FSP Analysis Example

Apache Mountains Main Fault, Delaware Basin, west Texas, USA

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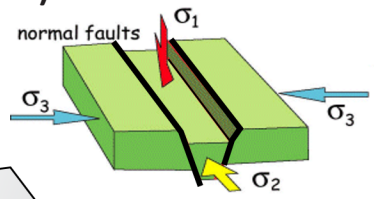
Bureau of Economic Geology

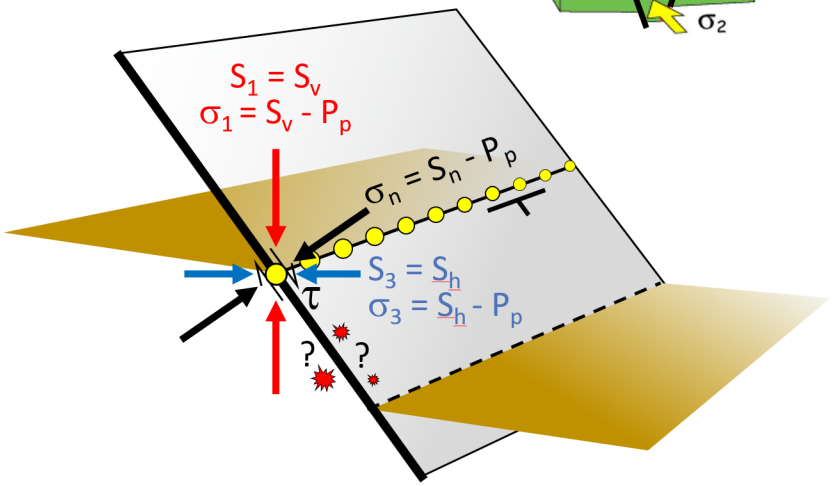
Fault Rupture Modeling and Sensitivity Analysis

Fault Slip Potential Analysis (FSP)

Andersonian Faulting *Law*:

normal fault case





Slip occurs when: $\tau/\sigma_n \geq \mu$

μ, the coefficient of friction, is typically assumed (~0.6-0.8) and stress state is typically balanced to criticality

Coulomb Failure Function: $CFF = \tau - \mu\sigma_n$

So, we care about: τ, σ_n, μ at ○ analysis points

P. Hennings

Analysis of fault slip potential is used to assess the sensitivity or likelihood of actual or hypothetical faults to slip or rupture as subject to natural or anthropogenically-altered subsurface conditions

Analysis of slip potential can be performed either deterministically (**DFSP**) or probabilistically (**PFSP**) at either natural (unperturbed) Pp or anthropogenically-elevated (perturbed) Pp

see Walsh and Zoback (2016), Hennings et al. (2021)

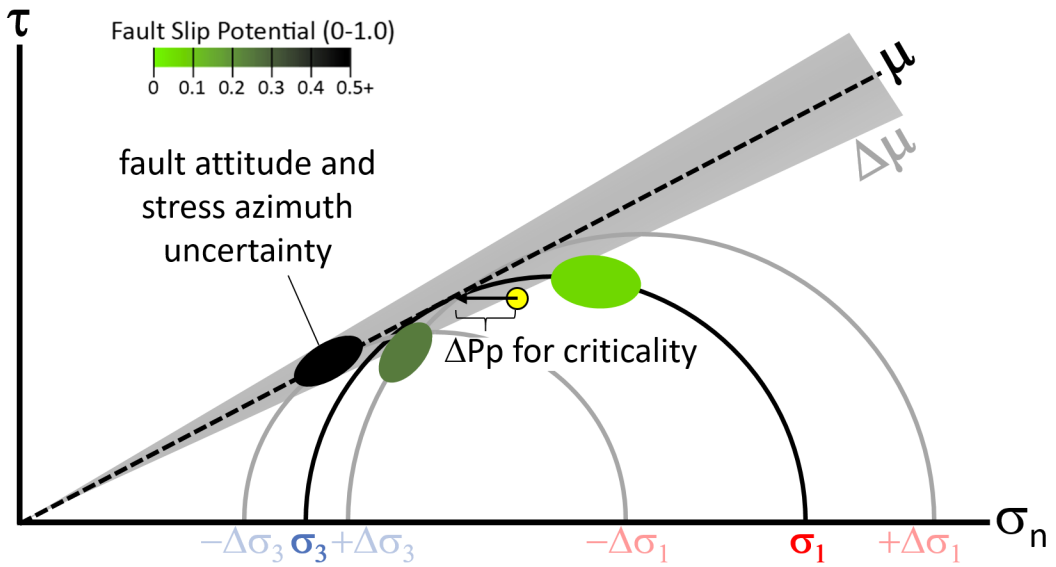


Figure: Introduction to Fault Slip Potential analysis (FSP) (P. Hennings)

Publication Resources for Fault Slip Potential Analysis

Walsh, F.R., and Zoback, M.D., 2016, Probabilistic assessment of potential fault slip related to injection-induced earthquakes: Application to north-central Oklahoma, USA: Geology, doi: 10.1130/G38275.1.

Lund Snee, J.E., and Zoback, M.D., 2020, Multiscale variations of the crustal stress field throughout North America: Nature Communications, doi: 10.1038/s41467-020-15841-5

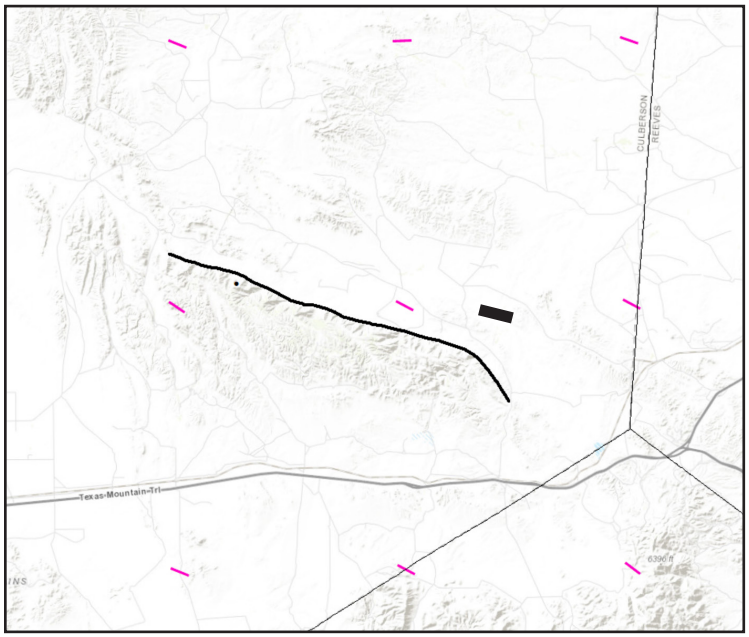
Hennings, P.H., Lund Snee, J-E., Osmond, J.L., DeShon, H.R., Dommisse, R., Horne, E.A., Lemons, C. and Zoback, M.D., 2019, Injection-Induced Seismicity and Fault Slip Potential in the Fort Worth Basin, Texas, Bulletin of the Seismological Society of America, https://doi.org/10.1785/0120190017

Hennings, P.H., 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, 2021, Pore Pressure Threshold and Fault Slip Potential for Induced Earthquakes in the Dallas-Fort Worth Area of North Central Texas, Geophysical Research Letters, https://doi.org/10.1029/2021GL093564

Hennings, P.H., Dvory, N., Horne, E.A., Li, P., Savvaidis, A., Zoback, M., 2021, Stability of the Fault Systems that Host Induced Earthquakes in the Delaware Basin of West Texas and Southeast New Mexico, The Seismic Record, https://doi.org/10.1785/03202100202

Morris, A.P., Hennings, P.H., Horne, E.A., Smye, K.M., (2021) Stability of Basement-Rooted Faults in the Delaware Basin of Texas and New Mexico, USA, Journal of Structural Geology, https://doi.org/10.1016/j.jsg.2021.104360

Fault Slip Potential demonstration and discussion



Example Fault - the outcropping Apache Mountains flanking fault, southwest Delaware Basin margin

Fault Inputs

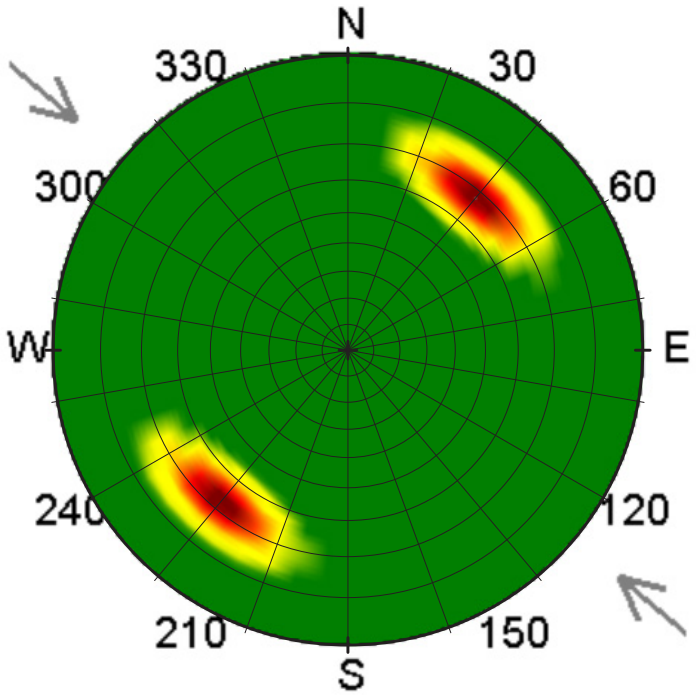
Friction Coefficient mu: 0.6

○ Random Faults

◉ Enter Faults

	X [East km]	Y [North km]	Strike [Deg]	Dip [Deg]	Length [km]
1	575.2093	3.4444e+03	328.2645	60	1.0006
2	574.6693	3.4452e+03	327.0323	60	1.0006
3	574.1006	3.4460e+03	322.9094	60	1.0006
4	573.4860	3.4468e+03	322.0265	60	1.0006
5	572.8231	3.4476e+03	309.8551	60	1.0006
6	571.9983	3.4481e+03	299.8475	60	1.0006
7	571.0835	3.4485e+03	289.0996	60	1.0006
8	570.1377	3.4488e+03	288.1622	60	1.0006
9	569.1711	3.4491e+03	281.8064	60	1.0006
10	568.2032	3.4493e+03	287.1735	60	1.0006
11	567.2476	3.4496e+03	287.2702	60	1.0006
12	566.2876	3.4499e+03	284.1576	60	1.0006
13	565.3117	3.4501e+03	282.3963	60	1.0006
14	564.3344	3.4504e+03	282.4392	60	1.0006
15	563.3578	3.4506e+03	282.6633	60	1.0006
16	562.3815	3.4508e+03	282.6633	60	1.0006

Polar Plot - representative of stress state in terms of pore pressure increase required to achieve instability



◉ Specify All Three Stress Gradients [psi/ft]

○ Use A-Phi Model

Vertical Stress Gradient [psi/ft]	1.12
Max Horiz. Stress Gradient [psi/ft]	0.9
Min Horiz. Stress Gradient [psi/ft]	0.63
Max Hor Stress Direction [deg N CW]	
Initial Res. Pressure Gradient [psi/ft]	
Reference Depth for Calculations [ft]	

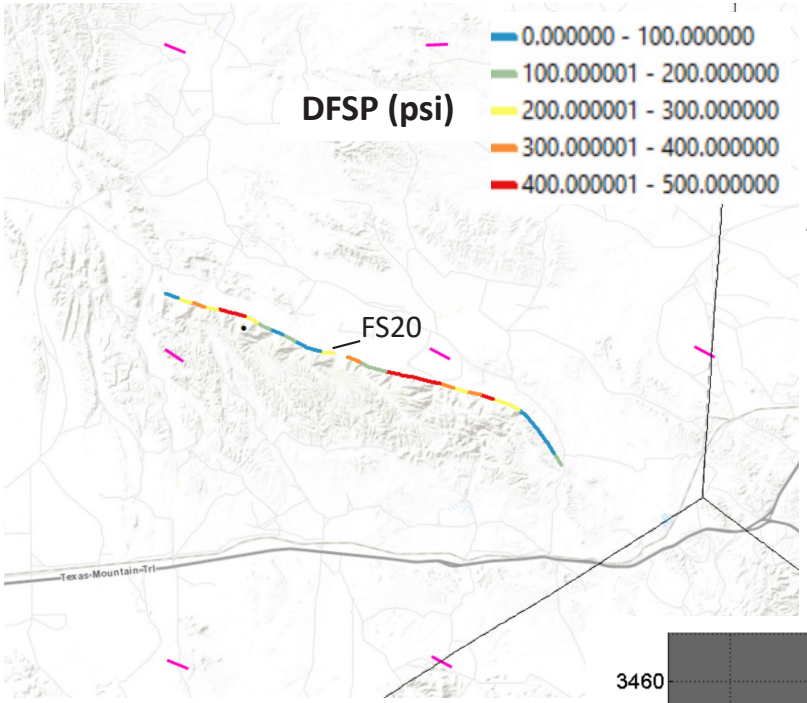
○ Specify All Three Stress Gradients [psi/ft]

◉ Use A-Phi Model

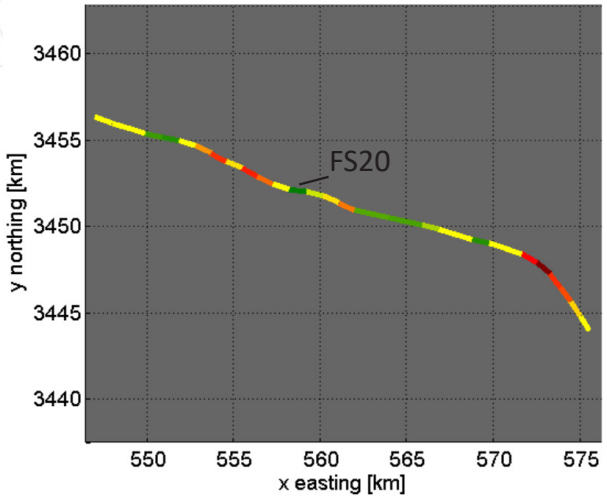
Vertical Stress Gradient [psi/ft]	1.12
A-Phi Parameter	0.55102
☑ Min Horiz Stress Grad Available [psi/ft]	0.63
Max Hor Stress Direction [deg N CW]	130
Initial Res. Pressure Gradient [psi/ft]	0.4
Reference Depth for Calculations [ft]	10000

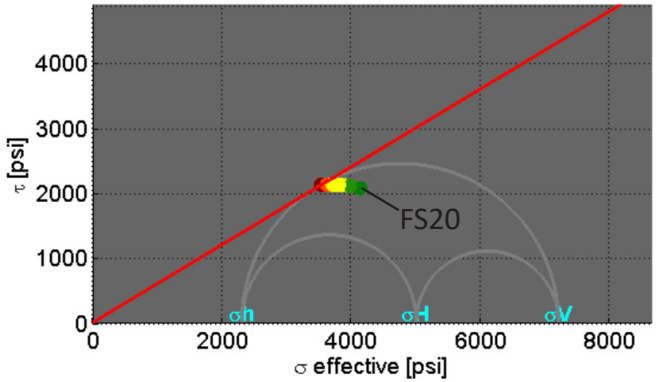
Stress Inputs - deterministic vs A_ϕ specification

Example of deterministic Fault Slip Potential (DFSP)

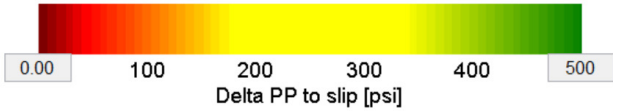


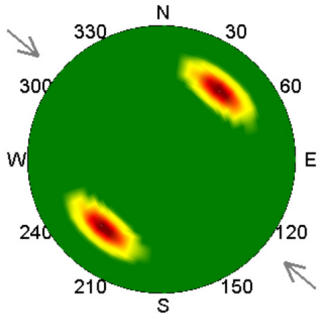
Apache Mountains Fault DFSP result

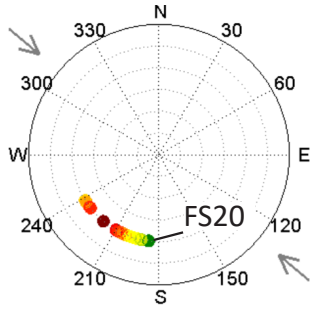




Apache Mountains Fault DFSP result and Mohr stress plot representation





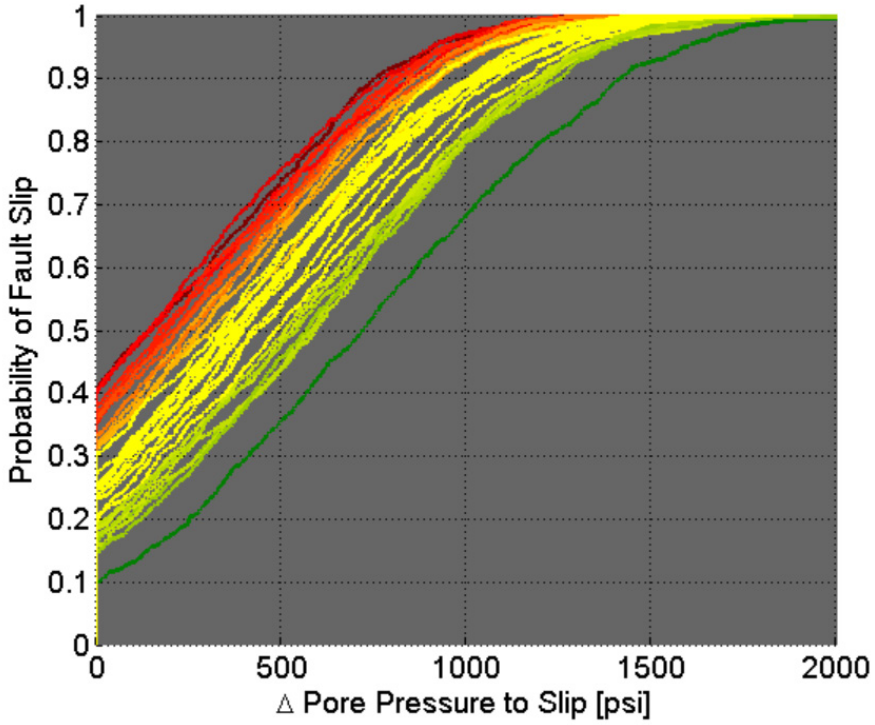


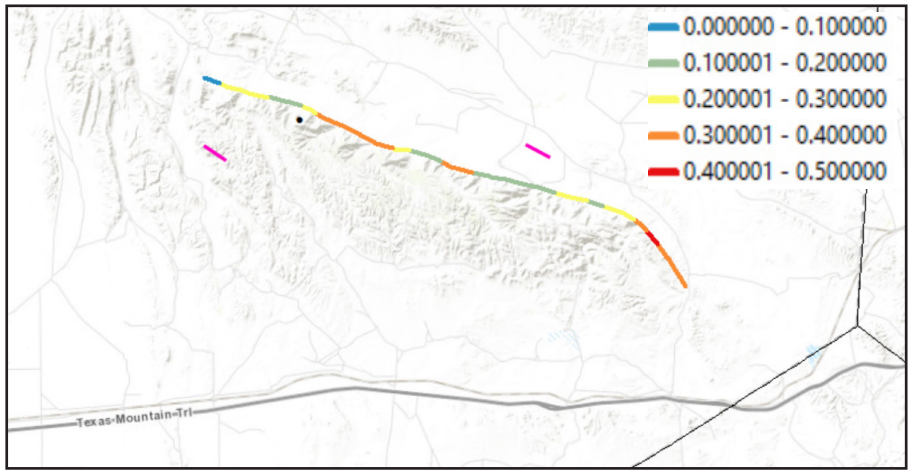
Probabilistic Fault Slip Potential (PFSP) inputs

Gradient based stress model is being used

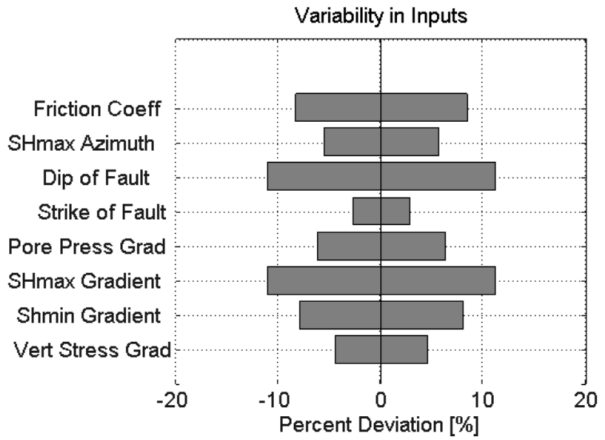
	Plus/Minus
Vertical Stress Grad [1.12 psi/ft]	0.05
Min Horiz. Grad [0.63 psi/ft]	0.05
Max Horiz. Grad [0.9 psi/ft]	0.1
Initial PP Grad [0.4 psi/ft]	0.025
Strike Angles [varying, degrees]	5
Dip Angles [60 degrees]	10
Max Horiz. Stress Dir [130 degrees]	10
Friction Coeff Mu [0.6]	0.05

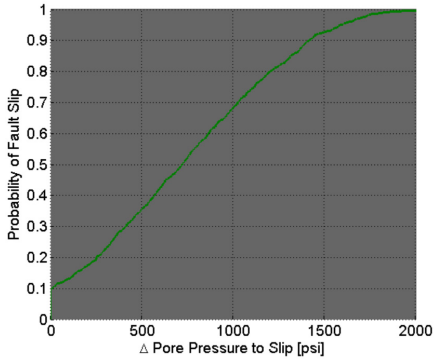
specified uncertainty ranges for PFSP analysis

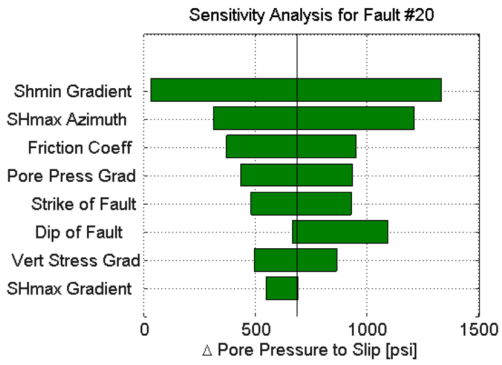




impact of geomechanical parameters on DFSP result







DFSP result for fault segment 20 and sensitivity analysis

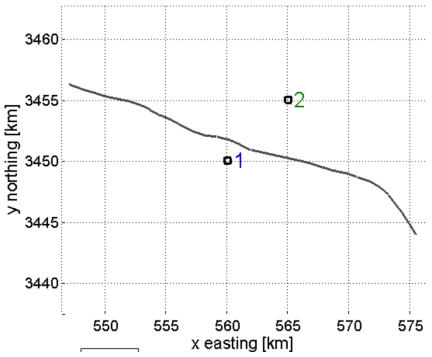
Evolution of Fault Slip Potential (PFSP) by Pore Pressure Change

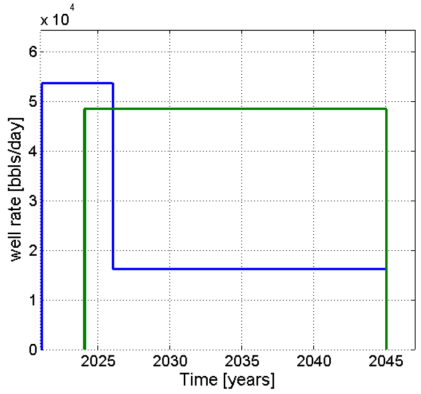
Enter Hydrologic Parameters

Load External Hydrologic Model

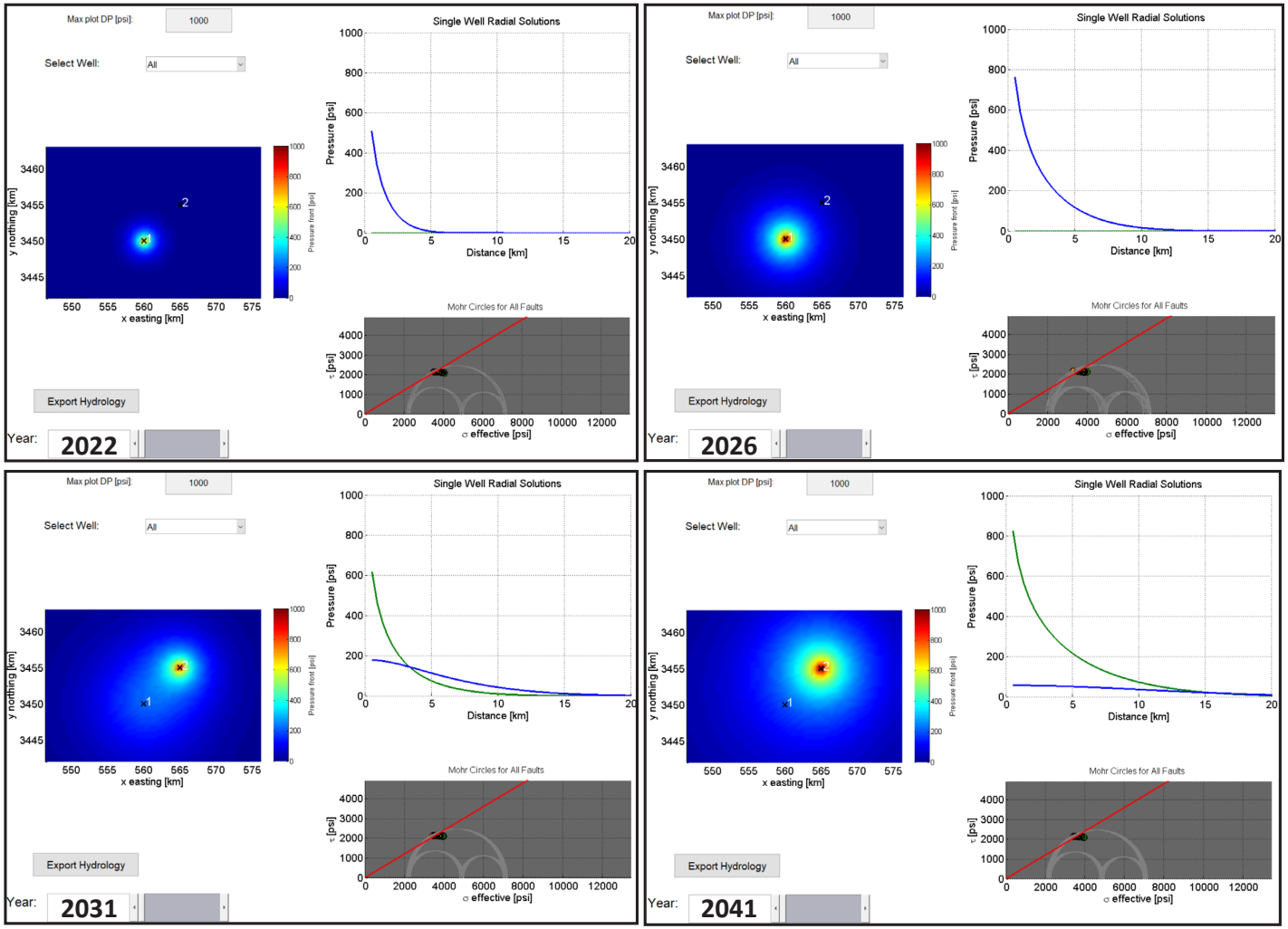
Aquifer Thickness [ft]	200
Porosity [%]	10
Permeability [mD]	100

aquifer parameters for pore pressure simulation



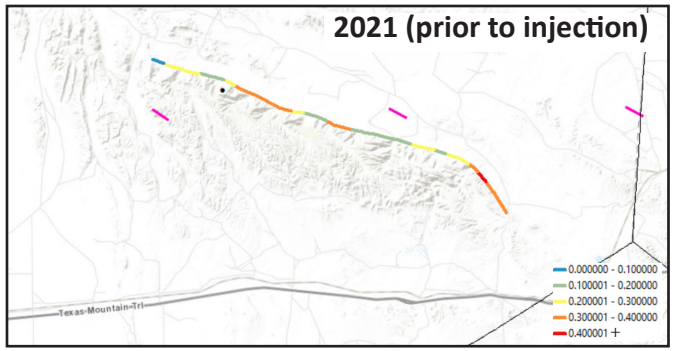


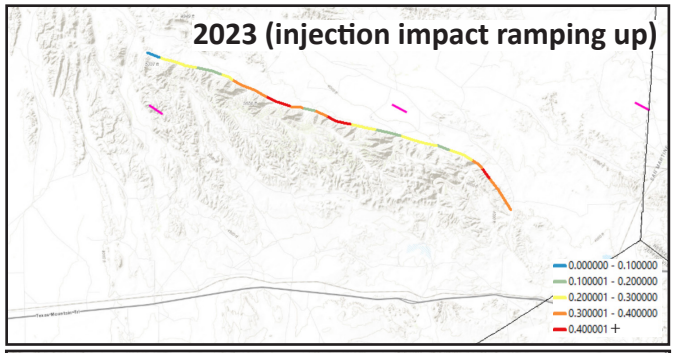
injection well configuration and pumping history

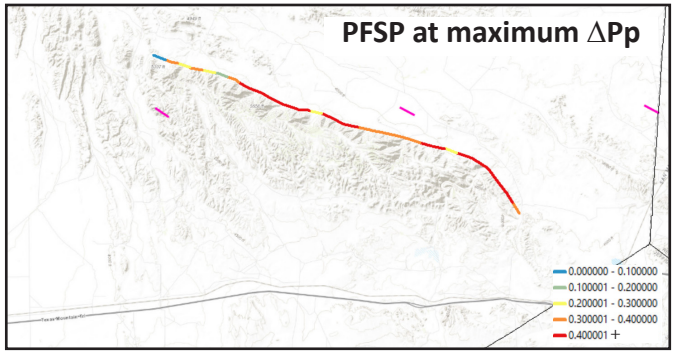


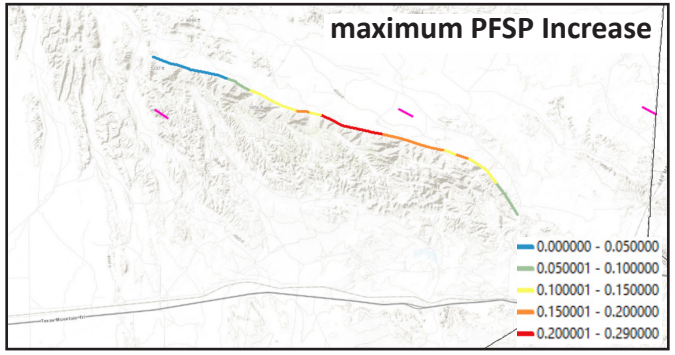
pore pressure model results and Mohr fault stability plots

summary PFSP maps









ΔPp and PFSP evolution at each fault segment