FSP Modeling and Its Use in the Permitting / Protested Hearing Process

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Outline

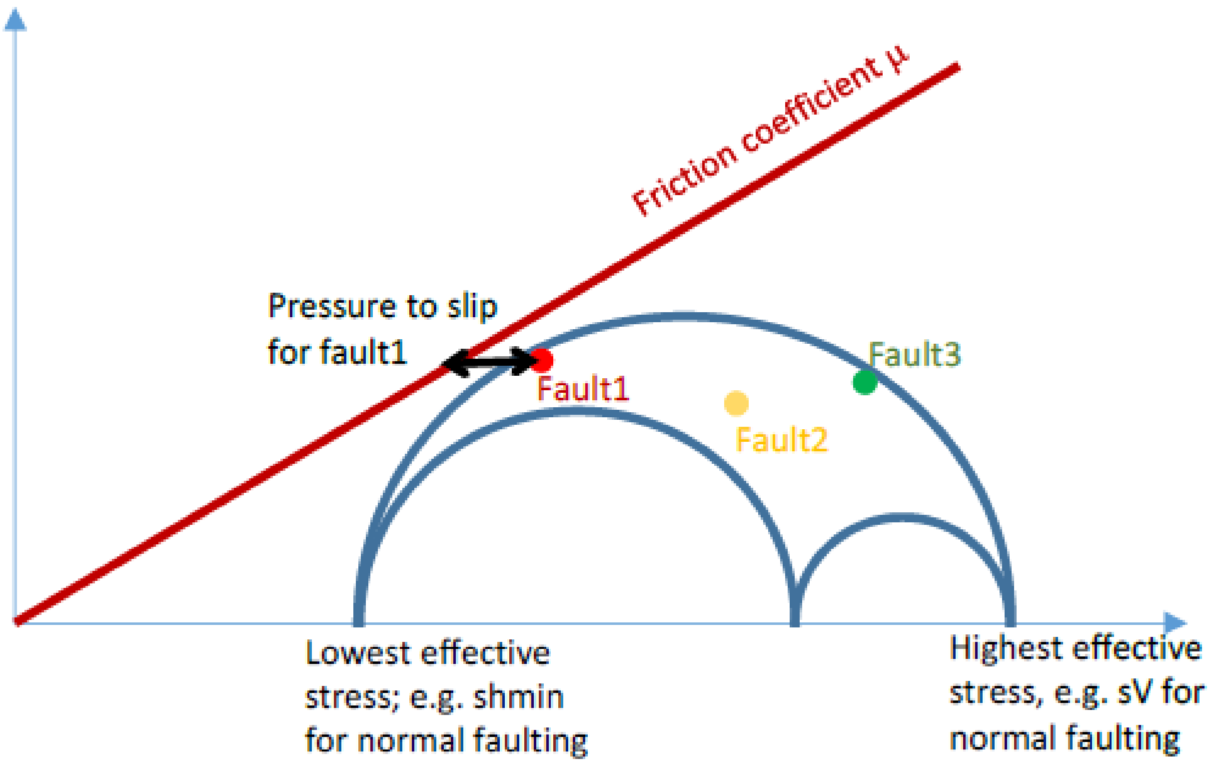
- What is FSP?
- Model Set-up and Data Sources
- Interpreting Results
- FSP Limitations and Assumptions
- References and Resources

What is FSP?

- Fault Slip Potential
  - Program Developed by Stanford Center for Induced and Triggered Seismicity with industry collaboration
- Provides probabilistic estimate of fault slip due to nearby fluid injection
  - Calculates probability of a fault exceeding the Mohr-Coulomb slip criteria
  - An additional tool used to help assist regulators in their assessment of the potential for injection-induced seismicity

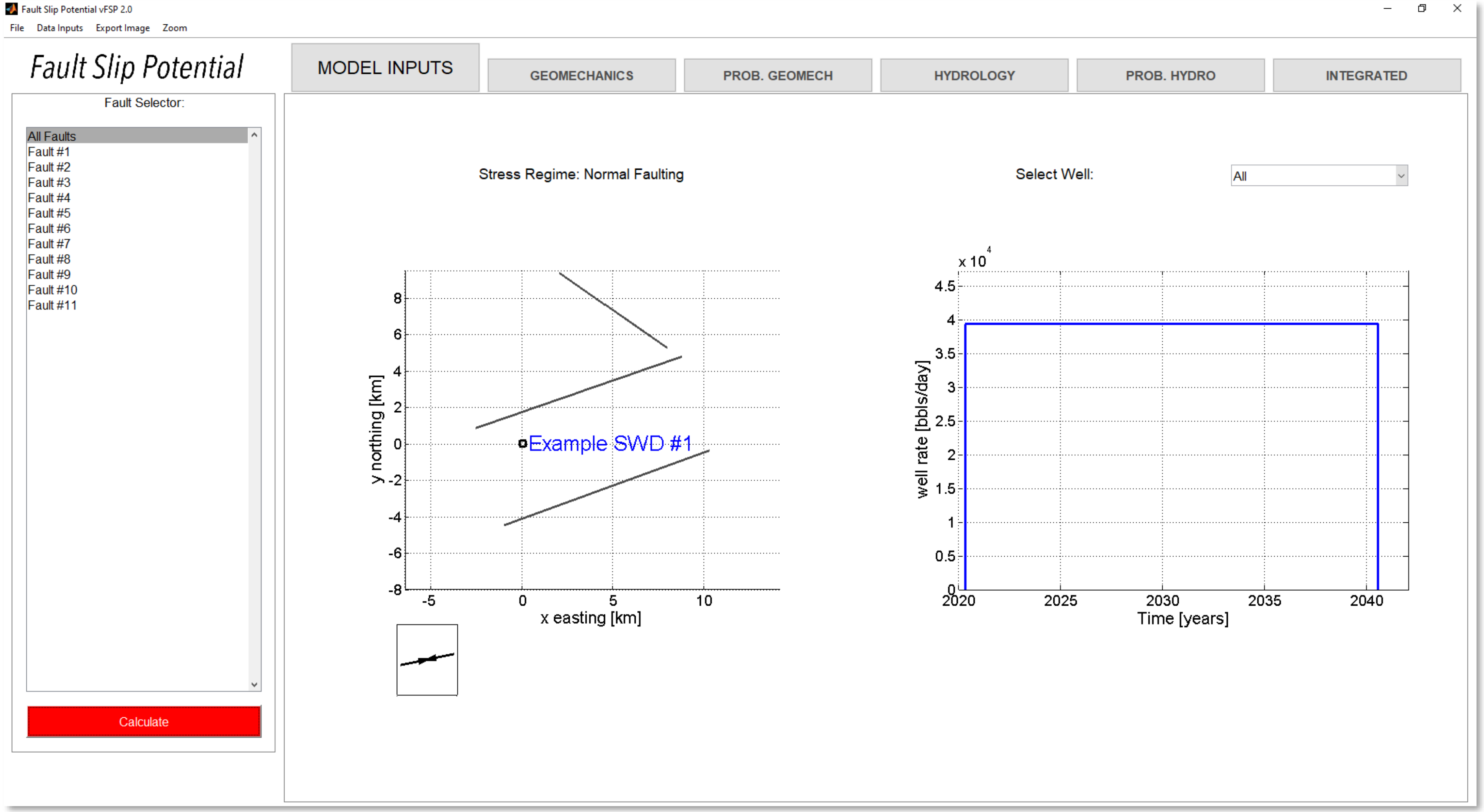
Mohr-Coulomb Failure Criterion

- Calculates failure point in relationship between shear and normal stresses
- Normal stress “clamps” fault shut
- Increased pore pressure, due to injection, can decrease normal stress and lead to fault slip



Source: Walsh et al. 2018

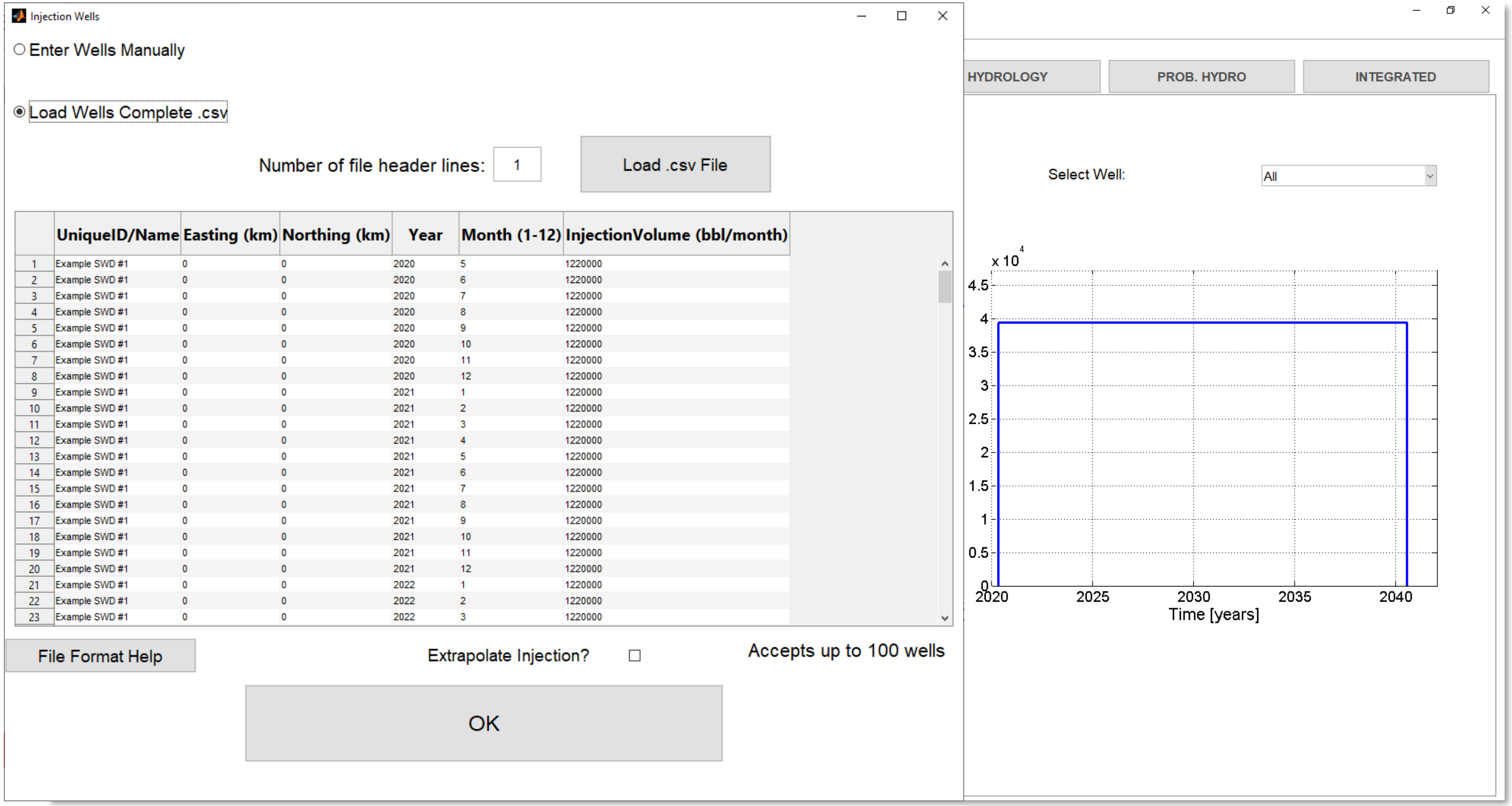
Model Setup



Input Data:

- Injection Volumes
- Faults
- Stress Properties
- Hydrogeology

Injection Volumes



	UniqueID/Name	Easting (km)	Northing (km)	Year	Month (1-12)	InjectionVolume (bbl/month)
1	Example SWD #1	0	0	2020	5	1220000
2	Example SWD #1	0	0	2020	6	1220000
3	Example SWD #1	0	0	2020	7	1220000
4	Example SWD #1	0	0	2020	8	1220000
5	Example SWD #1	0	0	2020	9	1220000
6	Example SWD #1	0	0	2020	10	1220000
7	Example SWD #1	0	0	2020	11	1220000
8	Example SWD #1	0	0	2020	12	1220000
9	Example SWD #1	0	0	2021	1	1220000
10	Example SWD #1	0	0	2021	2	1220000
11	Example SWD #1	0	0	2021	3	1220000
12	Example SWD #1	0	0	2021	4	1220000
13	Example SWD #1	0	0	2021	5	1220000
14	Example SWD #1	0	0	2021	6	1220000
15	Example SWD #1	0	0	2021	7	1220000
16	Example SWD #1	0	0	2021	8	1220000
17	Example SWD #1	0	0	2021	9	1220000
18	Example SWD #1	0	0	2021	10	1220000
19	Example SWD #1	0	0	2021	11	1220000
20	Example SWD #1	0	0	2021	12	1220000
21	Example SWD #1	0	0	2022	1	1220000
22	Example SWD #1	0	0	2022	2	1220000
23	Example SWD #1	0	0	2022	3	1220000

Data Sources:

- Railroad Commission of Texas (TX RRC)
- New Mexico Oil Conservation Division (NMOCD)

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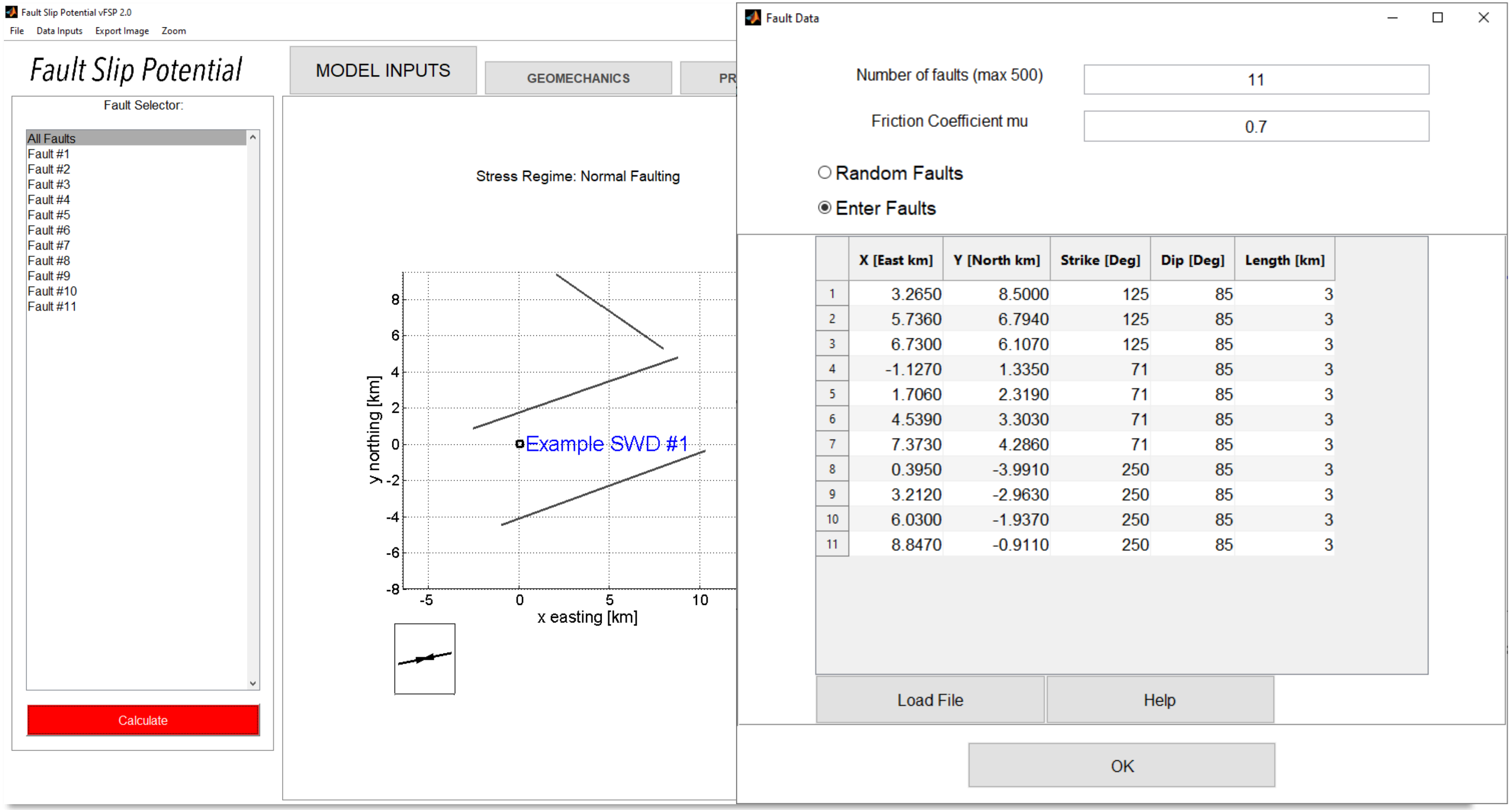
Faults



	X [East km]	Y [North km]	Strike [Deg]	Dip [Deg]	Length [km]
1	3.2650	8.5000	125	85	3
2	5.7360	6.7940	125	85	3
3	6.7300	6.1070	125	85	3
4	-1.1270	1.3350	71	85	3
5	1.7060	2.3190	71	85	3
6	4.5390	3.3030	71	85	3
7	7.3730	4.2860	71	85	3
8	0.3950	-3.9910	250	85	3
9	3.2120	-2.9630	250	85	3
10	6.0300	-1.9370	250	85	3
11	8.8470	-0.9110	250	85	3

Data Sources:

- Railroad Commission of Texas (TX RRC)
- Texas Bureau of Economic Geology (BEG)
- 2D/3D Seismic Data
- Published Research

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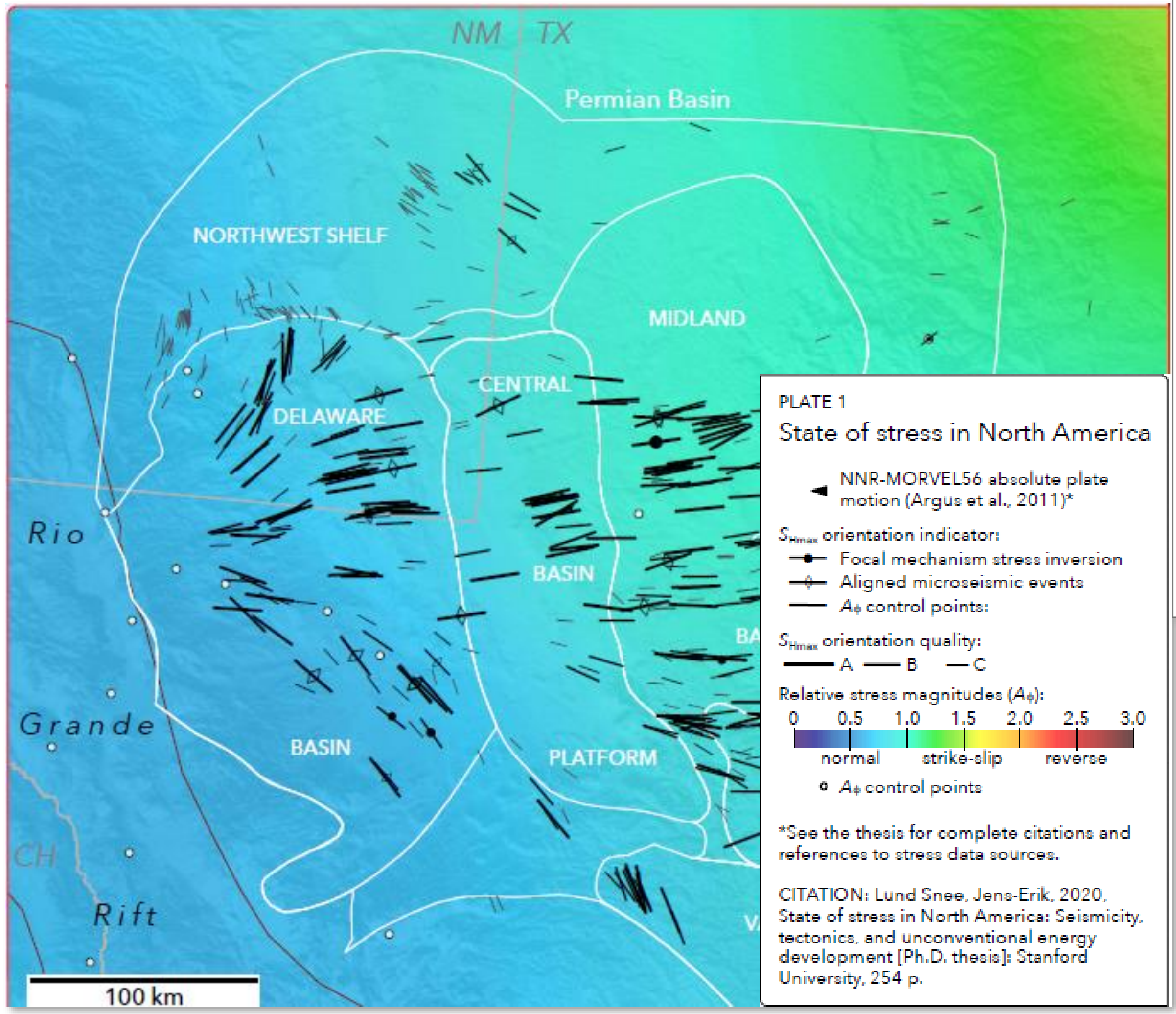
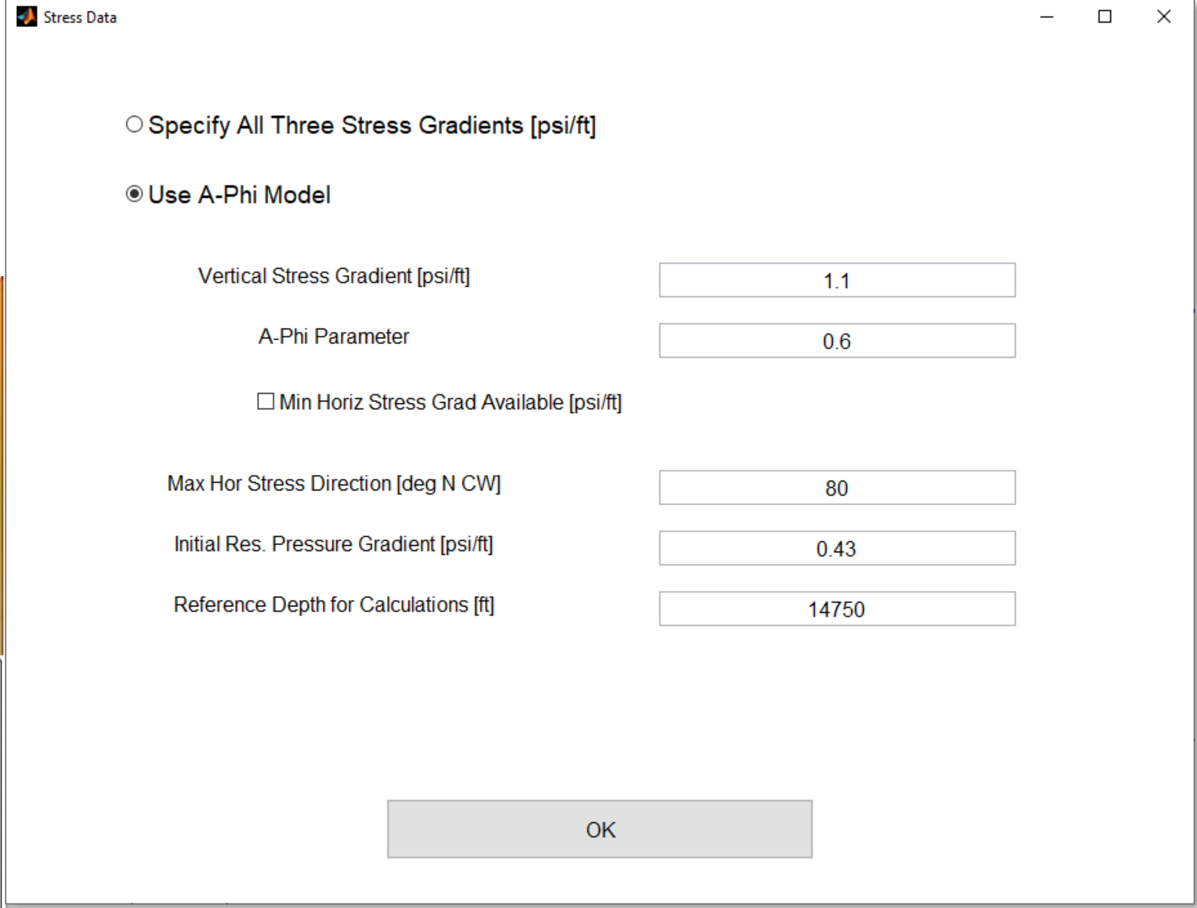
Stress



Source: Lund Snee 2020



Data Sources:

- Stanford Center for Induced and Triggered Seismicity (SCITS)
  - Snee & Zoback publications
- Event focal mechanism inversions
- Frac jobs

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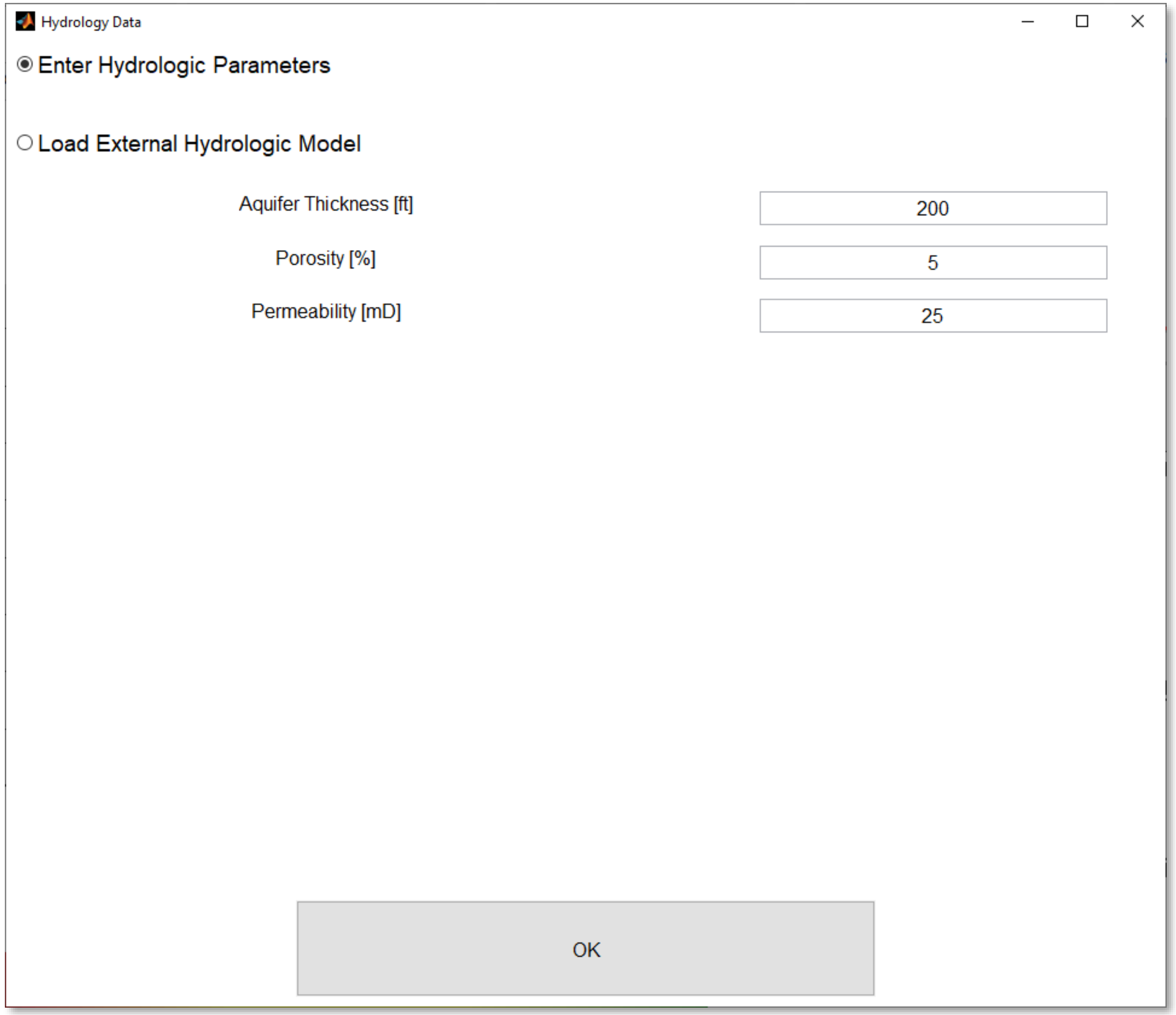
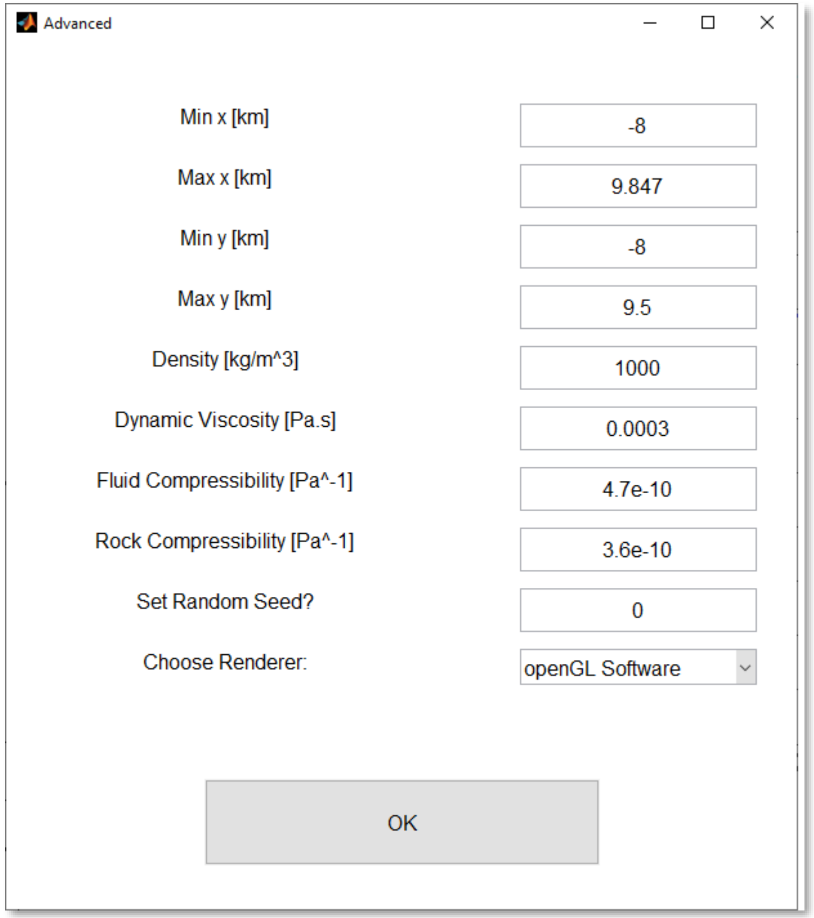
Hydrology





Data Sources:

- Geophysical logs (NMOCD & TX RRC)
- Published research

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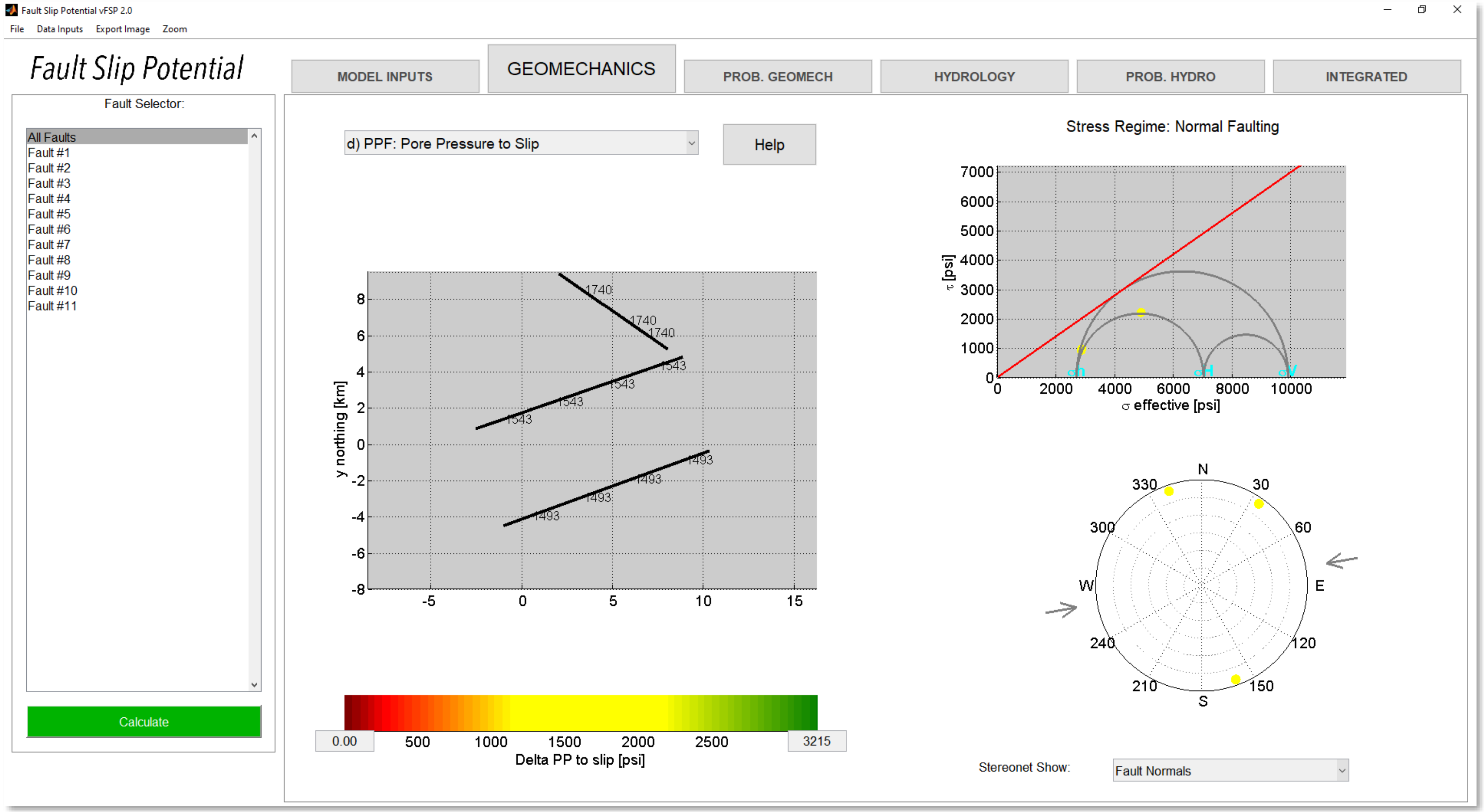
Geomechanics



- Estimated pore pressure to slip (for each fault)
- Mohr-Coulomb Failure Criterion

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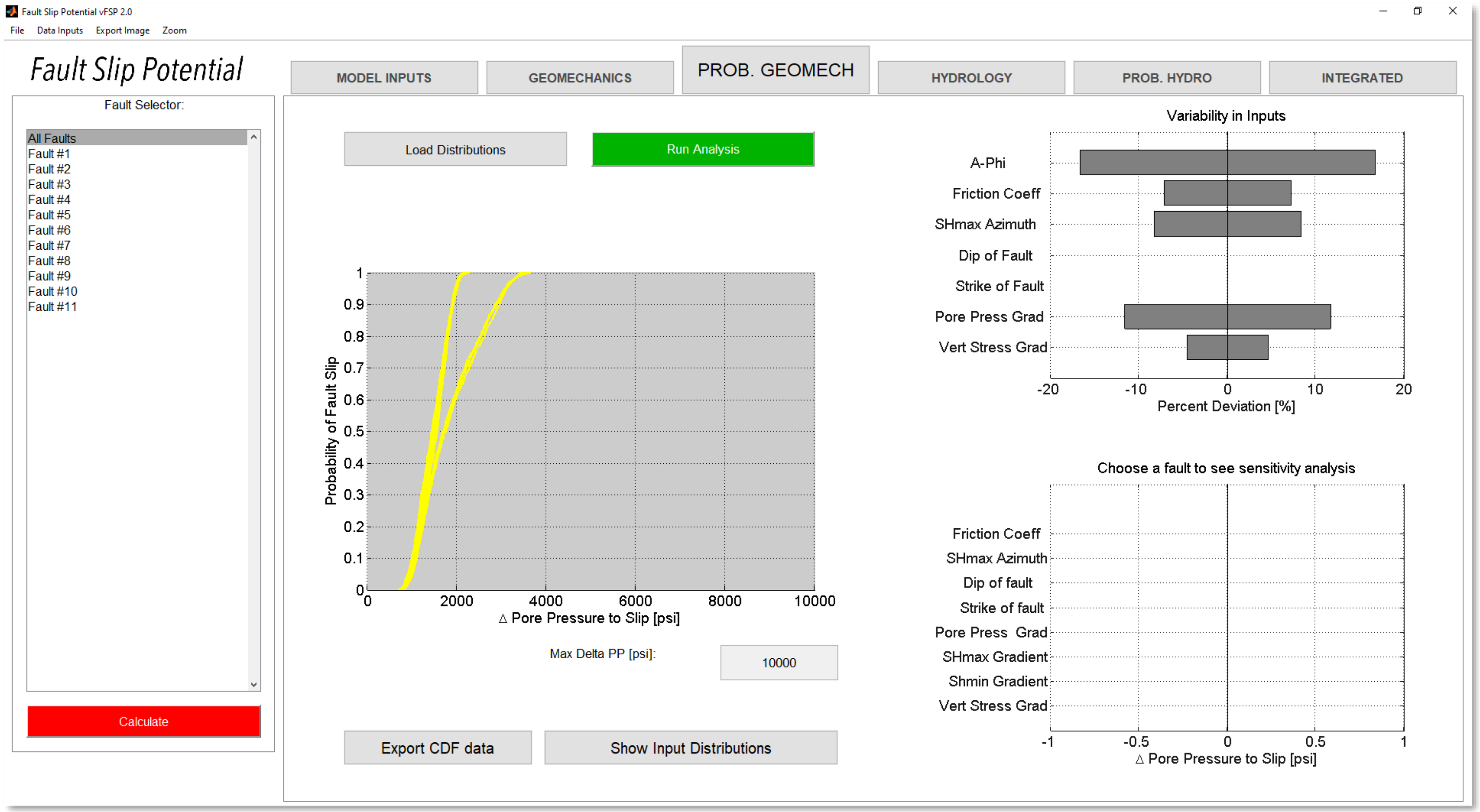
Probabilistic Geomechanics



- Monte Carlo simulation to account for parameter uncertainties
- Probability of slip for a given amount of pore pressure increase

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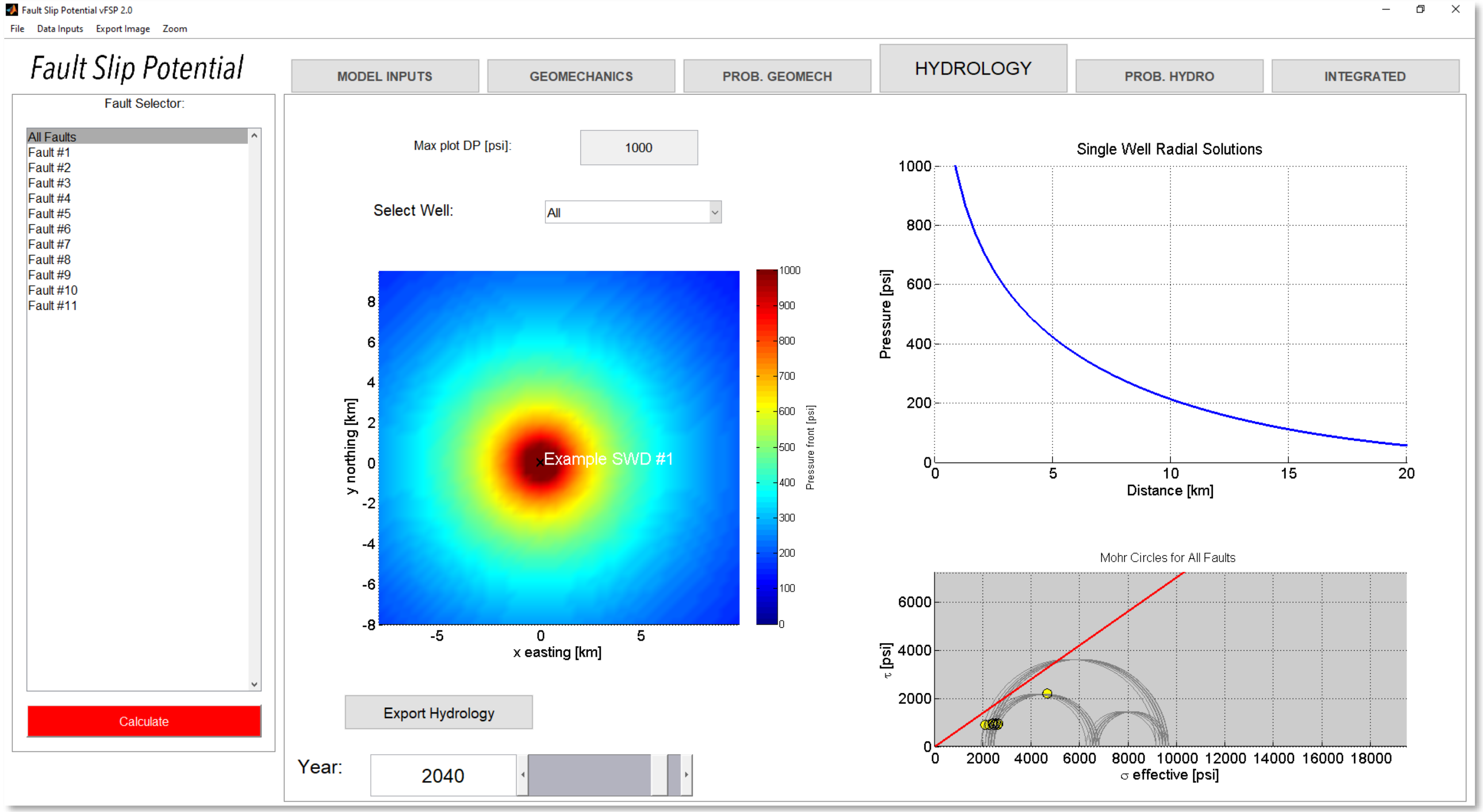
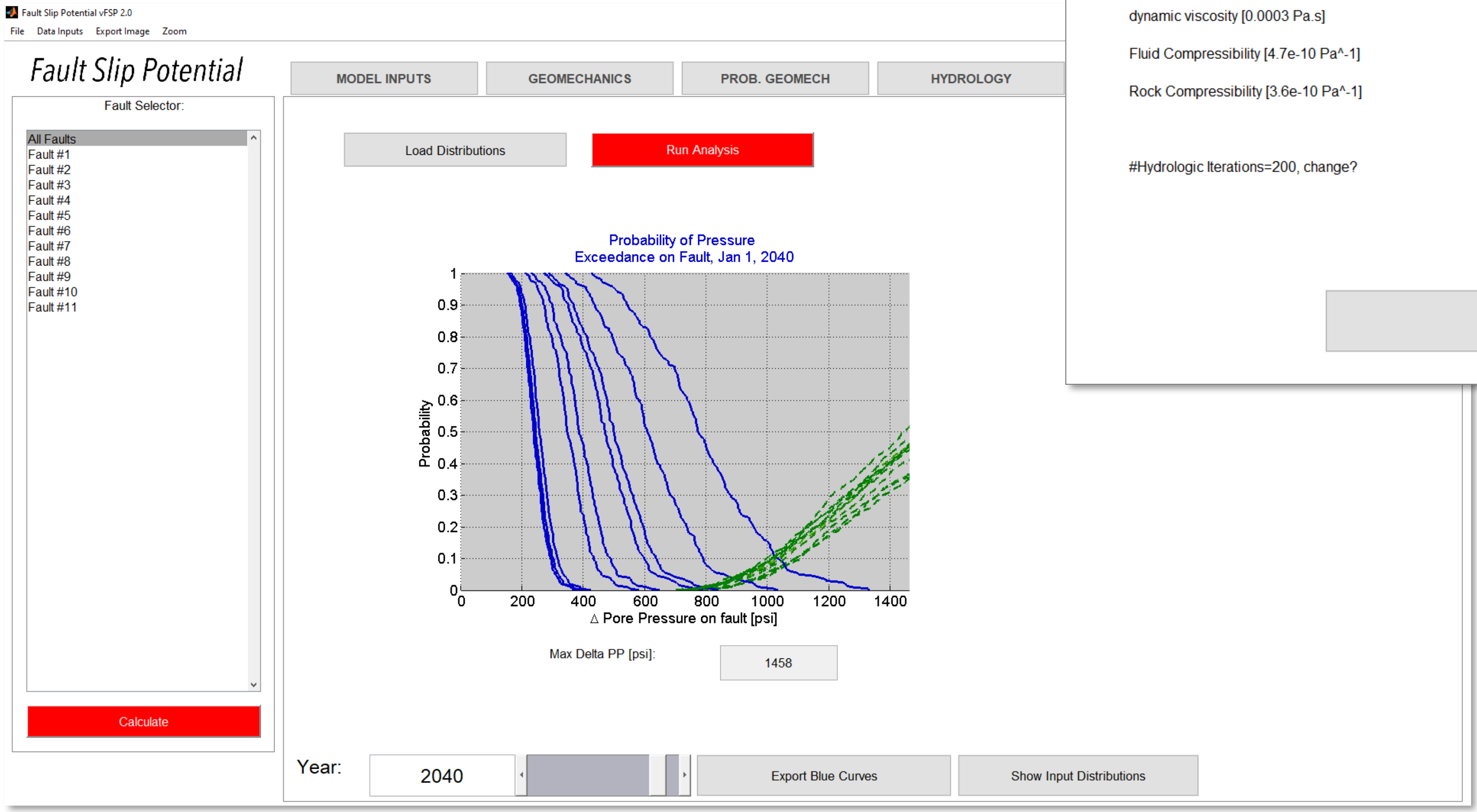
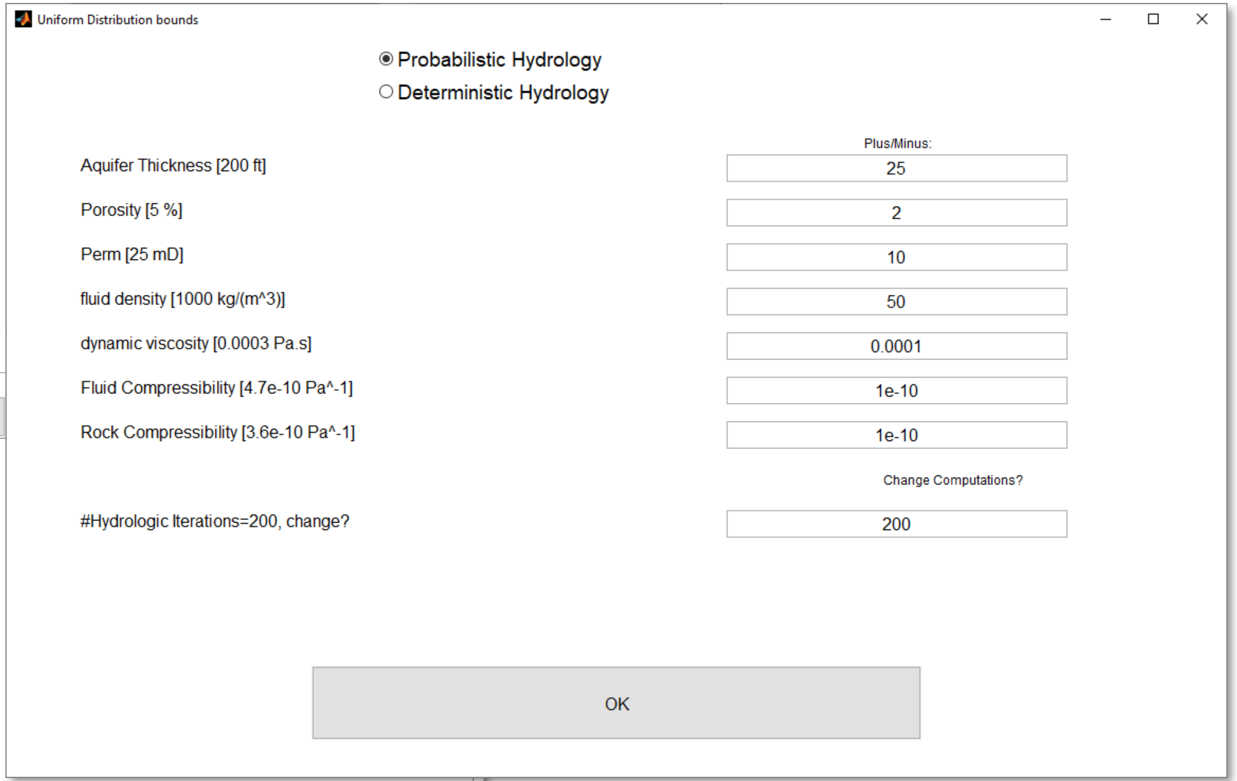
Hydrology



- Assumes Radial Flow (homogeneous & isotropic) pressure distribution

Probabilistic Hydrology





- Probability than any given fault surpasses the required pressure for fault slip

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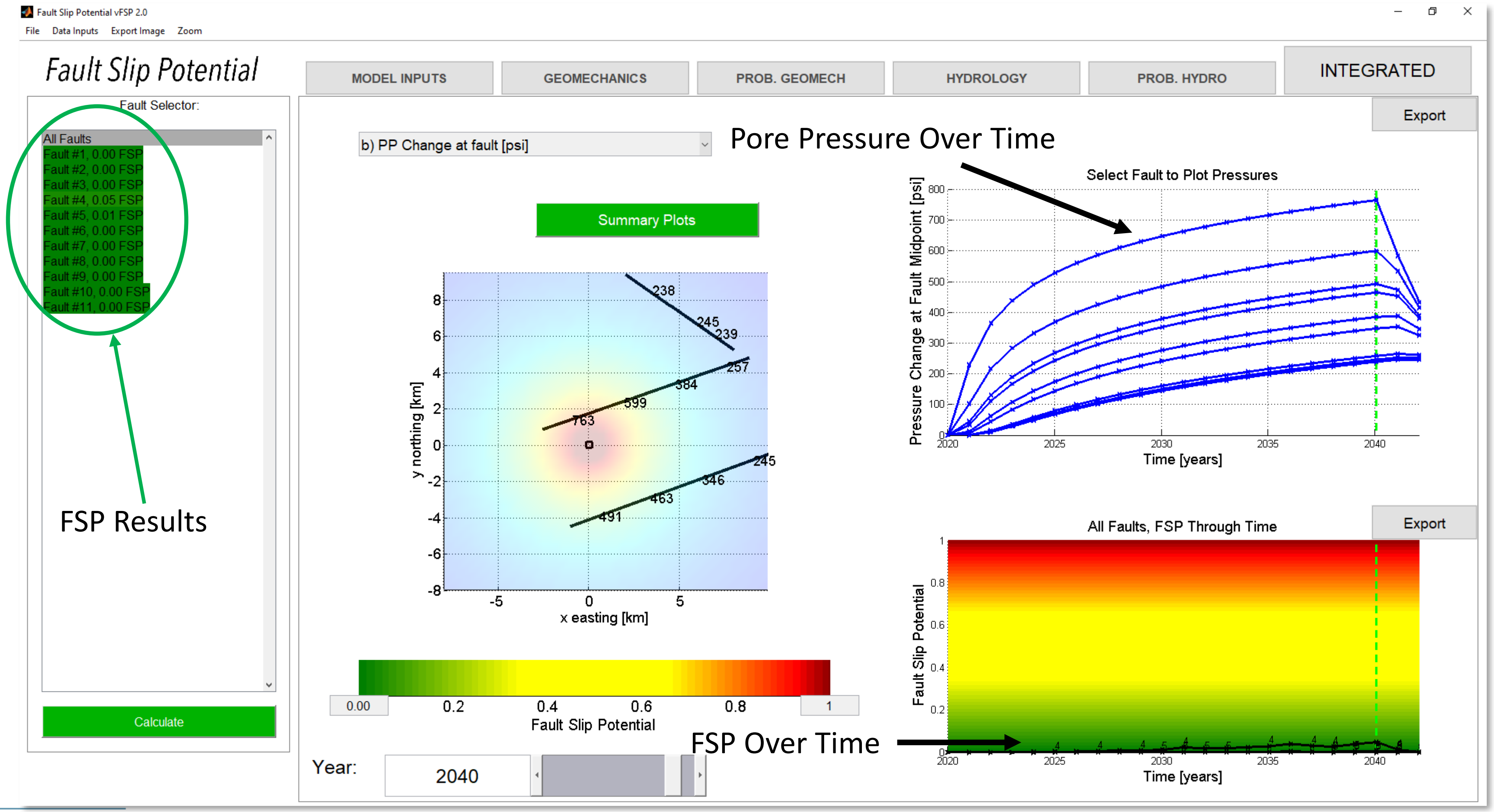
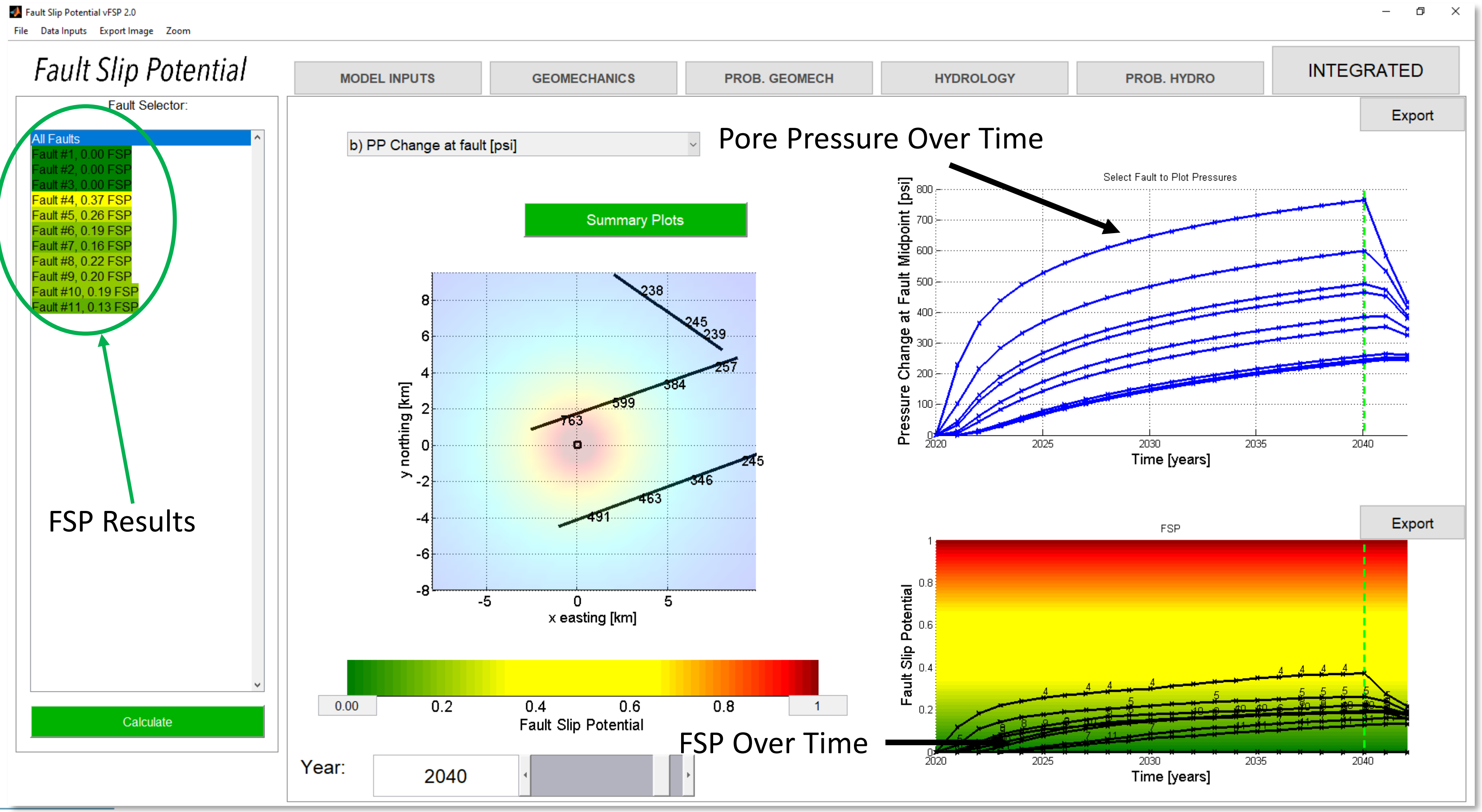
Results


Fault Slip Potential vFSP 2.0
File Data Inputs Export Image Zoom
Fault Slip Potential
MODEL INPUTS
GEOMECHANICS
PROB. GEOMECH
HYDROLOGY
PROB. HYDRO
INTEGRATED
Export
Fault Selector:
All Faults
Fault #1, 0.00 FSP
Fault #2, 0.00 FSP
Fault #3, 0.00 FSP
Fault #4, 0.05 FSP
Fault #5, 0.01 FSP
Fault #6, 0.00 FSP
Fault #7, 0.00 FSP
Fault #8, 0.00 FSP
Fault #9, 0.00 FSP
Fault #10, 0.00 FSP
Fault #11, 0.00 FSP
FSP Results
Calculate
b) PP Change at fault [psi]
Pore Pressure Over Time
Summary Plots
y northing [km]
x easting [km]
Fault Slip Potential
Year:
2040
Select Fault to Plot Pressures
Pressure Change at Fault Midpoint [psi]
Time [years]
All Faults, FSP Through Time
Fault Slip Potential
FSP Over Time
Time [years]

Results: S_{Hmax} at 70°



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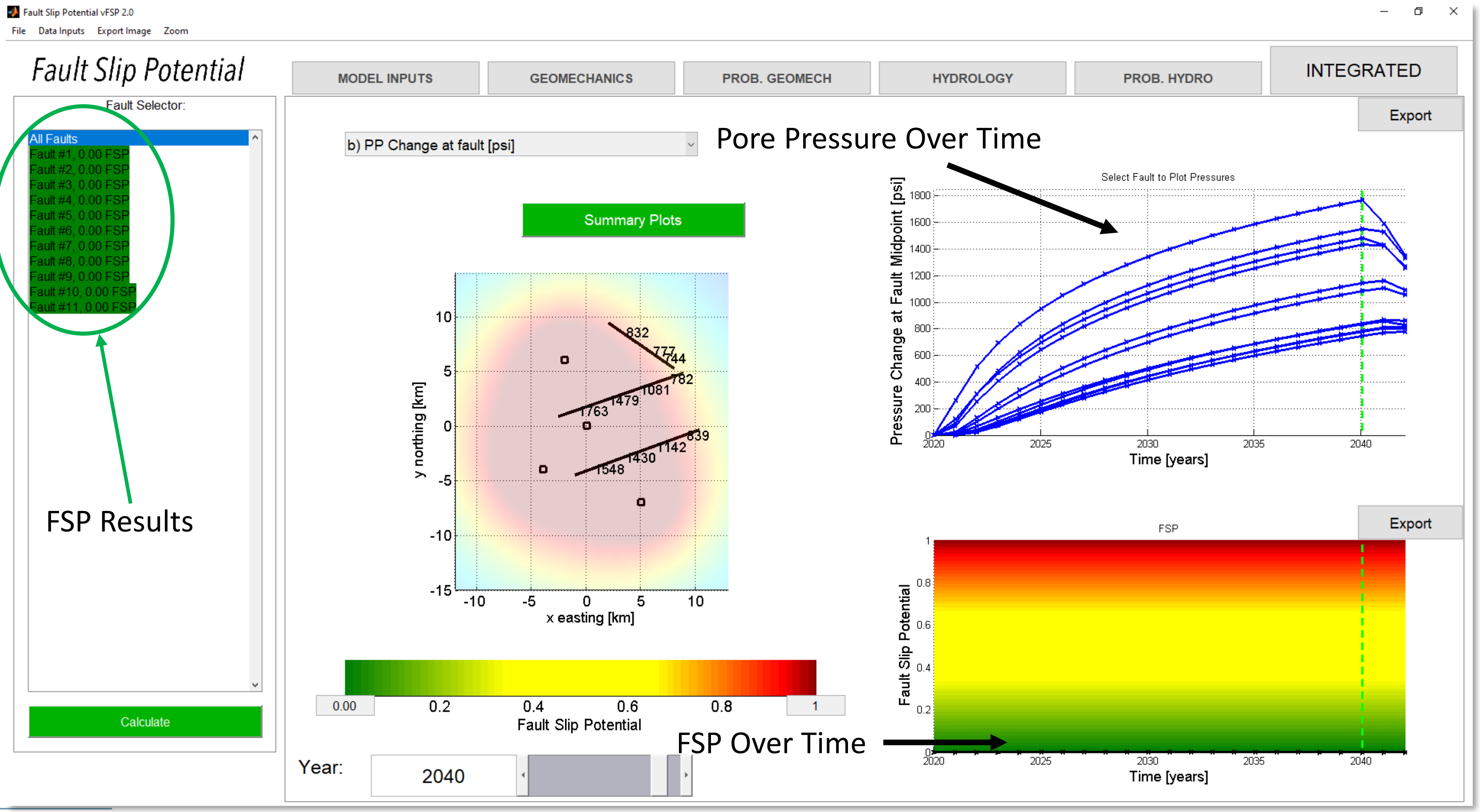
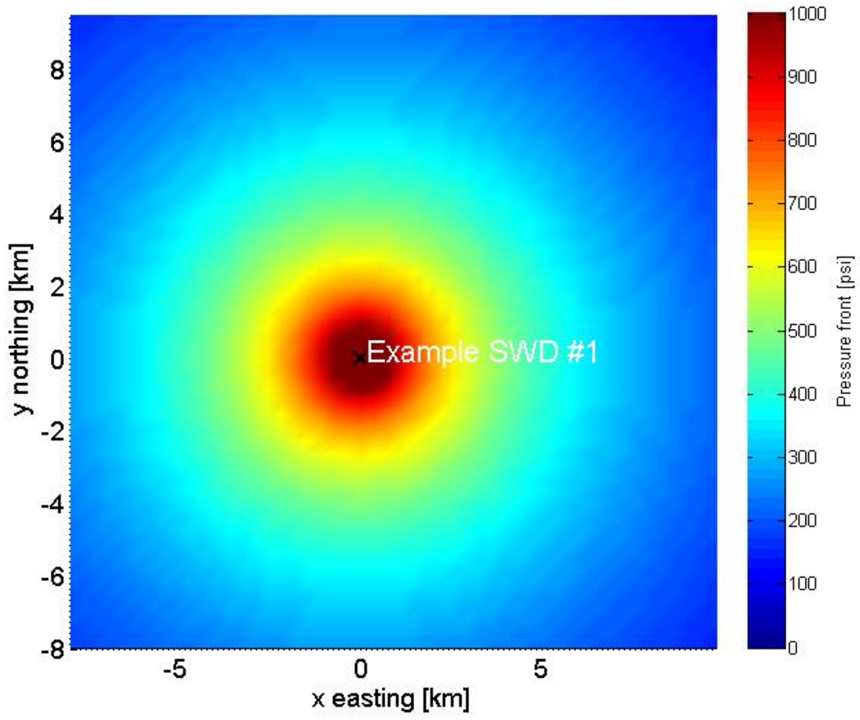
Results: Additional SWDs and S_{Hmax} at 0°

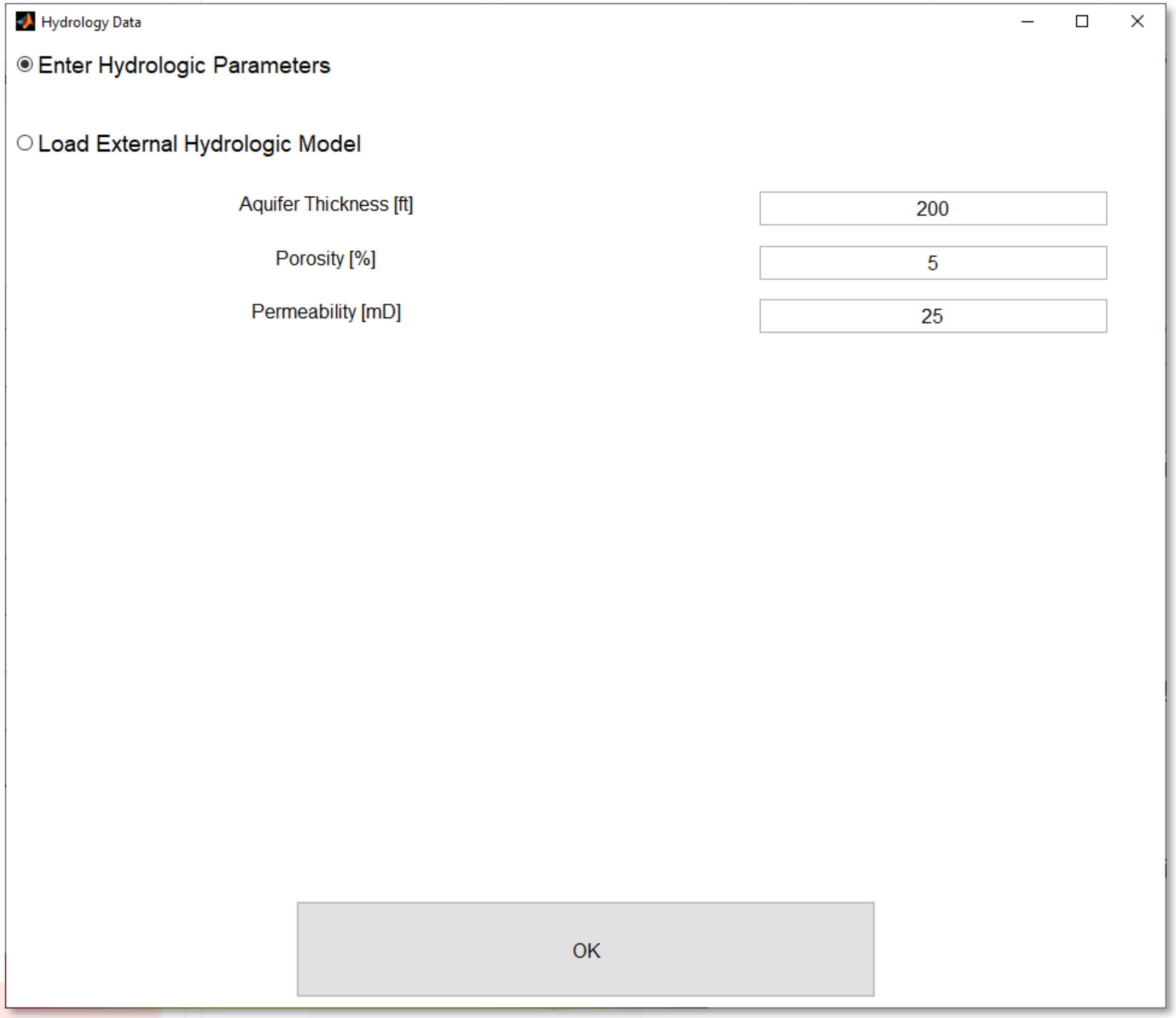


Model Limitations & Assumptions



- Simple radial flow of pressure
- Cannot account for preferential flow pathways (faults/fractures)
- Does not account for poroelastic stress transfer

Model Limitations & Assumptions



- Homogeneous & Isotropic geology
- Secondary porosity & permeability development are common in targeted injection reservoirs

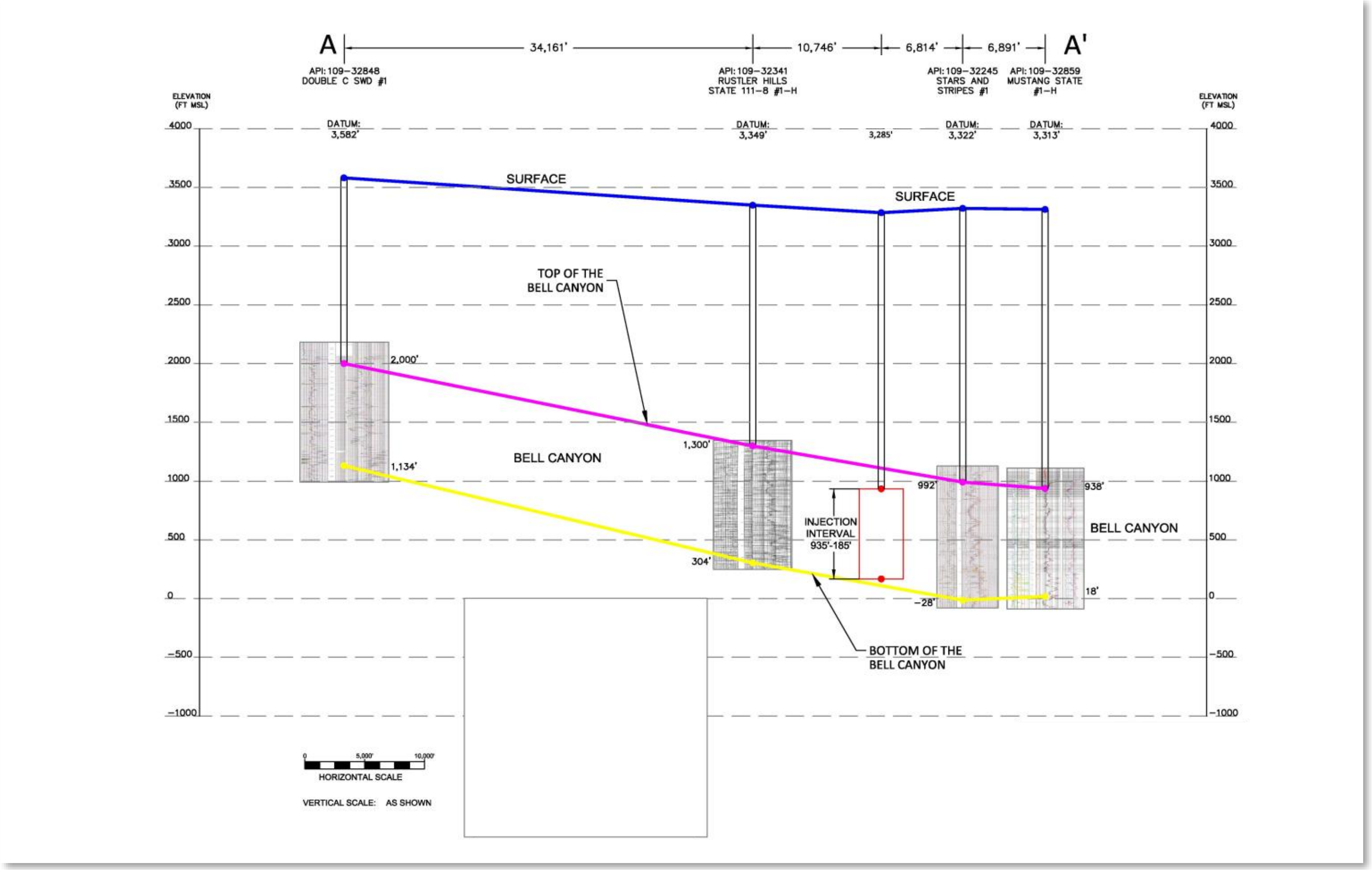
Model Limitations & Assumptions

DEVONIAN	Upper	Woodford
	Middle	Lower Devonian
SILURIAN	Middle	Silurian Sh.
		Fusselman
ORDOVICIAN	Upper	Montoya
	Middle	Simpson
	Lower	Ellenburger
CAMBRIAN	Upper	Cambrian
PRE - CAMBRIAN		Pre-Cambrian

Source: Keller et al. 1980

- Single-layer model to represent multi-layered reality
- Assumes pressure can transmit from injection zone to basement depth faults
- Assumes injection rates remains the same over the life span of the well

Supplementary Data



- Cross sections
- Geophysical log analysis
- Confining zone identification
- Historic seismicity review

Conclusions

- Fault Slip Potential modeling is frequently requested by regulators for SWDs with historic or recent seismicity within 100 square miles of a proposed SWD location
- Prepare and thoroughly review data:
  - Injection volumes
  - Faults
  - Hydrogeologic parameters
  - Stress field
- Be prepared to justify input parameters
- Supplement FSP with additional data
- Has limitations as it relies on numerous assumptions

FSP References and Resources

References

Walsh, F. R., Zoback, M. D., Lele, S. P., Pais, D., Weingarten, M., and Tyrrell, T. (2018) FSP 2.0: A Program for Probabilistic Estimation of Fault Slip Potential Resulting From Fluid Injection, User Guide from the Stanford Center for Induced and Triggered Seismicity, available at SCITS.Stanford.edu/software

Lund Snee, Jens-Erik, 2020, State of Stress in North America: Seismicity, Tectonics, and Unconventional Energy Development [Ph.D. thesis]: Stanford University, 254p.

Keller, Randy, et al., 1980, "A Regional Geological and Geophysical Study of the Delaware Basin, New Mexico and West Texas." New Mexico Geological Society Handbook, 31st Field Conference, pp. 105-111.

FSP Resources

FSP Download:

https://scits.stanford.edu/fault-slip-potential-fsp

Maximum Horizontal Stress Orientations:

https://www.jenseriklundsnee.com/resources

State GIS Viewers for Well Log Lookup:

http://www.emnrd.state.nm.us/OCD/ocdgis.html

https://www.rrc.state.tx.us/about-us/resource-center/research/gis-viewers/

Questions & Answers

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