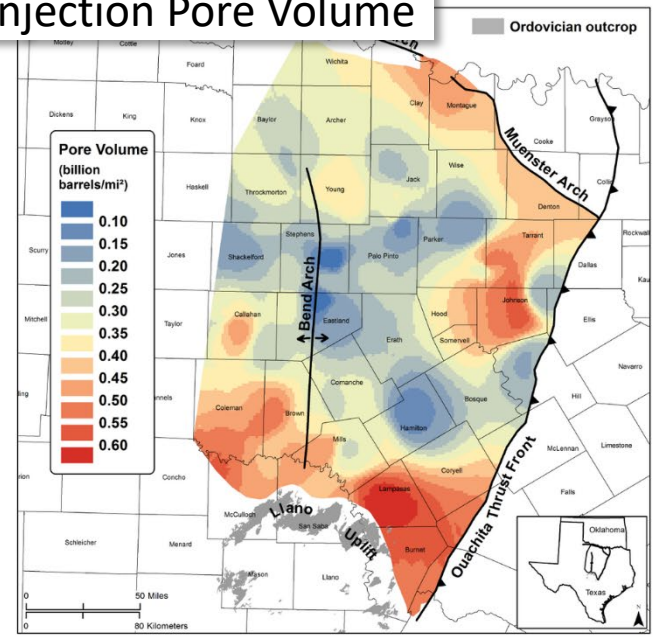
Basement Structure



Injection Isochore

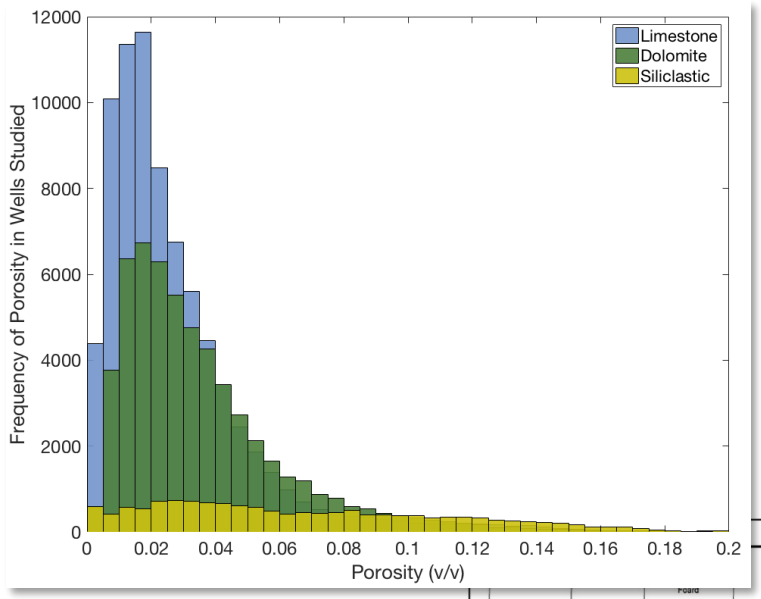


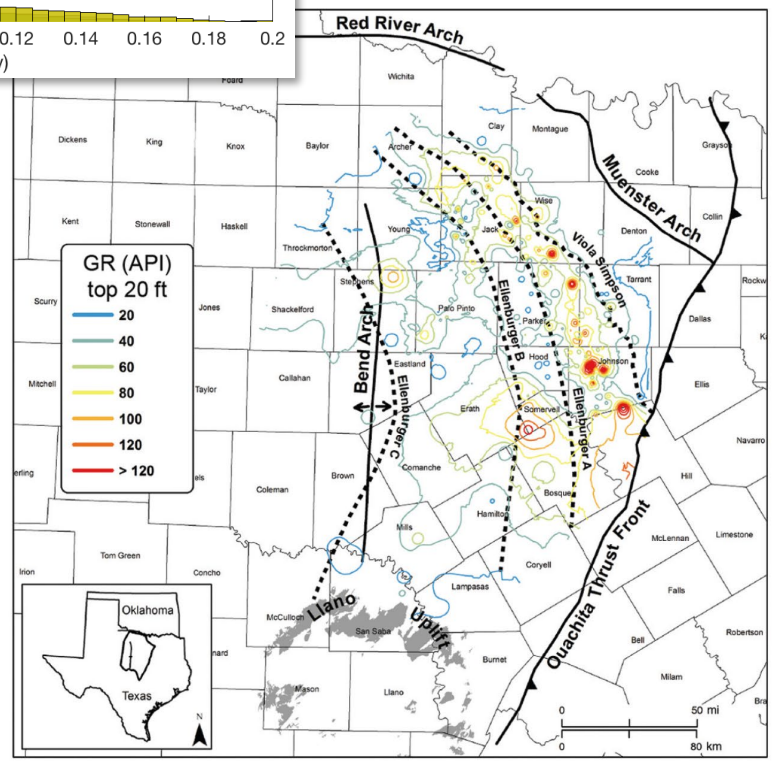
Injection Pore Volume

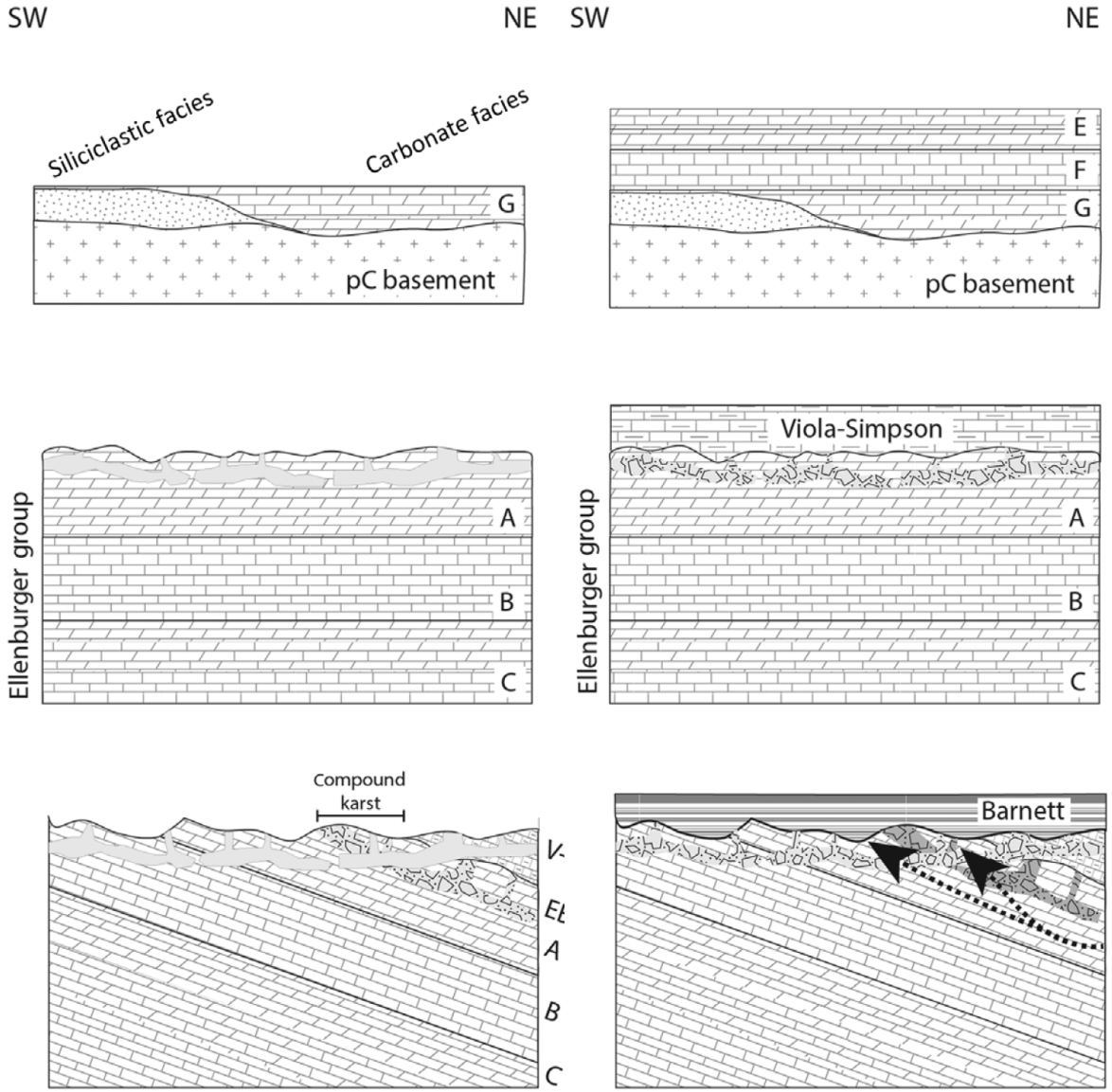


Bureau of Economic Geology TexNet CISR

Development of the Injection Geological Model

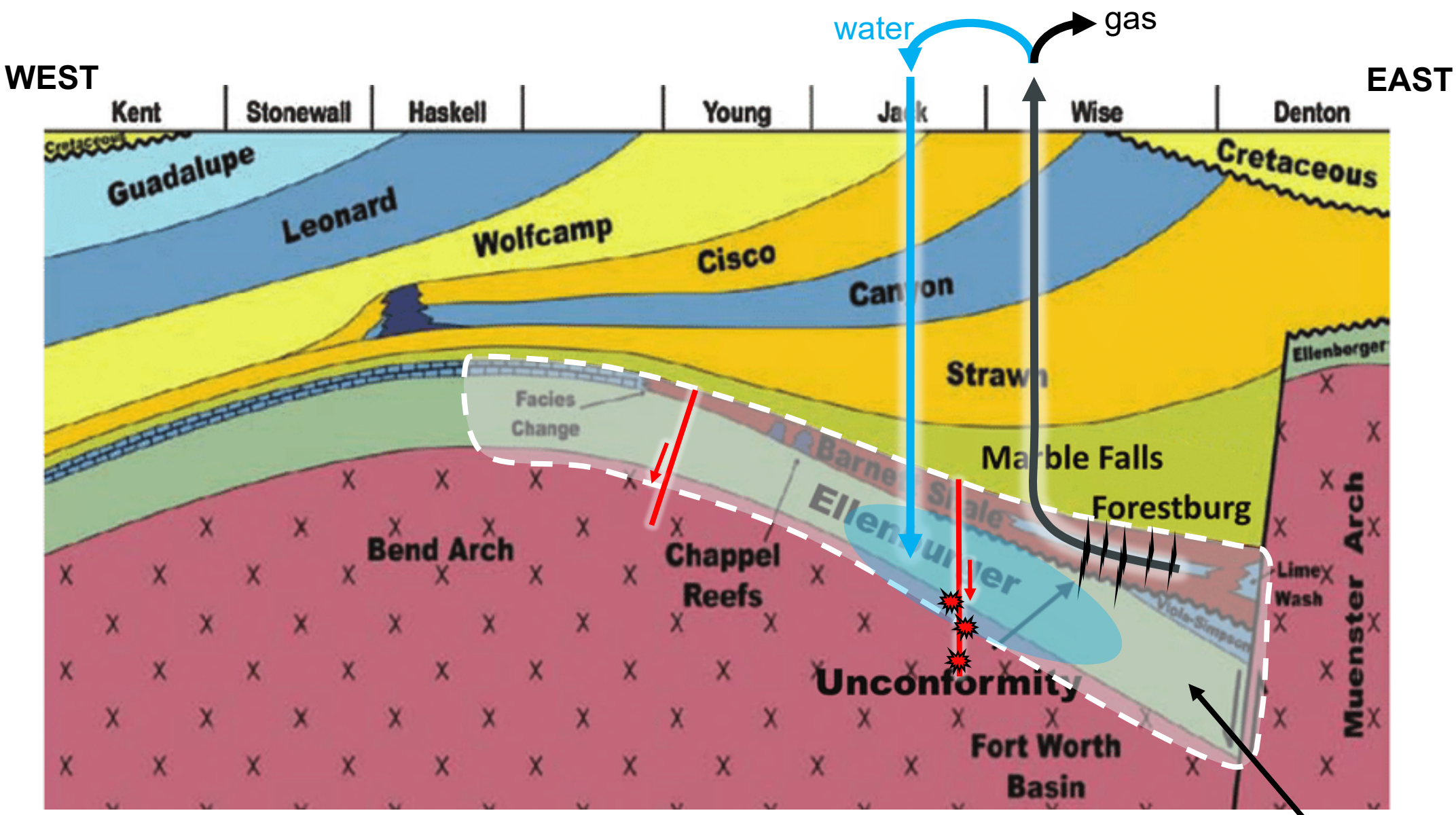




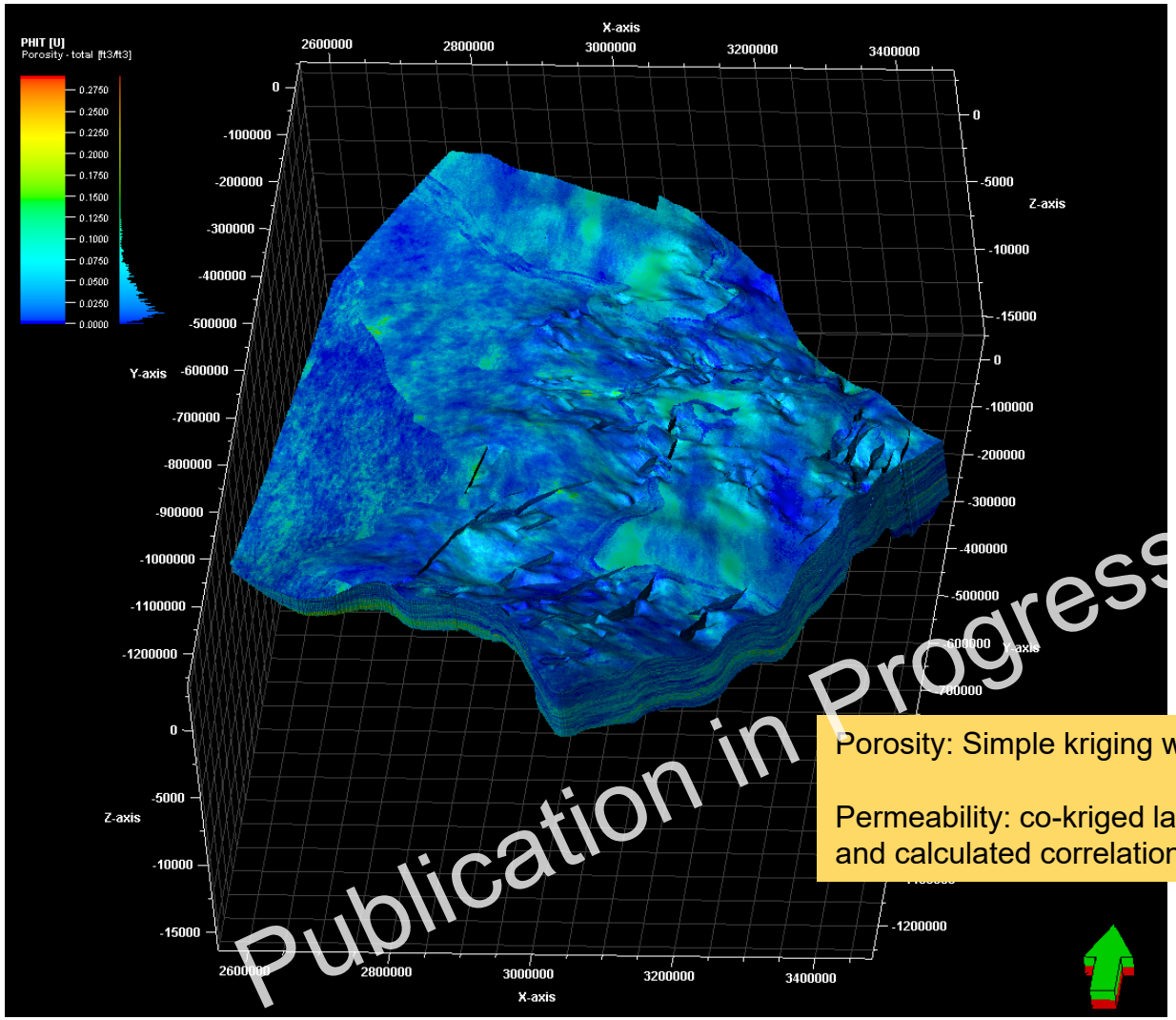


Smye et al. (2019)

Development of the Injection Hydrogeologic Model

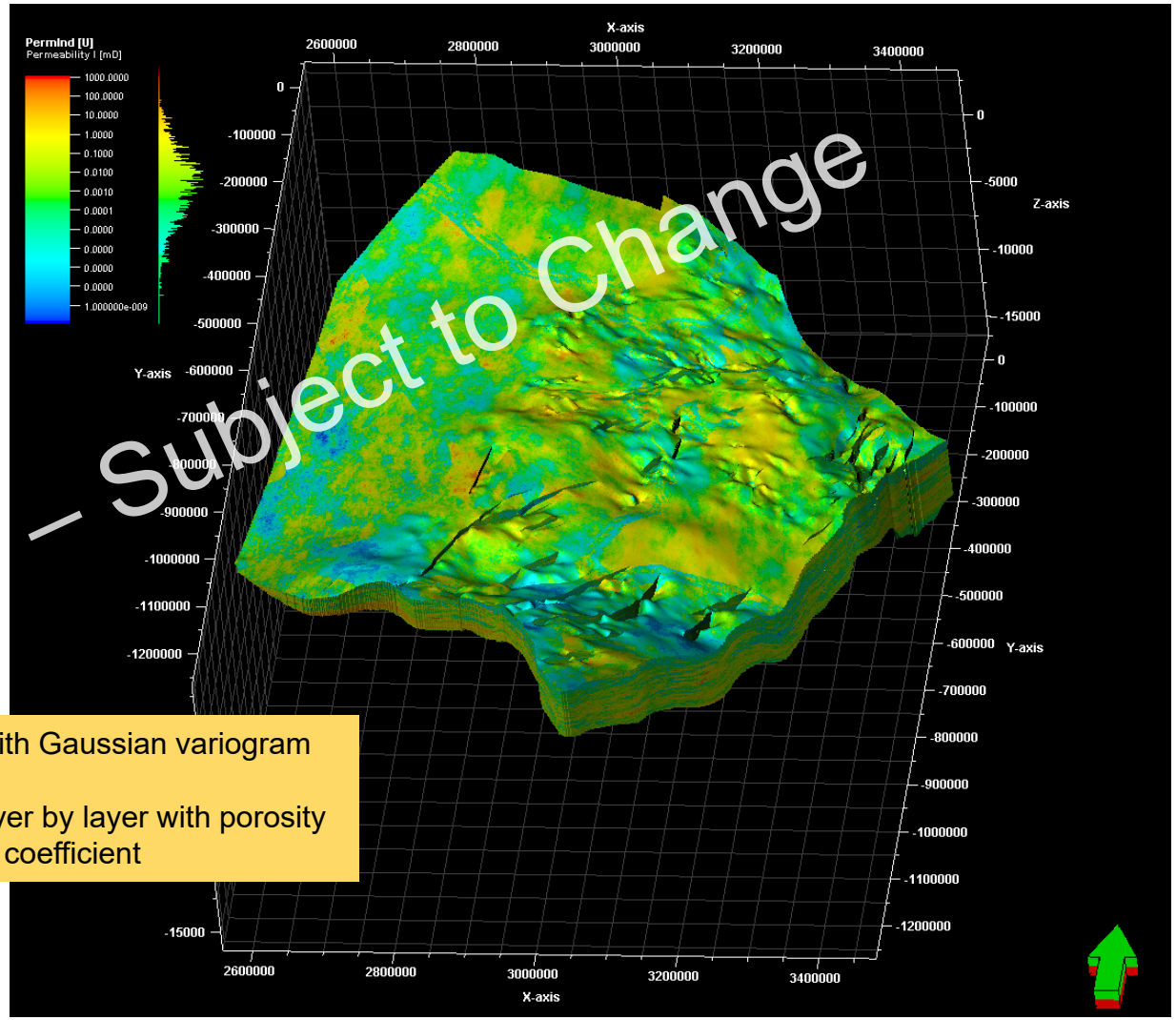


Populated Hydrogeologic Model



Porosity: Simple kriging with Gaussian variogram

Permeability: co-kriged layer by layer with porosity and calculated correlation coefficient

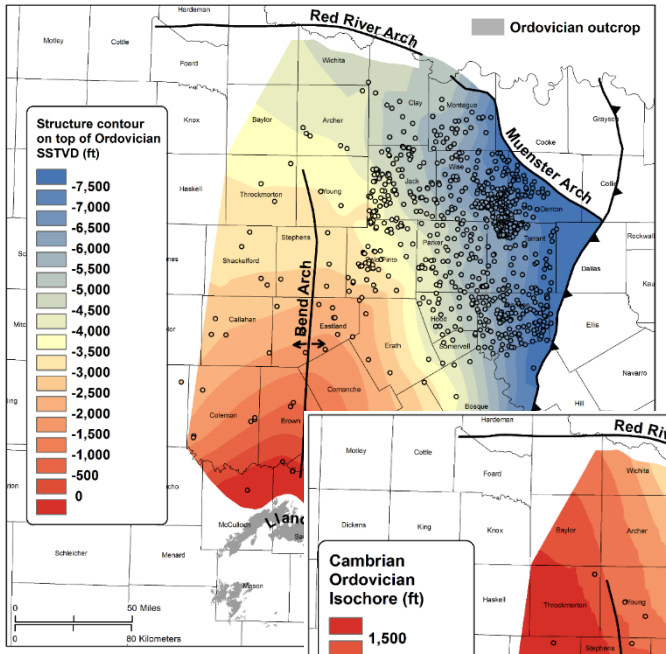


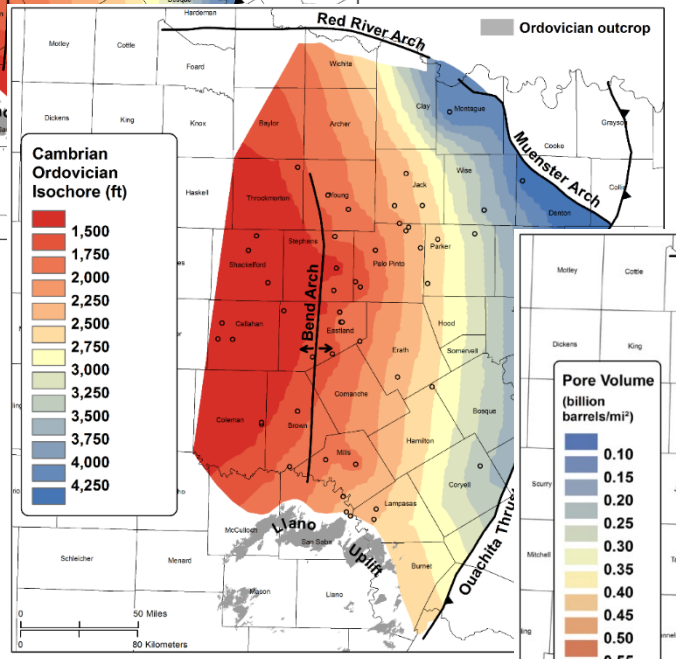
Porosity field – 1 to 5%

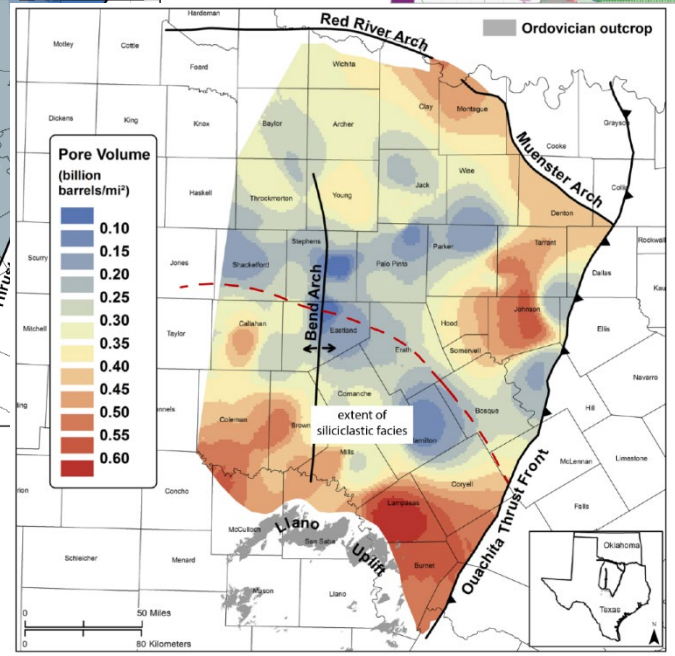
Permeability index field (matrix) – 0.01 μD to 10 mD

Gao, Nicot and others., in prep

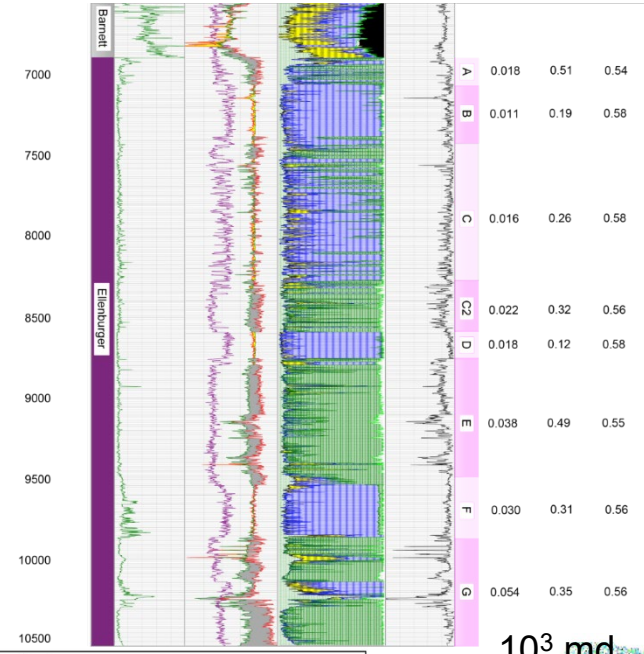
Components of Fort Worth Basin Injection Interval Geological Model

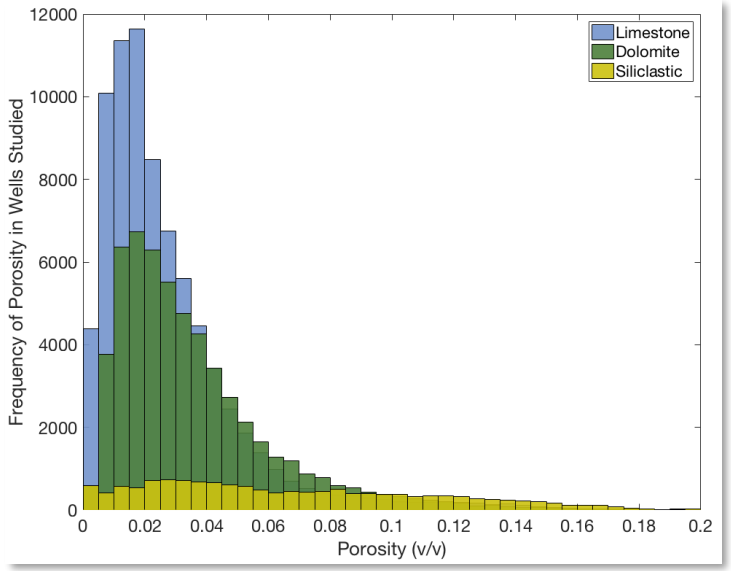


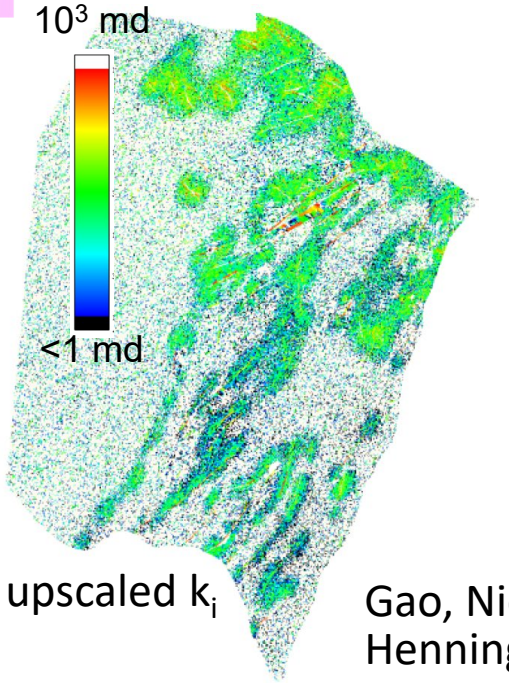




Smye et al. (2019)







upscaled k_i

Gao, Nicot and others., in prep
Hennings et al., in prep

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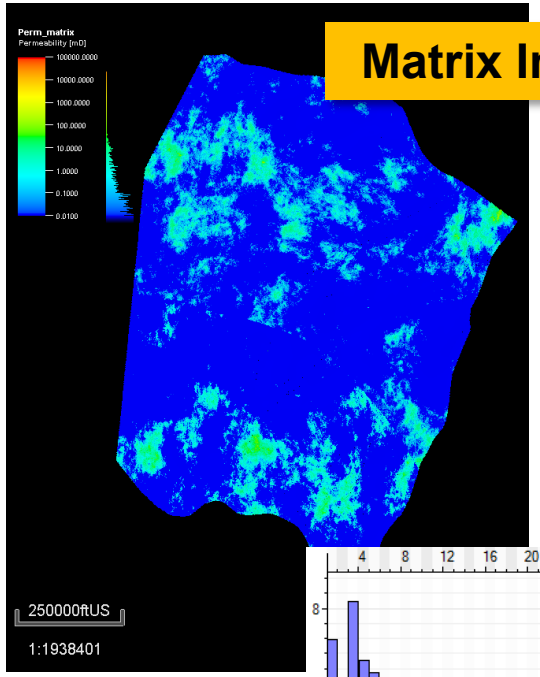
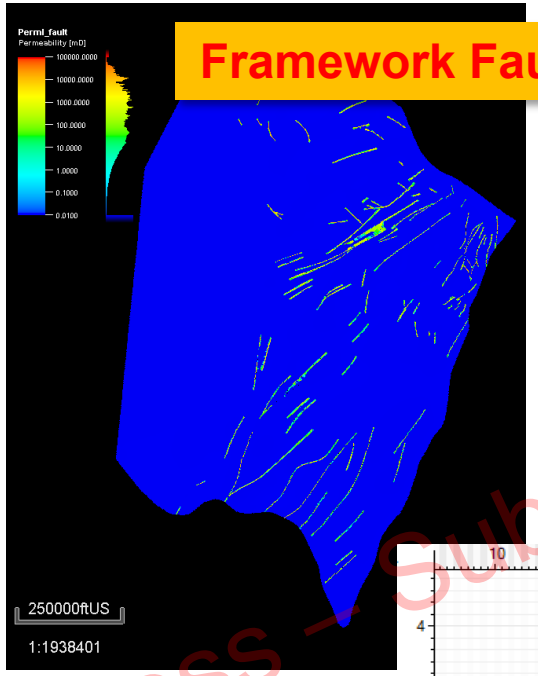
Matrix and Fault Permeability in Hydrogeologic Model



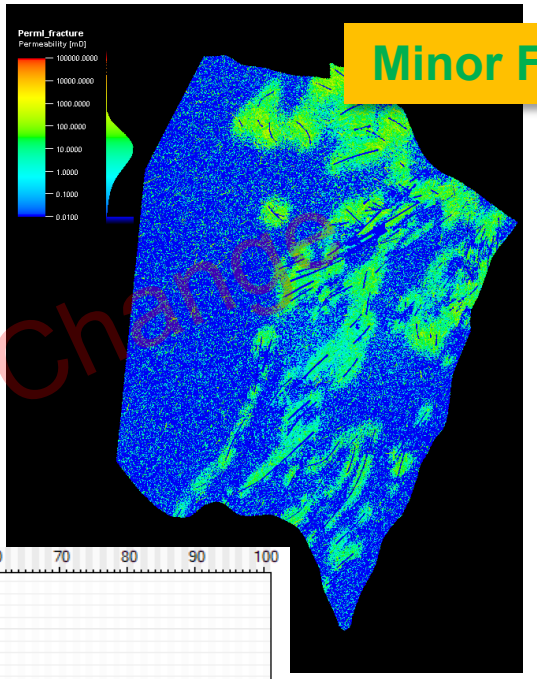
Matrix Index



Framework Faults

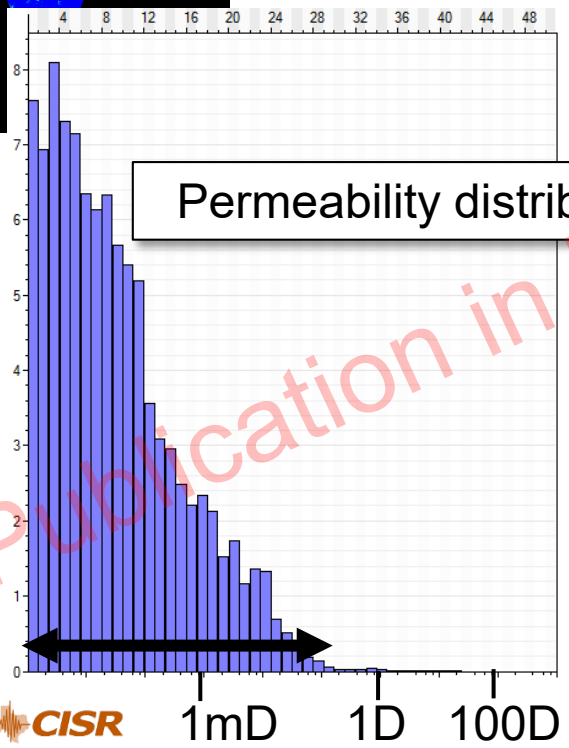
100 D

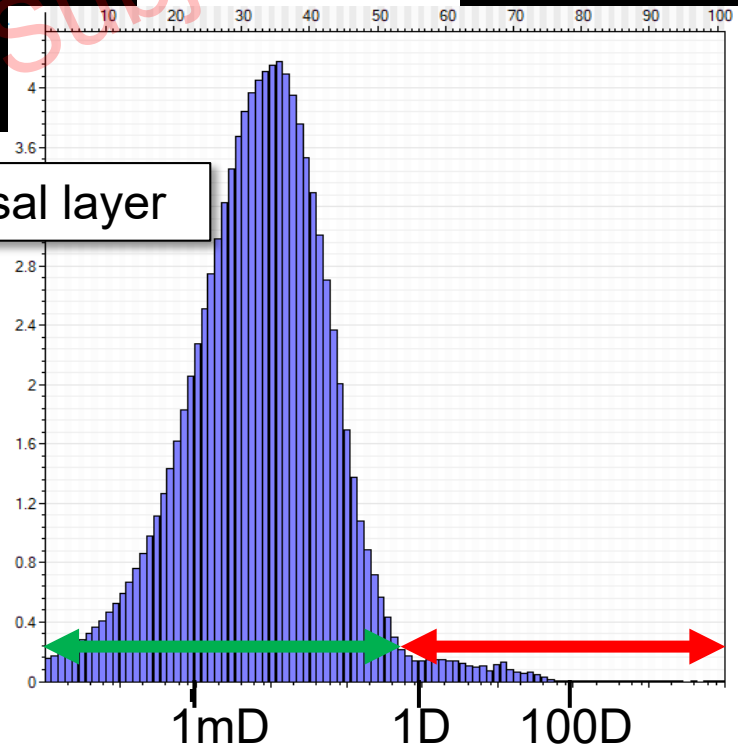
0.01 mD



Minor Faults

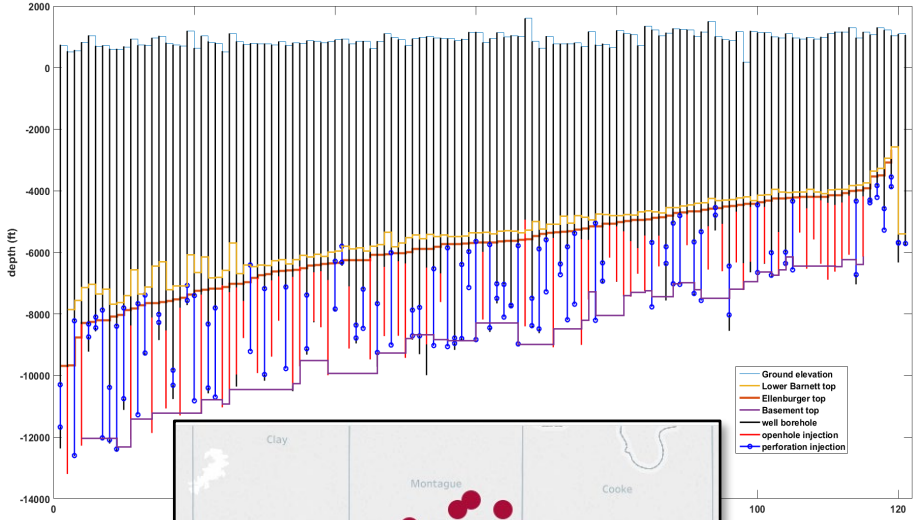
Permeability distribution in Ellenburger basal layer

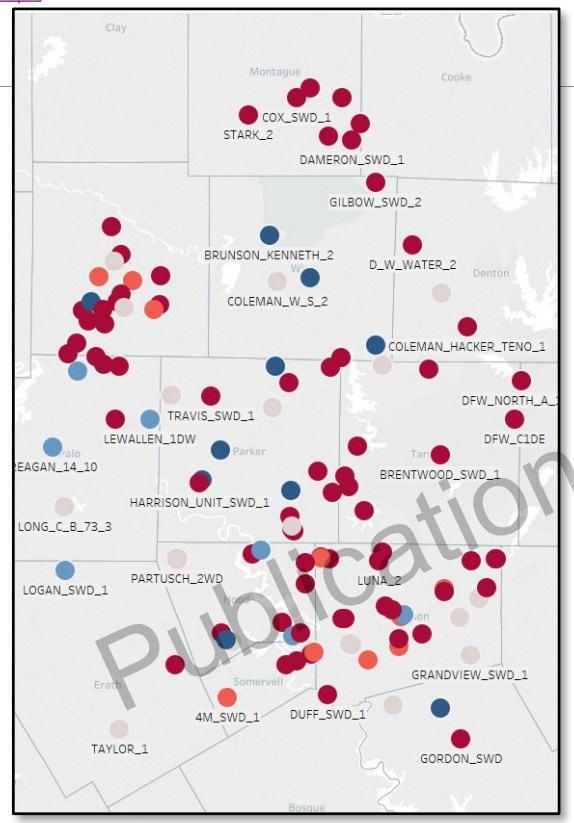


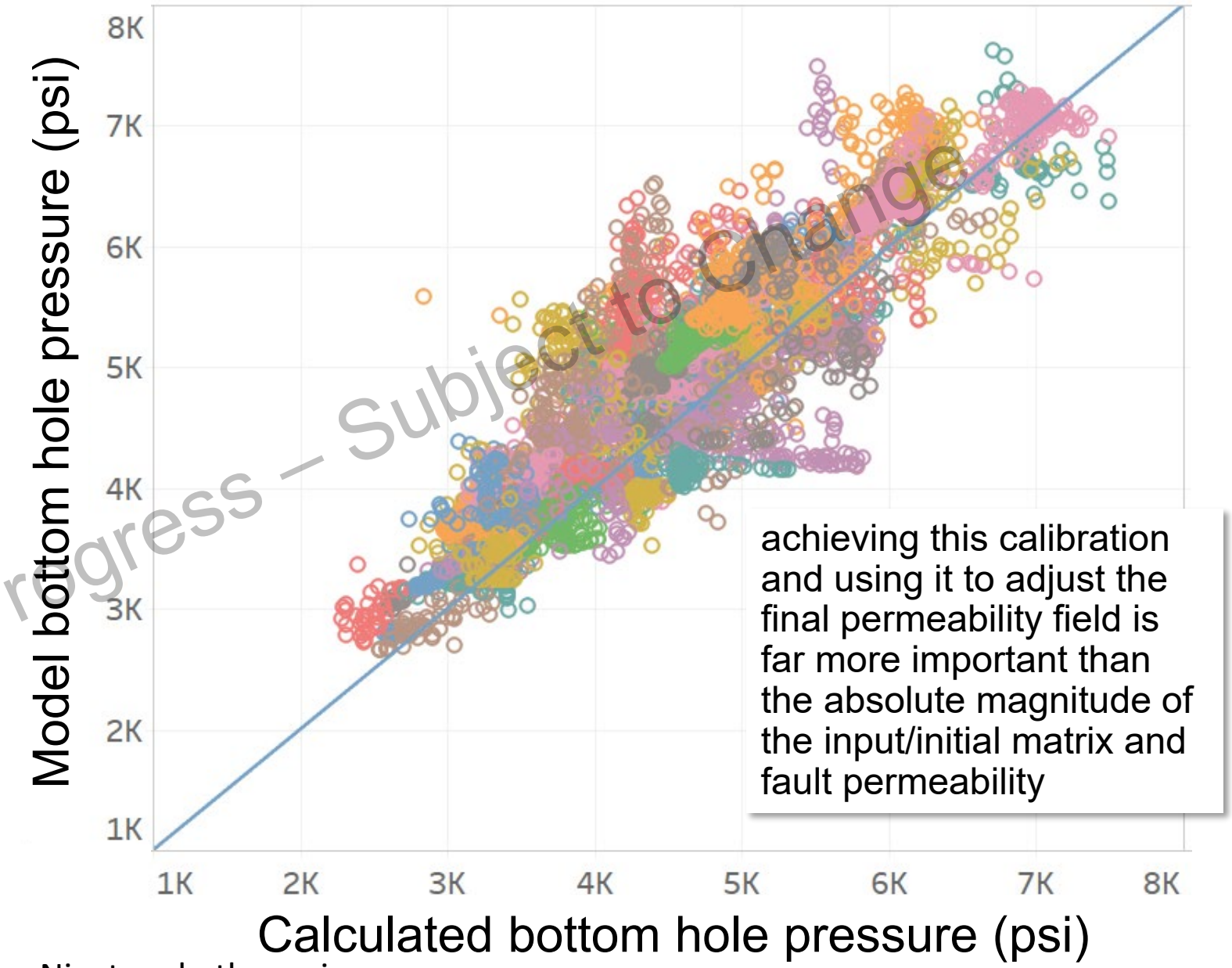


Gao, Nicot and others., in prep

Calibrating the Permeability Field with Wellhead Pressure Data



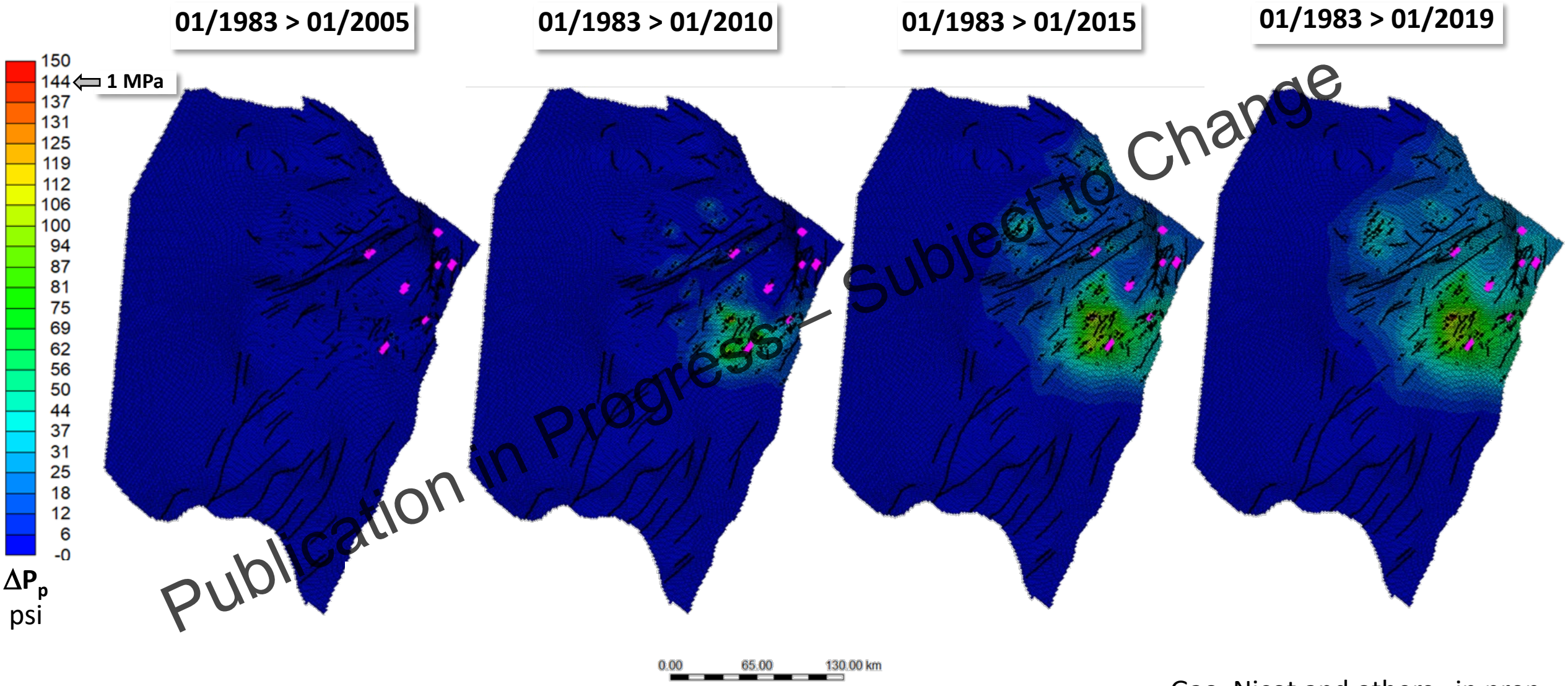




achieving this calibration and using it to adjust the final permeability field is far more important than the absolute magnitude of the input/initial matrix and fault permeability

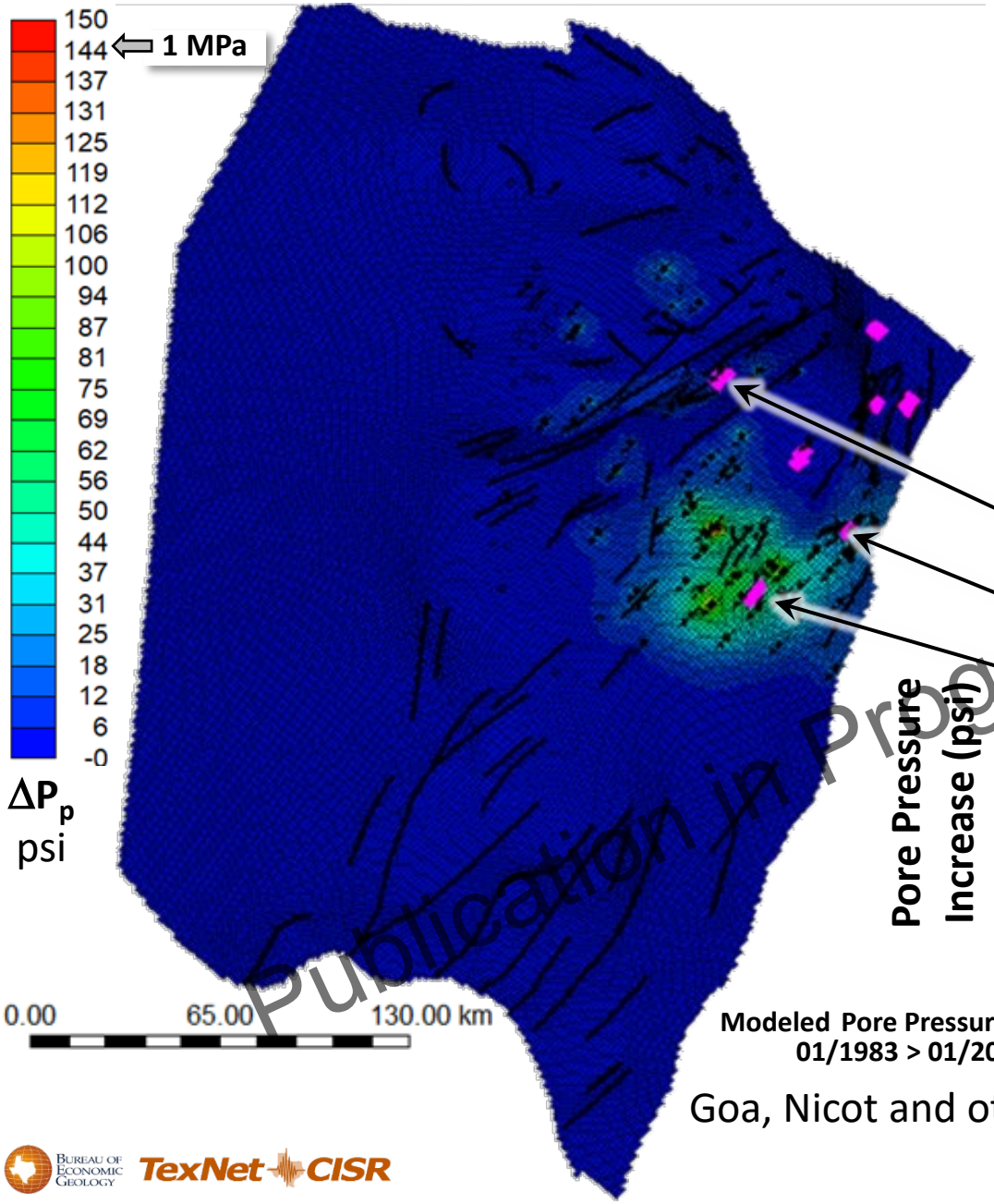
Gao, Nicot and others., in prep

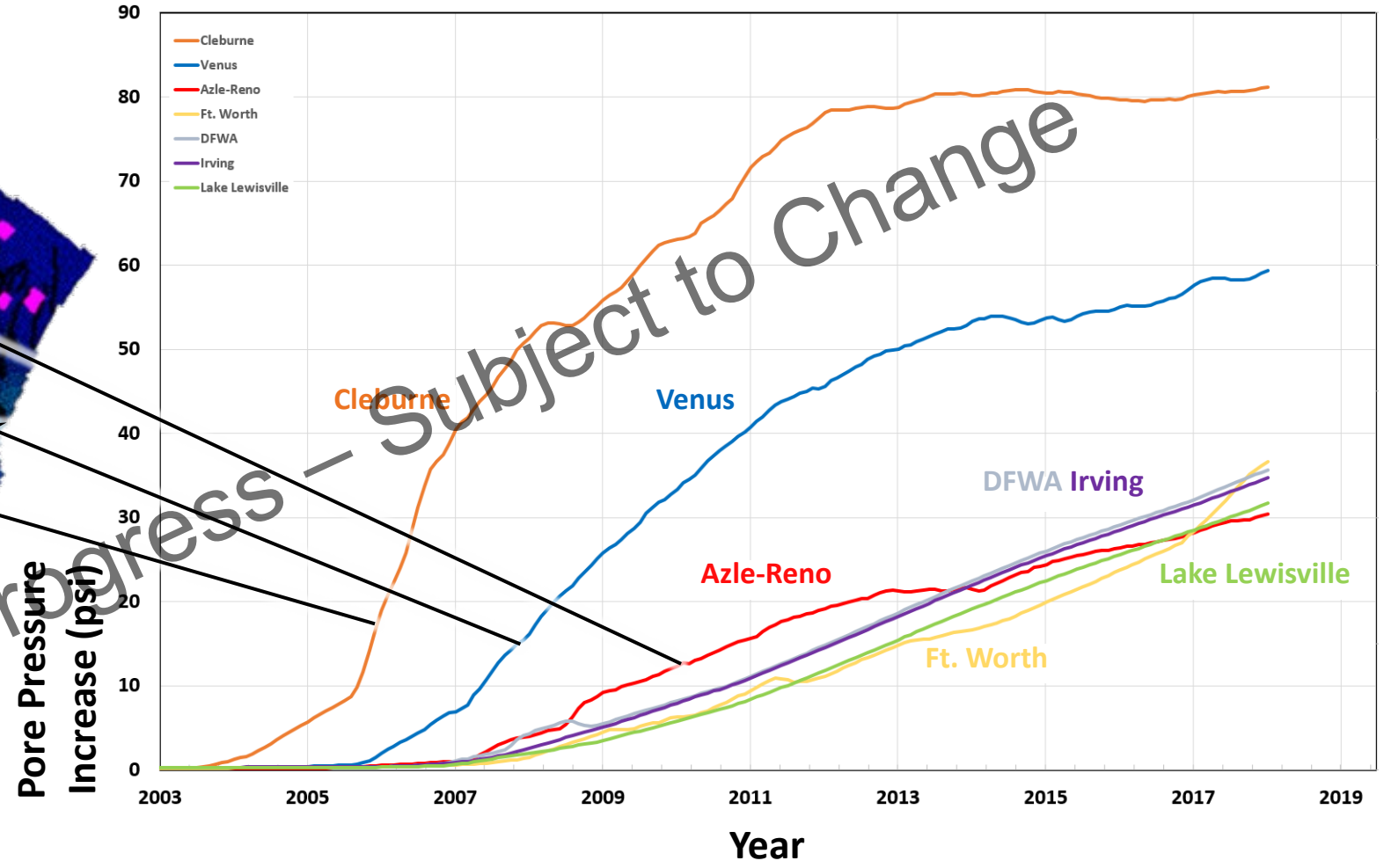
Fort Worth Basin Modeled Pp



Gao, Nicot and others., in prep

Fort Worth Basin Modeled Pp at the Earthquake Sequence Areas





Modeled Pore Pressure Change
01/1983 > 01/2015

Goa, Nicot and others., in prep

Gao, Nicot and others., in prep
Hennings et al., in prep

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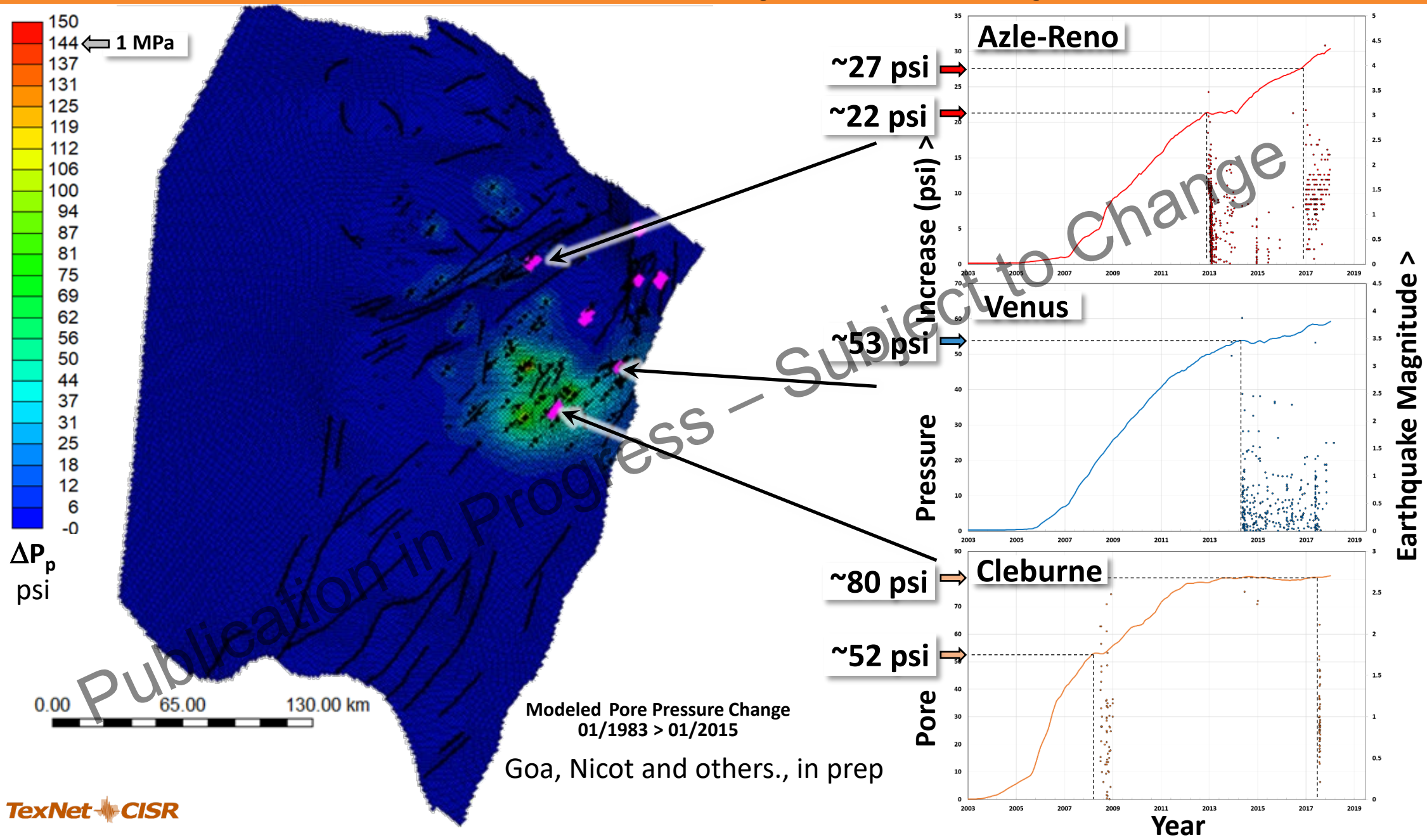
Fort Worth Basin Modeled Pp and Earthquake Onset



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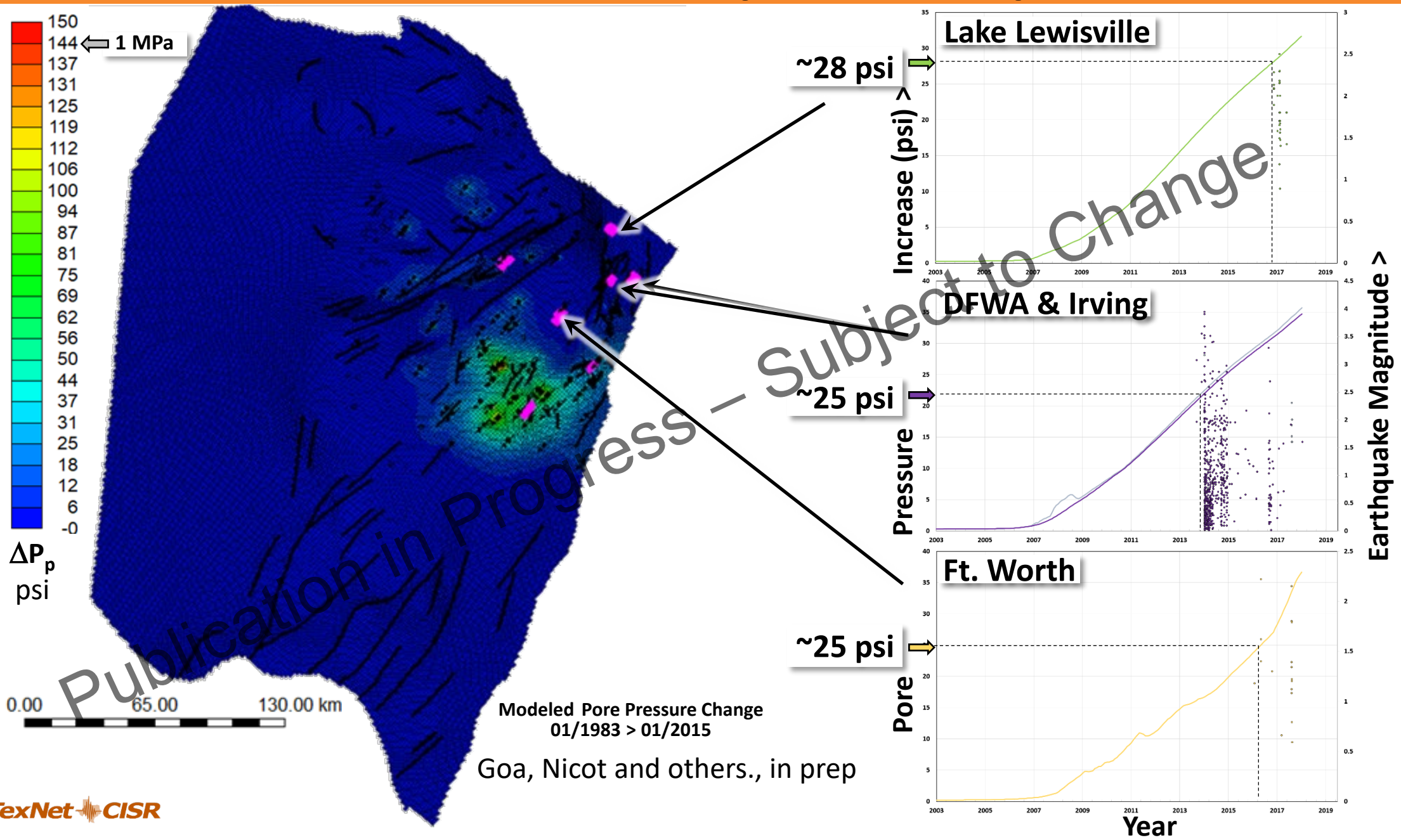
Fort Worth Basin Modeled Pp and Earthquake Onset



Modeled Pore Pressure Change
01/1983 > 01/2015

Goa, Nicot and others., in prep

Summary and Closing Thoughts

- **What is the deterministic nature of the seismicity hazard, the geology of it?**
  - Basin is highly faulted, and considerably more so than our new fault maps show
  - Most faults are natively critically-stressed
- **How has the hazard changed?**
  - The faults are stable in their native neotectonic state but are easily reactivated
  - The fault population that has hosted earthquakes is indistinguishable from the whole population
  - Long distance inducement along permeable faults is likely
- **What specific operational influences caused the hazard to change?**
  - Can interpret, build, and populate a detailed geological model – available to public
  - ΔPp from SWD activities is the broad and strong consensus, no evidence of HF-inducement
  - The most sensitive faults can be reactivated with ΔPp of 10s of psi
- **What now and what's next?**
  - The hazard has subsided but it is not back to its native state
  - The hazard must be managed at the scale of the geologic system – the whole basin
  - *Time-sequence fault slip potential analysis using hydrogeologic model*
  - *Development of a realistic and calibrated physics-based earthquake rate forecast*
  - *Additional site-specific, fully-coupled reservoir models (BEG, TAMU, SMU)*

Thank You