Fault Slip Potential (FSP) Model of Deep Injection in Northern Culberson-Reeves Texas and Southern New Mexico

Jim Moore
February 27, 2024

FSP Software Versions

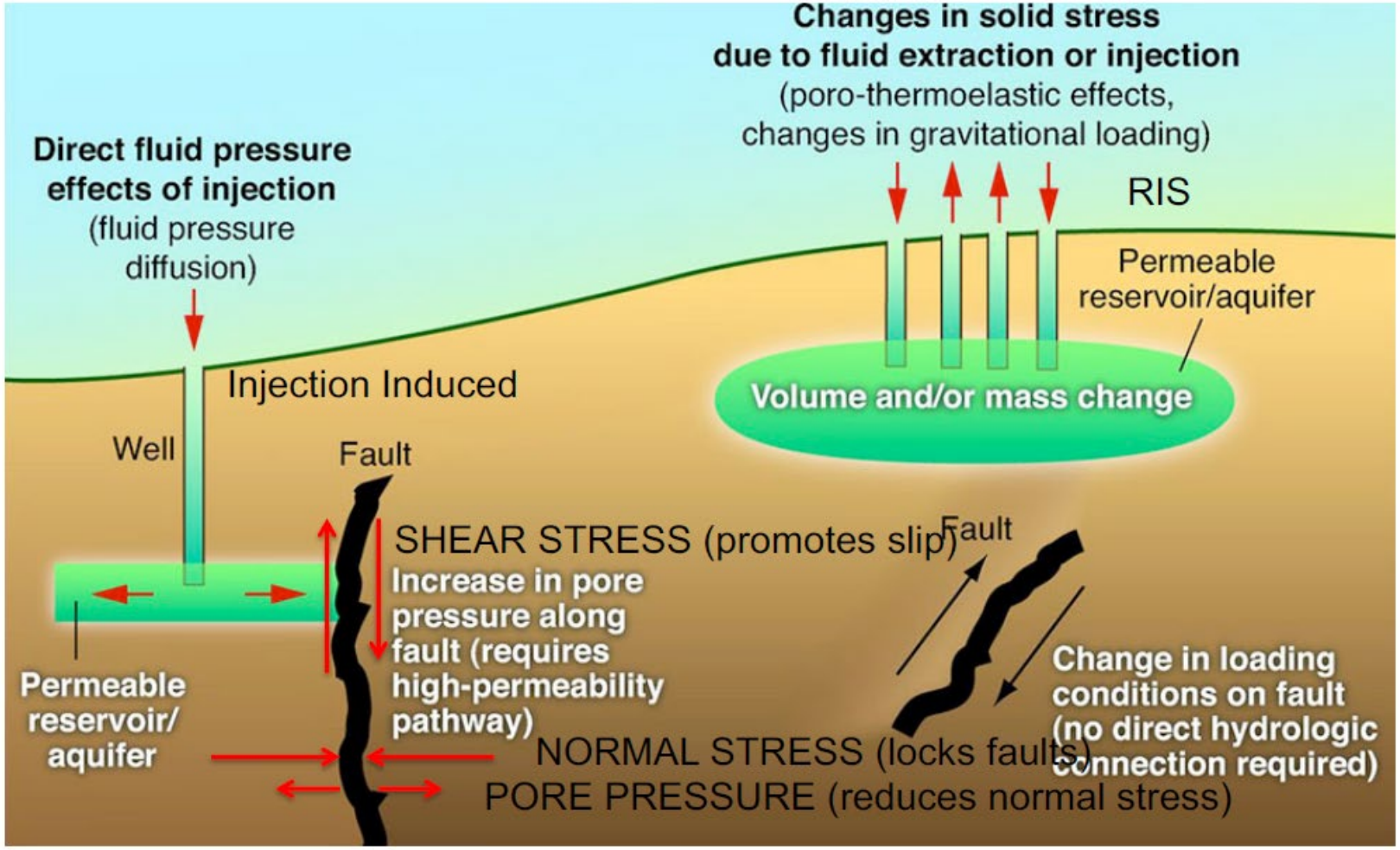
- **FSP 1.0**
  - Released March 2, 2017.
  - Matlab-based script.
  - Source code owned and developed by ExxonMobil Upstream Research.
  - Licensed, distributed and supported by Stanford University.
- **FSP 2.0**
  - Modified November 2018.
- **FSP 2.0**
  - Support organization change as of September 1, 2023.
  - New support partner is UT Austin BEG/TexNet/CISR.
  - https://www.beg.utexas.edu/texnet-cisr/fsp

Useful Definitions & Concepts

- **Mohr-Coulomb slip**
  - Response of brittle rock materials to shear stress and normal stress.
  - Friction is important.
  - Effective normal stress is decreased from an increase in pore pressure.

- **Fault Slip Potential (FSP)**
  - A methodology for calculating the cumulative probability of a known fault exceeding Mohr-Coulomb slip criteria from fluid injection.
  - FSP runs two modes:
  - Deterministic
  - Probabilistic

Change in Pore Pressure Impacts Faults



https://earthquake.usgs.gov/research/induced/modeling.php

Possible Causes of TX Seismicity & Statement of Problem

- Natural tectonics
- Completion stimulation, fracking
- Shallow disposal - proximal
- Deep disposal - proximal
- Deep disposal - distal
- Poroelastic stressing

- Make an FSP model using both TX & New Mexico deep disposal injection volumes
- Use methodology of modifying reservoir parameters to achieve good history matching to earthquake dates & locations

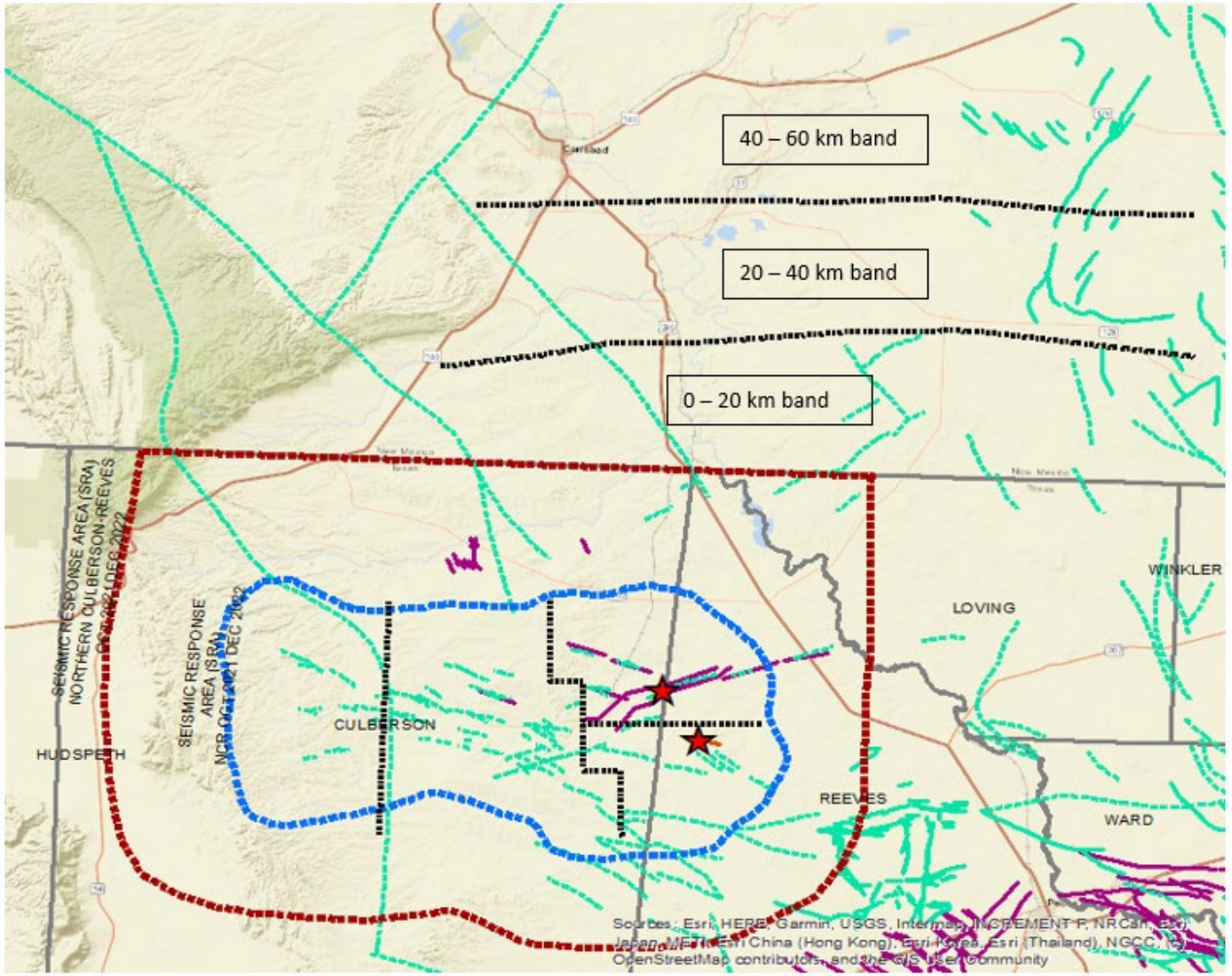
History of Seismicity & the RRC Response in NCR

- 1/31/2020 – M3.5 Mentone area event
- 3/4/2020 – Established Seismic Investigation Region (SIR), later named
- 3/26/2020 – M5.0 Mentone event
- 10/22/2021 – Established NCR Seismic Response Area (SRA)
- 3/1/2022 – Established NCR Operator Led Response Plan (OLRP)
- 11/16/2022 – M5.4 Coalson event, 12/9/2022 Amendment of OLRP
- July 2023 – Completed the FSP Model
- 11/8/2023 – M5.2 Coalson event
- 12/19/2023 – NCR SRA deep disposal permit suspension effective 1/12/2024

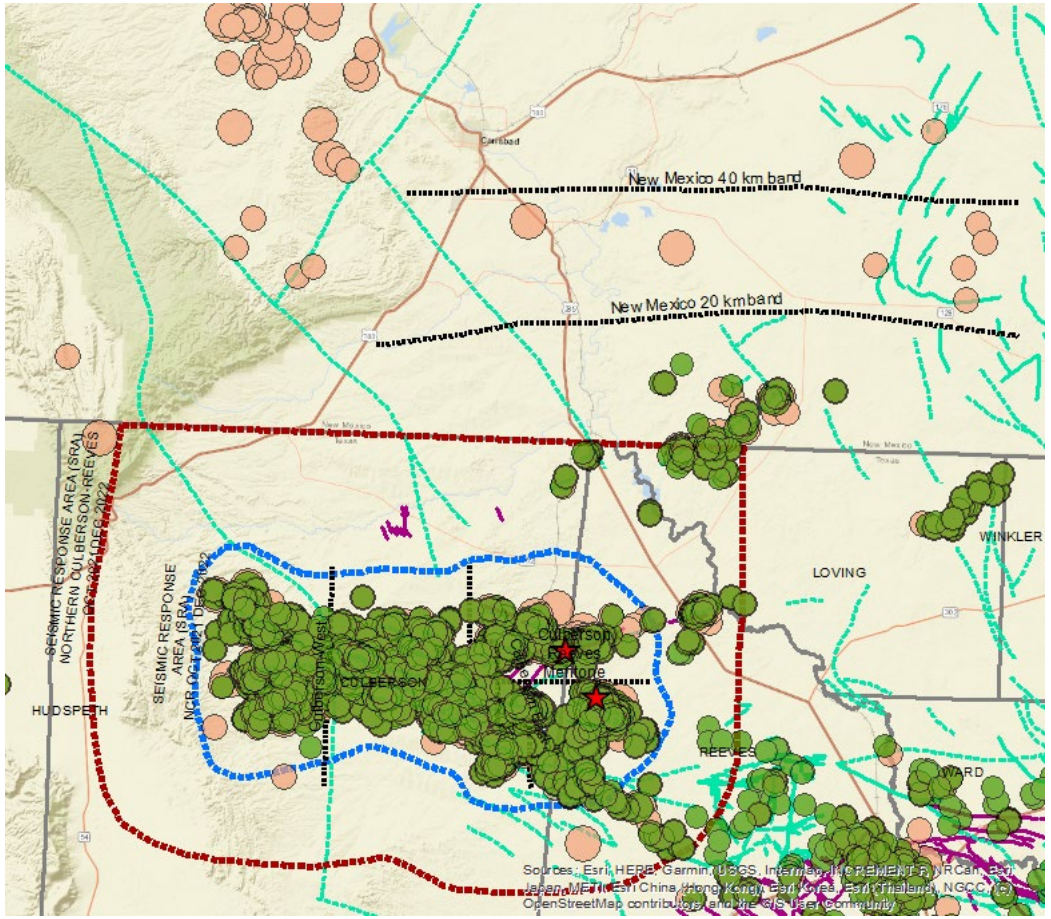
FSP Model Analysis

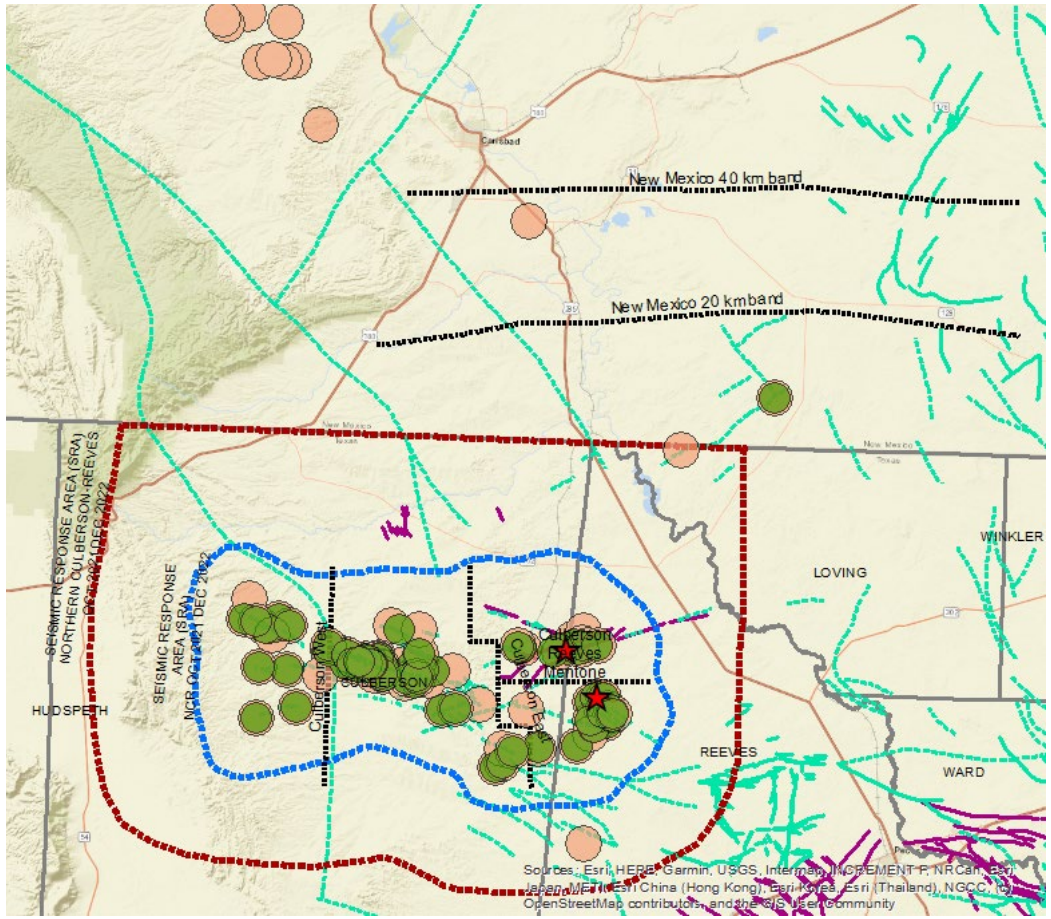
- Given: 117 Deep Injection Wells from NM Oil Conservation Division (OCD) plus 23 Deep Injection Wells from NCR
- Plot NCR and NM injection volume history
- Reduce the number of wells input to FSP from 140 to 100
- Key faults at locations of M3.5+
- FSP Model Inputs: Wells Injection Volumes, Stress Data, Reservoir Data
- Key Observation – “Typical reservoir data” generated an FSP model with no fault slip potential
- Using the good history match methodology, compare the pressure contributions of the NCR and NM wells to the FSP model at the key faults

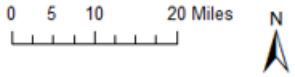
Map: Scope of Project Area



Map: Earthquakes M2.0+ and M3.5+

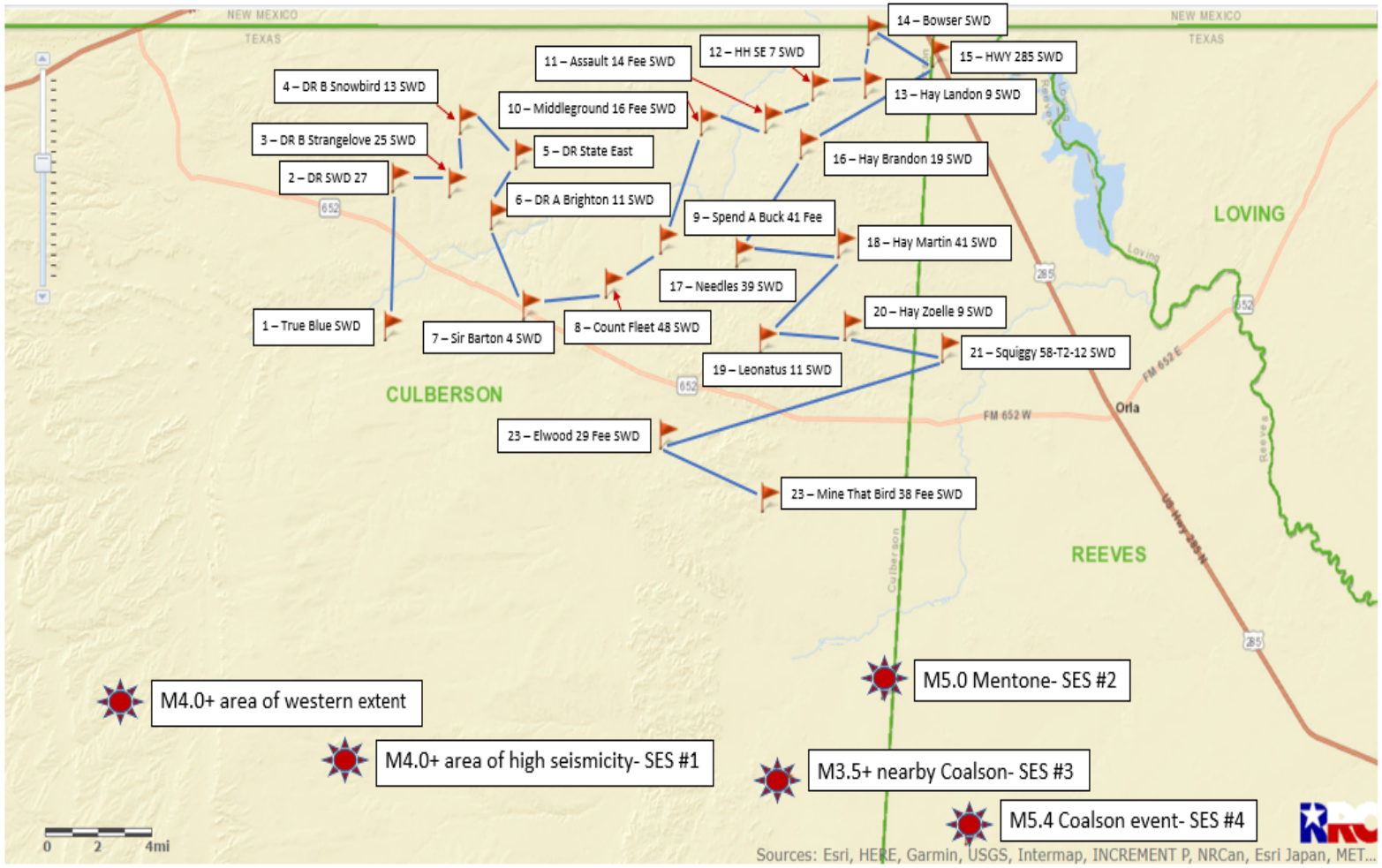






- USGS & BEG TexNet earthquakes: date range 1/1/2017 to 7/15/2023.
- 120 M3.5+ events inside the blue boundary

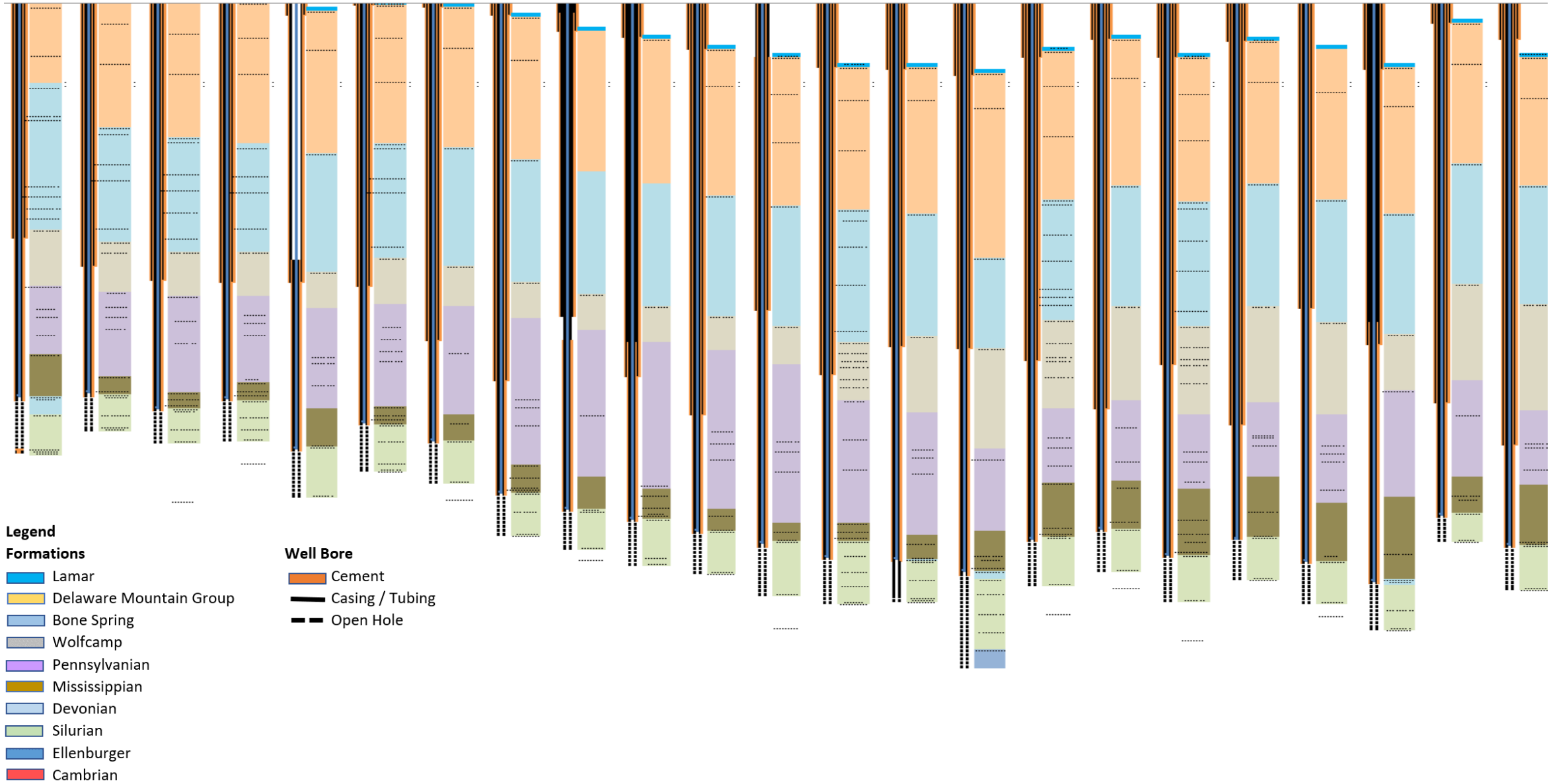
23 Deep Disposal Wells in NCR, TX & SES Locations



Line of section "Wellbore Sketch - Seismic Investigation – Northern Culberson-Reeves Deep Disposal" &

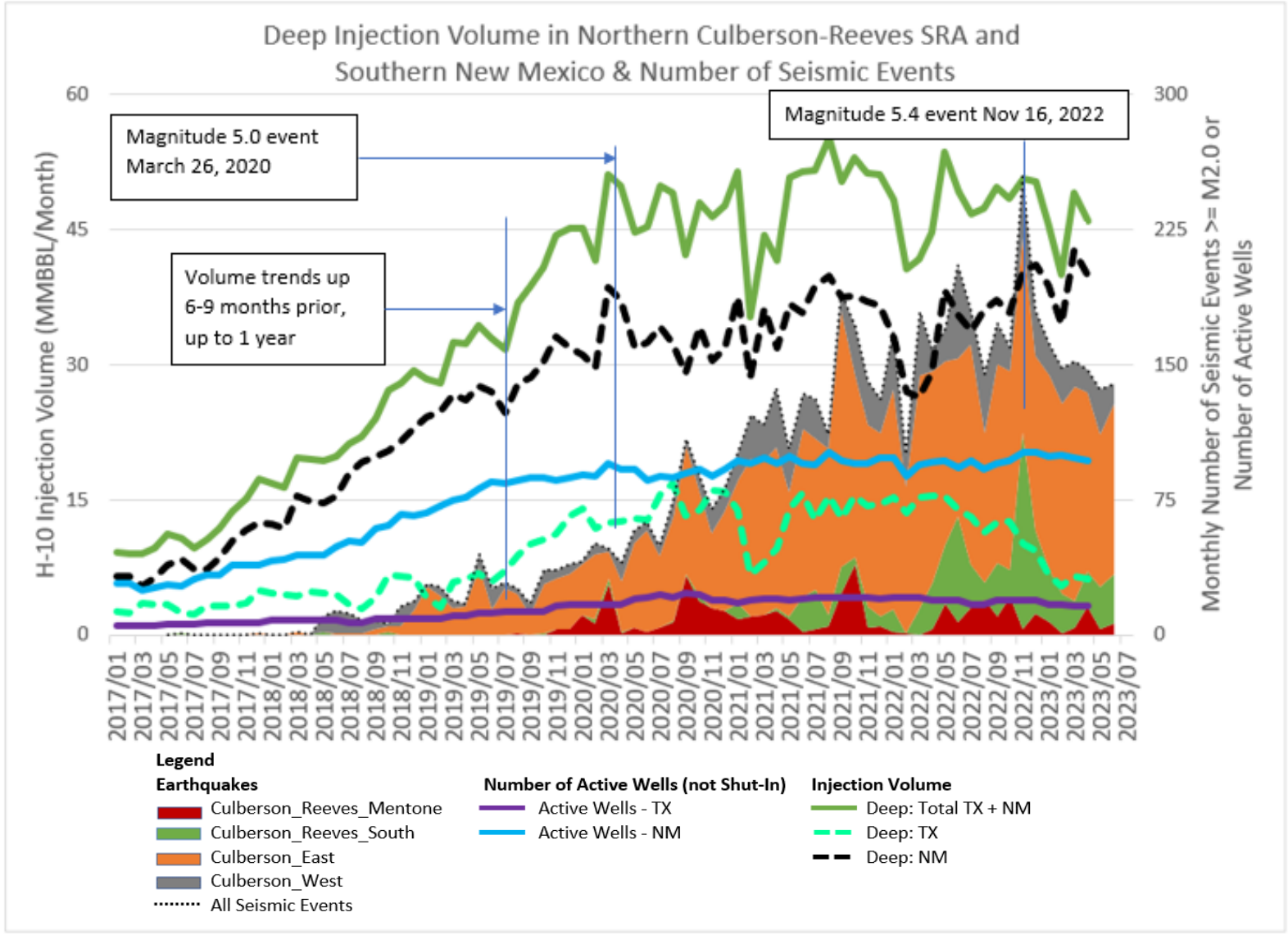
Location of Seismic Events of Significance (SES)

Wellbore Sketch of 23 Deep Disposal Wells in NCR, TX

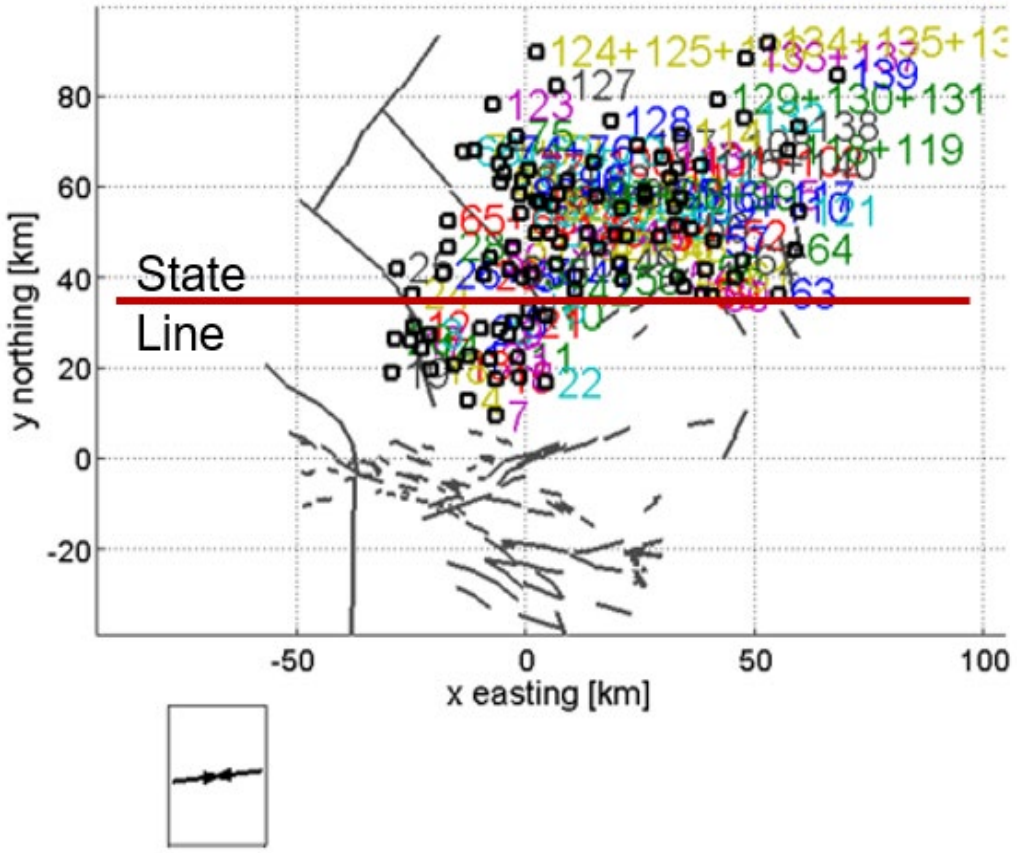


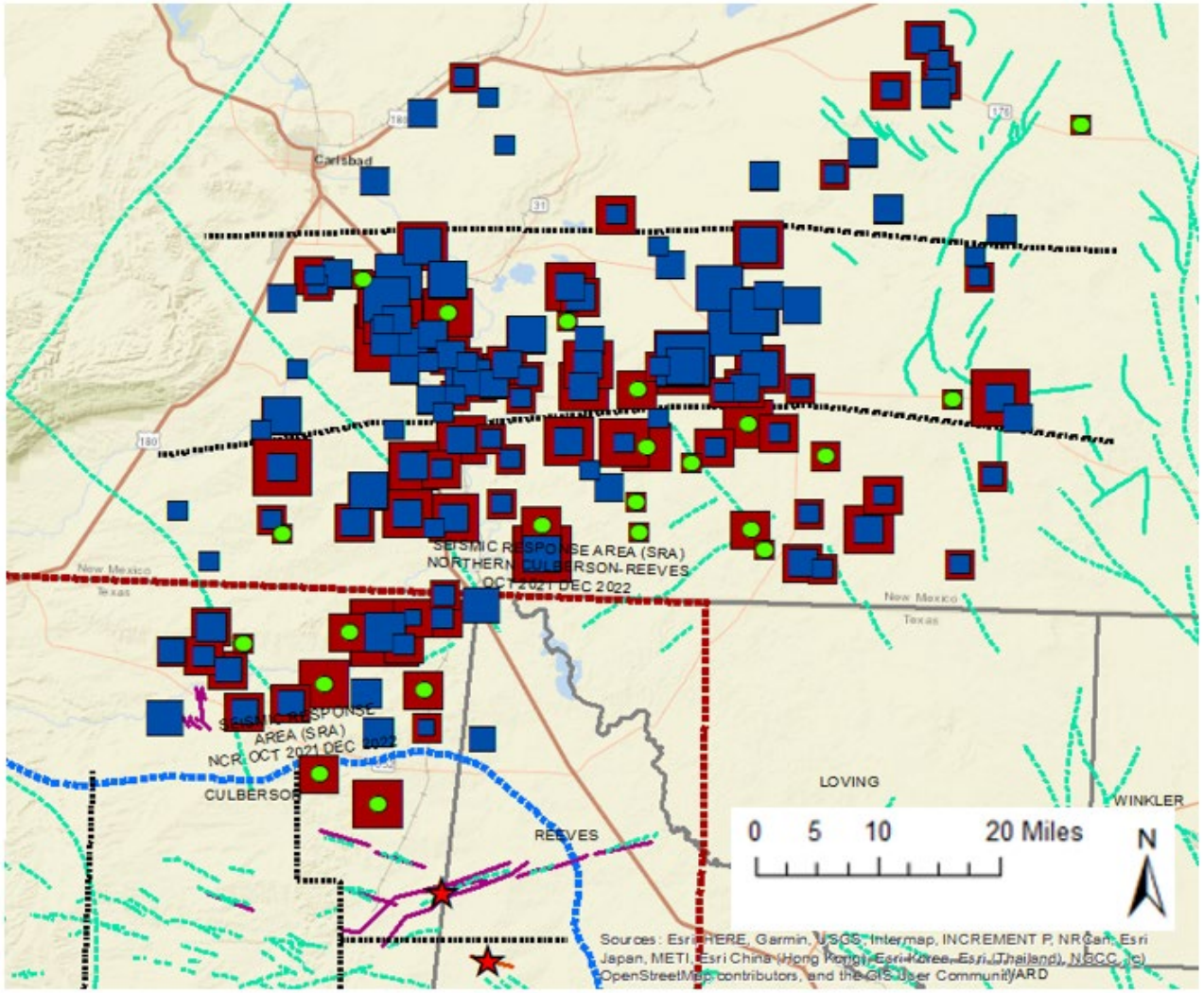
Deep Injection & Seismicity Analysis: NCR, TX and Southern New Mexico

- The graph is useful to estimate spatial/temporal correlation of injection and seismicity.
- Largest volume contributor is New Mexico.
- After the Nov.16, 2022 Coalson event, NCR injection trends downward, and the NM injection trends upward.



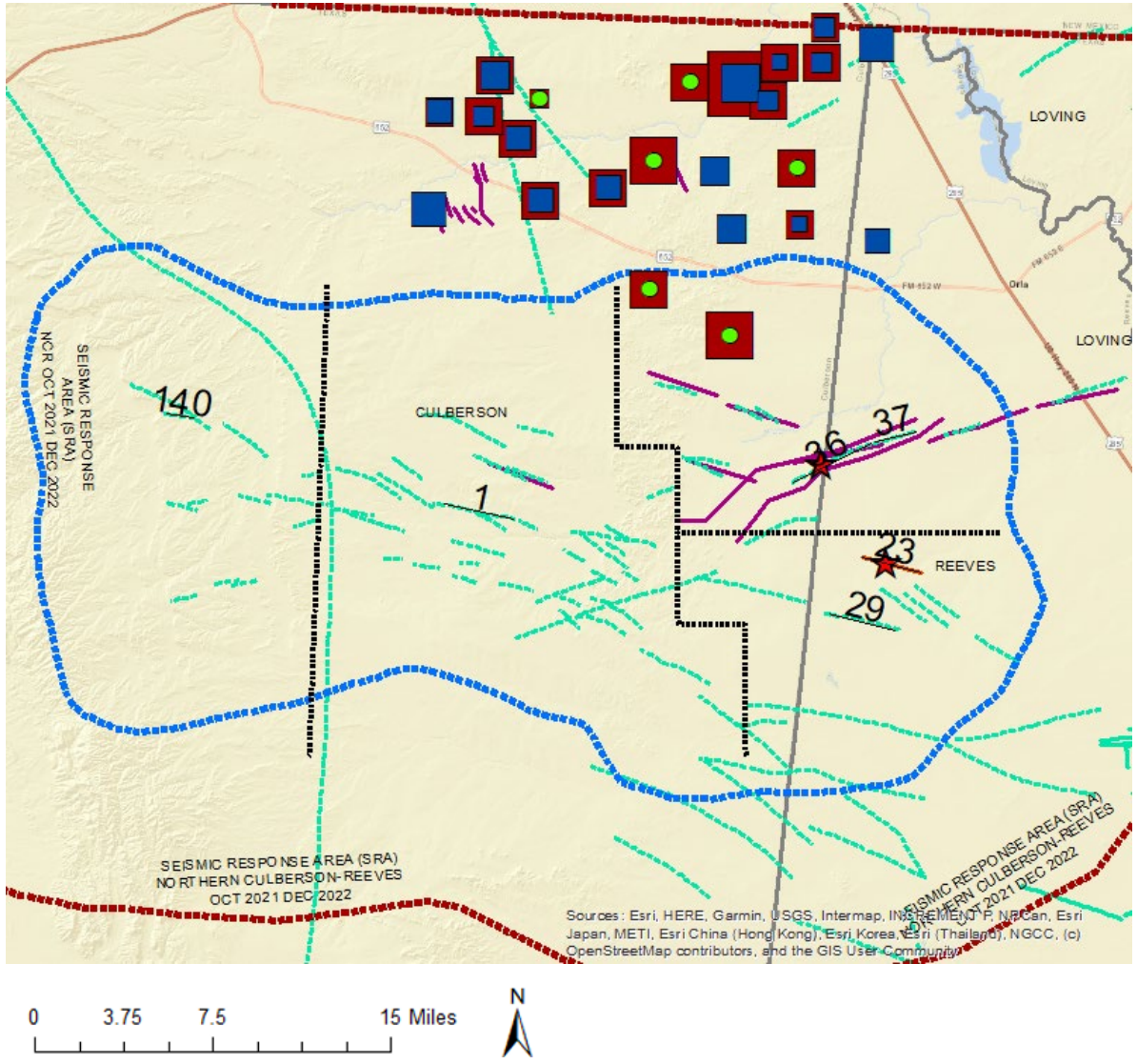
FSP Model 100 Wells & Map of 140 Deep Injection Wells





Map: SES Locations and Nearby FSP Fault Numbers

- SES: Seismic Event of Significance
- Culberson East 11-07-2019
  - Fault no. 1
- Mentone 3-26-2020
  - Fault no. 37
- Culberson West 4-28-2021
  - Fault no. 140
- Coalson 11-16-2022
  - Fault 23

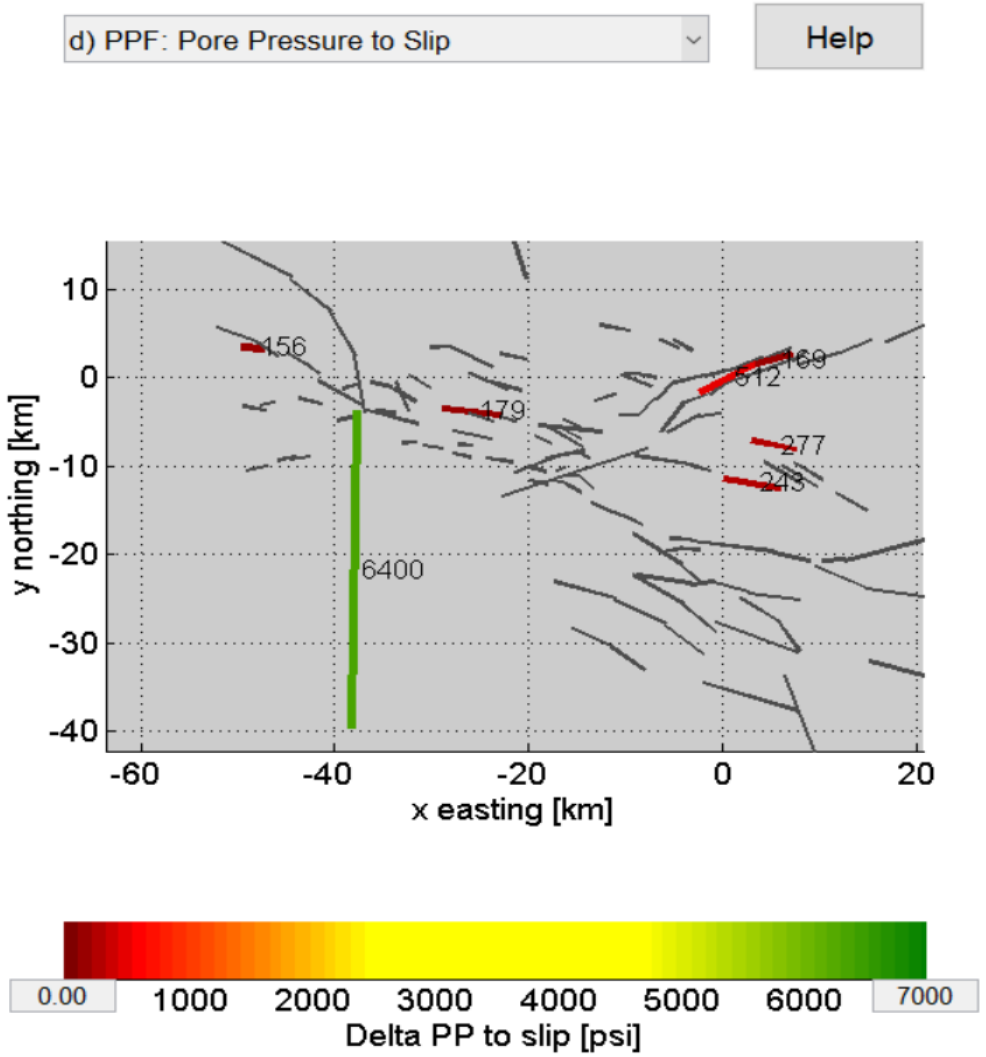


FSP Model Inputs: Stress Data

Stress Data	
Vertical Stress Gradient [psi/ft]	1.11
Max Hor Stress Direction [deg N CW]	85
Reference Depth for Calculations [ft]	16300
Initial Res. Pressure Gradient [psi/ft]	0.44
Upper-Min. Horiz. Stress Gradient [psi/ft]	
Min. Horiz. Stress Gradient [psi/ft]	0.655
Lower-Min. Horiz. Stress Gradient [psi/ft]	
Max. Horiz. Stress Gradient [psi/ft]	0.928
A Phi Parameter	0.6
Reference Friction Coefficient [mu]	0.6

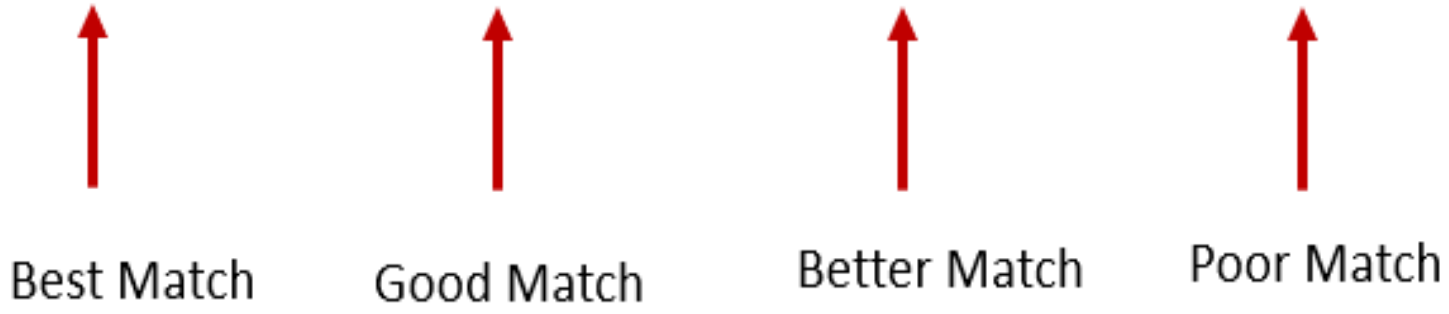
FSP Pore Pressure to Slip

- Pore Pressure to Slip is calculated for each fault by FSP.
- Fault 1, Culberson East: 179 psi
- Fault 23, Coalson: 277 psi
- Fault 29, Coalson: 243 psi
- Fault 36, Mentone: 512 psi
- Fault 37, Mentone: 169 psi
- Fault 140, Culberson West: 156 psi
- Fault not likely to slip is Fault 143: 6400 psi.



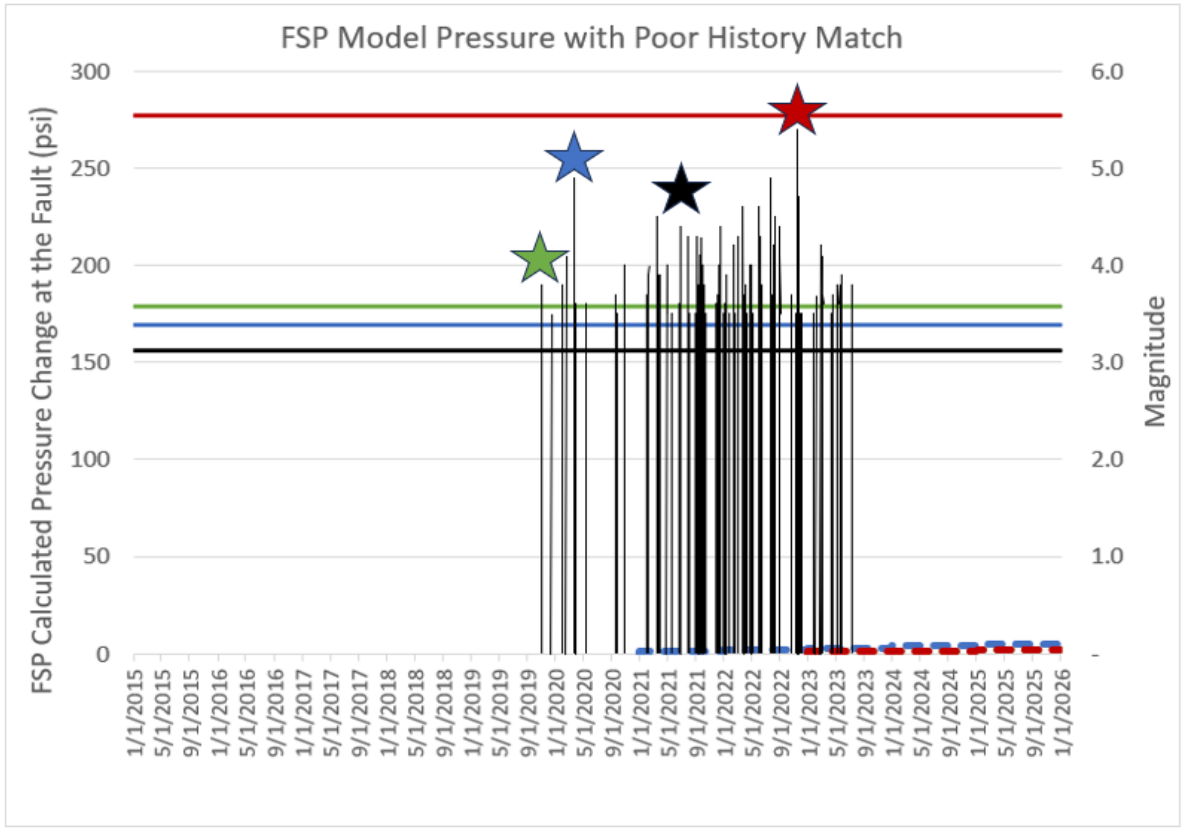
Method of History Matching Using Reservoir Parameters

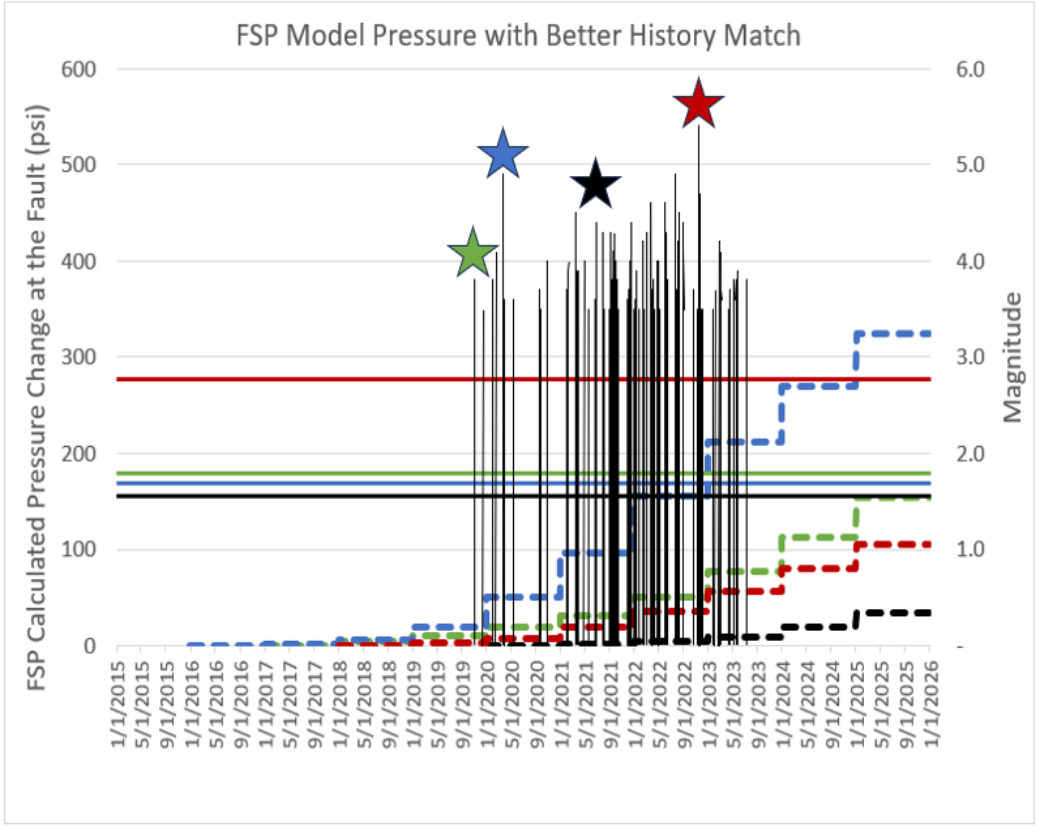
FSP Model Values	RRC Model B-3	RRC Model B-2	RRC Model B-1	Typical Model A
Formations	**Silurian, Devonian**	**Silurian, Devonian**	**Silurian, Devonian**	**Silurian, Devonian**
Reservoir Data				
Aquifer Thickness [ft]	12	10	20	828
Porosity [%]	15	10	15	25
Permeability [mD]	2000	1000	500	300



- Final model acting as a thin, high permeability reservoir

Comparison of Model Runs Poor & Better History Match

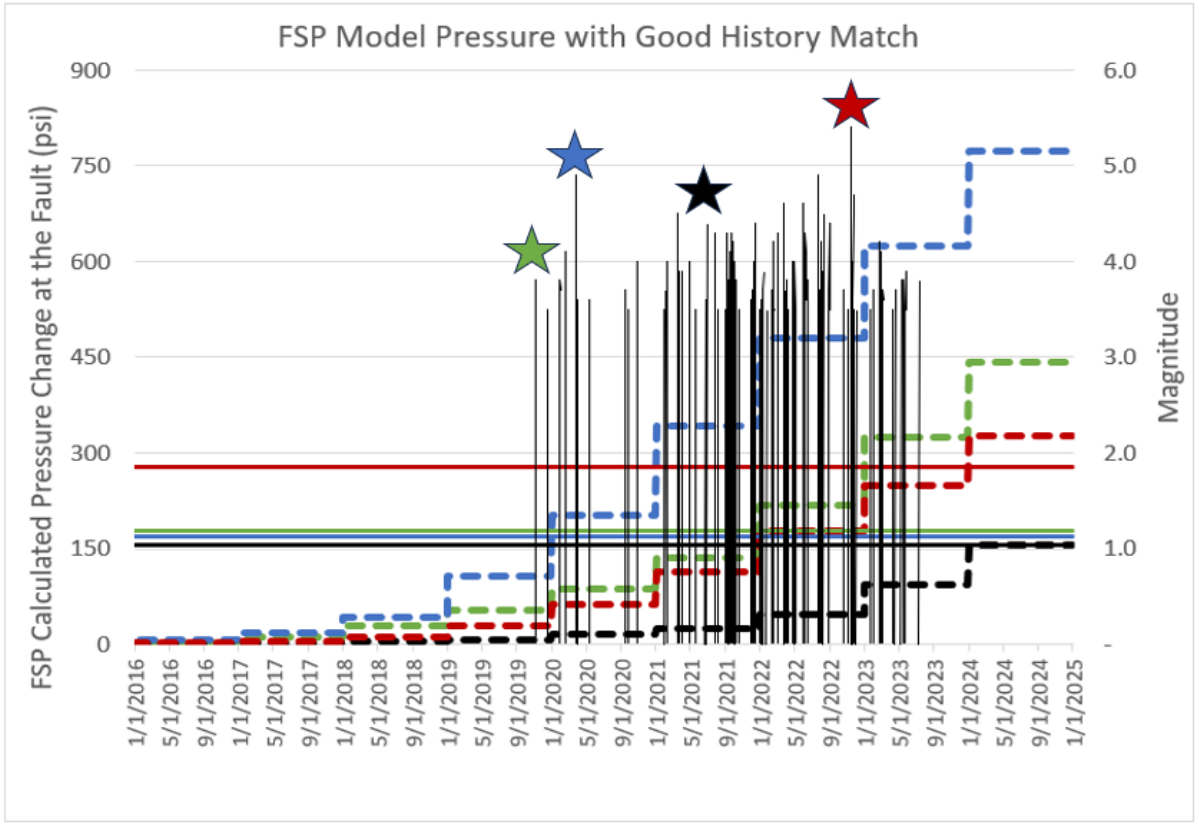


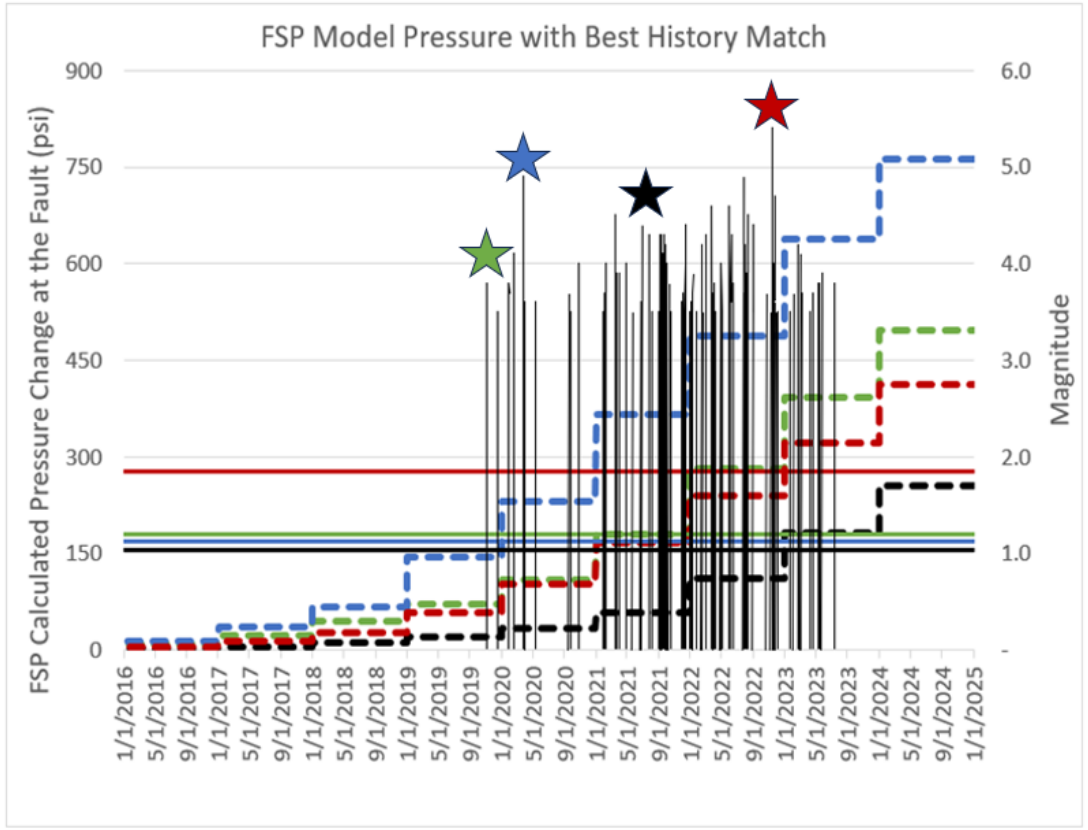


- Pressure Change Fault #1 Culberson East
- Pressure Change Fault #37 Mentone
- Pressure Change Fault #140 Culberson West
- Pressure Change Fault #23 Coalson
- Pore Pressure to Slip Fault #1
- Pore Pressure to Slip Fault #37
- Pore Pressure to Slip Fault #140
- Pore Pressure to Slip Fault #23
- NCR Seismicity M3.5+

- Culberson East SES 11-7-2019
- Mentone SES 3-26-2020
- Culberson West SES 4-28-2021
- Coalson SES 11-16-2022

Comparison of Model Runs Good & Best History Match





- Pressure Change Fault #1 Culberson East
- Pressure Change Fault #37 Mentone
- Pressure Change Fault #140 Culberson West
- Pressure Change Fault #23 Coalson
- Pore Pressure to Slip Fault #1
- Pore Pressure to Slip Fault #37
- Pore Pressure to Slip Fault #140
- Pore Pressure to Slip Fault #23
- NCR Seismicity M3.5+

- Culberson East SES 11-7-2019
- Mentone SES 3-26-2020
- Culberson West SES 4-28-2021
- Coalson SES 11-16-2022

Proceed with 3 Model Runs using Best History Match

Model Run 1

- NCR Wells: OLRP volumes June 2023 – 2033
- NM Wells: Average volumes for each well from June 2023 – 2033

Model Run 2

- NCR Wells: OLRP volumes June 2023-2024
- NCR Wells: 19 wells at 5K BBL/Day 2025, Shut-in 2026 - 2033
- NCR Wells:4 wells at OLRP volumes 2025-2033
- NM Wells: Average volumes for each well from June 2023 – 2033

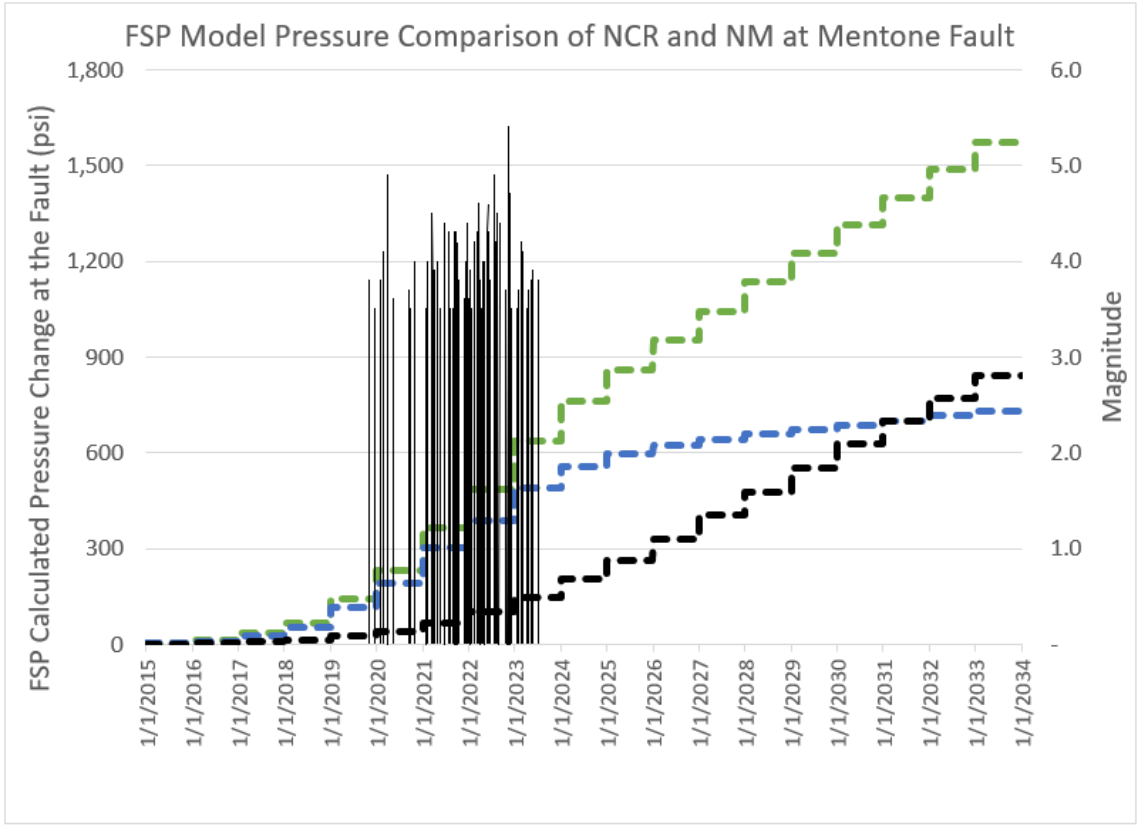
Model Run 3

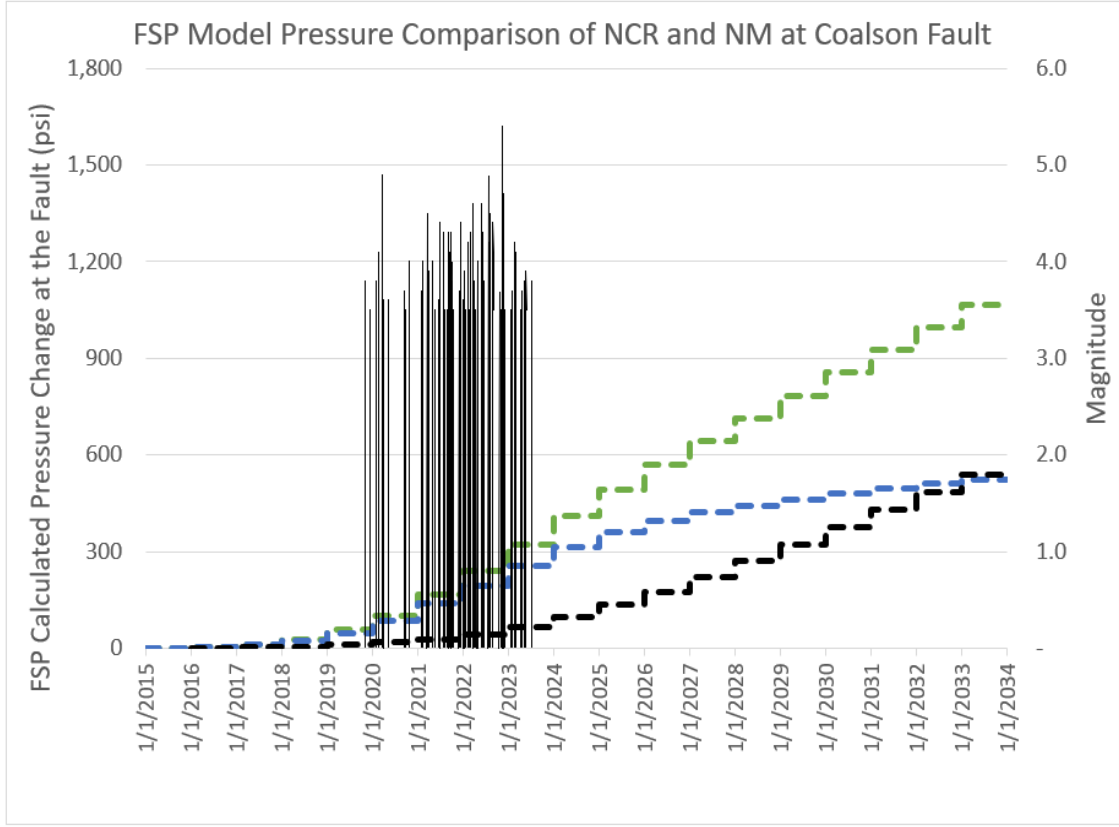
- NCR Wells: OLRP volumes June 2023 – 2033
- NM Wells: Maximum volumes for each well from June 2023 – 2028
- NM Wells: Average volumes for each well from 2029 - 2033

Definition of Terms

- NCR Wells OLRP Volumes
  - 19 Wells at 7.5K BBL/Day
  - 4 Wells at 10K BBL/Day
- NM Wells Average Volume
  - 30MM BBL/Month
- NM Wells Maximum Volume
  - 41MM BBL/Month

FSP Model Run 1

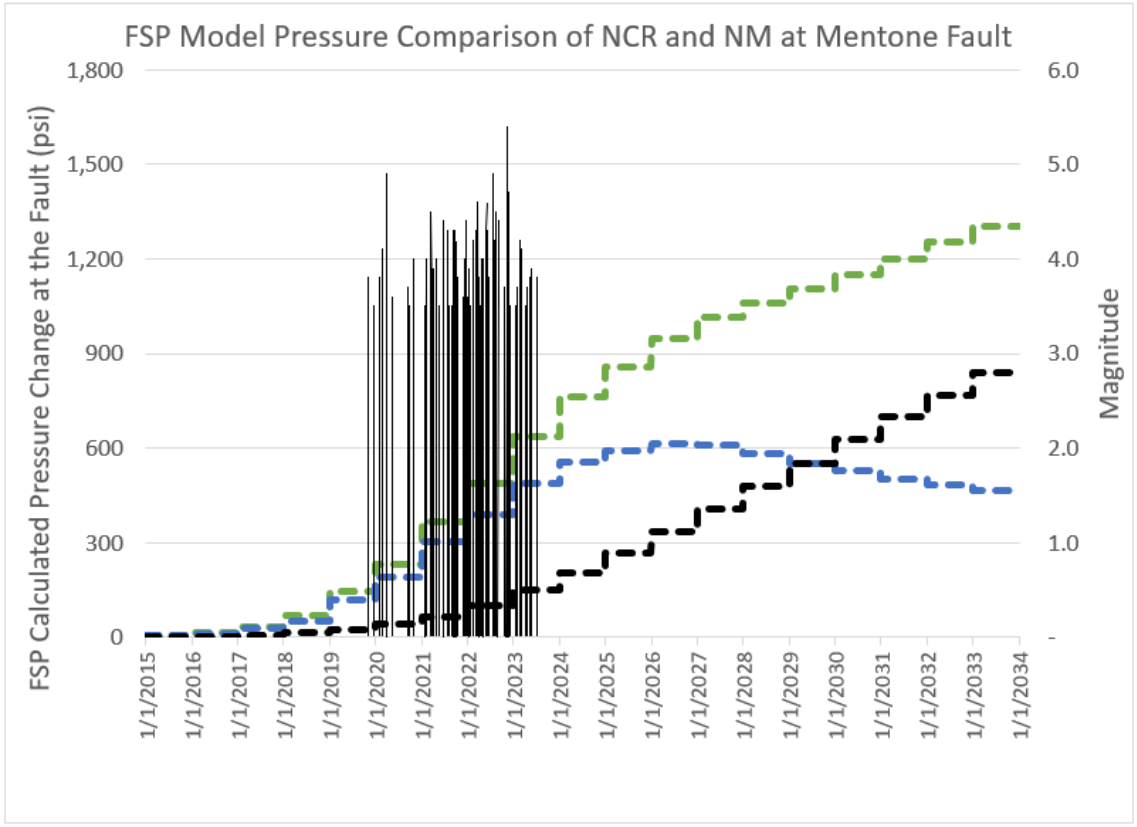


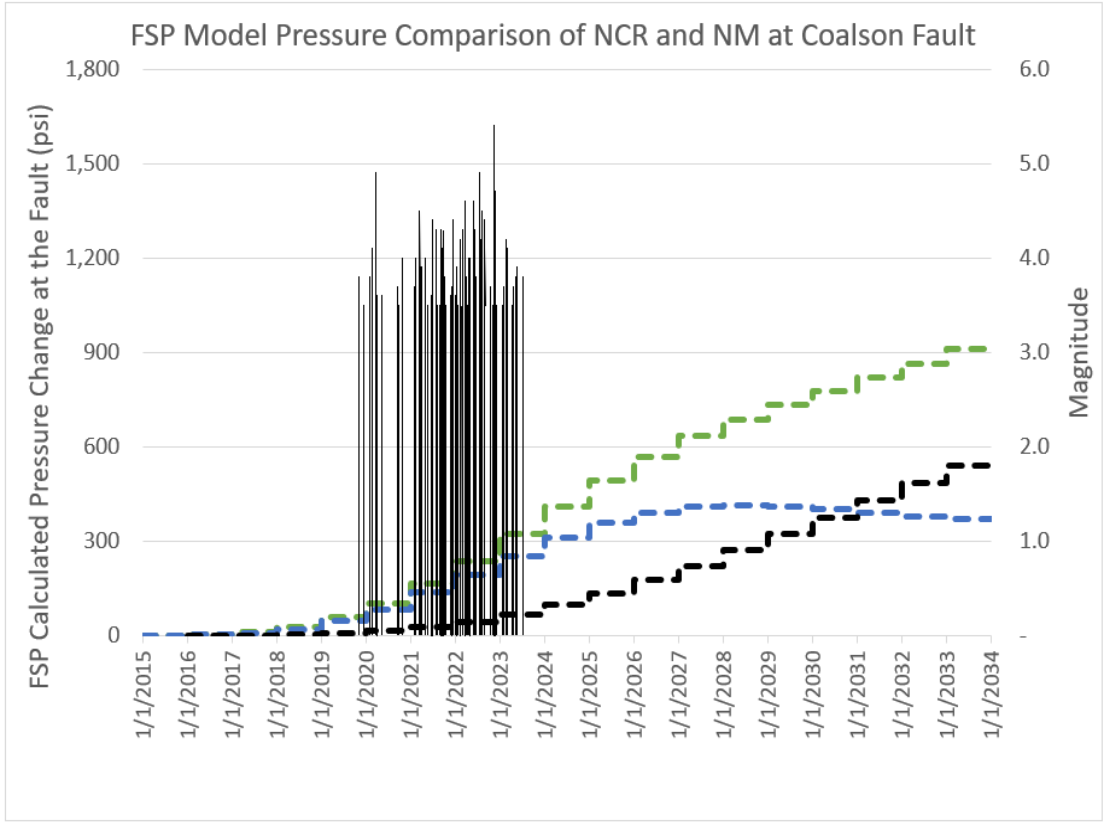


Total Pressure Change at Fault
NCR Contribution to Pressure Change at Fault
NM Contribution to Pressure Change at Fault
NCR Seismicity M3.5+

- Model Run 1
- NCR Wells: OLRP volumes June 2023 – 2033
- NM Wells: Average volumes for each well from June 2023 – 2033

FSP Model Run 2





Total Pressure Change at Fault

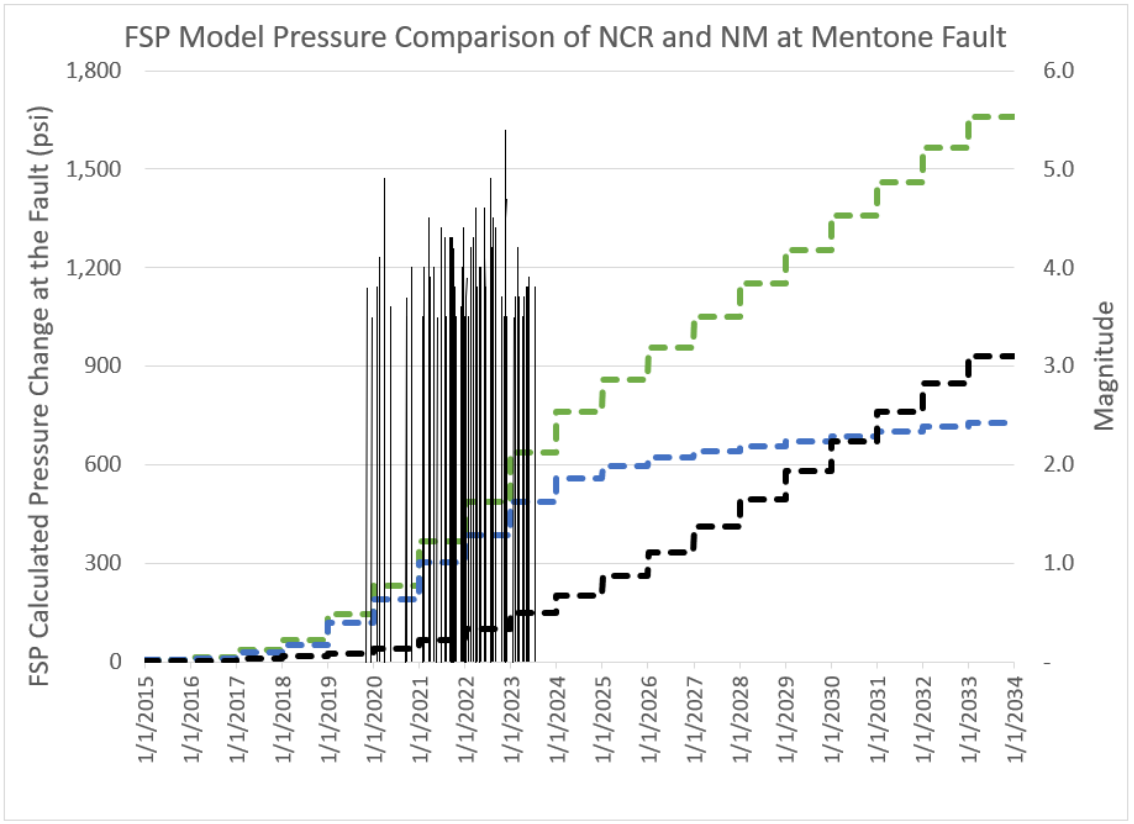
NCR Contribution to Pressure Change at Fault

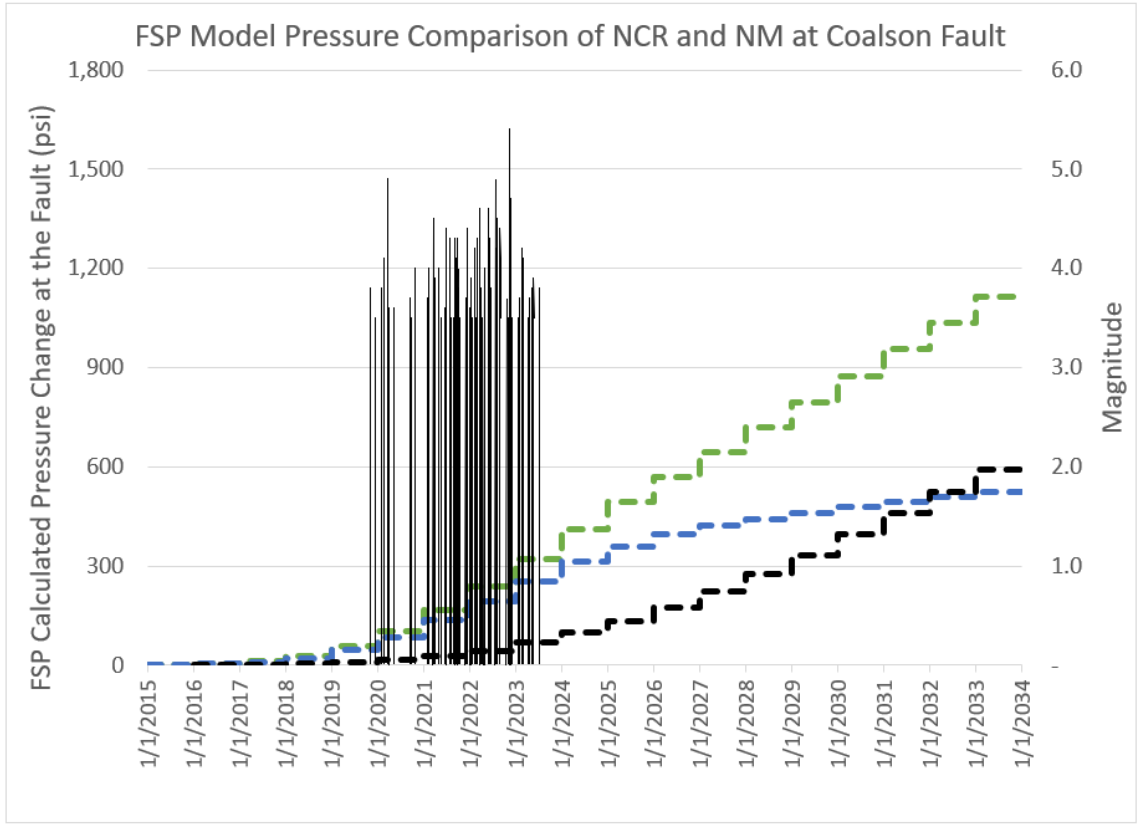
NM Contribution to Pressure Change at Fault

NCR Seismicity M3.5+

- Model Run 2
- NCR Wells: OLRP volumes June 2023 – 2024
- NCR Wells: 19 Wells at 5K BBL/day 2025, Shut-In 2026 – 2033
- NCR Wells: 4 Wells at OLRP volumes 2025 - 2033
- NM Wells: Average volumes for each well from June 2023 – 2033

FSP Model Run 3





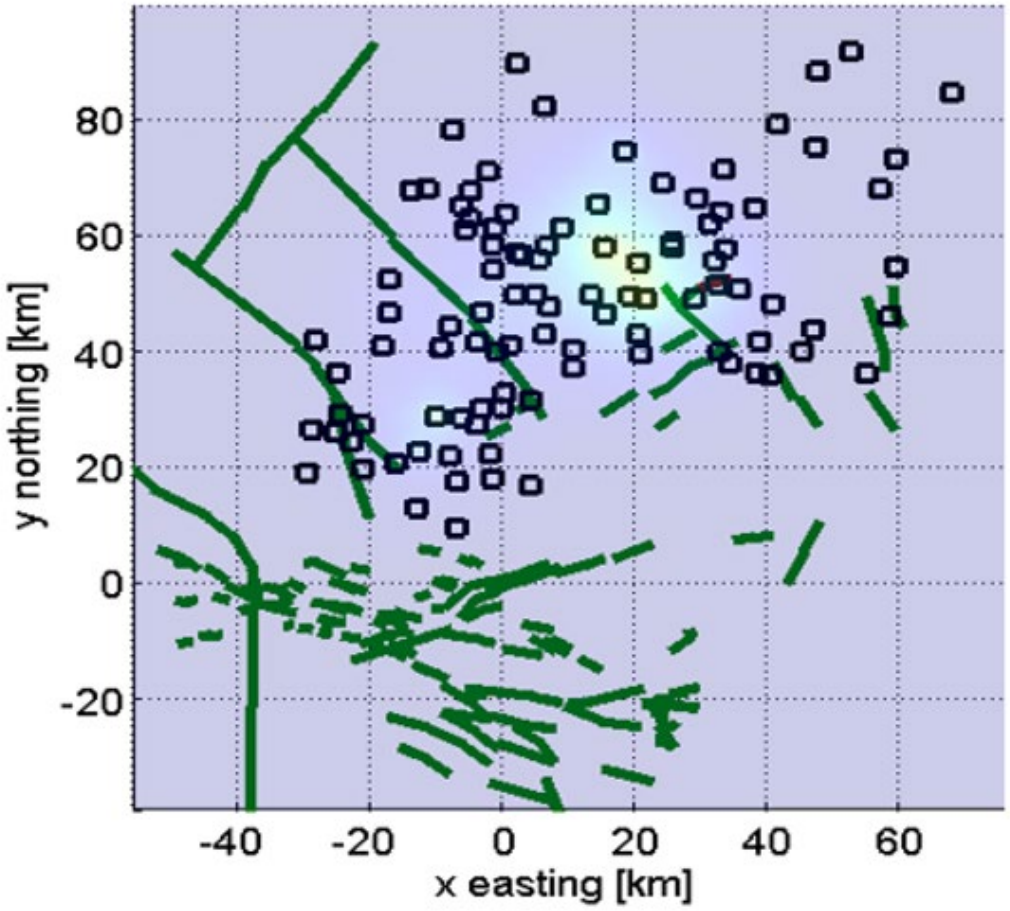
- Total Pressure Change at Fault
- NCR Contribution to Pressure Change at Fault
- NM Contribution to Pressure Change at Fault
- NCR Seismicity M3.5+

- Model Run 3
- NCR Wells: OLRP Volumes June 2023 – 2033
- NM Wells: Max. Volumes for each well from June 2023 – 2028
- NM Wells: Avg. Volumes for each well from 2029 – 2033

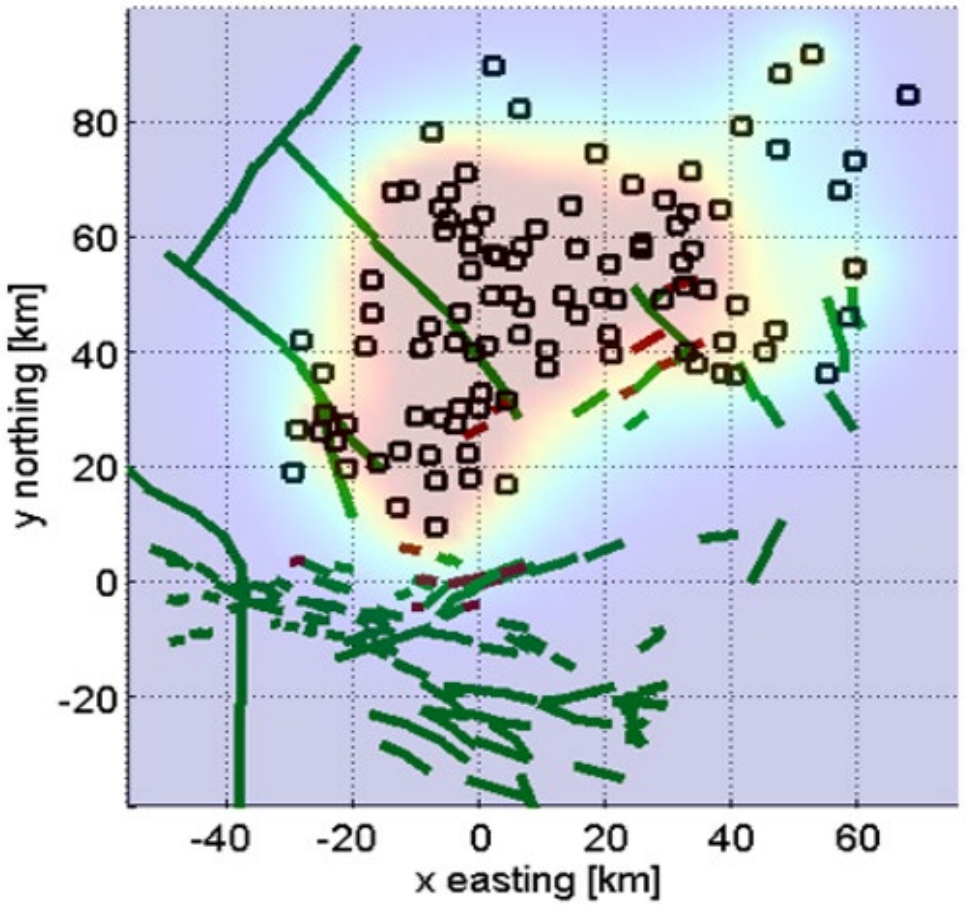
Pressure Contributions of NM & NCR

	Model Run 1	Model Run 2	Model Run 3
Mentone Fault No. 37	NM > NCR in 2032	NM > NCR in 2030	NM > NCR in 2031
Coalson Fault No. 23	NM > NCR in 2033	NM > NCR in 2031	NM > NCR in 2032

FSP Model Run 1 Years 2015 & 2020

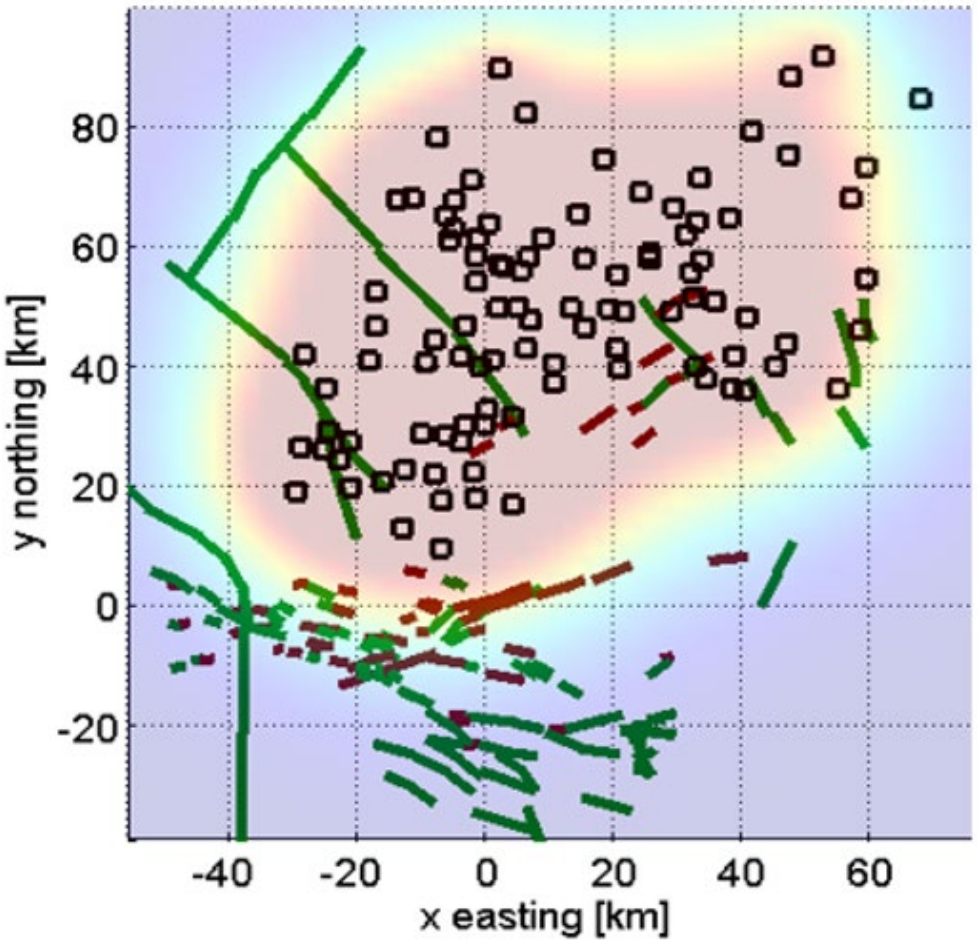


Year: 2015

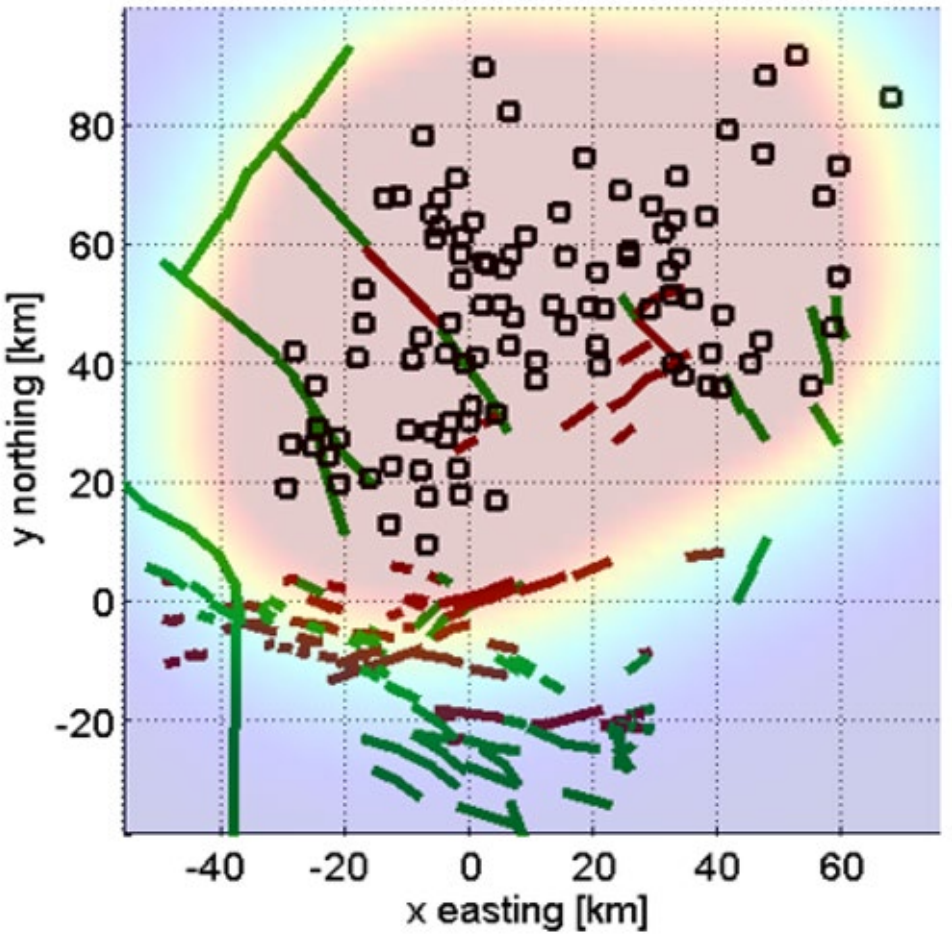


Year: 2020

FSP Model Run 1 Years 2023 & 2025

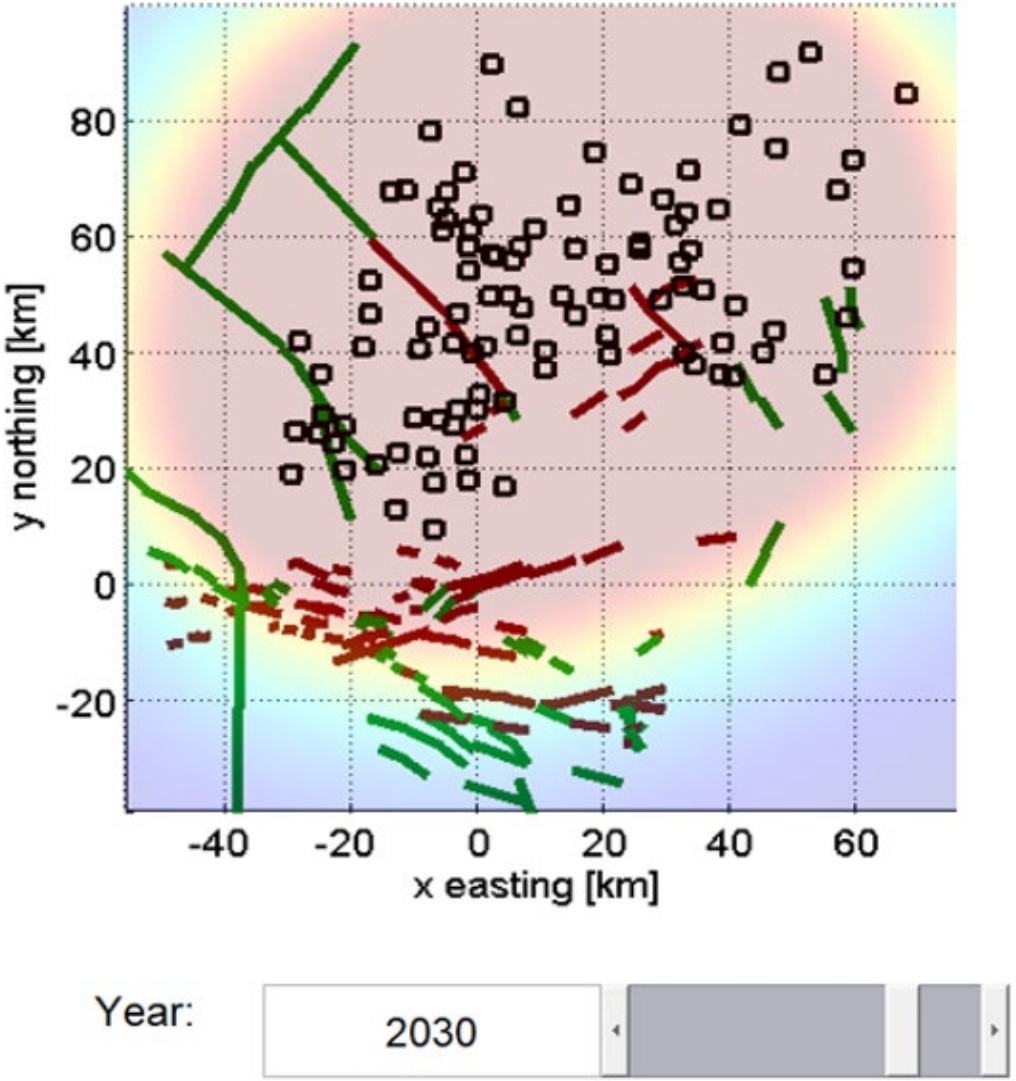


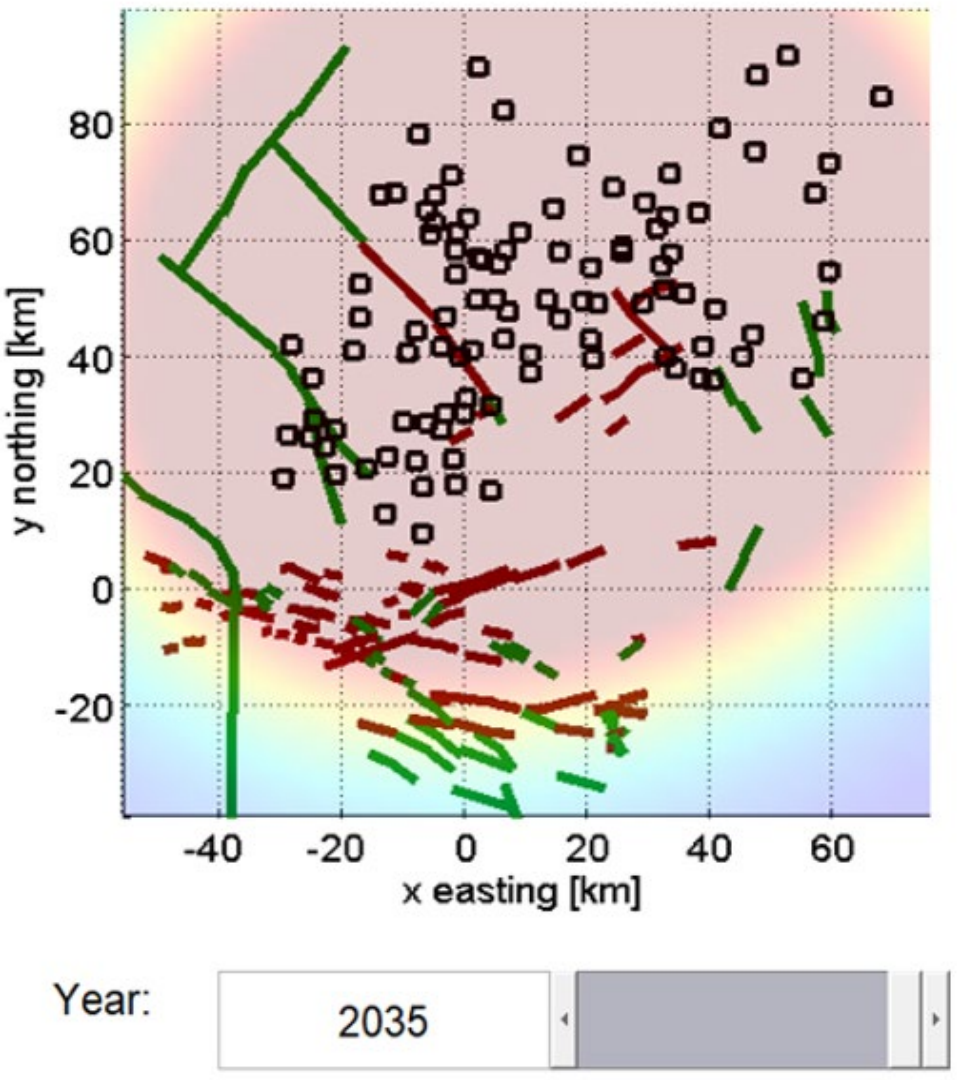
Year: 2023



Year: 2025

FSP Model Run 1 Years 2030 & 2035





Conclusions (1 of 2)

- NMOCD & RRC injection volume history through April, 2023.
- Combining 140 wells into 100 wells was some effort, but it did work.
- Best history match performance:
  - Culberson East Fault No. 1 – Fault Slip is 1 year late.
  - Mentone Fault No. 37 – Fault Slip is on time.
  - Culberson West Fault No. 140 – Fault Slip is 1 year late.
  - Coalson Fault No. 23 – Fault Slip is on time.

Conclusions (2 of 2)

- Mentone Fault:
  - The cumulative pressure on the Mentone Fault is continously increasing.
  - Currently Texas wells are exerting more pressure on the fault.
  - NM will exceed Texas wells by 2030-2032.
- Coalson Fault:
  - The cumulative pressure on the Coalson Fault is continuously increasing.
  - Currently Texas wells are exerting more pressure on the fault.
  - NM will exceed Texas wells by 2031-2033.
- Recommendation:
  - Share and compare results with BEG (done).

Acknowledgements

- UIC Team and all the folks working on induced seismicity at RRC
- Sikandar Sohail, RRC intern & senior in Petroleum Engineering at UT Austin
- Staff of New Mexico Oil Conservation Division
- Ankush Singh, Tim Tyrrell (circa 2018-2019)
- Stefan Hussenoeder, ExxonMobil
- Todd Reynolds, FSP methodology of modifying reservoir parameters to achieve good history matching in 2022
- Guidance and support over several years to present from BEG/TexNet/CISR
  - Some of those folks: Peter Hennings, Alan Morris, Alexandros Savvaidis, Lily Horne, Katie Smye, JP Nicot, Aaron Averett
  - Bureau of Economic Geology (BEG)
  - Center for Injection and Seismicity Research (CISR)