October 30, 2014

Risk Management of Induced Seismicity: Technical Elements & Research Opportunities

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U.S. Department of Energy
Informational Briefing on Subsurface Technology and Engineering Challenges and R&D Opportunities: Stress State and Induced Seismicity

Washington, D.C.

Overview of Key Research Opportunities

- **Improving the knowledge of natural tectonics and subsurface stress / pressure conditions and identification of significant faults systems prone to slip (considering both the deeper basement and shallower geologic horizons)**

- **Improving the understanding of ground shaking behavior and seismic wave attenuation characteristics**

- **More broadly establishing a cohesive, integrated, and interdisciplinary technical framework for defining fit-for-purpose approaches for risk management of potential induced seismicity**

- **Developing effective capabilities and methods, based on sound-science, to identify and differentiate naturally-occurring earthquakes from induced earthquakes**

Background

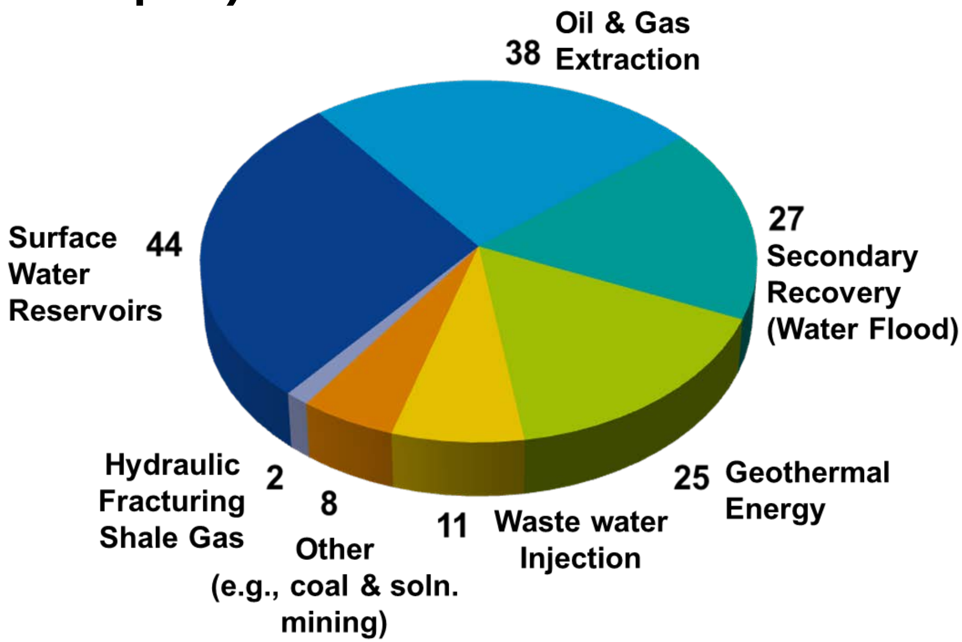
The vast majority of seismic events are due to natural causes, but under unique conditions can be due to anthropogenic sources

Global Earthquake Frequency (from USGS Estimates)	
Magnitude	**Annual Average**
8 and higher	1 [a]
7 – 7.9	15 [a]
6 – 6.9	134 [b]
5 – 5.9	1319 [b]
4 – 4.9	13,000 (estimated)
3 – 3.9	130,000 (estimated)
2 – 2.9	1,300,000 (estimated)

a. Based on observations from 1900
b. Based on observations from 1990

http://earthquake.usgs.gov/earthquakes/eqarchives/year/eqstats.php

- **1 million "naturally" occurring earthquakes / year (globally from USGS estimates)**
- **~155 cases of induced seismicity documented globally in over the last ~80+ years (per 2012 NAS report)**



As documented in the National Academies report, the number of sites where seismic events of M > 0 have occurred that are caused by or likely related to energy development (between 1926-2012)

Understanding "Faults of Concern"

- A fault "optimally" oriented for movement;
- located in a critically stressed region;
- of sufficient size, and possesses sufficient accumulated stress / strain, such that fault slip has the potential to cause a ***significant*** earthquake

The vast majority of faults are stable and/or will not produce a significant earthquake

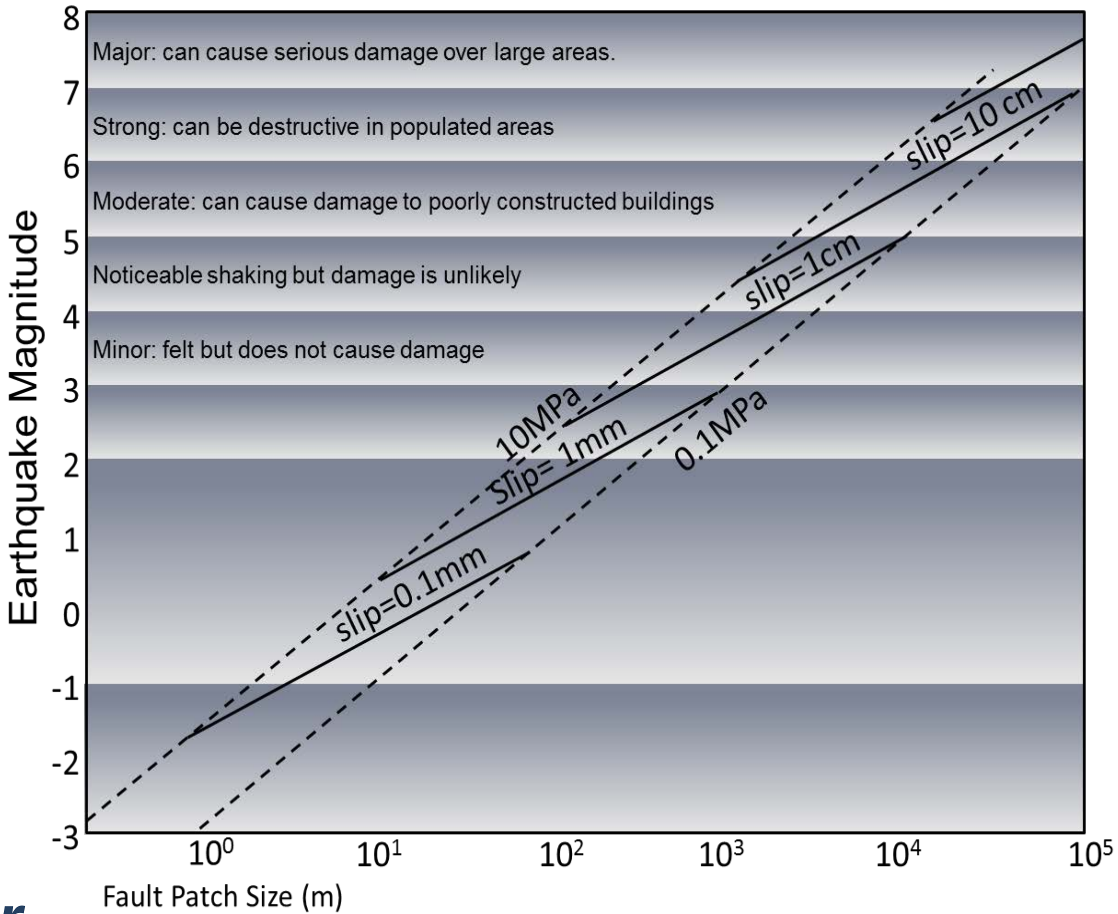


FIGURE: *The relationships between earthquake magnitude, the size of a section of a fault (dimension in the figure is length in meters, representing the diameter of a circular fault patch) that slips in an earthquake and the amount of fault slip based on widely-used seismic scaling relations. Courtesy of Stanford University Professor Mark Zoback.*

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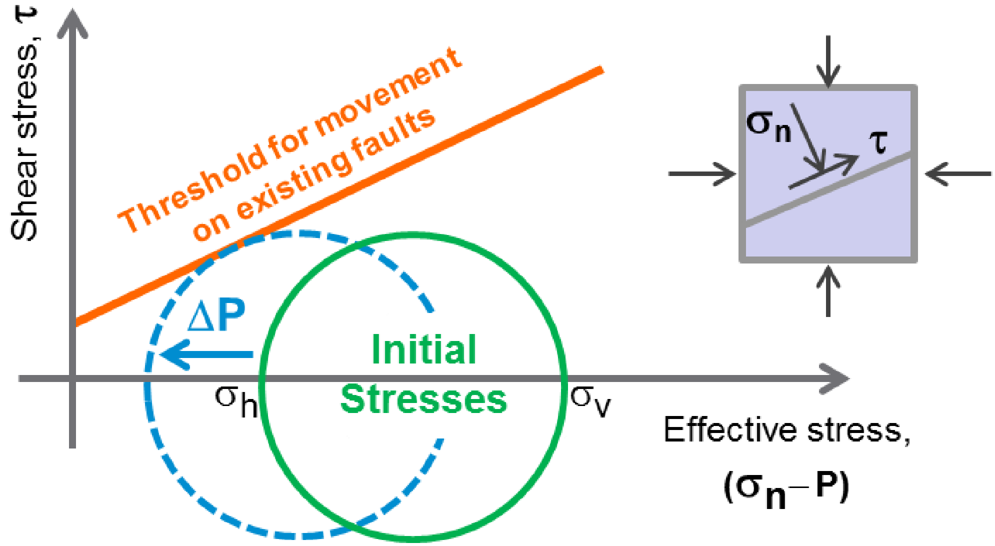
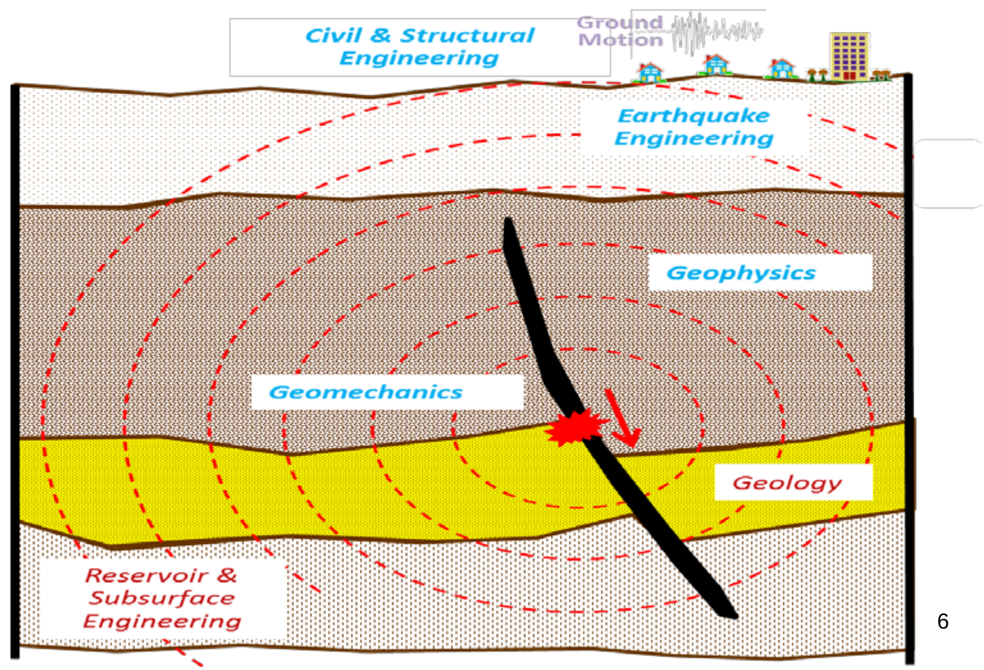
Identifying "Faults of Concern"

- **Understanding the subsurface stress field**



- **Understanding the location, size, and orientation of the faults**

- **Noting that multiple technical disciplines are required to inform the understanding**



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The National Academy's Report Has Further Motivated A Need for Improved Understanding of "Induced Seismicity Risk"

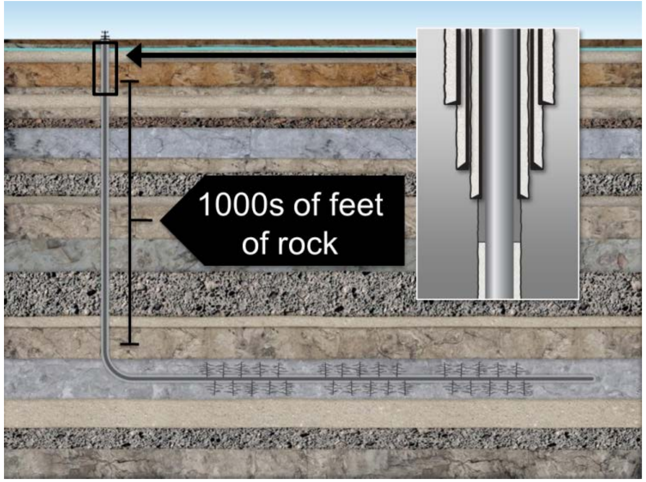
National Academy of Sciences Report
Major Findings

1. "The process of **hydraulic fracturing** a well as presently implemented for shale gas recover **does not pose a high risk** for inducing felt seismic events
2. Injection for **disposal of waste water** derived from energy technologies into the subsurface **does pose some risk** for induced seismicity, but very few events have been documented over the past several decades relative to the large number of disposal wells in operation; and
3. CCS, due to the large net volumes of injected fluids, may have potential for inducing larger seismic events."

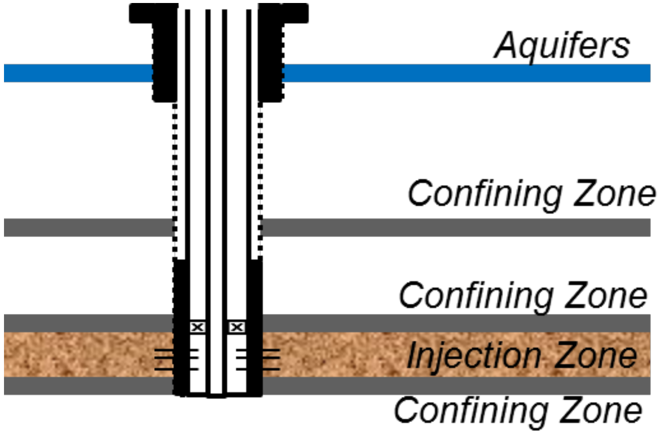
NAS (June 2012), "Induced Seismicity Potential in Energy Technologies", http://www.nap.edu/catalog.php?record_id=13355

Waste Water Disposal and Hydraulic Fracturing are Significantly Different (Volumes, Time Duration, Pressures)

Hydraulic Fracturing



Waste Water Disposal



Characterizing the Risk

Ground Shaking: Key to Understanding Risk

Potential Damage	MMI	Perceived Shaking	Approximate Magnitude*	Peak Acceleration (%g)	Peak Velocity (cm/s)
None	I	Not Felt	1.0 - 3.0	<0.17	<0.1
	II	Weak	3.0-3.9	0.17-1.4	0.1-1.1
	III				
	IV	Light	4.0-4.9	1.4-3.9	1.1-3.4
Very Light	V	Moderate	4.0-4.9	3.9-9.2	3.4-8.1
Light	VI	Strong	5.0-5.9	9.2-18	8.1-16
Moderate	VII	Very Strong	5.0-6.9	18-34	16-31
Moderate/ Heavy	VIII	Severe	6.0-6.9	34-65	31-60
Heavy	IX	Violent	6.0-6.9	65-124	60-116
Very Heavy	X	Extreme	>7.0	>124	>116
	XI				
	XII				

*Magnitudes correspond to intensities that are typically observed at locations near the epicenter of earthquakes of these magnitudes

Primary Structure

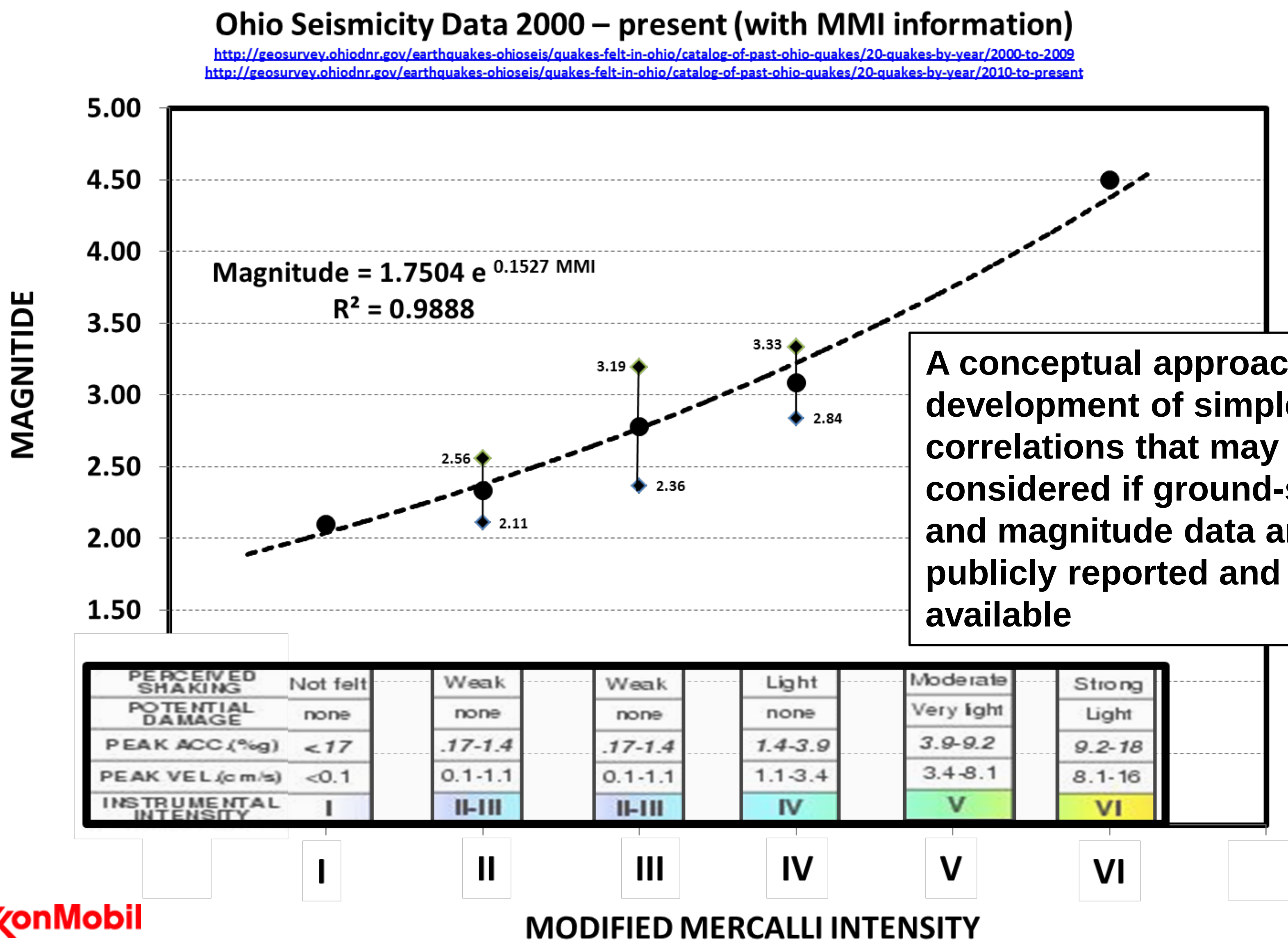
- **Seismicity has little to no impact in well built ordinary structures when MMI < ~V – VI**
- **Seismicity at levels MMI < ~V – VI can cause damage in primitive and/or aging structures built without considering earthquake resistance**

Humans & Secondary Components

- **Much more sensitive to small tremors**
- **Highly dependent on**
  - **Local soil conditions**
  - **In-structure local motion amplification**

Wald, D.J., Worden, B.C., Quitoriano, V., and Pankow, K.L., 2005, ShakeMap manual: technical manual, user's guide, and software guide: U.S. Geological Survey, 132 p. Wald, D.J., Quitoriano, V., Heaton, T.H., and Kanamori, H., 1999, Relationship between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California: Earthquake Spectra, v. 15, no. 3, p. 557-564.

A Conceptual Approach for Developing Simple Ground Shaking Correlations When Data is Limited



A conceptual approach for development of simple correlations that may be considered if ground-shaking and magnitude data are publicly reported and available

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Effective Risk Management Considers Probability and Consequences

- **Risk is the combination of *Probabilities* and *Consequences***
- **A standard engineering approach is using a risk matrix to identify risk level**
- **With risk level identified, risk mitigation approaches can be more effectively evaluated and selected**

Probability

Consequence

	Very Likely	**Somewhat Likely**	**Unlikely**	**Somewhat Unlikely**	**Very Unlikely**
1 MMI > VIII	High	High	High	Medium	Low
2 MMI: VI - VII	High	High	Medium	Low	Very Low
3 MMI: V - VI	Medium	Medium	Low	Very Low	Very Low
4 MMI: II - IV	Low	Very Low	Very Low	Very Low	Very Low

A Generic Example of a Possible Risk Matrix for Induced Seismicity Based on Ground Shaking (MMI)

Potential Probability Considerations

Probability	Fluid Volume	Formation Character	Tectonic / Faulting / Soil Conditions	Operating Experience	Public Sensitivity & Tolerance	Local Construction Standards
A Very Likely	Large volumes of injection in immediate or close proximity to active faults. Reservoir pressure rising and approaching fracture pressure	Deeper injection horizon; highly consolidated formations. Low KH sand of limited lateral continuity	Large-scale developed/active faults are present at depths that could be influenced by pressure / fluid communication associated with injection; strongly consolidated formation; soil conditions amplify vibrational modes	Past injection experience in region with damaging levels of ground shaking	High population density & historically low background seismicity	Primitive construction and limited/no engineering applied for earthquake resistant designs
B Somewhat Likely	Large or moderate volumes of fluid injected in proximity to active faults. Reservoir pressure rising above initial pressure	Moderate depth injection horizons; highly consolidated formations. Marginal KH sand of marginal lateral continuity	Large-scale developed/active faults may possibly be present, but not identified; strongly consolidated formation, soil conditions may amplify vibrational modes	Limited injection experience historically in region	Moderate / high population density and/or historically low / moderate background seismicity	Sound construction practices, but age/vintage of building construction pre-dates earthquake engineering design principles.
C Unlikely	Moderate fluid volume of injection; remote from any active fault. Reservoir pressure is near initial reservoir pressure	Shallow injection horizon; highly consolidated formations. Moderate KH sand with moderate lateral continuity	Faults well identified, and unlikely to be in influenced by pressure / fluid associated with injection; moderately consolidated formation	Significant injection experience historically in region with no damaging levels of ground shaking	Moderate population density and historically moderate / high background seismicity	Ground vibration and seismic activity routinely considered in civil / structural designs and routinely implemented in majority of buildings
D Very Unlikely	Small fluid volume of injection; remote from any active fault. Reservoir pressure is constant below initial pressure	Shallow injection horizon; weakly consolidated formations. Good KH sand with good lateral continuity	Stable stress environment; minimal faulting; if faults present, too small to induce any surface felt seismicity; weakly consolidated or unconsolidated formation, soil conditions may dampen vibrational modes	Significant injection experience historically in region with no surface felt ground shaking	Low population density & historically moderate background seismicity	Rigorous earthquake engineering civil / structural designs routinely implemented and required
E Very Highly Unlikely	Small fluid volume of injection; remote from any active faults. Reservoir pressure is constant below initial pressure	Shallow injection horizon, Poorly consolidated formations. High KH sand of extensive lateral continuity	Stable stress environment; no significant faults, weakly consolidated or unconsolidated formation, soil conditions may dampen vibrational modes	Significant injection experience historically across wide geographic region with no surface felt ground shaking	Low population density & historically high background seismicity	Rigorous earthquake engineering civil / structural designs routinely implemented and required

Potential Probability Considerations

Probability	Fluid Volume	Operating Experience	Local Construction Standards
A Very Likely	Large volumes of injection in immediate or close proximity to active faults. Reservoir pressure rising and approaching fracture pressure	**Past injection experience in region with damaging levels of ground shaking**	Primitive construction and limited/no engineering applied for earthquake resistant designs
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Potential Probability Considerations

Probability	Tectonic / Faulting / Soil Conditions
A Very Likely	Large-scale developed/active faults are present at depths that could be influenced by pressure / fluid communication associated with injection; strongly consolidated formation; soil conditions amplify vibrational modes
B Somewhat Likely	Large-scale developed/active faults may possibly be present, but not identified; strongly consolidated formation, soil conditions may amplify vibrational modes
C Unlikely	Faults well identified, and unlikely to be in influenced by pressure / fluid associated with injection; moderately consolidated formation
D Very Unlikely	Stable stress environment; minimal faulting; if faults present, too small to induce any surface felt seismicity; weakly consolidated or unconsolidated formation, soil conditions may dampen vibrational modes
E Very Highly Unlikely	Stable stress environment; no significant faults, weakly consolidated or unconsolidated formation, soil conditions may dampen vibrational modes

Potential Consequence Considerations

Consequence	Safety / Health	Environmental	Public	Financial
1 *Mod. Merc. Ind.* *> VIII*	Potential fatalities and serious injuries; building structural damage.	Potential widespread long-term significant adverse affects. Possible release of potentially hazardous compounds – extended duration &/or large volumes in affected area (large chemical static / transport vessels and pipelines break).	Ground shaking felt in large region. Possible extensive mobilization of emergency 1st responders. Possible disruption of community services for extended time.	$$$$
2 *Mod. Merc. Ind.* *VI – VII*	Potential serious injuries; building cosmetic & secondary building content damage.	Potential localized medium term significant adverse effects. Possible release of potentially hazardous compounds short-duration &/or limited volumes (large vessels break).	Ground shaking felt by all in local area. Possible mobilization of emergency 1st responders. Possible disruption of community services for brief time.	$$$
3 *Mod. Merc. Ind.* *V – VI*	Potential minor injuries in isolated circumstances; building secondary content damage.	Possible release of potentially hazardous compounds in limited volumes (e.g., containers break).	Ground shaking possibly felt by sensitive few at site. Possible limited site impact and possible limited mobilization of 1st responder(s).	$$
4 *Mod. Merc. Ind.* *< V*	Potential first aid in isolated circumstances; isolated secondary building content damage.	Possible release of potentially hazardous compounds in very small volumes (e.g., small containers break).	Possible minor public complaints.	$

Risk Characterization:

Case Examples

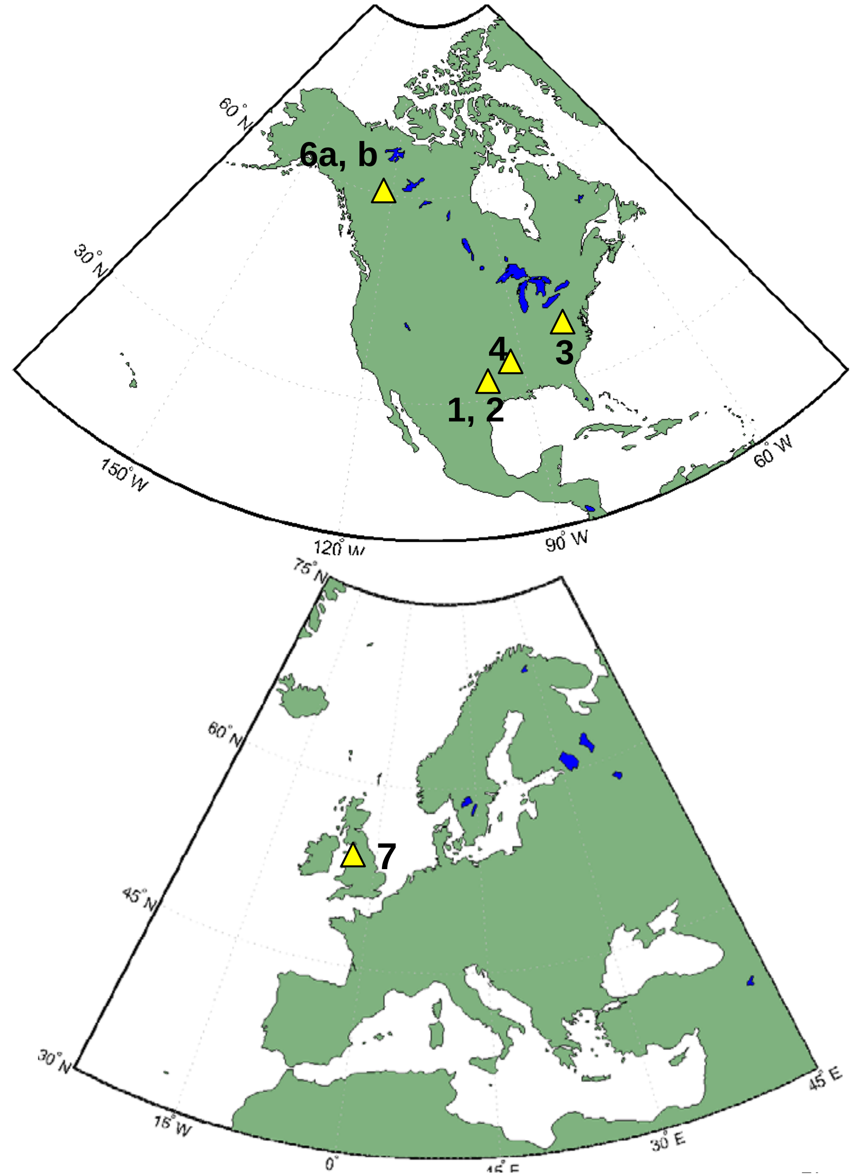
Disposal and Hydraulic Fracturing Case Examples

Disposal

1. Dallas-Forth Worth Airport, Texas
2. Dallas-Fort Worth, Cleburne, TX
3. Braxton, West Virginia
4. Guy-Greenbriar, Arkansas
5. General Case – Injection Well

Hydraulic Fracturing

6. Horn River Basin, Canada
   a) Etsho
   b) Tattoo
7. Bowland Shale, UK
8. General Case – HF Well
   - *Microseisms always created*



Example Assessments
Waste-Water Disposal & Hydraulic Fracturing

Disposal

1. Dallas-Forth Worth Airport, Texas
2. Dallas-Fort Worth, Cleburne, TX
3. Braxton, West Virginia
4. Guy-Greenbriar, Arkansas
5. General Case – Injection Well

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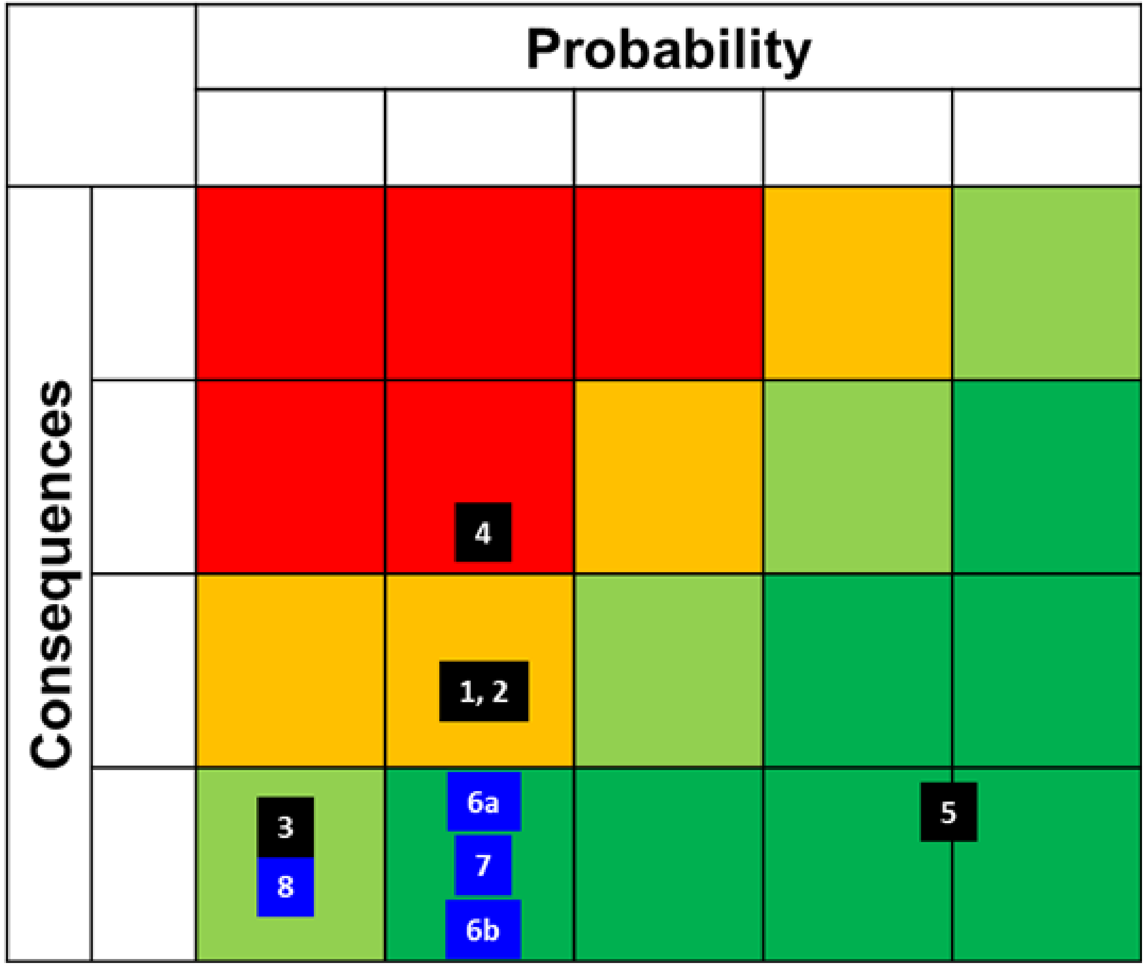


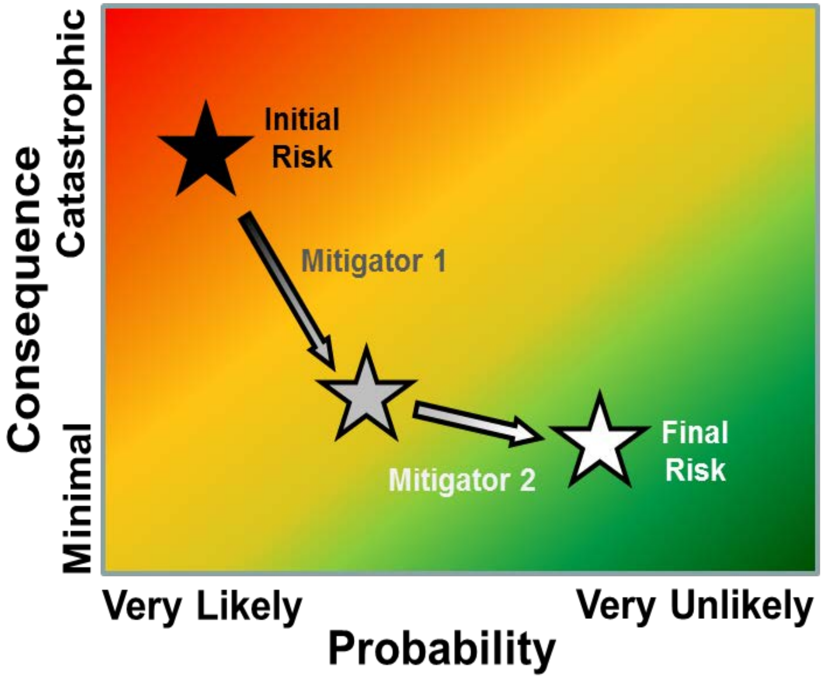
Note: assessment of probability & consequence for the specific examples based on hindcast evaluation of observed seismicity and publicly-reported information.

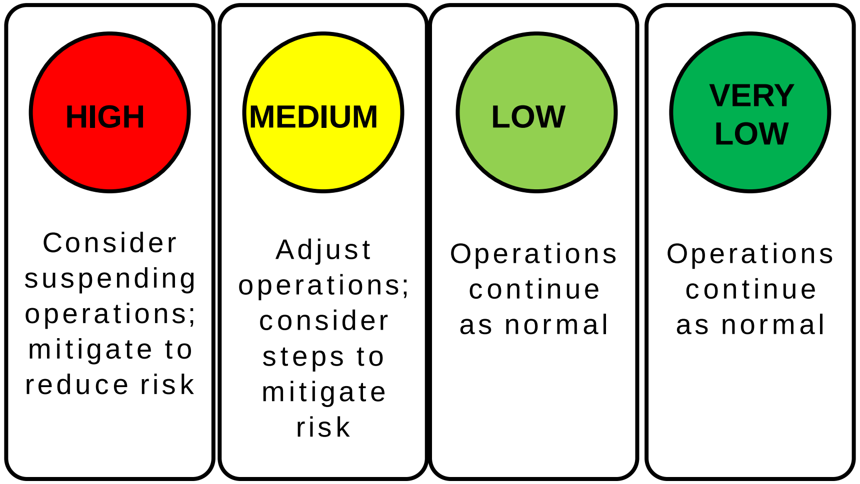
Risk Management:

Mitigation and Traffic Light Systems

Risk Mitigation Should Be Based on Risk Level and Local Conditions

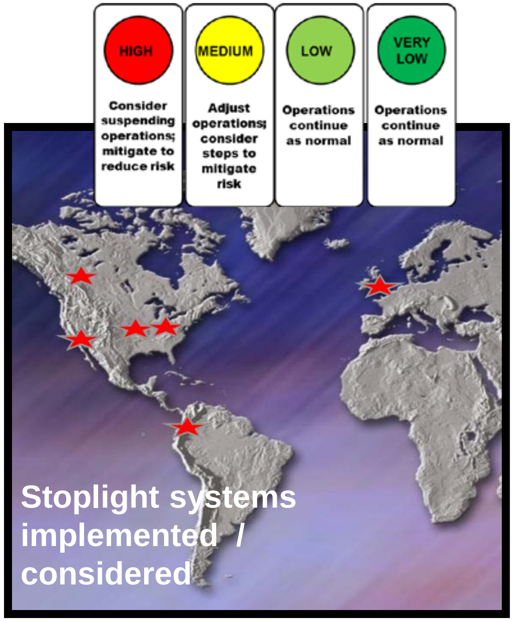
- **Selecting well locations**
  - ➢ **available fault maps**
  - ➢ **historical seismicity records**
- **Monitoring for presence of any previously unidentified faults during well drilling**
- **Avoiding injection of fluids into the basement**
- **Avoiding injection adjacent to identified and significant “faults of concern”**
- **Fit-for-purpose traffic light systems based on risk level**
- **Education & training**





Traffic Light Systems: Considering The Local Situation

- **Are being considered with a high degree of variability due to political and regulatory differences**
- **Should be selected based on risk level and local conditions**



Remote

Rural

Suburban

Metropolitan

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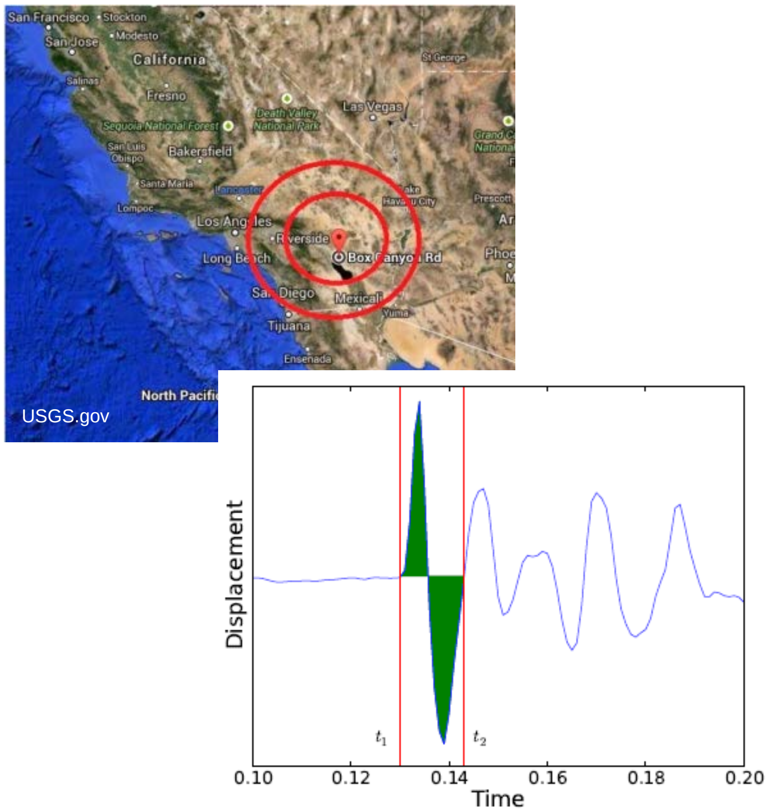
Evaluating Causality:

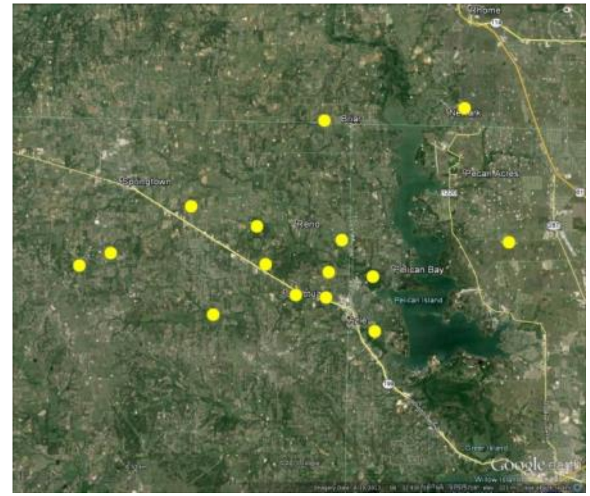
Is Challenged by Difficulty in Precisely Locating Seismic Events; Coupled to Poor Understanding of Natural Tectonics

Understanding Precision, Accuracy, and Sensitivity of Event Detection

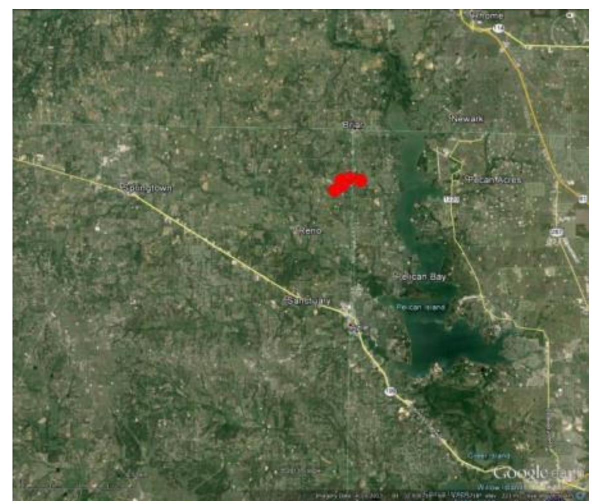
- Location errors
- Magnitude errors



Location Accuracy Can Be Highly Variable



Epicenter locations by USGS-NEIC



Re-located epicenters

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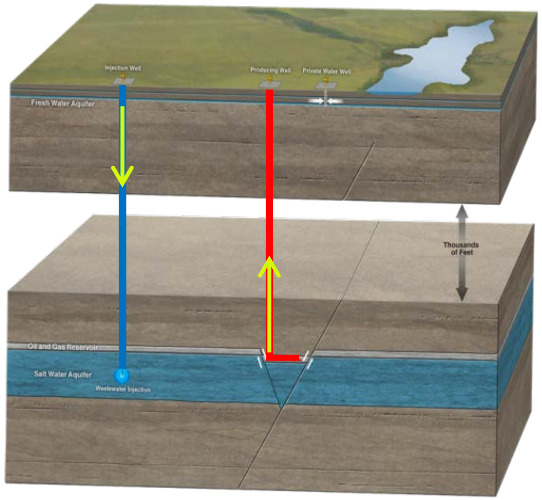
Images and permission for use provided courtesy of W.L. Ellsworth (USGS), and A. Stork (Bristol University)

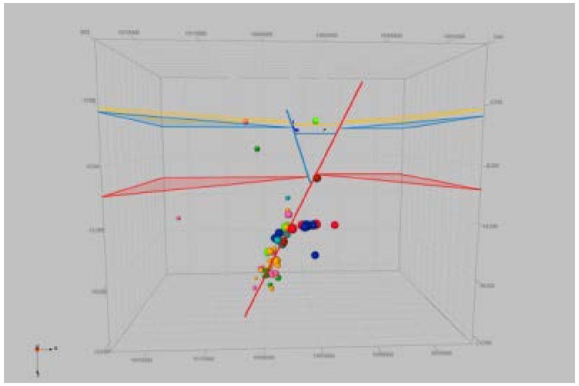
Causality Investigations: Should Consider All Possible Sources

- **4-D investigation of all of the available data**
- **Identify and characterize reactivated faults**
- **Accurately locate hypocenters**
- **Evaluate seismicity data via Gutenberg-Richter relationship**
- **Perform reservoir modeling to evaluate subsurface pressure**
- **Integrate all available data**
- **Maintain a monitoring plan**
- **Stakeholder and regulator engagement and collaboration**

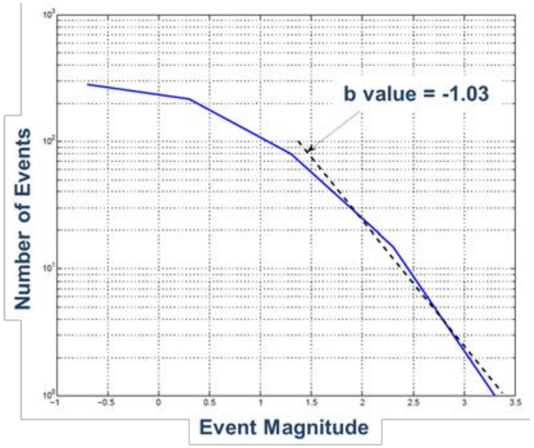
Surface/subsurface characterization



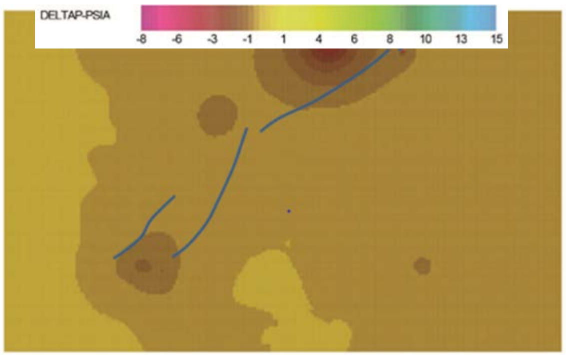
Accurate hypocenters



b-value analysis



reservoir modeling



Summary

Concluding Perspectives

- **Approaches to assess and manage seismicity risk should be encouraged**
- **Seismicity monitoring and mitigation should be considered in local areas where induced seismicity is of significant risk**
- **Traffic light system thresholds should be established based on risk level and considering ground shaking hazards relative to local conditions**
- **If anomalous seismicity occurs, pursue collaboration between industry, regulatory agencies, and the research community to design a plan to identify all possible factors that may be leading to the observed seismicity**

Overview of Key Research Opportunities

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