

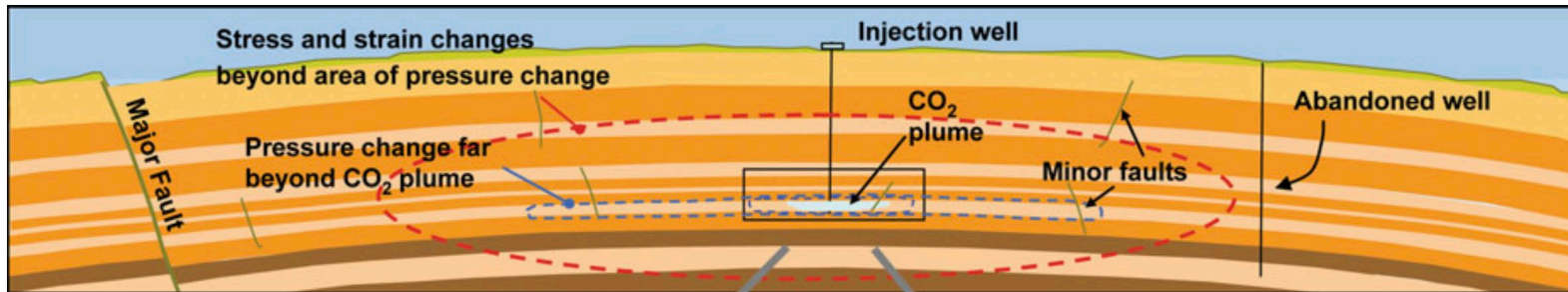
Seismic hazard assessment protocol for potential CO₂ storage sites

Arjun Kohli

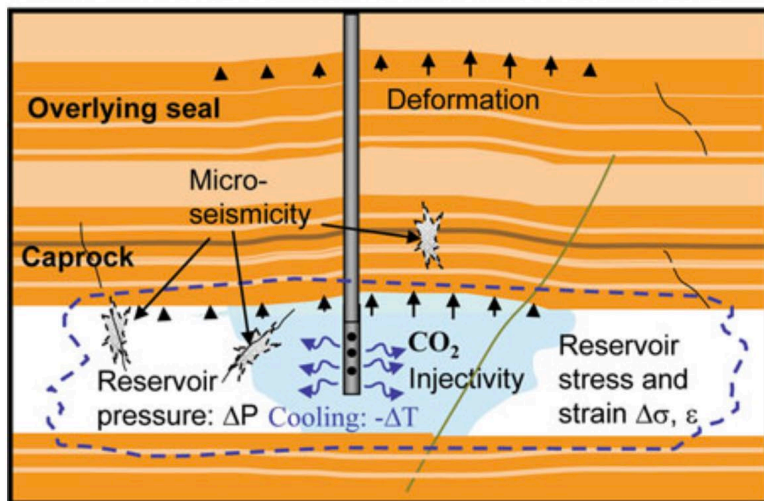
Nov 19, 2024



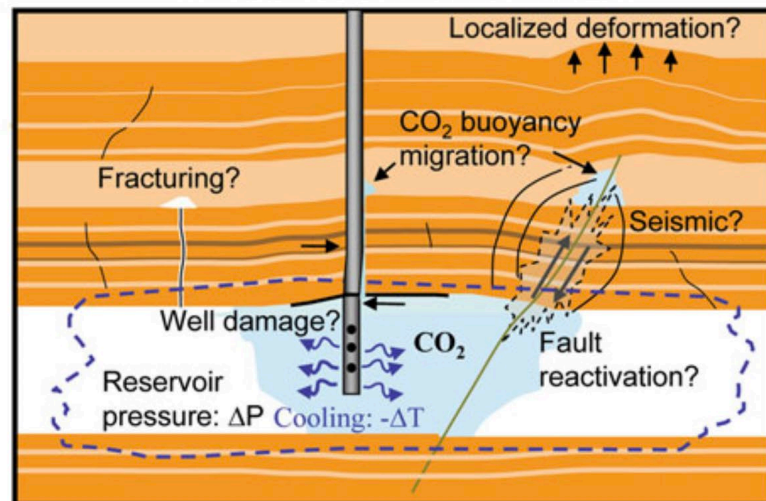
Stanford | Doerr | Stanford Center
School of Sustainability | for Carbon Storage



Injection-induced stress, strain and deformation

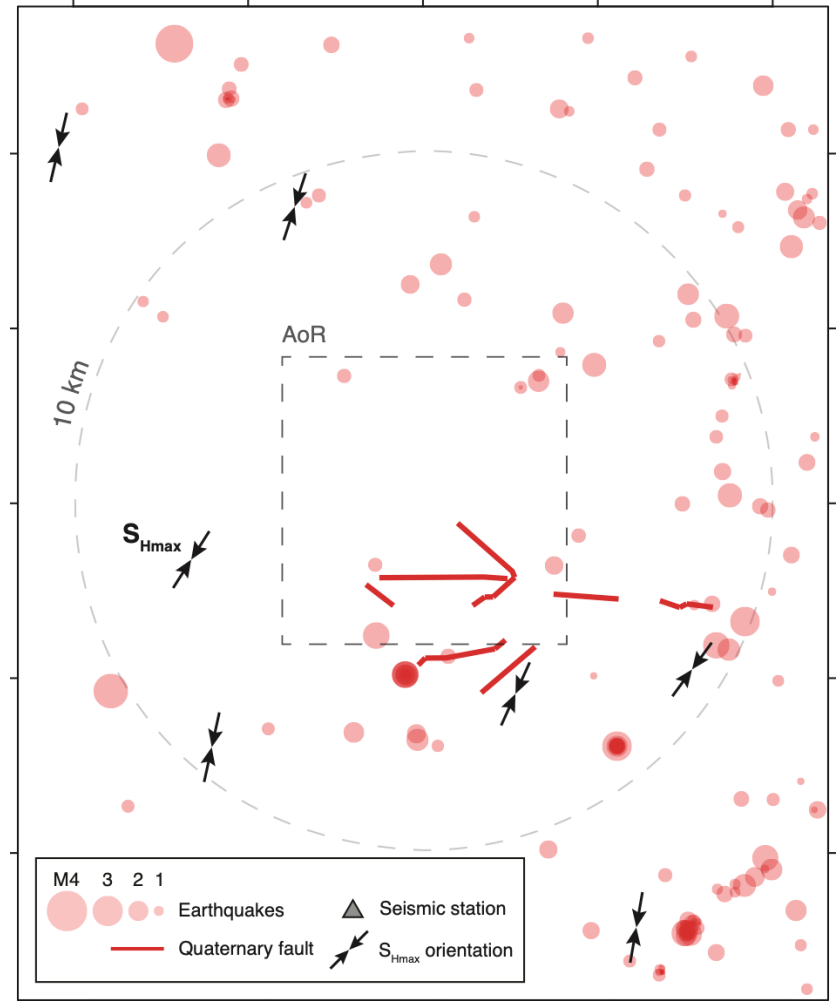


Unwanted mechanical changes

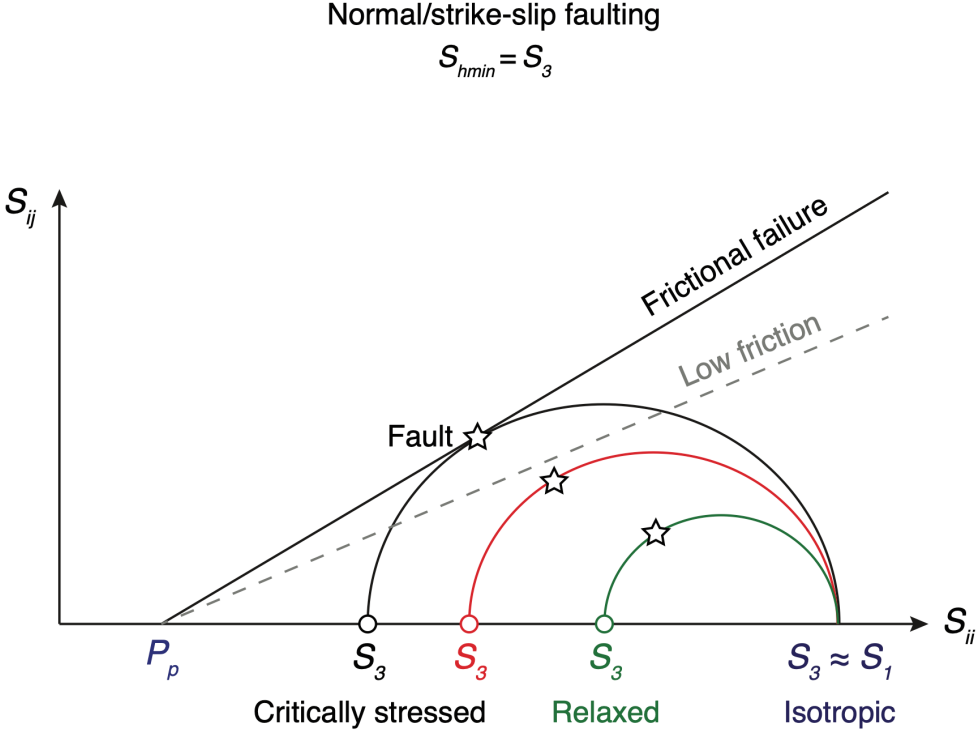
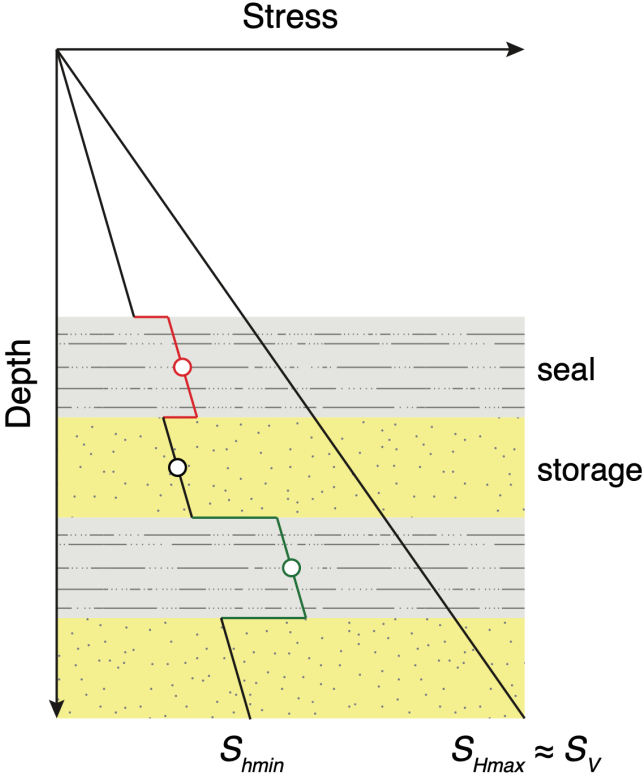


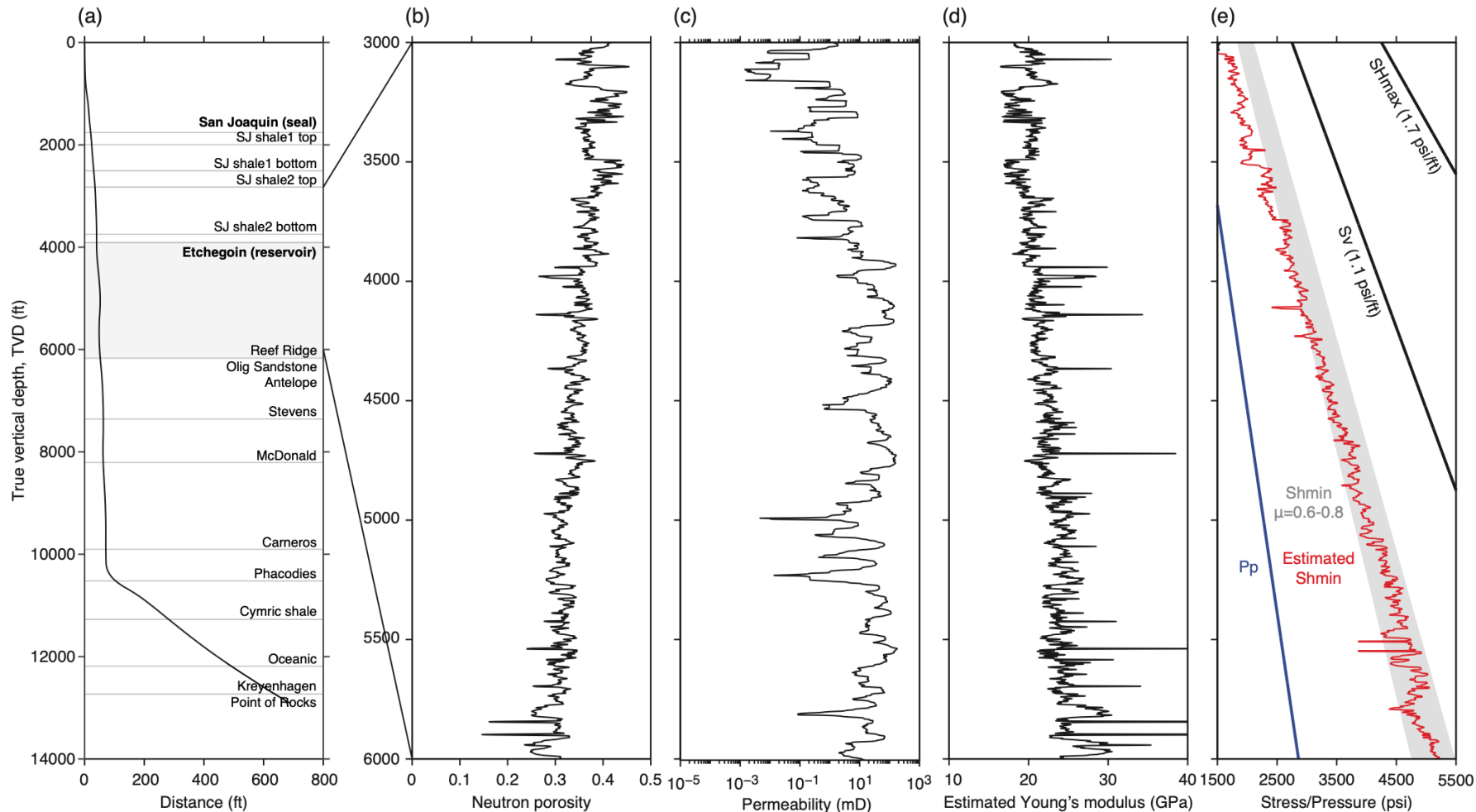
Site scale approach

- Stress
 - Integrate density logs (S_V)
 - Borehole stress indicators (S_{Hmax} azimuth)
 - Focal mechanism inversion ($S_{Hmax} / S_V / S_{hmin}$)
- Faults
 - Mohr-Coulomb analysis
 - Probabilistic geomechanical model (FSP)
- Seismicity
 - Build/QC earthquake catalog
 - Distinguish natural vs induced seismicity
 - What scales of seismicity and ground shaking?

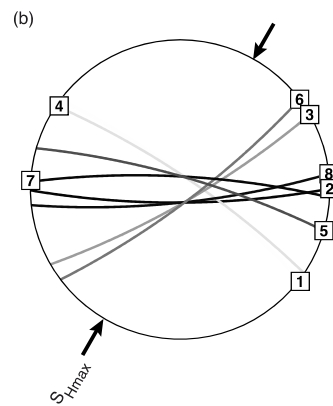
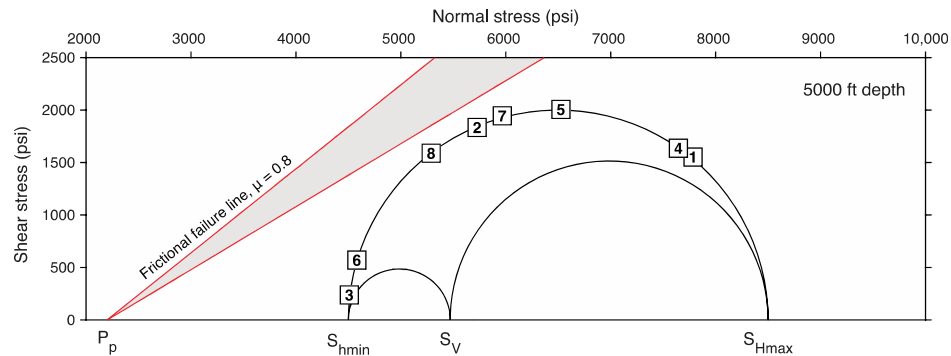
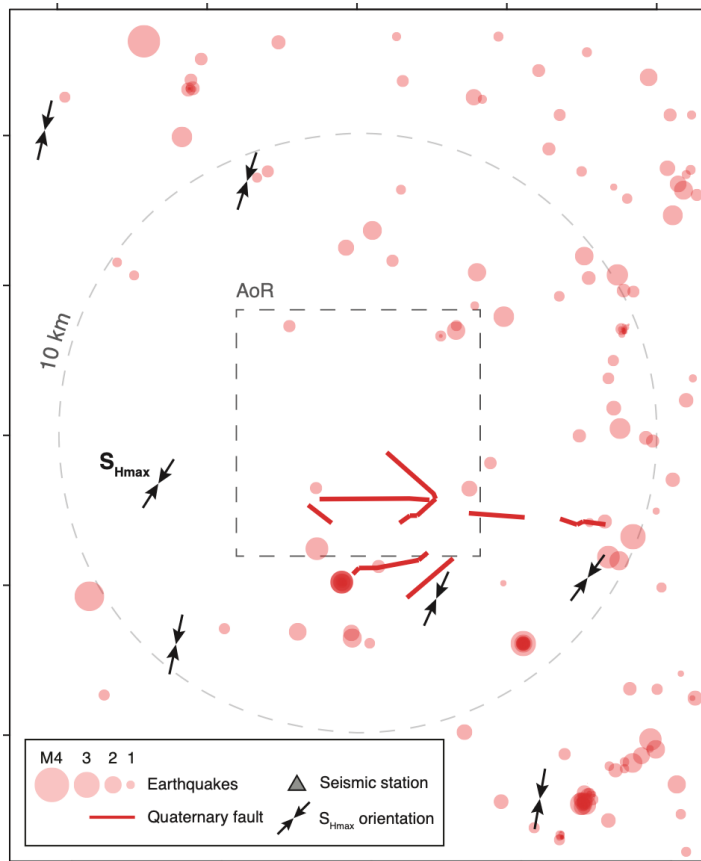


Stress variations in geological storage

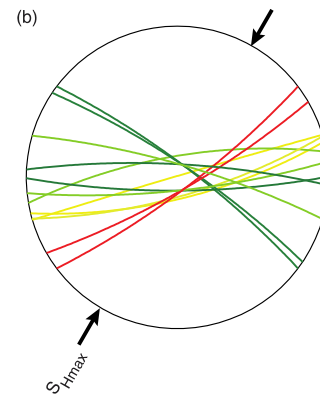
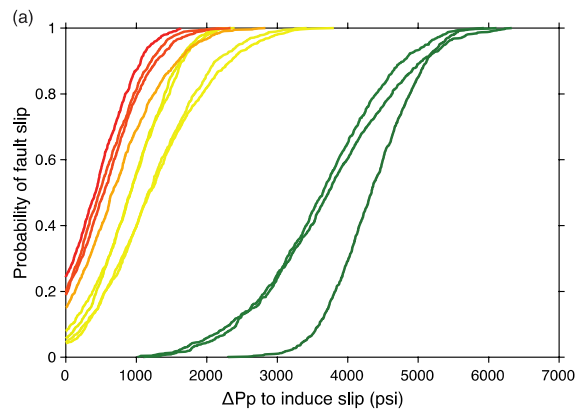
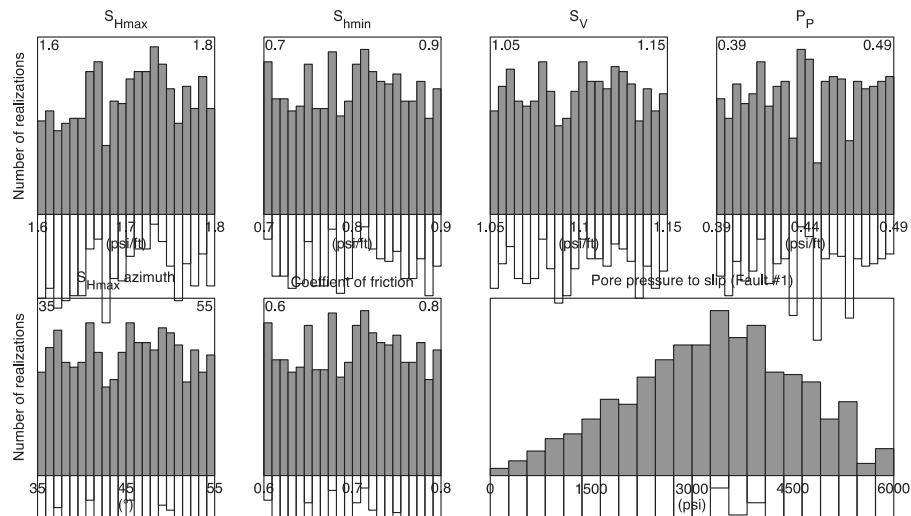
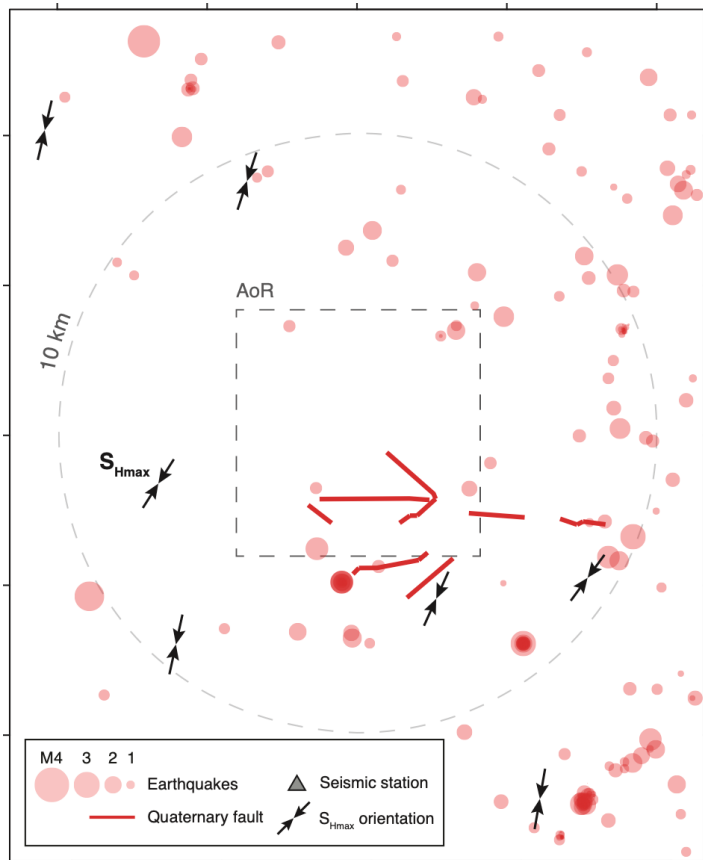


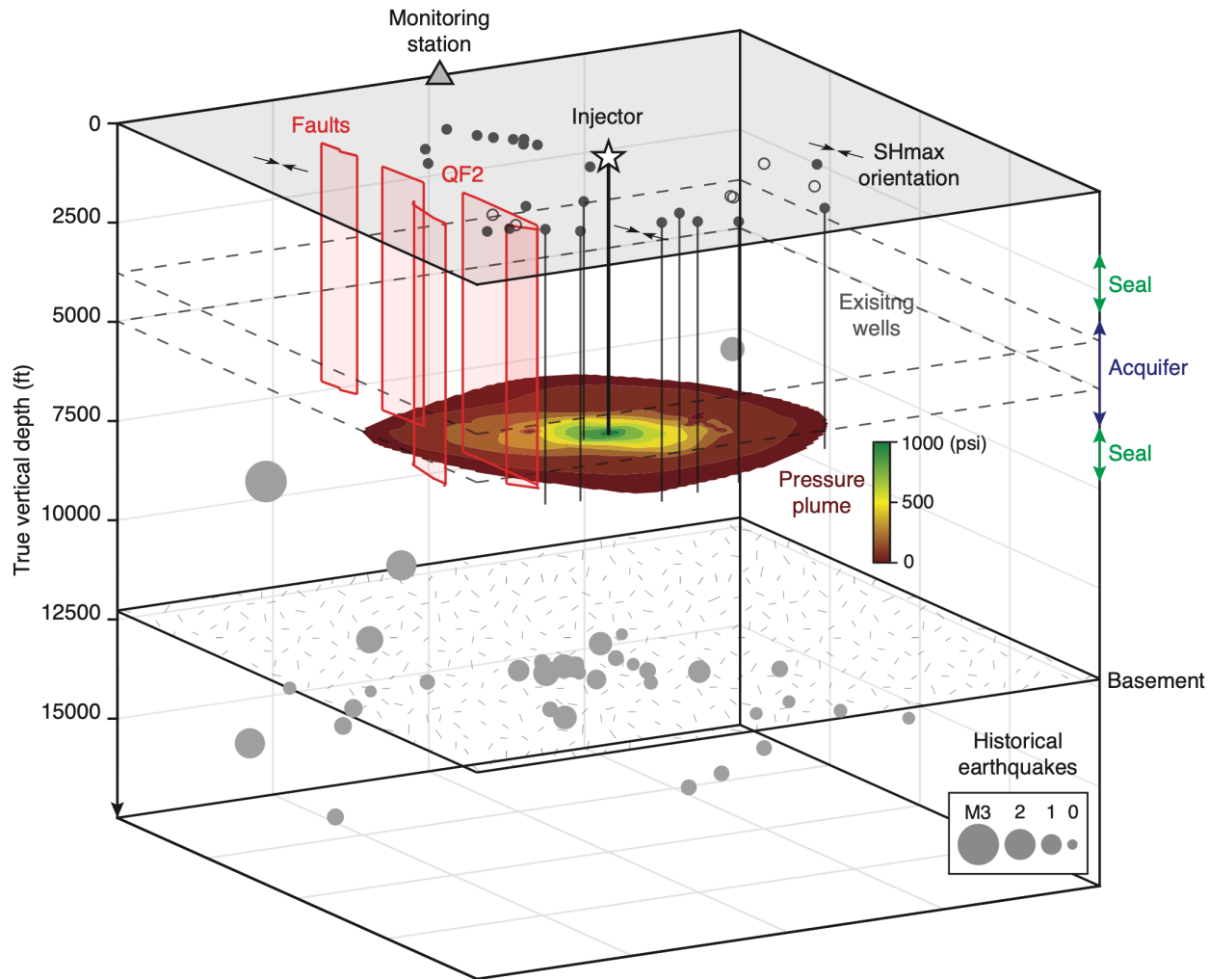


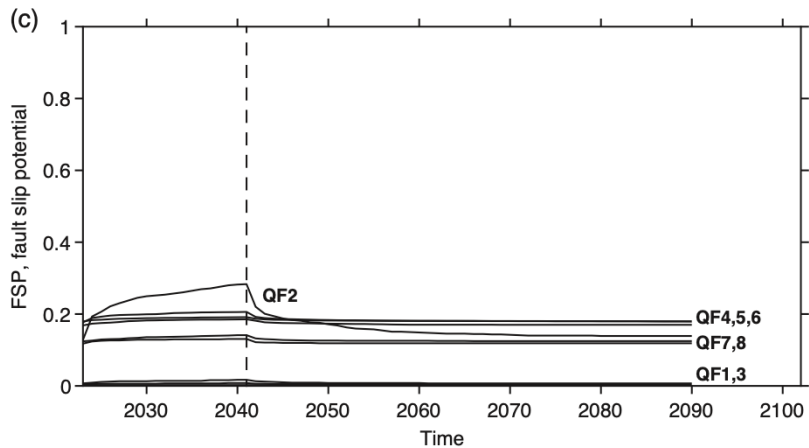
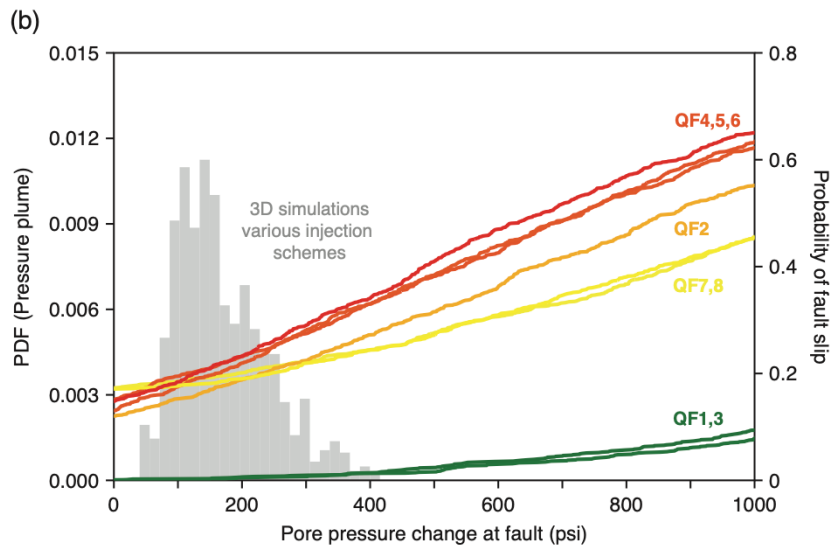
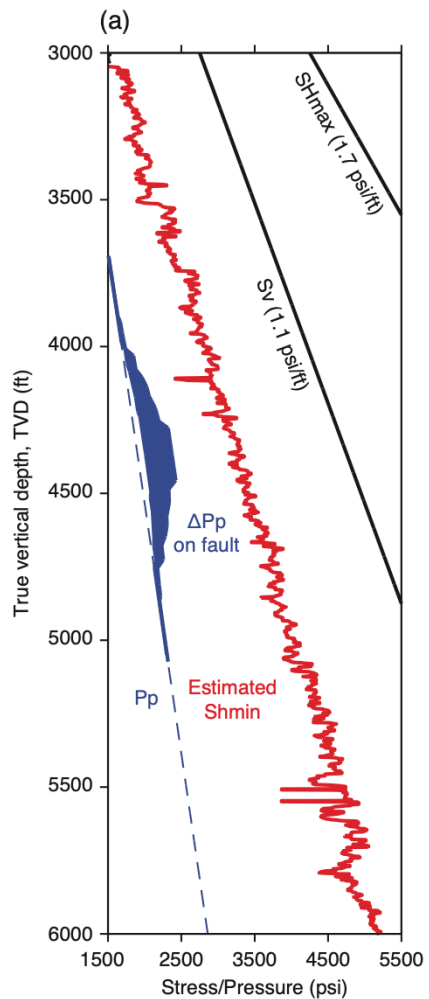
Mohr-Coulomb analysis



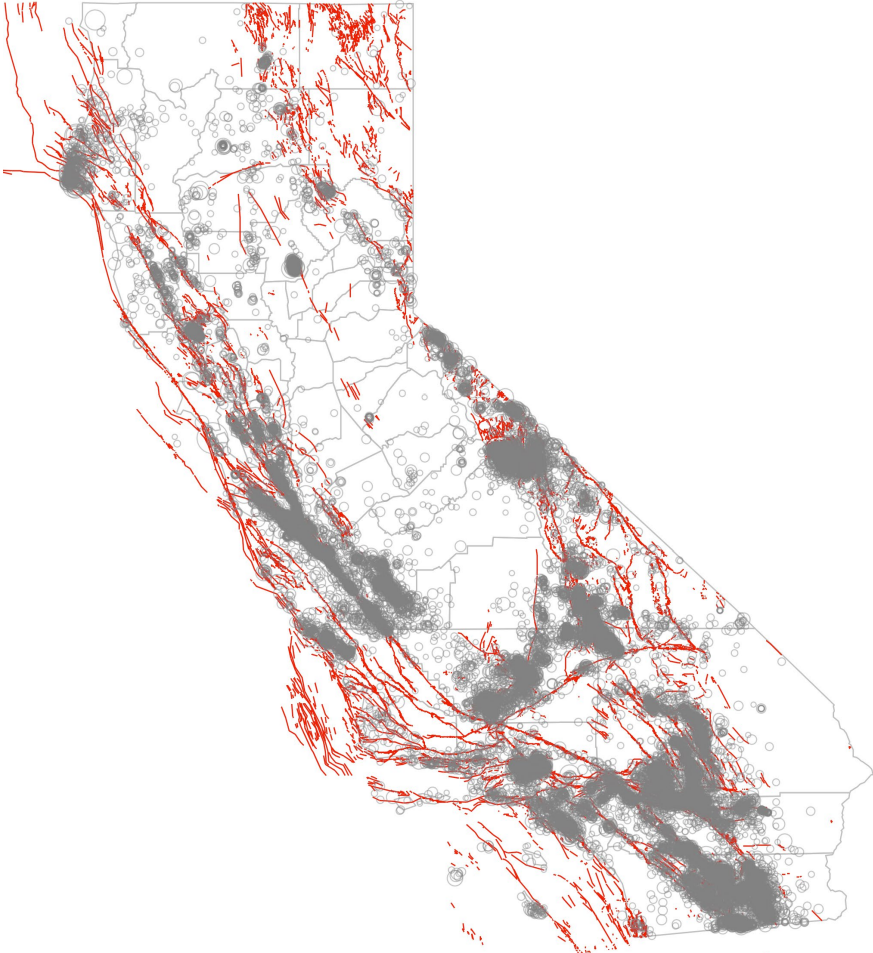
Probabilistic fault slip model



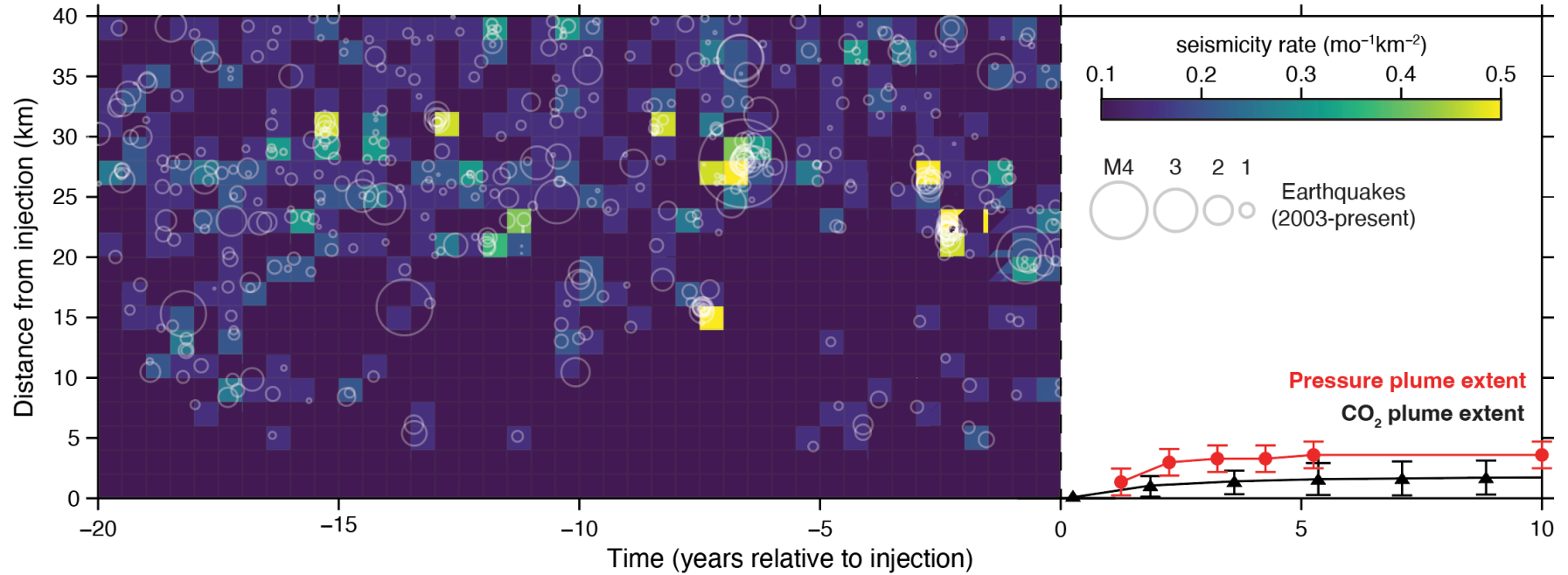




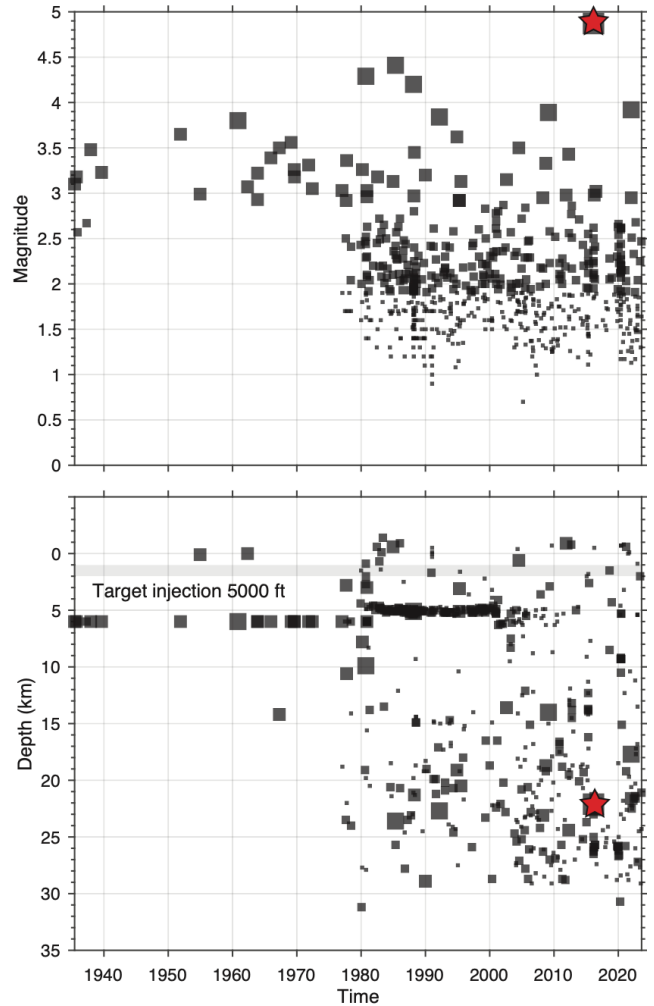
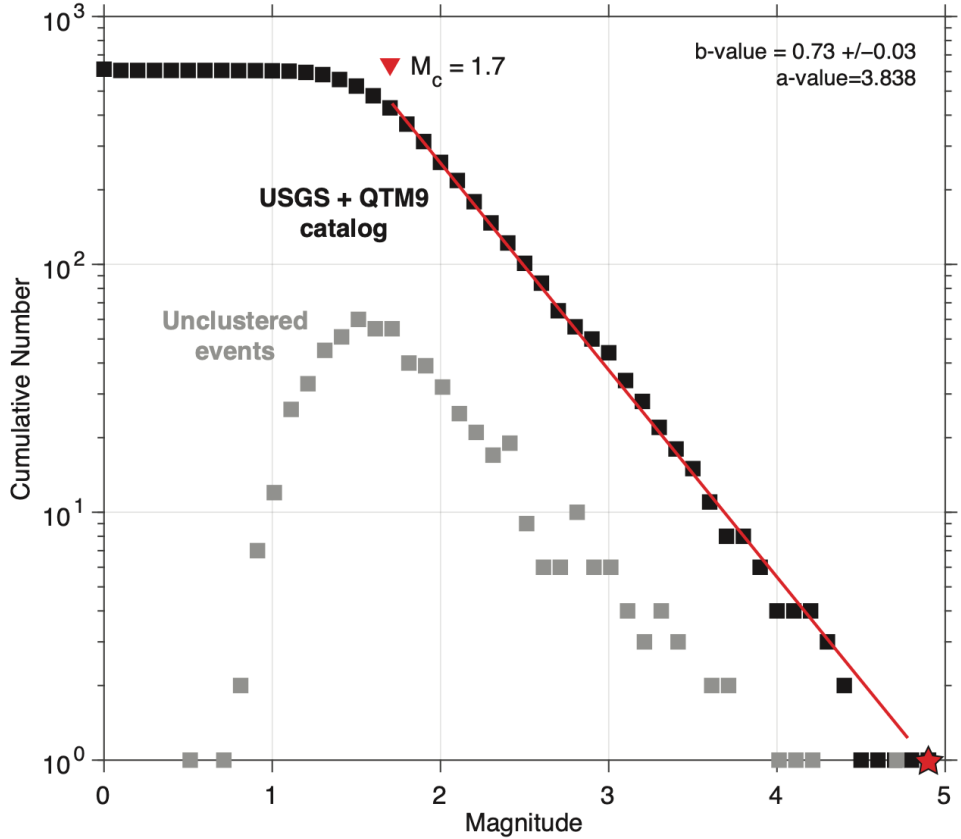
CA CCS earthquake catalog



How do we distinguish induced seismicity?



Seismic statistics



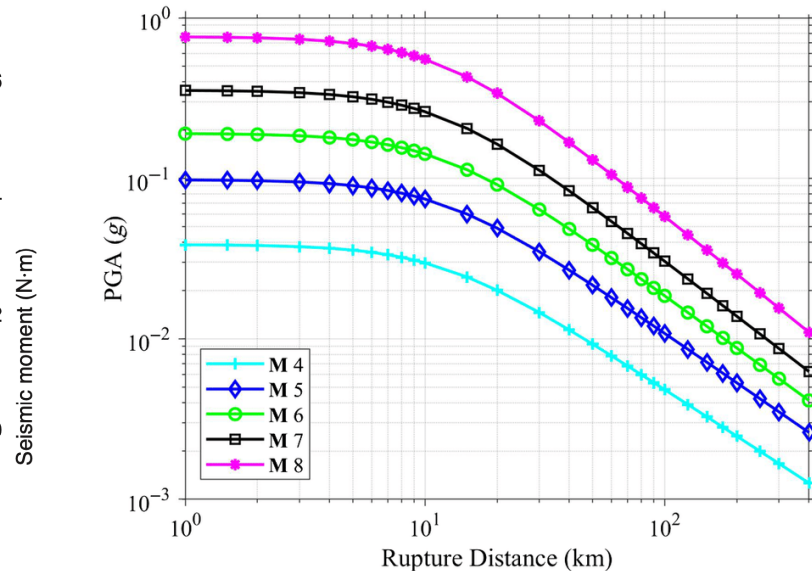
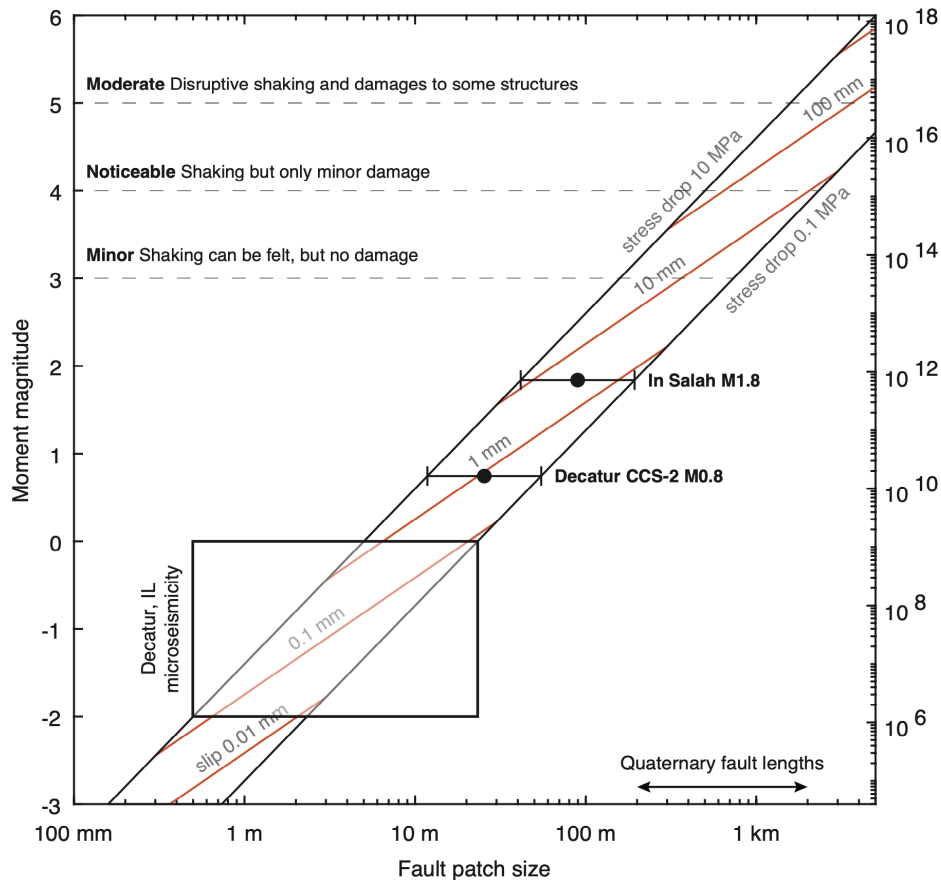
	Criteria	Description	Action
Area of interest (AOI)	Thermal plume	Region where thermal stresses are >1% of initial	If event with threshold characteristics or shaking occurs in thermal plume, refer to traffic light protocol.
	Pressure plume	Region where change in pressure is >1% of initial	If event with threshold characteristics or shaking occurs in pressure plume, refer to traffic light protocol.
	Strain plume	Region where strains are >0.1%	If event with threshold characteristics or shaking occurs in strain plume, refer to traffic light protocol.
	Slip on mapped fault	Earthquakes or swarm on mapped faults in seal, reservoir, or underburden	If event with threshold characteristics or shaking occurs on mapped fault, refer to traffic light protocol.
Seismic characteristics	Event magnitude	Event magnitude can be obtained real time from USGS API	If event >M3 in AOI refer to red light protocol. If <M3, assess seismic characteristics and ground shaking.
	Spatial seismicity rate	2x2 km x 1 month grid	If density > 0.2 mo ⁻¹ km ⁻¹ in area of interest, assess other seismic characteristics and shaking criteria and refer to traffic light protocol if necessary.
	Gutenberg-Richter	G-R statistics for earthquake swarms	Additional aseismic data is needed to determine thresholds for changes in G-R statistics.
Ground shaking	Peak ground acceleration	PGA for nearby population centers	If PGA > 0.1 g, assess area of interest and seismic characteristics and refer to traffic light protocol if necessary.
	Perceived shaking	Felt reports to USGS or operator	If perceived shaking > Strong (PGA 0.9–1.8) reported, assess area of interest and seismic characteristics, and refer to traffic light protocol if necessary.
	Reported damage		Criteria, and refer to traffic light protocol.

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC. (%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL. (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Traffic light system for CO₂ storage

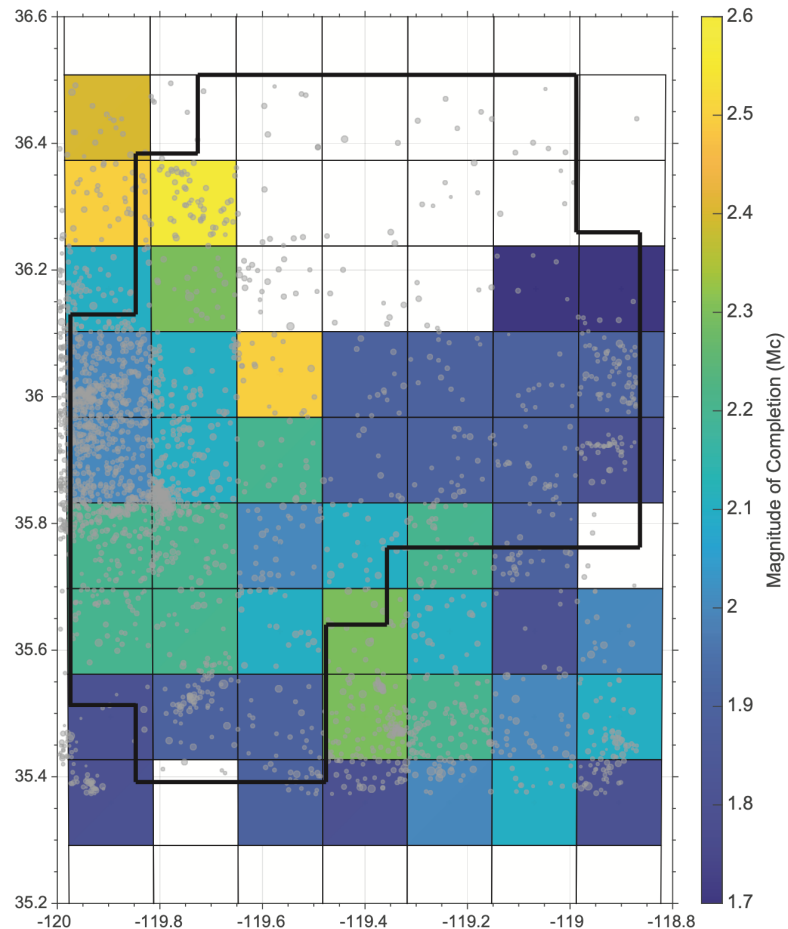
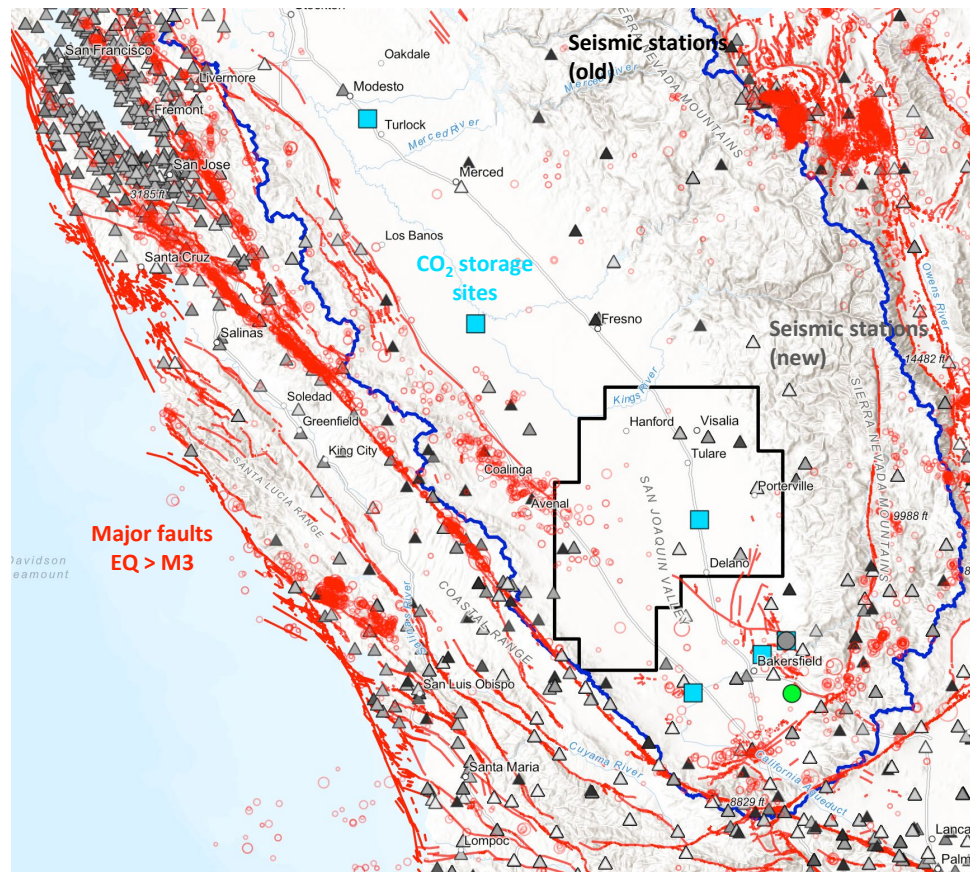
State	Threshold conditions	Action
	<ul style="list-style-type: none"> - Seismic events <M1.5⁽²⁾ in AOI⁽¹⁾ - Spatial seismicity rate <0.2 mo⁻¹km⁻² - Monitoring well expected dP 	<ol style="list-style-type: none"> 1. Continued operations at current levels
	<ul style="list-style-type: none"> - Seismic events M1.5-2.0⁽²⁾ in AOI⁽¹⁾ - Spatial seismicity rate 0.2-0.4 mo⁻¹km⁻² - Monitoring well dP 1% greater than model 	<ol style="list-style-type: none"> 1. Continued operations at current levels 2. Within 24 hours of the incident, notify the Underground Injection Control (UIC)
	<ul style="list-style-type: none"> - Seismic event >M2.0⁽²⁾ in AOI⁽¹⁾ and/or felt report⁽³⁾ - Spatial seismicity rate >0.5 mo⁻¹km⁻² - Seismic event >M1.5 on mapped fault - Seismic event >M1.5 above/below storage unit - Monitoring well dP 5-10% greater than model 	<ol style="list-style-type: none"> 1. Injection rate reduction 2. Vent CO₂ from surface facilities 3. Within 24 hours of the incident, notify the UIC Program Director 4. Limit access to wellhead 5. Coordinate evacuation plans, if necessary 6. Monitor well diagnostics (pressure, temperature, etc.) 7. Check for leaks to groundwater 8. If USDW contamination detected, shutdown operations. 9. Review seismic and operational data for space-time correlation. 10. Report findings to UIC Program Director and amend operating conditions
	<ul style="list-style-type: none"> - Seismic event >M3.0⁽²⁾ in AOI⁽¹⁾ and/or felt report⁽³⁾ and/or damage report⁽⁴⁾ - Spatial seismicity rate >1 mo⁻¹km⁻² - Seismic event >M2.0 on mapped fault - Seismic event >M2.0 above/below storage unit - Monitoring well dP >10% greater than model 	<ol style="list-style-type: none"> 1. Shutdown procedure 2. Vent CO₂ from surface facilities and shut in well 3. Within 24 hours of the incident, notify the UIC Program Director 4. Limit access to wellhead 5. Coordinate evacuation plans, if necessary 6. Monitor well diagnostics (pressure, temperature, etc.) 7. Check for leaks to groundwater 8. If USDW contamination detected, shutdown operations. 9. Review seismic and operational data for space-time correlation. 10. Report findings to UIC Program Director and amend operating conditions

What scales of seismicity and ground shaking matter?



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC. (%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL. (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Regional scale monitoring



- Seismic hazard assessment protocol
 - Stress, faults, and seismicity map
 - Stress and pore pressure change on nearby faults
 - Seismic characterization and criteria for natural vs. induced seismicity
- Blue Star site
 - Strike-slip stress state, 8 mapped faults within 10 km of injector
 - Background seismicity rate within 5 km is relatively low (<0.1 events/mo/km²)
 - Fault slip potential $<10\%$ on nearest fault (QF2) in optimized injection scenario
- Measurement, monitoring, and verification
 - Monitoring requires induced seismicity criteria + traffic light response system
 - Control shape and magnitude of pressure plume to minimize risk of induced seismicity