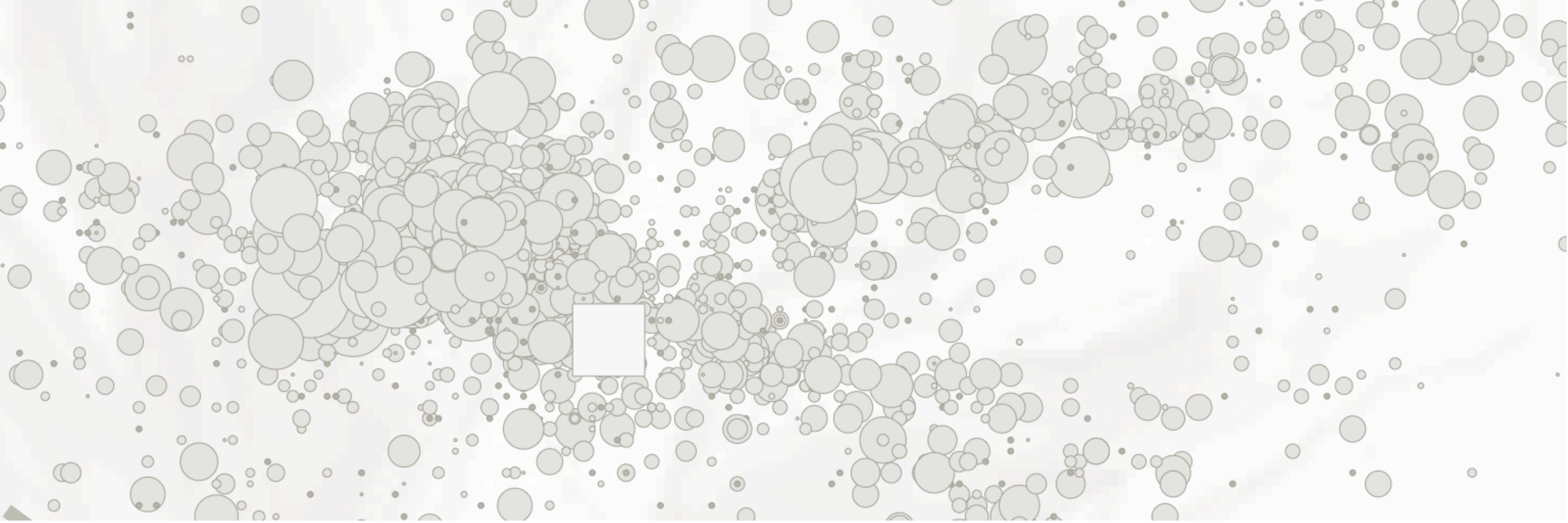

Risk Management and Induced Seismicity

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Outline

1. General introduction to Risk Assessment / Management at carbon storage operations.

2. More specific discussion of Induced Seismicity Risk Management.

Seismicity observed at CO_2 injection operations

Operation	Category	Max Observed Magnitude	Seismicity Type
Aneth USA	CO2-EOR	**M** 0.8	Type II
Cogdell USA	CO2-EOR	**M** 4.4	Type I
Weyburn Canada	CO2-EOR	**M** -1	Type II
Decatur USA	Dedicated Storage	**M** 1	Type I
In Salah Algeria	Dedicated Storage	**M** 1	Type I & II

Type I = Seismicity concentrated within overpressured zone.
Type II = Seismicity outside overpressured zone.

Aneth: Rutledge 2010, Zhou et al. 2010, Soma & Rutledge 2013. **Cogdell**: Gan and Frohlich 2013, Davis and Pennington 1989. **Weyburn**: Whittaker et al. 2011, White et al. 2011, Verdon et al. 2010 & 2011. **Decatur**: Will et al. 2014, Couëslan et al. 2014, Kaven et al. 2014 & 2015. **In Salah:** Oye et al. 2013, Goertz-Allman et al. 2014, Verdon et al. 2015.

Terminology

In general, risk consists of three parts (Kaplan & Garrick 1981):

① One or more scenarios of concern

- e.g. an earthquake causes strong ground motion

② The *probability* of a given scenario occurring (**hazard**)

- e.g. annual probability of exceeding a certain ground motion acceleration

③ The *probability* of damage that would result (**risk**)

- e.g. annual probability of exceeding a structural damage threshold.

Note: Different communities use different formalisms to describe risk. Terminology becomes clearer when quantitative metrics are assigned.

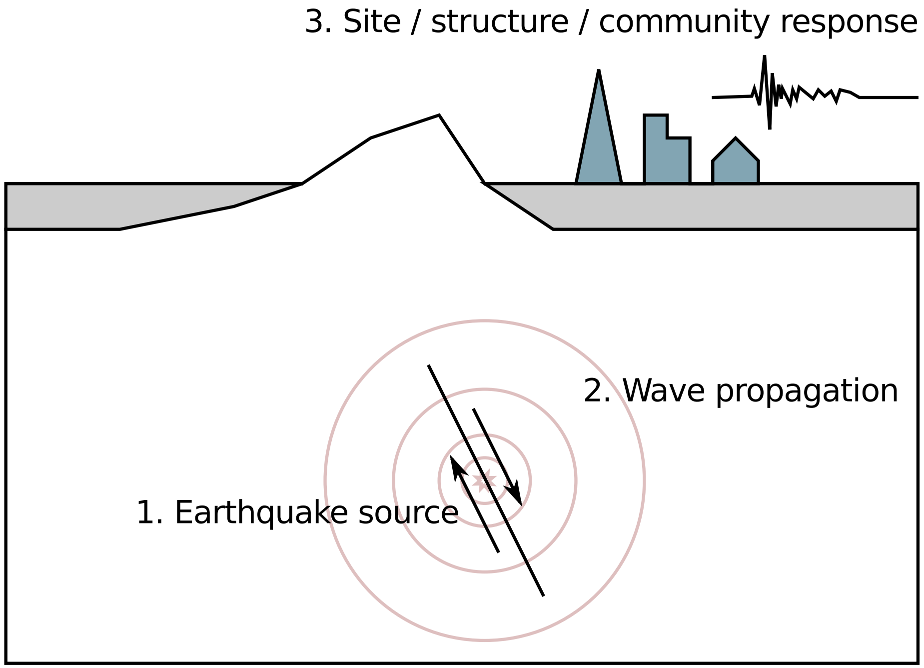
Four key induced seismicity risks

Induced events can potentially lead to …

- Infrastructure damage
- Public nuisance
- Brine leakage
- CO_2 leakage

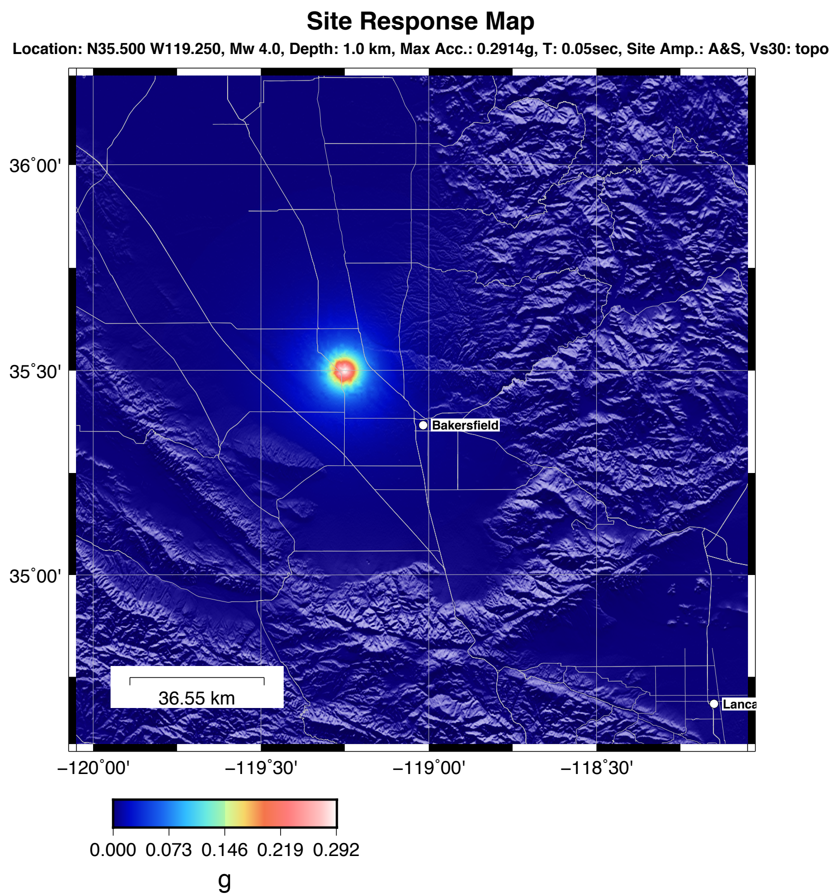
Mostly an **onshore** problem, but fault reactivation and subsequent leakage is a concern for **offshore** operations as well.

Overall risks are governed by a complex system

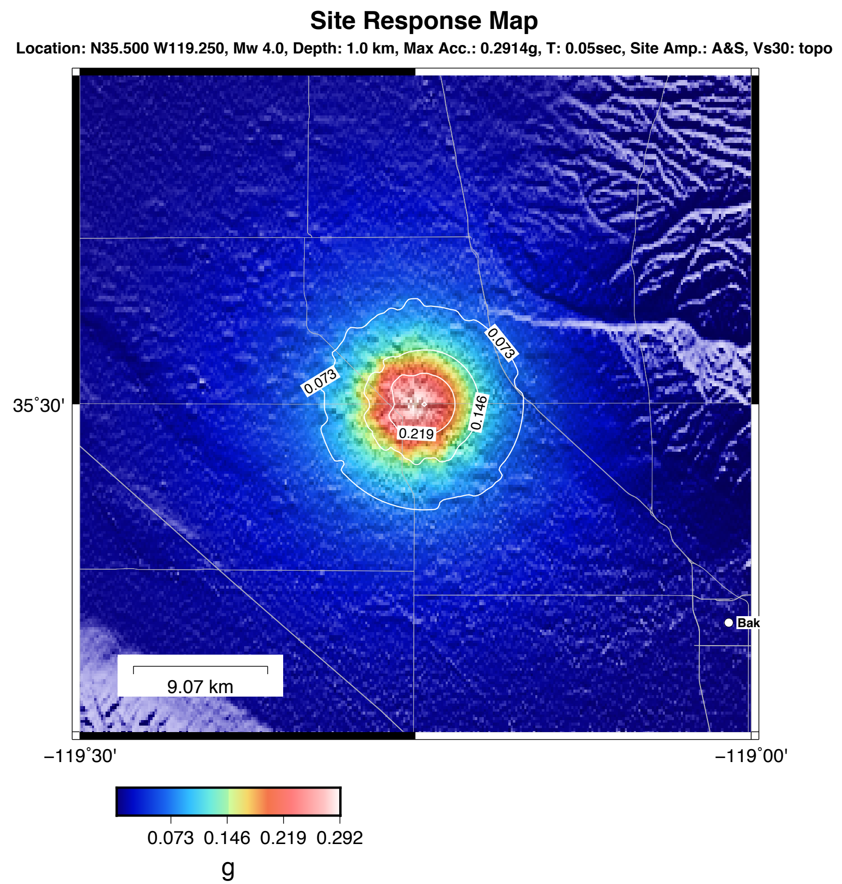


- Risk management should address the full event chain:
  - Reduce the probability of the scenario happening (reduce hazard)
  - Reduce the probability of damage (increase robustness)

Ground motion prediction for a hypothetical Mw 4.0 earthquake at 1 km depth



Map of site response for an induced event In San Joaquin Valley

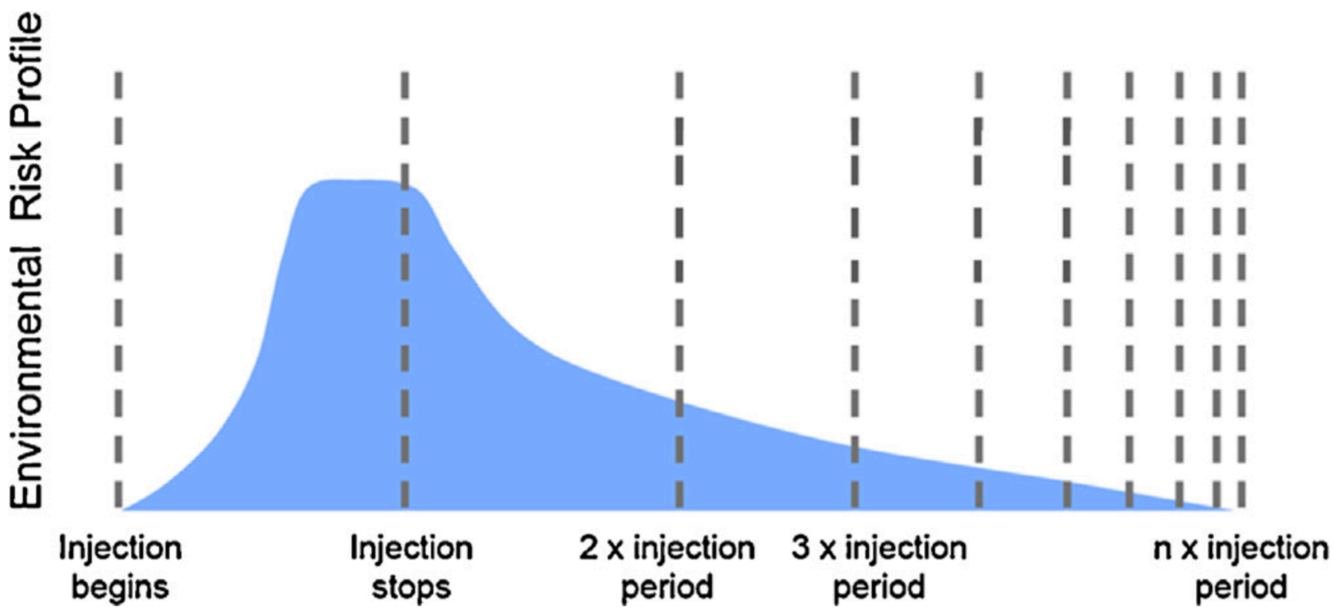


Larger scale map showing detailed accelerations in Kimberlina area

[Lee et al. 2016]

Risk management also needs to adapt with time

- The intrinsic risk evolves with time
- Our knowledge of risk evolves with time
- Carbon storage operations have a limited budget

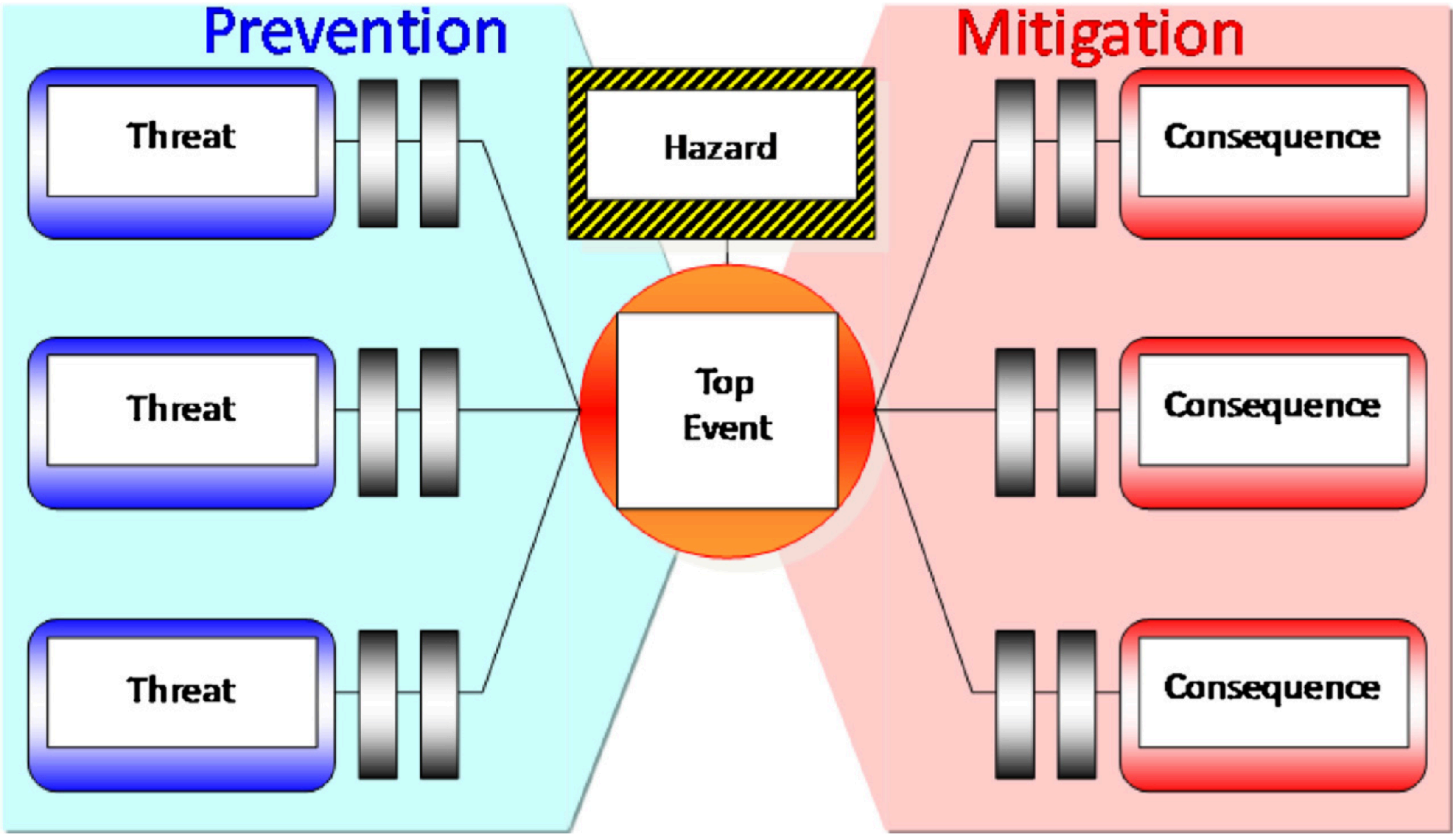


[Benson 2007]

Numerous risk management frameworks are available

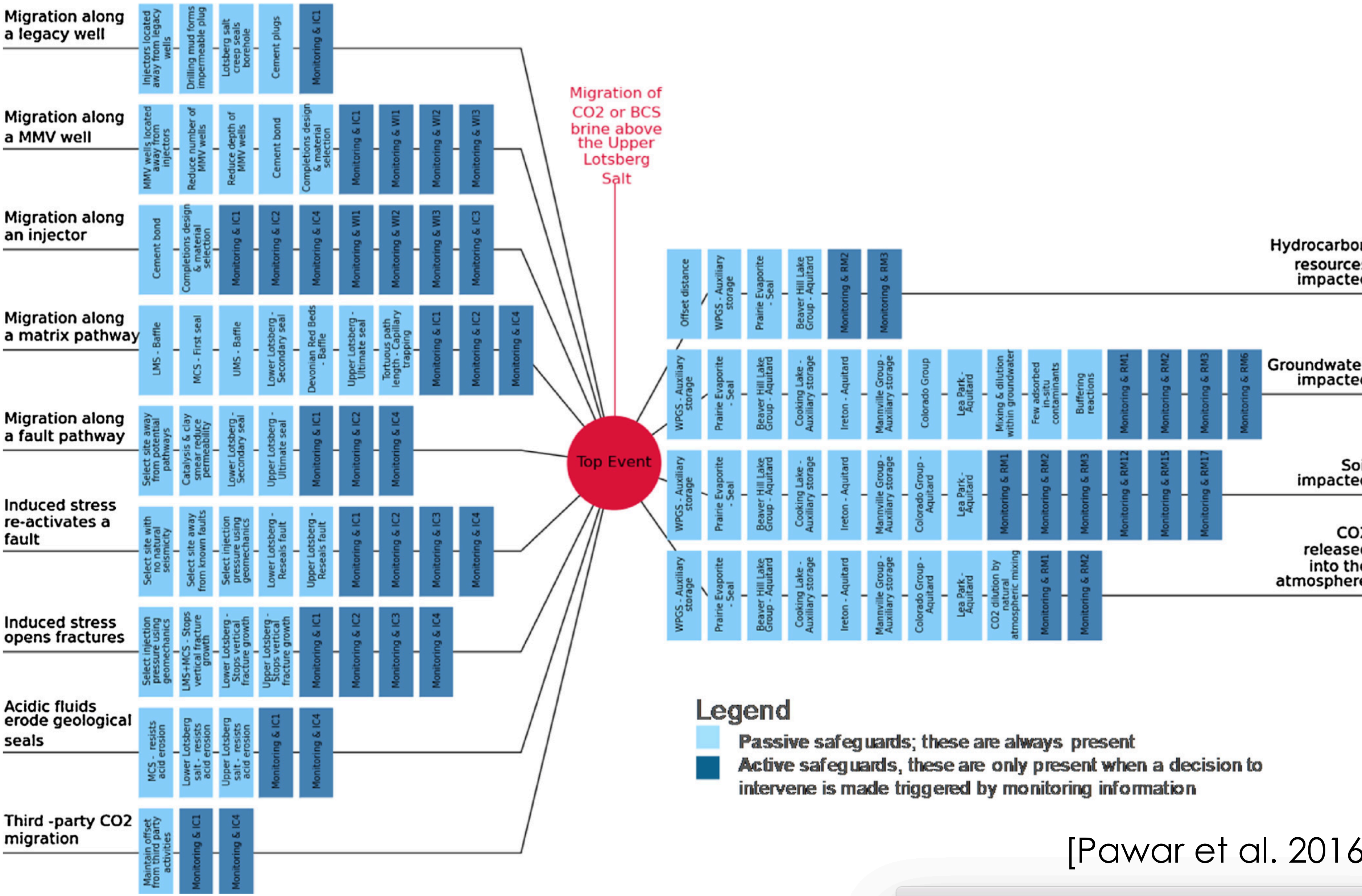
- All have essentially the same process
  1. Identify all scenarios of concern
  2. Quantify hazard / risk for each scenario
  3. Add safeguards to reduce unacceptable risk scenarios
  4. Iterate
- They differ mostly in how things are "quantified":
  - Qualitative expert opinion up to a full probabilistic risk assessment
- **In many ways, having a rigorous process is more important than the final numbers it produces.**

“Bow-tie” method



[Pawar et al. 2016]

Quest project bow-tie



[Pawar et al. 2016]

Probabilistic Seismic Risk Assessment

Major components:

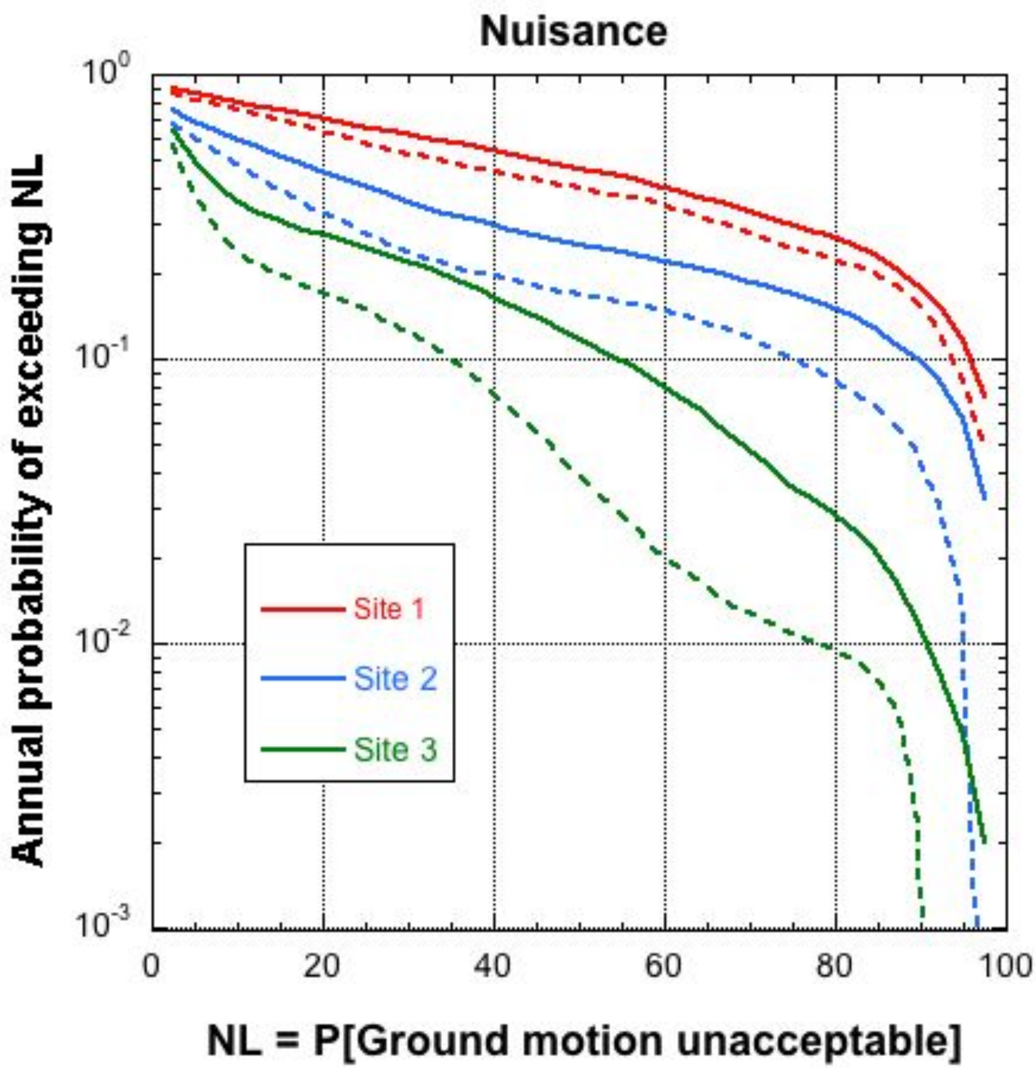
① Seismic source characterization

② Ground motion prediction

③ Hazard estimation

④ Structural and community vulnerability

⑤ Risk estimation



[Foxall et al. 2014]

Three key hurdles to effective seismicity management:

① Faults are pervasive, and current tools to identify and characterize them have intrinsic limitations.

② The relationship between fluid injection, seismic activity, and damage is complex, and projects have little time to figure it out.

③ The knobs we can turn to reduce seismicity often have a lag before taking effect, can increase cost, and can reduce storage rates.

Seismicity management schemes must acknowledge these realities.

Phased approach to seismicity management

- Projects are always budget- and data-limited
- Risk management should adapt to available information

- Phases
  - Site-screening
  - Pre-injection
  - Injection & Stabilization
  - Mitigation phase

- Categories
  - Monitoring & Characterization
  - Modelling & Analysis
  - Operations & Management

Phased approach to seismicity management for CCS

Phase	*Monitoring & Characterization*	*Modeling & Analysis*	*Operations & Management*
Site-screening	• Collect regional stress estimates. • Collect regional seismicity estimates. • Collect regional fault characterizations.	• Back-of-the-envelope evaluations. • Identify red-flag site characteristics, sensivitive infrastructure, etc.	• Screen out high-risk sites. • Choose best site to balance seismic risk and other priorities.
Pre-injection	• Perform baseline 3D seismic survey. • Identify faults and other structures. • Assess seismic resolution and limits of fault visibility. • Perform site characterization (Table 2). • Deploy basic microseismic array	• Estimate overpressure buildup and maximum plume extents. • Perform reactivation analysis (Coulomb-slip analysis) for observed faults. • Estimate likely M_{max} for unknown faults. • Develop initial PSHA and PLHA.	• Alter operations strategy to address any newly-identified concerns. • Engage with local community on potential seismic impacts. • Identify appropriate traffic light thresholds or other triggers for action.
Injection & Stabilization	• Monitor microseismicity. • Monitor above-zone pressure. • Monitor aquifer water-quality. • Perform regular falloff, interference, and other well tests.	• Frequently update PSHA and PLHA with measured seismicity. • Analyze seismicity for statistical changes, correlations with pressure fluctuations, indications of previously unobserved faults, and/or indications of out-of-zone flow.	• Implement traffic light (or similar) seismicity management scheme. • Ensure timely collection, analysis, and interpretation of monitoring data. • Continuously re-evaluate quality and sensitivity of monitoring plan.
If concerning seismicity occurs (Mitigation phase)	• Quickly deploy additional surface geophones, targeted at problem areas. • Consider additional geophone wells. • Increase frequency and/or density of other monitoring techniques. • Perform controlled injection tests to probe seismic behavior.	• Implement full PSRA and PLRA for high-priority risks (critical infrastructure, drinking-water resources, etc).	• Immediately reduce, halt, or backflow injection at problem wells. • Update local community on situation and ongoing operations. • Implement damage remediation and reimbursement plans if necessary. • Evaluate major strategy changes, such as alternate injection locations or active-pressure management wells.

Site characterization recommendations

Category	*Characteristics*	*Primary Methods*
Structure	*stratigraphy*	reflection seismic, drilling logs
	faults	reflection seismic, microseismic, welltest analysis
	fractures	borehole imaging, mud losses, structural inferences, welltests
Stress	*vertical stress*	density log
	min horizontal stress	leak-off, extended leak-off, formation integrity tests
	max horizontal stress	borehole breakout, tensile failure observations
	formation pressure	drillstem test, wireline tools, gauges
	formation temperature	wireline tools, gauges
Poromechanics	*bulk modulus, Poisson ratio, Biot coefficient*	core, sonic logs
	compressive and tensile strength	core
	thermal expansion	core
	fracture cohesion, friction, dilation	core
	fault frictional properties	core, outcrops, lithologic inferences
Fluid flow	*matrix permeability, porosity*	core, log and seismic inferences, history-matching
	fracture permeability, aperture, connectivity	core, history-matching
	fault permeability	lithologic inferences, history-matching
	injection rate, pressure, temperature	wellhead and bottom-hole sensors
Seismicity	*background seismicity*	microseismic array, regional arrays
	injection-related seismicity	microseismic array
	tectonic regime	regional assessment
	velocity and attenuation model	velocity analysis, borehole calibration
Aquifer impacts	*hydrologic properties*	piezometers, core, history-matching
	geochemistry	core, lithologic inferences
	water-quality	water-sampling
Surface impacts	*soil conditions*	site geotechnical assessment, VS30 assessment
	infrastructure fragility curves	structural assessment
	community sensitivity	questionnaires, townhalls, and other public forums

Conclusions

① Induced seismicity is an important issue, and cannot be ignored. Operators should develop rigorous seismicity management plans.

② That said, experience with waste-water injection suggests problematic sites are rare compared to overall number of wells drilled.

③ GCS sites will benefit from the high site characterization requirements under Class VI regulations.

④ Not going forward with CCS is a choice that carries its own risks. We should accept some seismic risk to lower climate change risk.

References

- J.A. White and W. Foxall (2016). **Assessing induced seismicity risk at CO_2 storage projects: Recent progress and remaining challenges**. Int. J. Greenhouse Gas Control 49:413-424.

- Pawar et al. (2016). **Recent advances in risk assessment and risk management of geologic CO2 storage**. Int. J. Greenhouse Gas Control 40: 292-311.

- NRAP Induced Seismicity Working Group (2016). **Induced seismicity and carbon storage: Risk assessment and mitigation strategies.** NRAP Technical Report Series, NRAP-TRS-II-005-2016, US Department of Energy, National Energy Technology Laboratory, 56 pp.

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