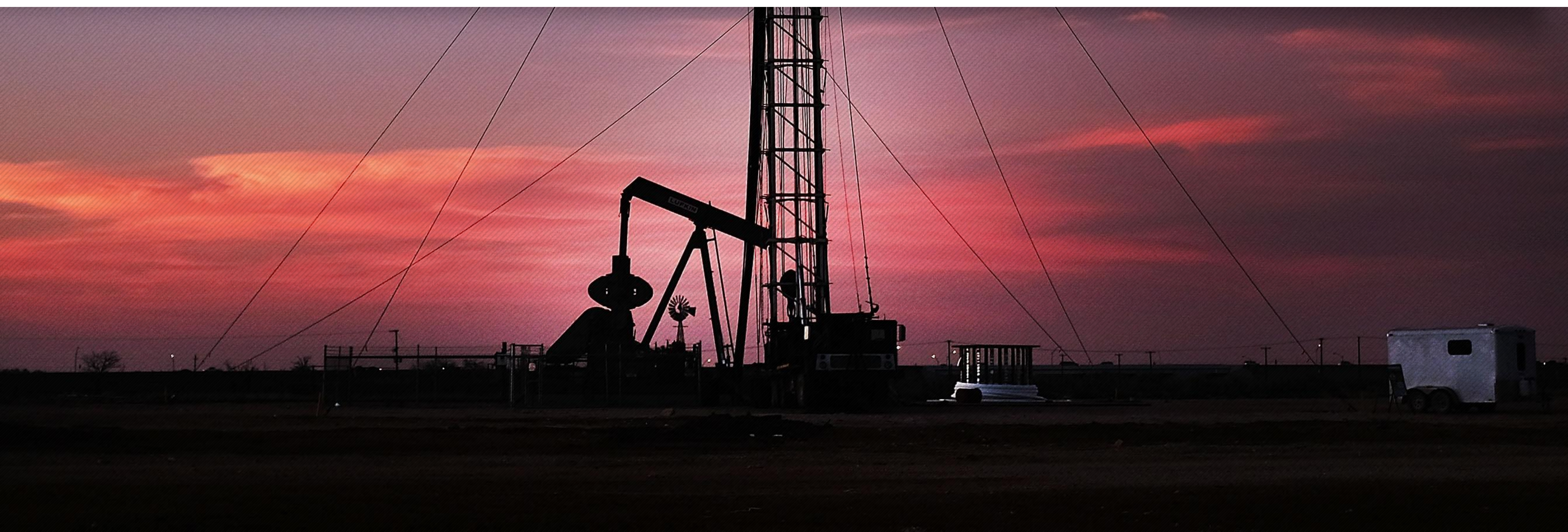
Managing the Risks of Hydraulic Fracturing Induced Seismicity

Ryan Schultz

RISC Webinar, October 6th 2020.



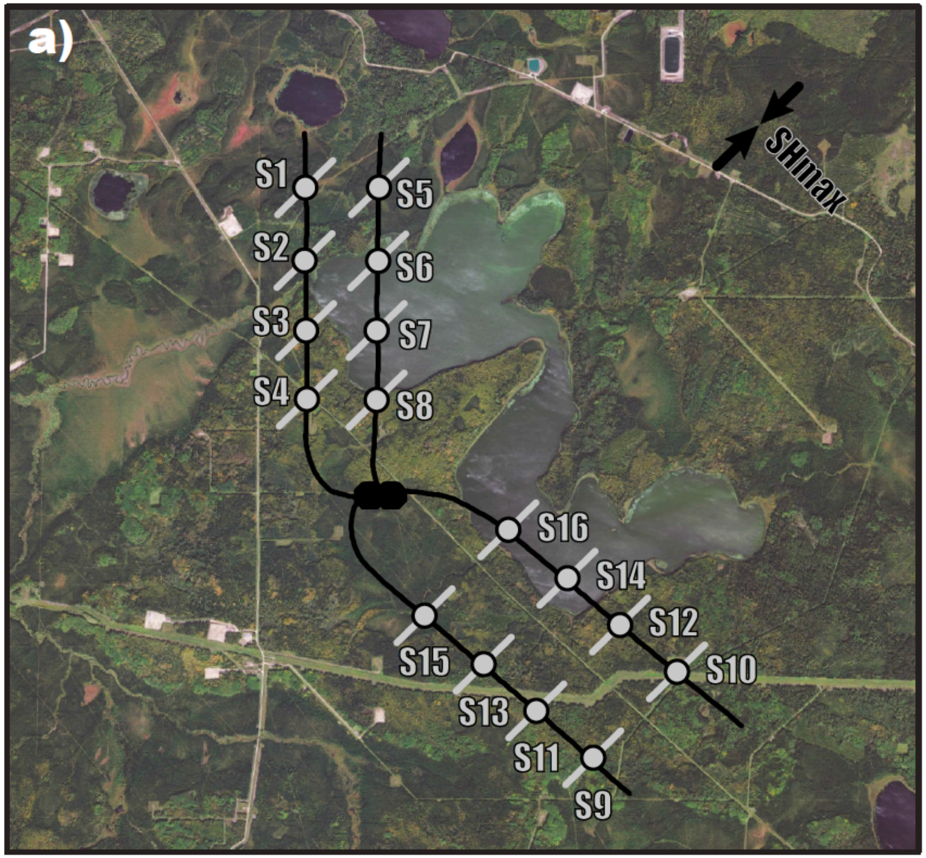
Induced Earthquakes

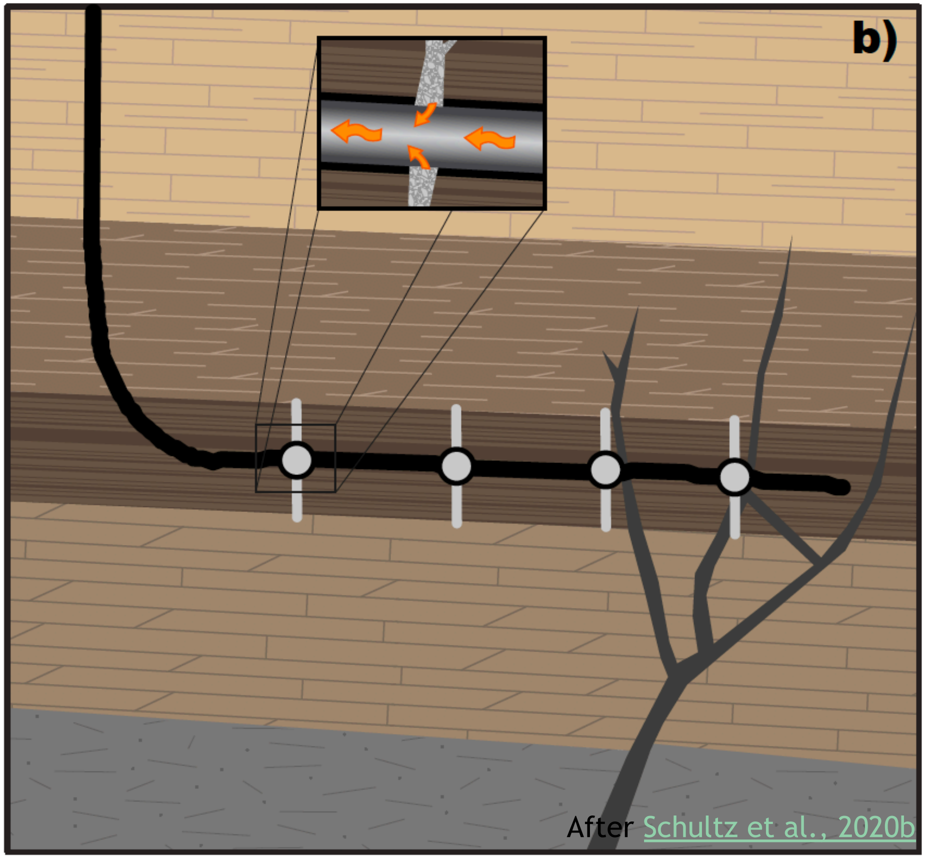
- 2019 SPE/SEG IS Workshop in Dallas [Hillman, 2019].
- Public perceptions on induced earthquakes in Texas.
  - *Why is this happening?*
  - *Am I safe?*

Hydraulic Fracturing Induced Earthquakes

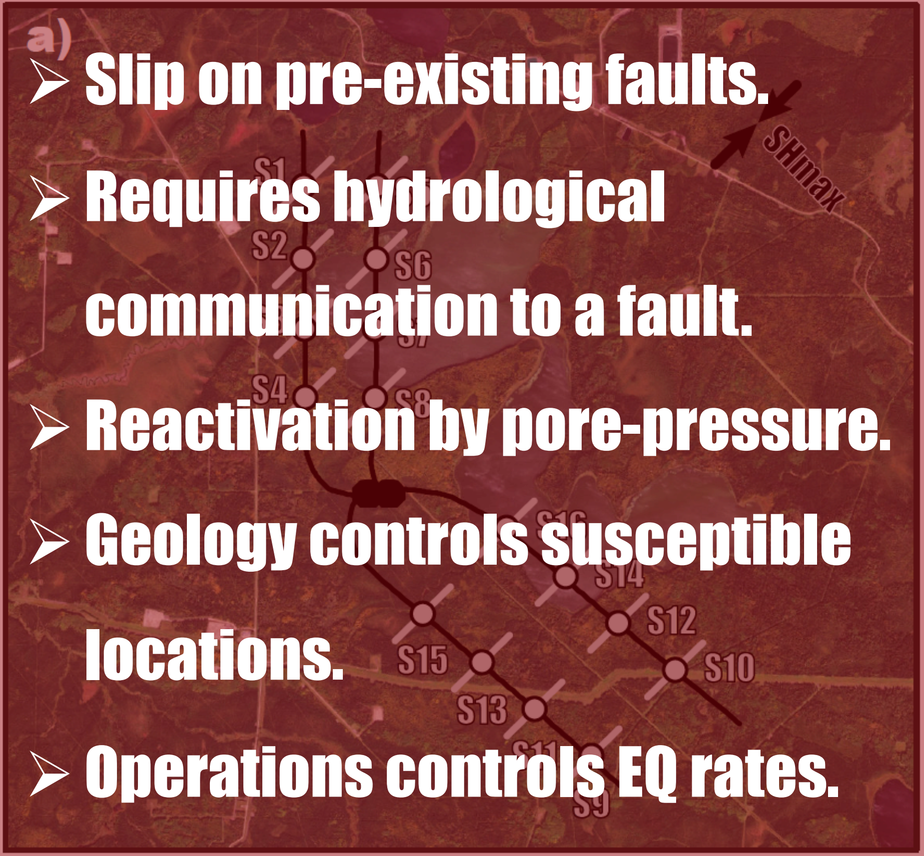
- Numerous cases worldwide.
- Events often large enough to be felt (3-4 Mw).
- Large events (5.7 M_L) in China caused economic and human losses.
- Moratoriums due to concerns.
- There's a need for effective management & understanding...

Conceptual Model of HF IS

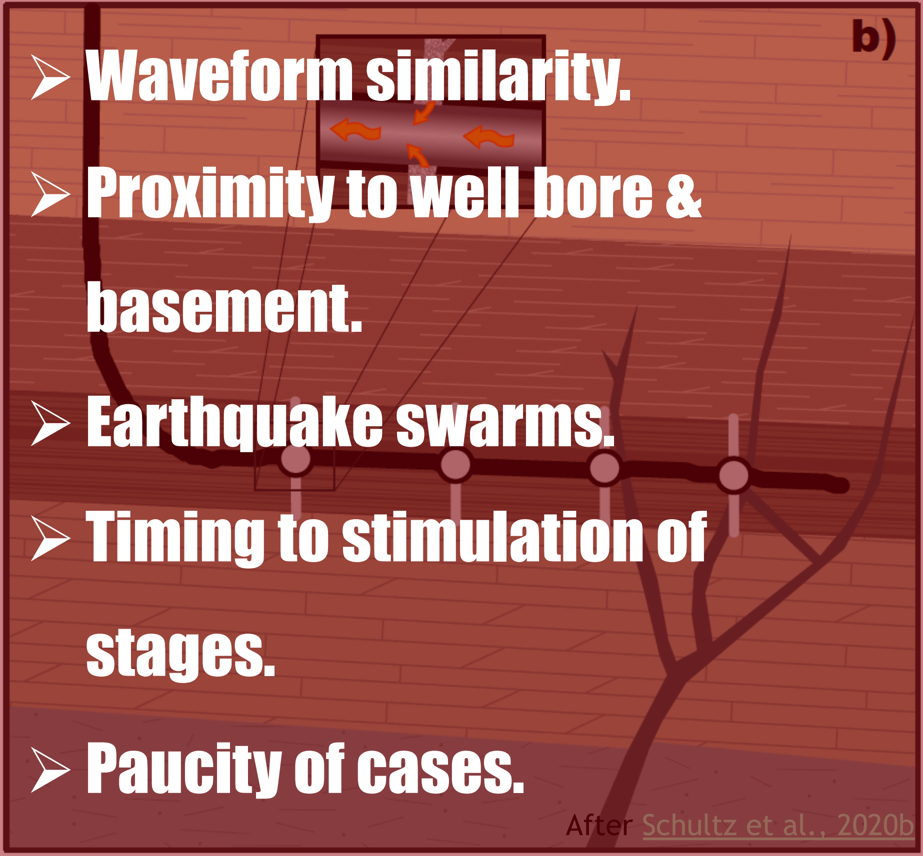




Conceptual Model of HF IS



- Slip on pre-existing faults.
- Requires hydrological communication to a fault.
- Reactivation by pore-pressure.
- Geology controls susceptible locations.
- Operations controls EQ rates.

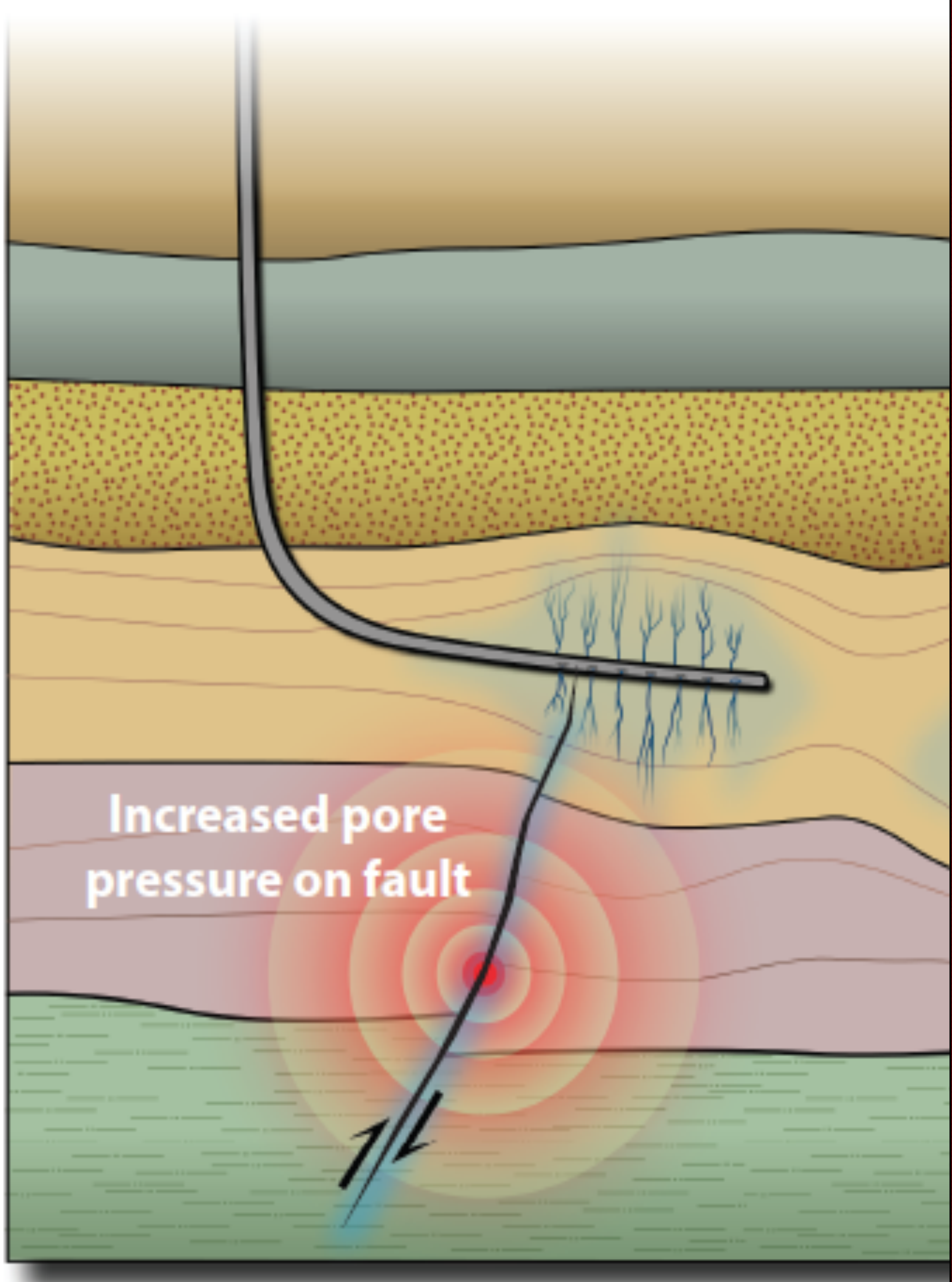


- Waveform similarity.
- Proximity to well bore & basement.
- Earthquake swarms.
- Timing to stimulation of stages.
- Paucity of cases.

After Schultz et al., 2020b

Hydraulic Communication

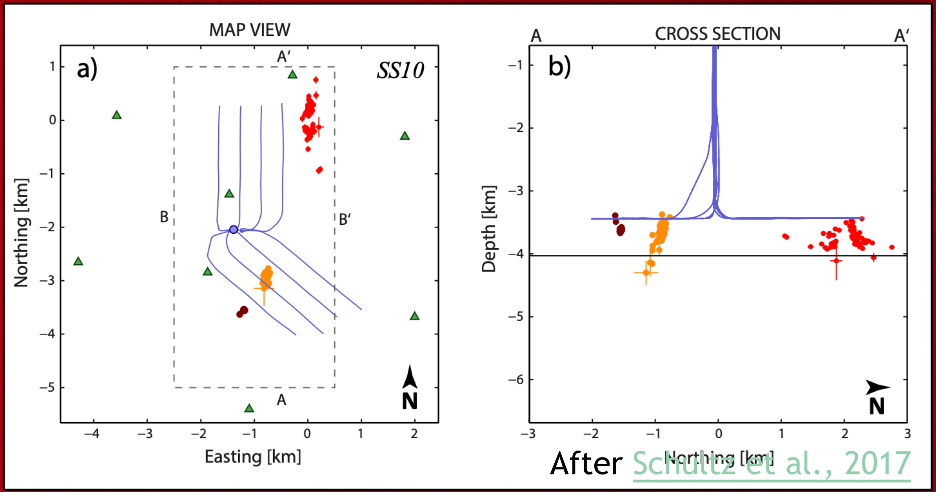
- Proximity to well bore.
- Asymmetry of events around wells.
- Stage selective earthquake productivity.
- Association with fluid-flow geological conditions .



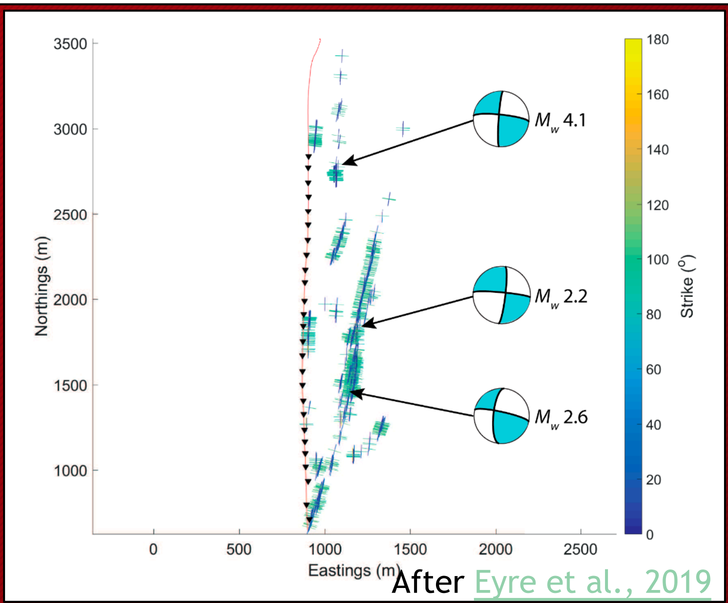
After Schultz et al., 2017

Proximity to Well Bore

- Fault directly contacts contemporaneous stage.
- Hypocentres on one side of fault.
- Only certain stages appear to be seismogenic.



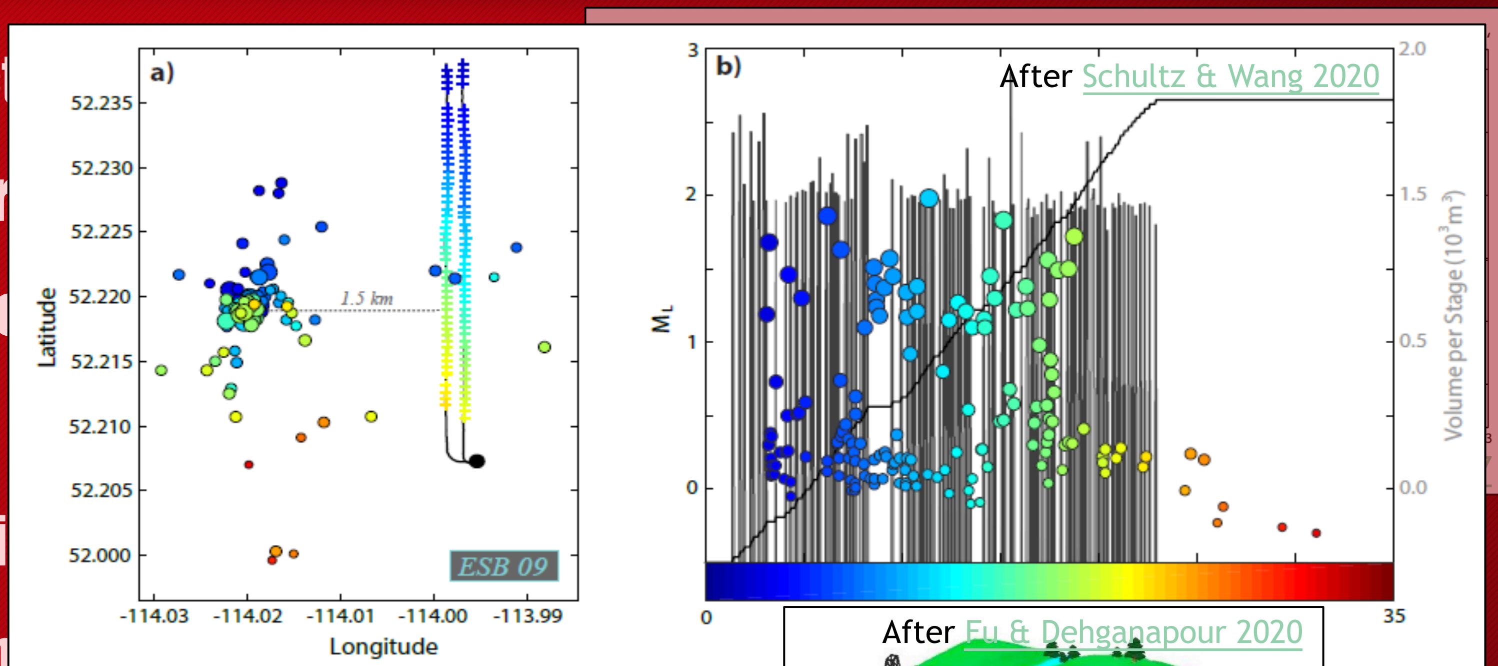
After Schultz et al., 2017

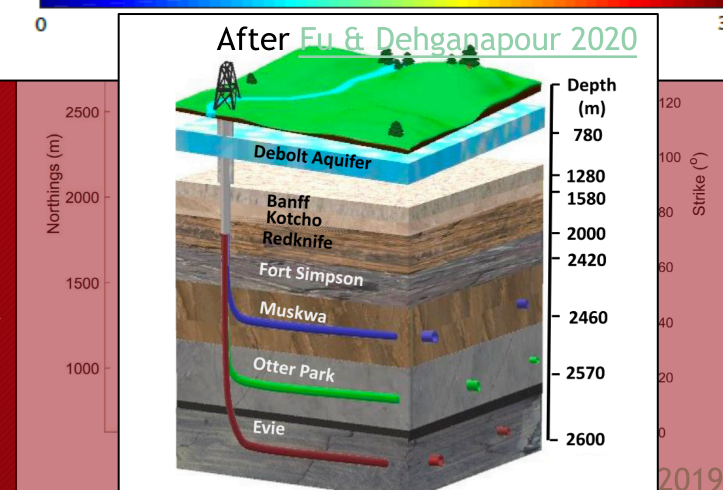


After Eyre et al., 2019

Proximity to Well Bore

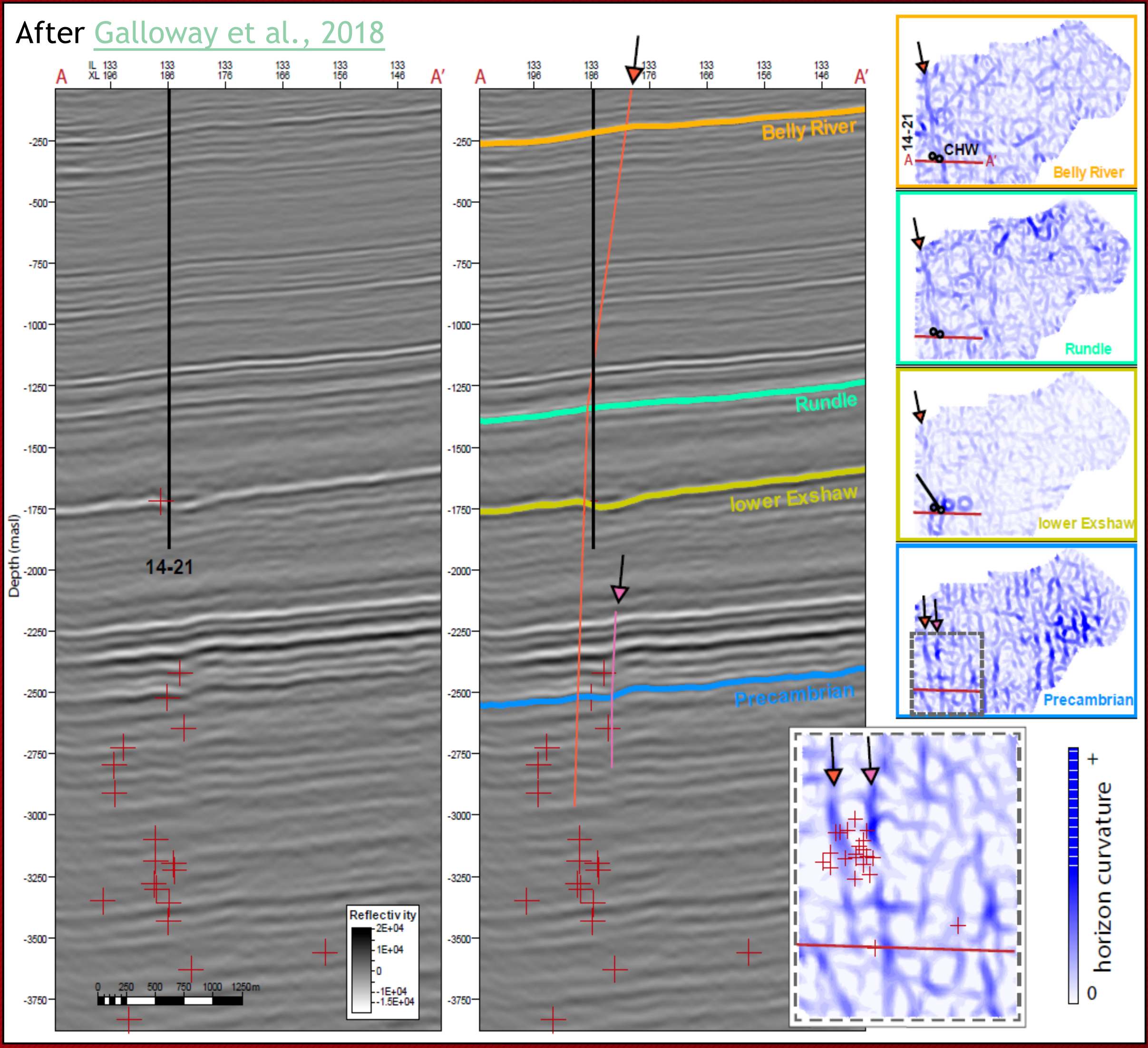
- Fault direct
  contempor
- Hypocentr
  fault.
- Only certai
  seismogen...
- Even exceptional cases are plausible for fracture propagation & fluid-flow limits (1+ km).





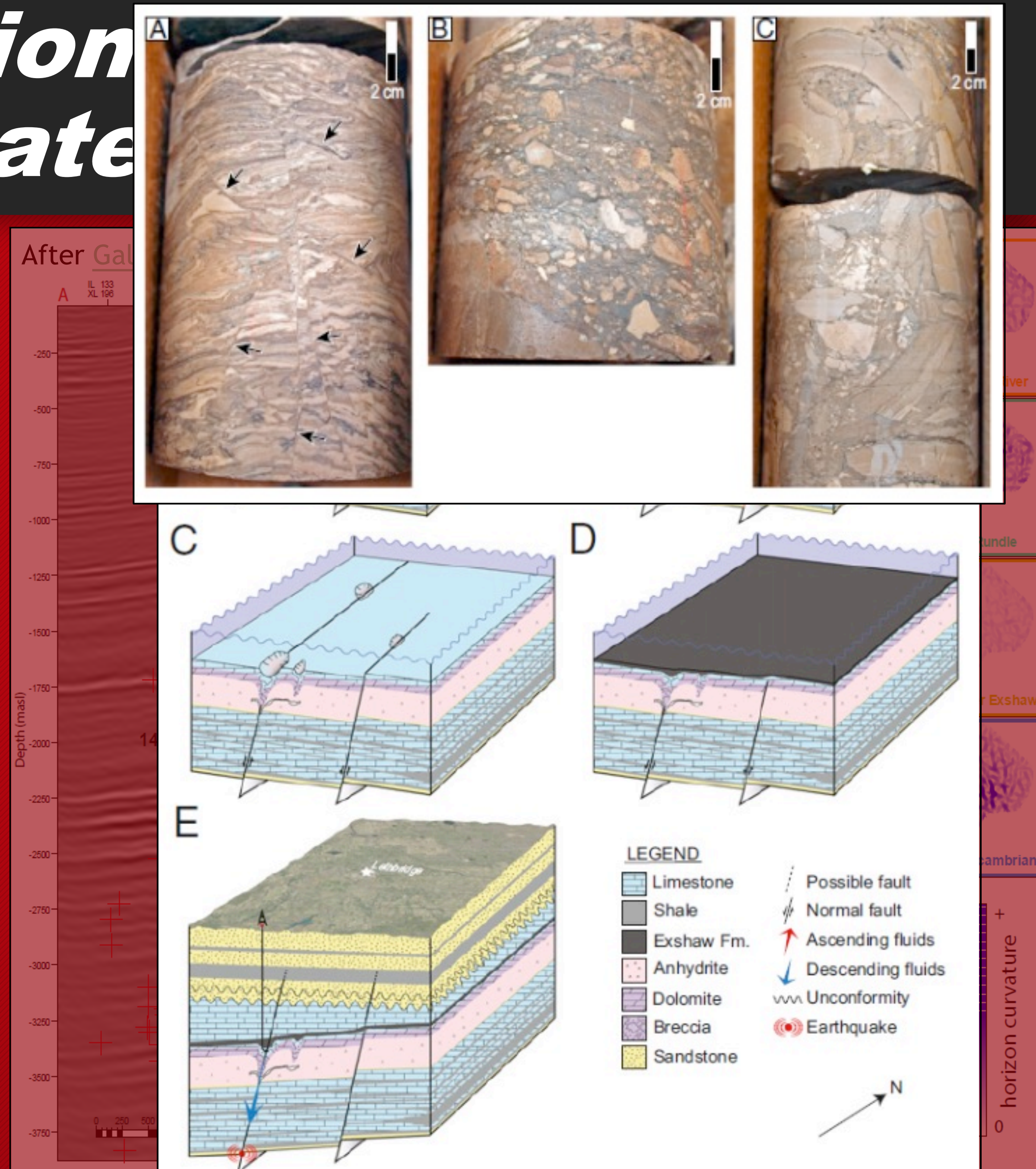
Association with Fluid-Flow Related Geology

- Fault directly contacts well bore.
- Hypocentres below stimulation interval.
- Coincident circular feature.



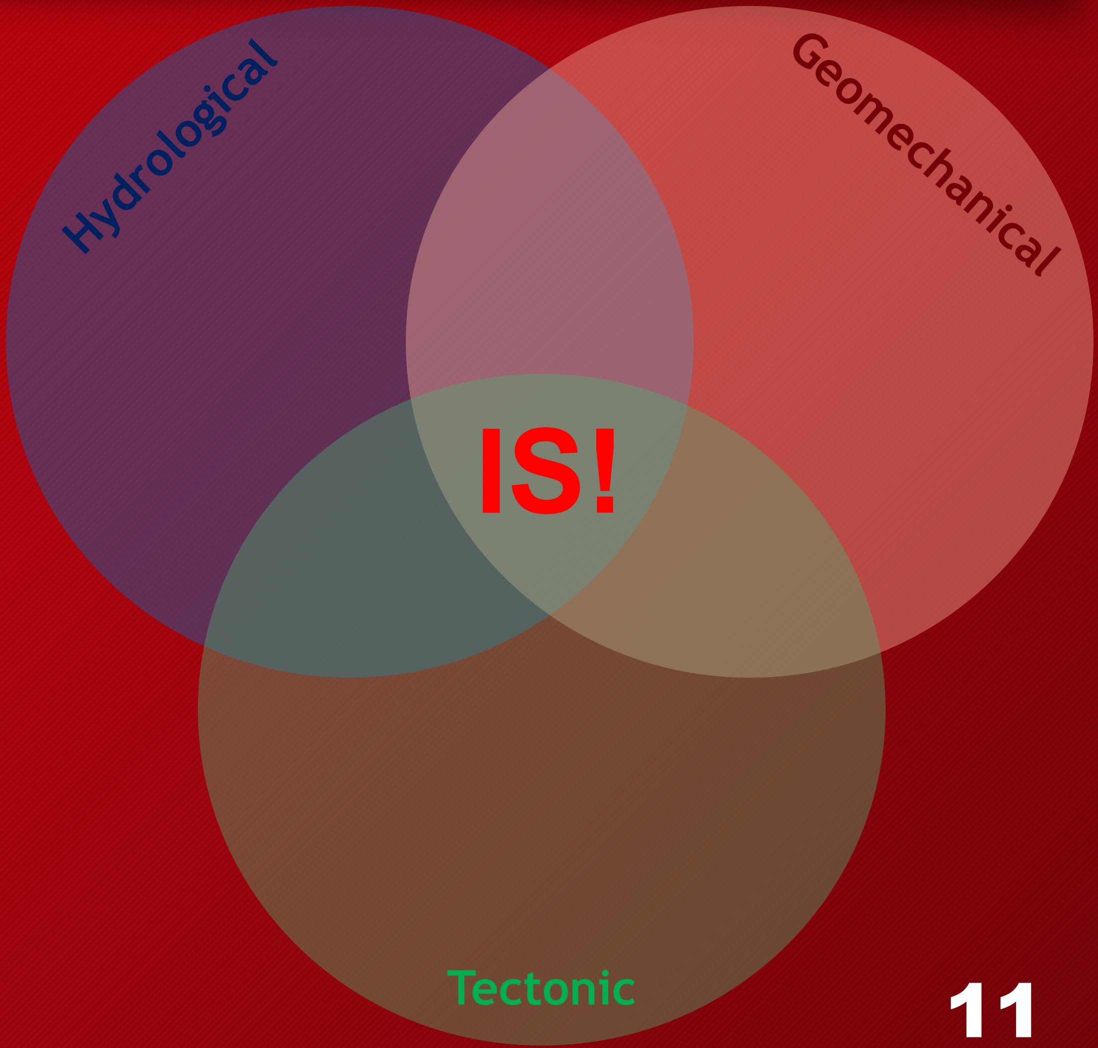
Association… Relate…

- Fault contacts well.
- Hypocentres below stimulation interval.
- Coincident circular feature.
- Brecciation in analogous cores.
- Karst infers ancient fluid-flow along fault.



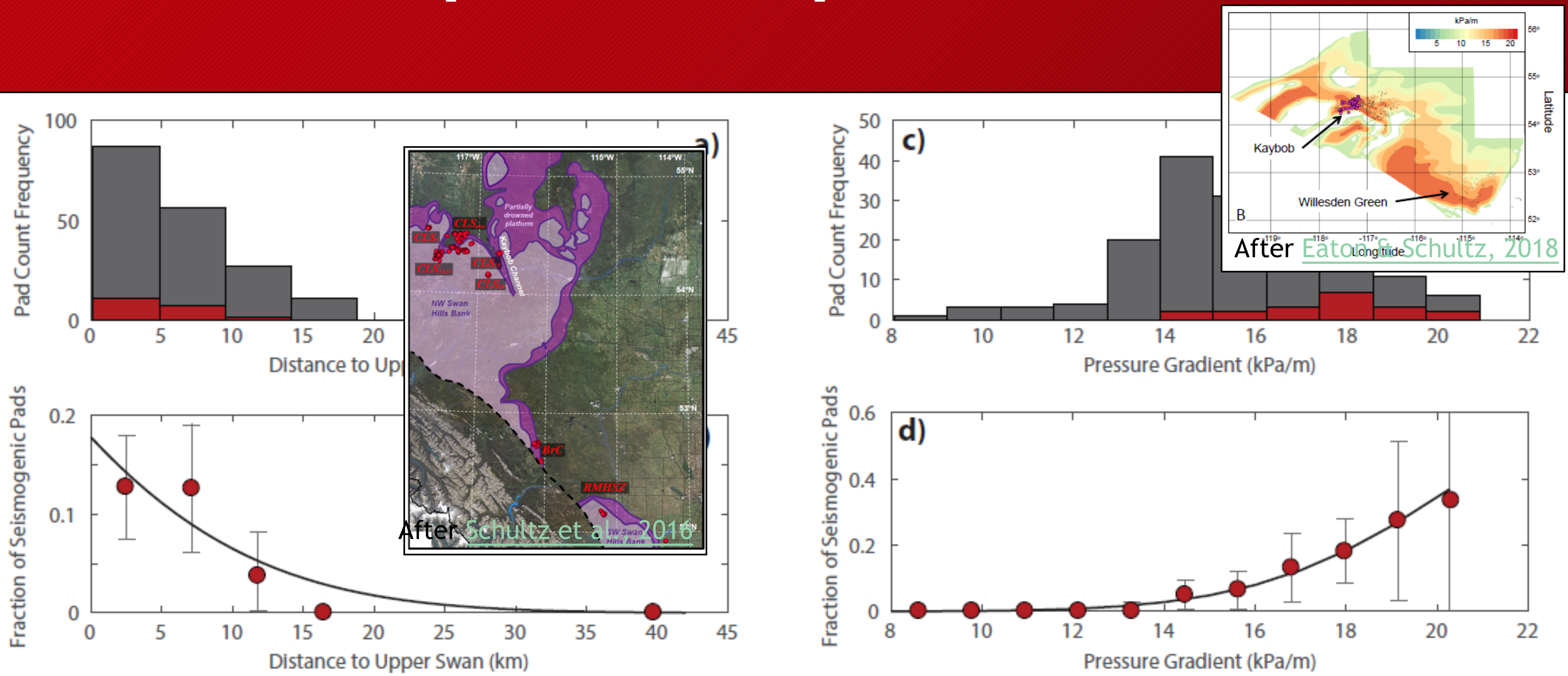
Geologically Susceptible Conditions

- HF IS requires the right conditions.
  - A fault that's critically stressed.
  - Hydraulic connection from well to fault.
- Overlapping conditions appears to be rare [Atkinson et al., 2016].



Proxies for Susceptibility

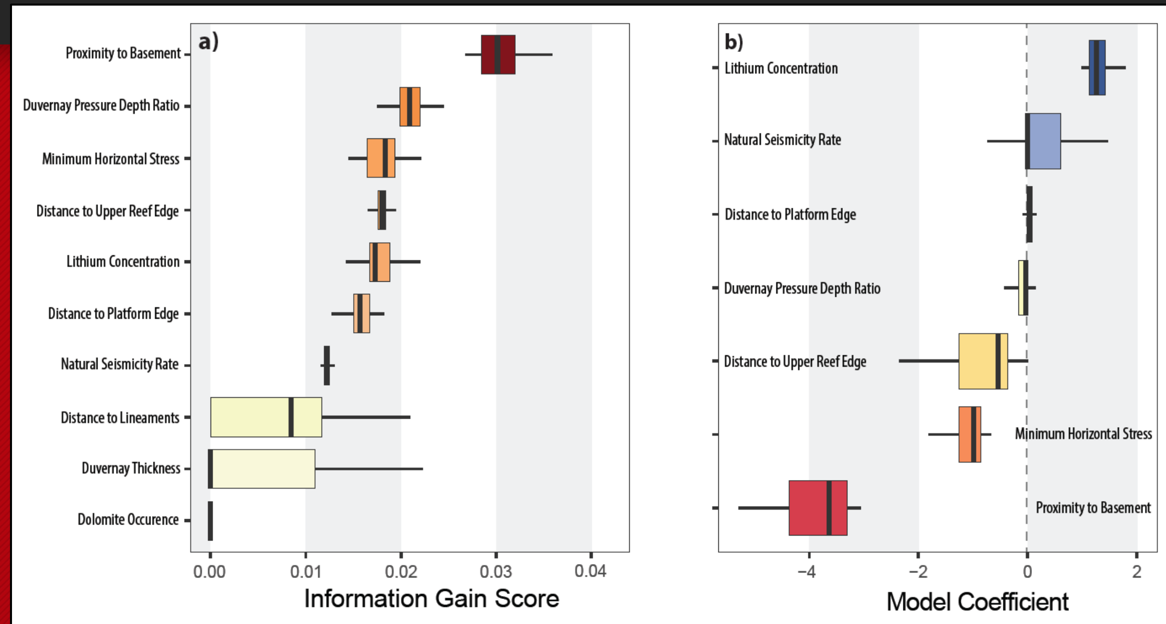
- Spatial biases in seismogenic regions is often statistically associated with proxies for susceptible conditions.

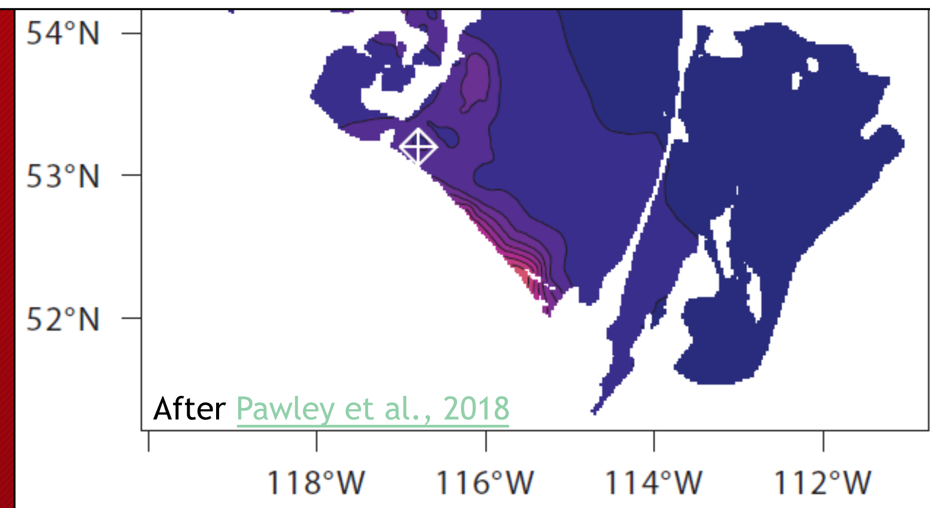


After Schultz et al., 2018

Machine Learning Model

- Built from all publicly available proxies.
- Trained using wells that did/did-not cause EQs.
- Provides hierarchy for which proxies are most important.
- Statistically better than guessing event locations.

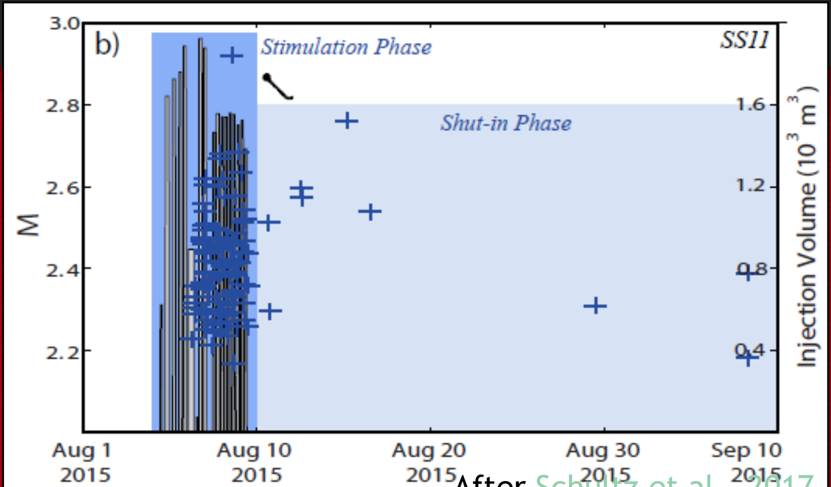




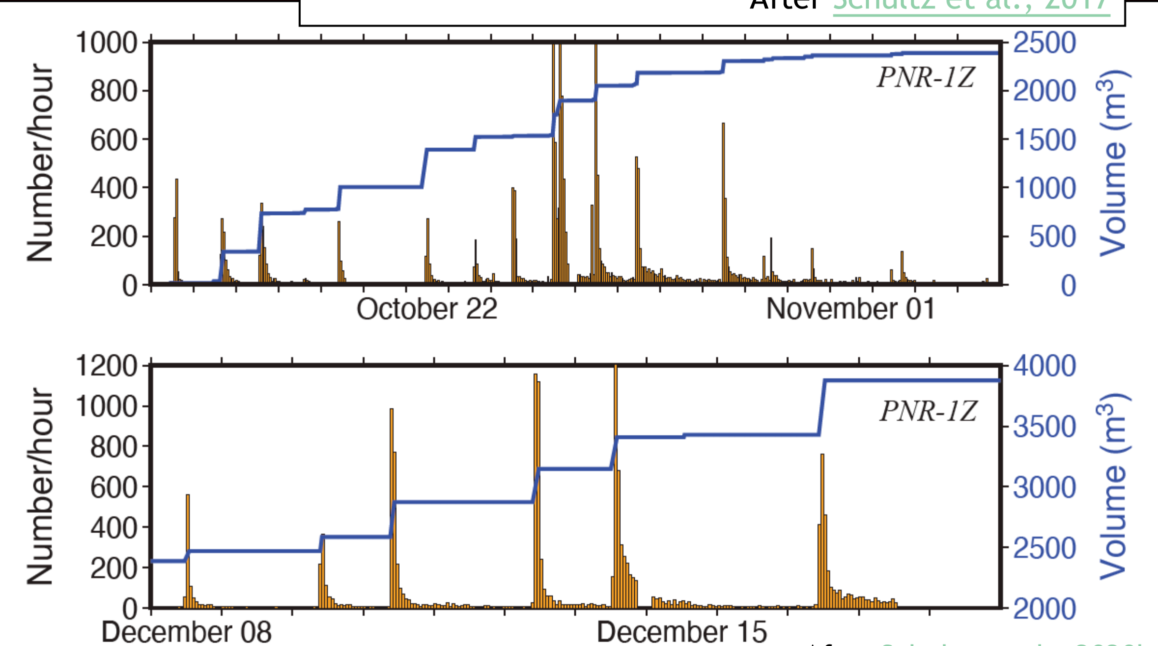
After Pawley et al., 2018

Operational Controls on Rate

- What controls EQ rates?
- Well stimulation at a gross level.
  - Events are dominantly during stimulation (~90%).
  - Events linger for weeks-months after shut-in.



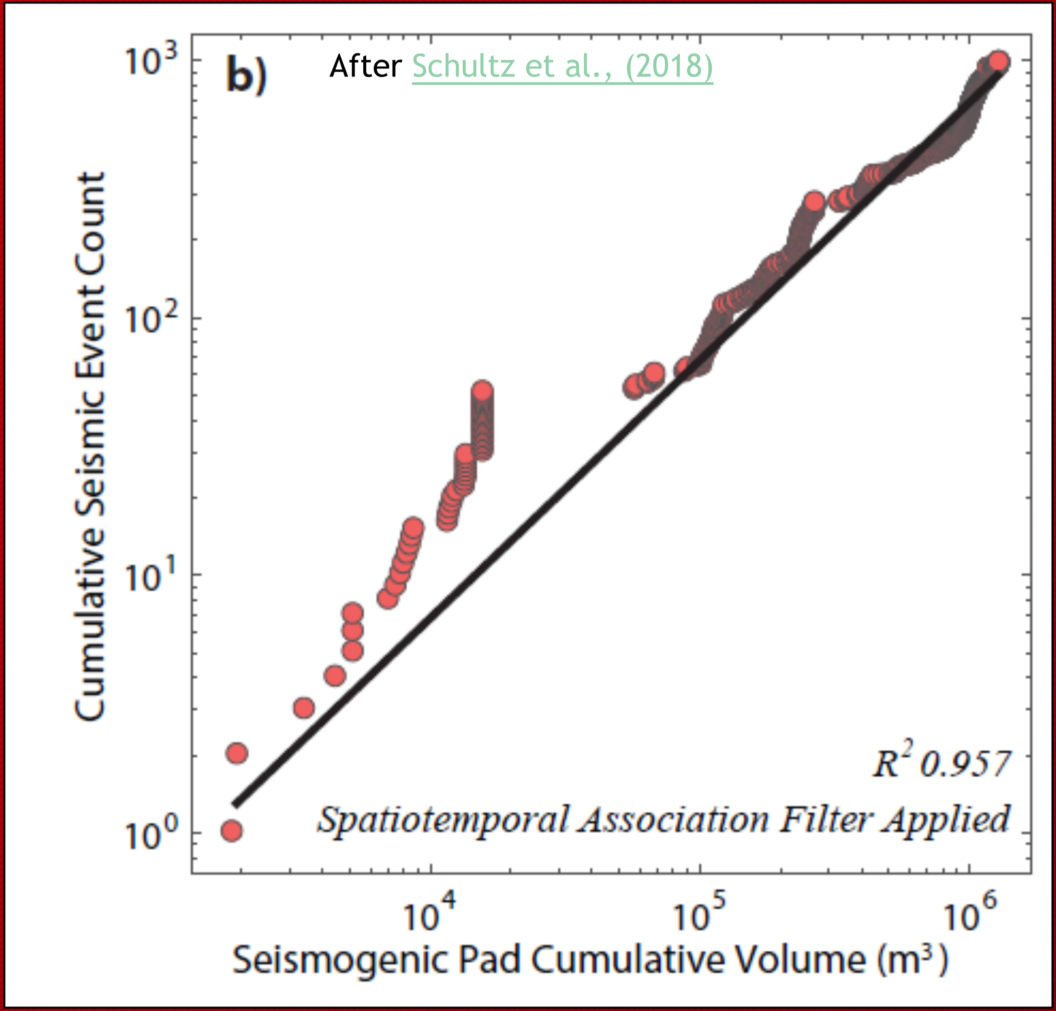
After Schultz et al., 2017



After Schultz et al., 2020b

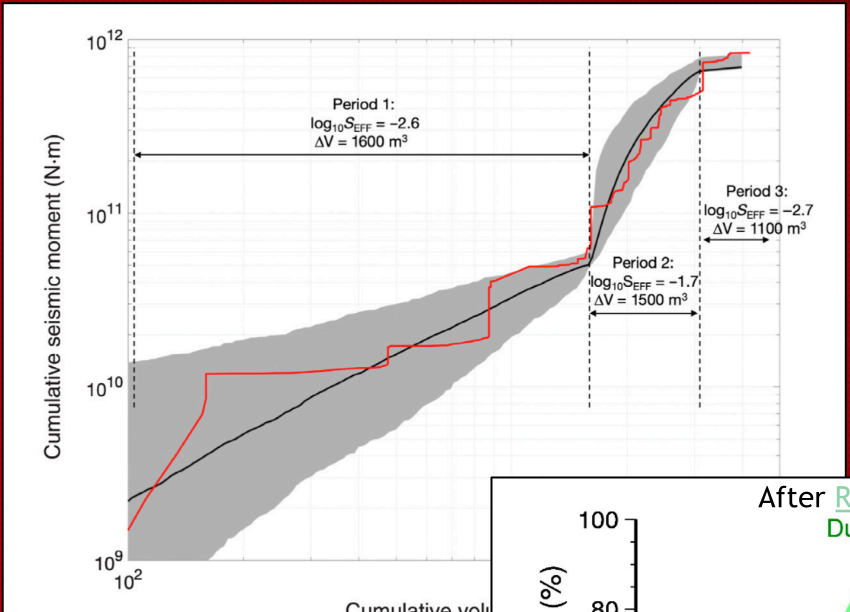
Seismogenic Index Model

- HF IS fits well to Shapiro's (2010) model of event count vs volume.
- Considers susceptible regions.
- Similar results to other works showing volume controlling EQ counts.

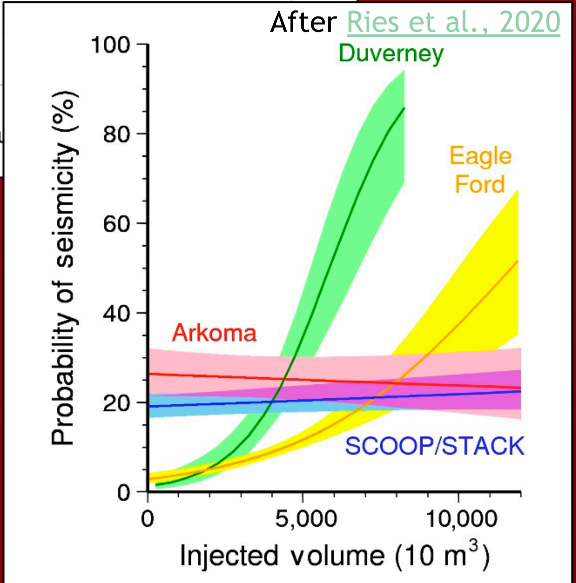


Rate Modelling Studies

- Forecasting techniques applied in the UK at PNR.
- Similar volume relationships observed in Eagle Ford HF IS.



After Clarke et al., 2019



After Ries et al., 2020

Unresolved Questions?

- How to best identify susceptible locations a priori?
- Effective (and validated) techniques for mitigation?
- Best approaches to forecasting events?
- Simple means to manage HF IS risks?
- *Am I safe?*

AGU ADVANCING EARTH AND SPACE SCIENCE

Reviews of Geophysics

REVIEW ARTICLE
10.1029/2019RG000695

Hydraulic Fracturing-Induced Seismicity

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Key Points:

- Induced seismicity caused by hydraulic fracturing has been recognized in basins around the world
- Common themes are observed in disparate cases of hydraulic fracturing-induced seismicity
- A better understanding of the commonalities will yield better recognition of cases and management of hazards/risks

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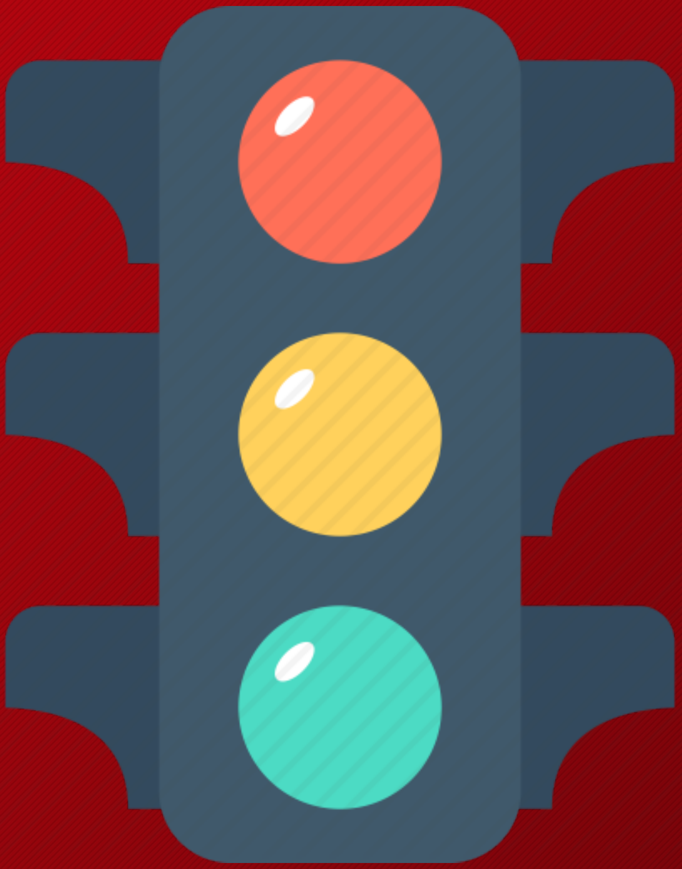
Abstract Hydraulic fracturing (HF) is a technique that is used for extracting petroleum resources from impermeable host rocks. In this process, fluid injected under high pressure causes fractures to propagate. This technique has been transformative for the hydrocarbon industry, unlocking otherwise stranded resources; however, environmental concerns make HF controversial. One concern is HF-induced seismicity, since fluids driven under high pressure also have the potential to reactivate faults. Controversy has inevitably followed these HF-induced earthquakes, with economic and human losses from ground shaking at one extreme and moratoriums on resource development at the other. Here, we review the state of knowledge of this category of induced seismicity. We first cover essential background information on HF along with an overview of published induced earthquake cases to date. Expanding on this, we synthesize the common themes and interpret the origin of these commonalities, which include recurrent earthquake swarms, proximity to well bore, rapid response to stimulation, and a paucity of reported cases. Next, we discuss the unanswered questions that naturally arise from these commonalities, leading to potential research themes: consistent recognition of cases, proposed triggering mechanisms, geologically susceptible conditions, identification of operational controls, effective mitigation efforts, and science-informed regulatory management. HF-induced seismicity provides a unique opportunity to better understand and manage earthquake rupture processes; overall, understanding HF-induced earthquakes is important in order to avoid extreme reactions in either direction.

Plain Language Summary Earthquakes can be induced by a number of anthropogenic sources. One category of induced earthquake is caused by hydraulic fracturing (HF)—a technique used by industry to produce petroleum from normally impermeable rocks. The widespread use of HF has resulted in a significant increase in induced earthquakes. In this paper, we provide a review of all the reported cases of HF-induced earthquakes: in Canada, the United States, the United Kingdom, and China. Some of these cases are exceptional, having events as large as 5.7 M_L or earthquakes triggered up to 1.5 km away. That said, there are common themes that are repeated in all of the cases: similar waveforms, swarm-like sequences, proximity to HF stimulation in time and space, and that only the small minority of HF wells induced earthquakes. Likely, these common themes are related to the physics of HF stimulation and the geology of the target formations. Many of the proposed interpretations are still open-ended research areas, such as consistent recognition of cases, proposed triggering mechanisms, geologically susceptible conditions, identification of operational controls, effective mitigation efforts, and science-informed regulatory management. Overall, a better understanding of these earthquakes will allow for adequately balanced management of their risks.

After Schultz et al., 2020b

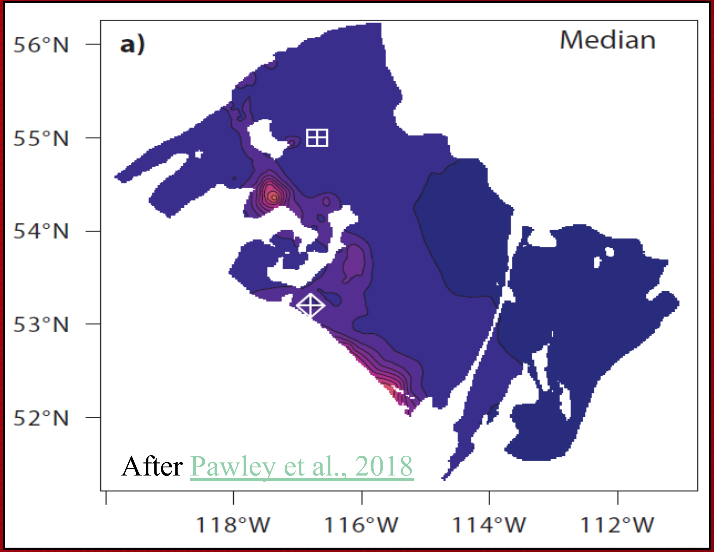
Traffic Light Protocols

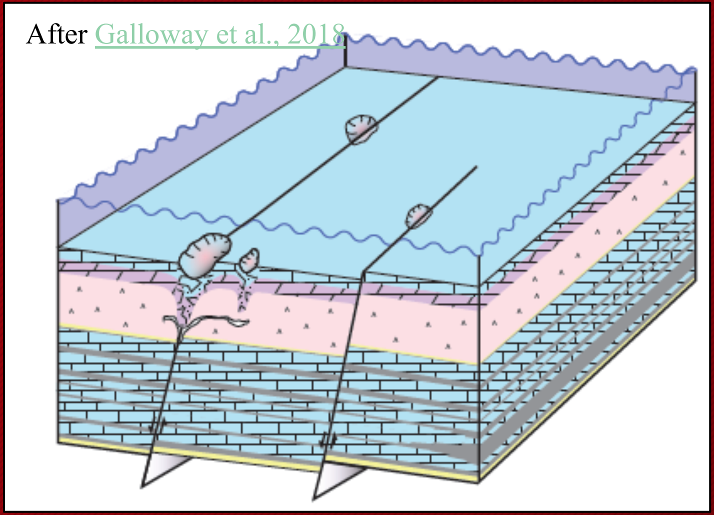
- Traffic light protocols are used to manage induced seismicity.
- Several already implemented for IS.
- Various thresholds and cases.
- Provide operational targets for green-, yellow,- and red-lights.
- Red-light defined as stopping point before exceeding a risk tolerance.
- *Best thresholds to set?*



Knowns about HF IS

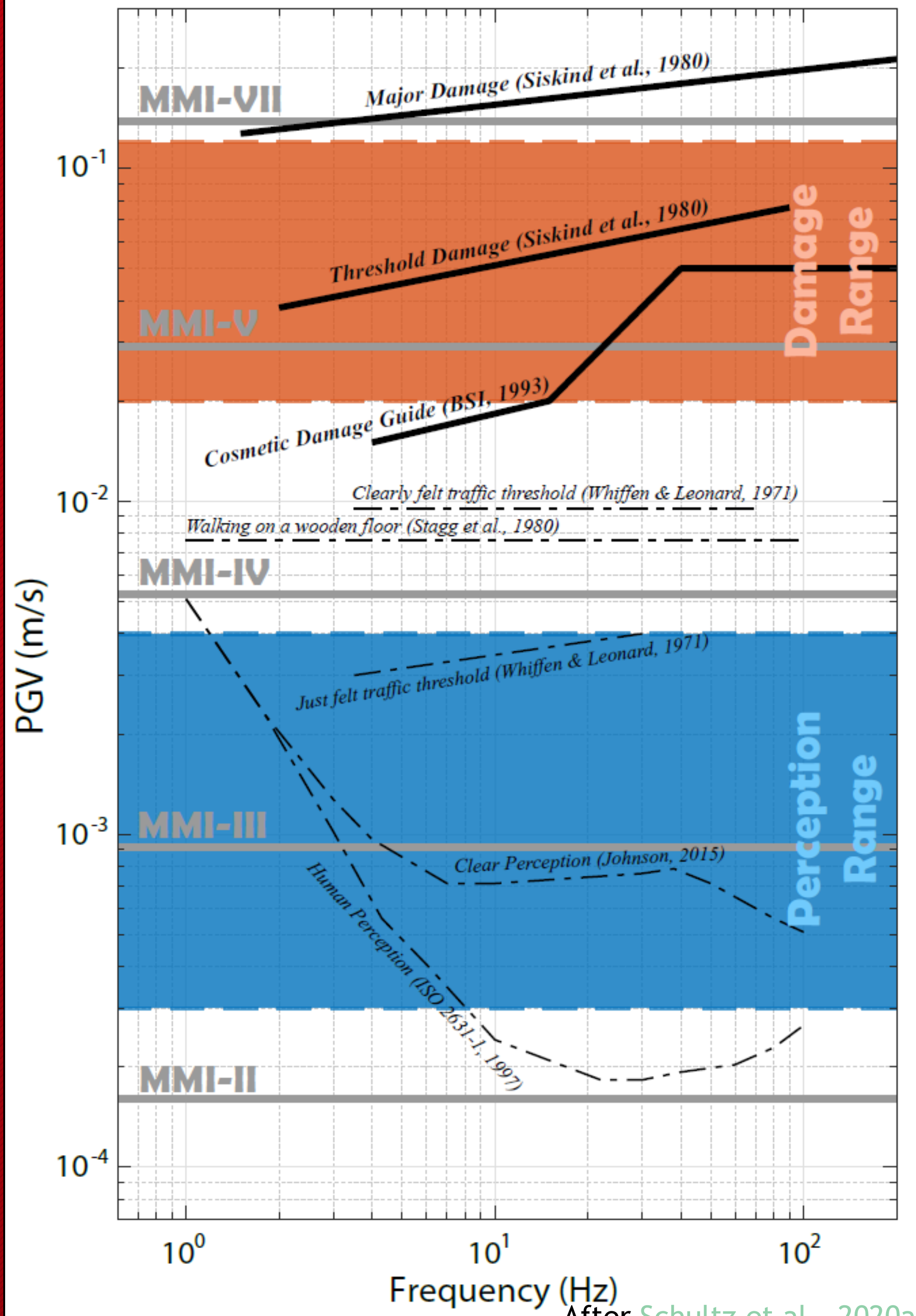
- Occur in shale basins (constrains EQ locations).
- Tend to be spatially biased in their locations, due to geology.
- Tend to occur near the stimulation interval or just into the shallow basement.





Ground Motion Thresholds

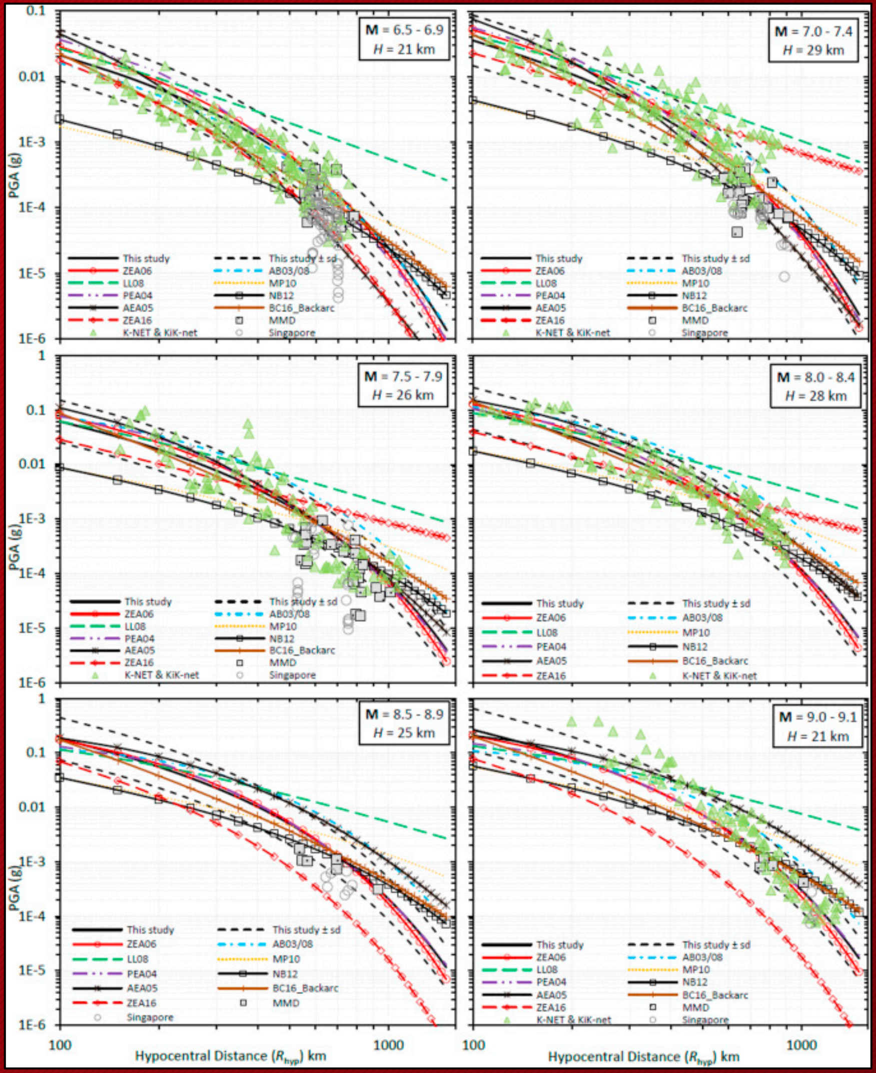
- Literature on perceptible and damaging thresholds.
- Often, jurisdictions have already defined acceptable blasting thresholds.
- But M_L is simpler…



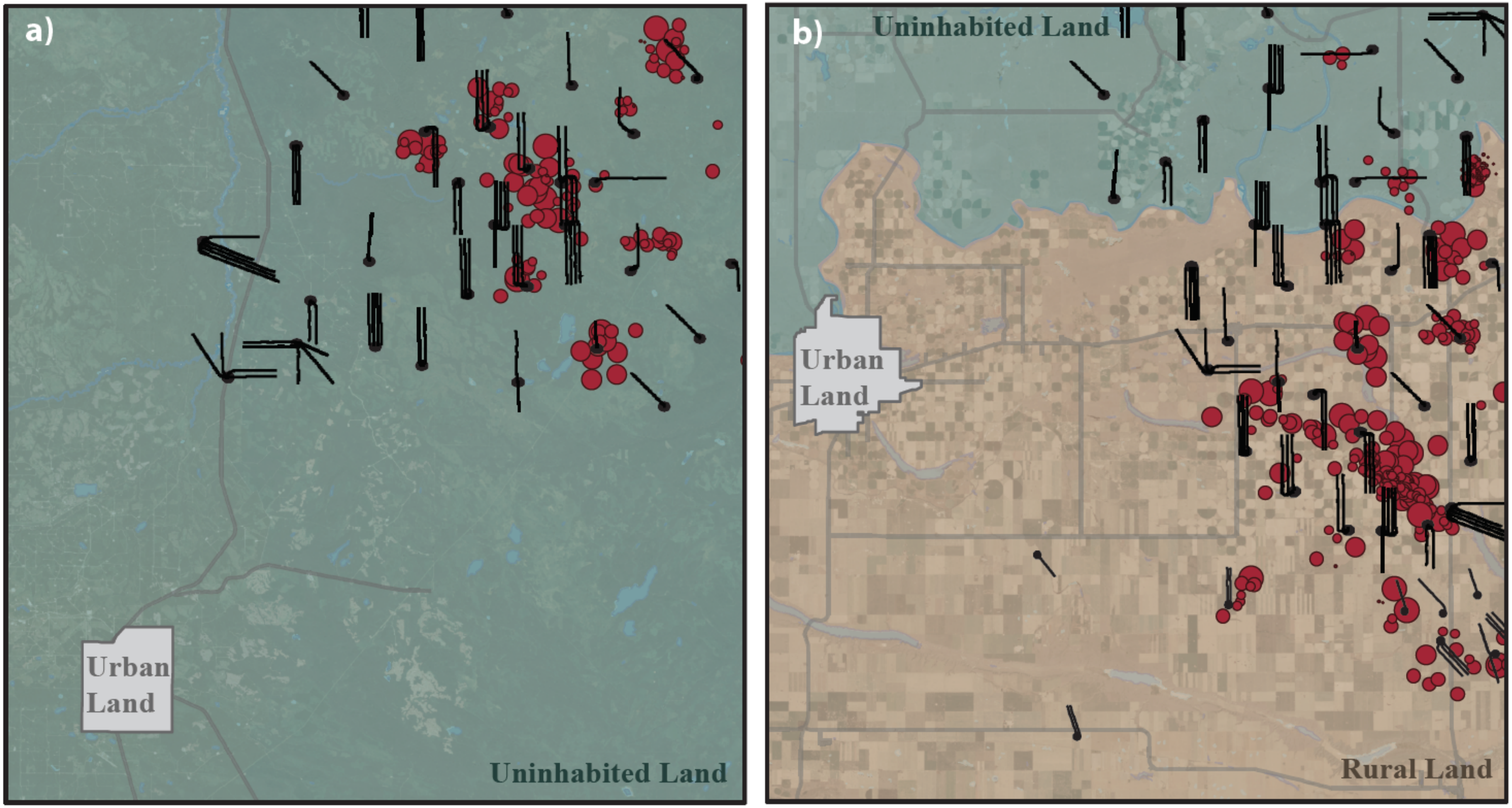
After Schultz et al., 2020a

GMPEs

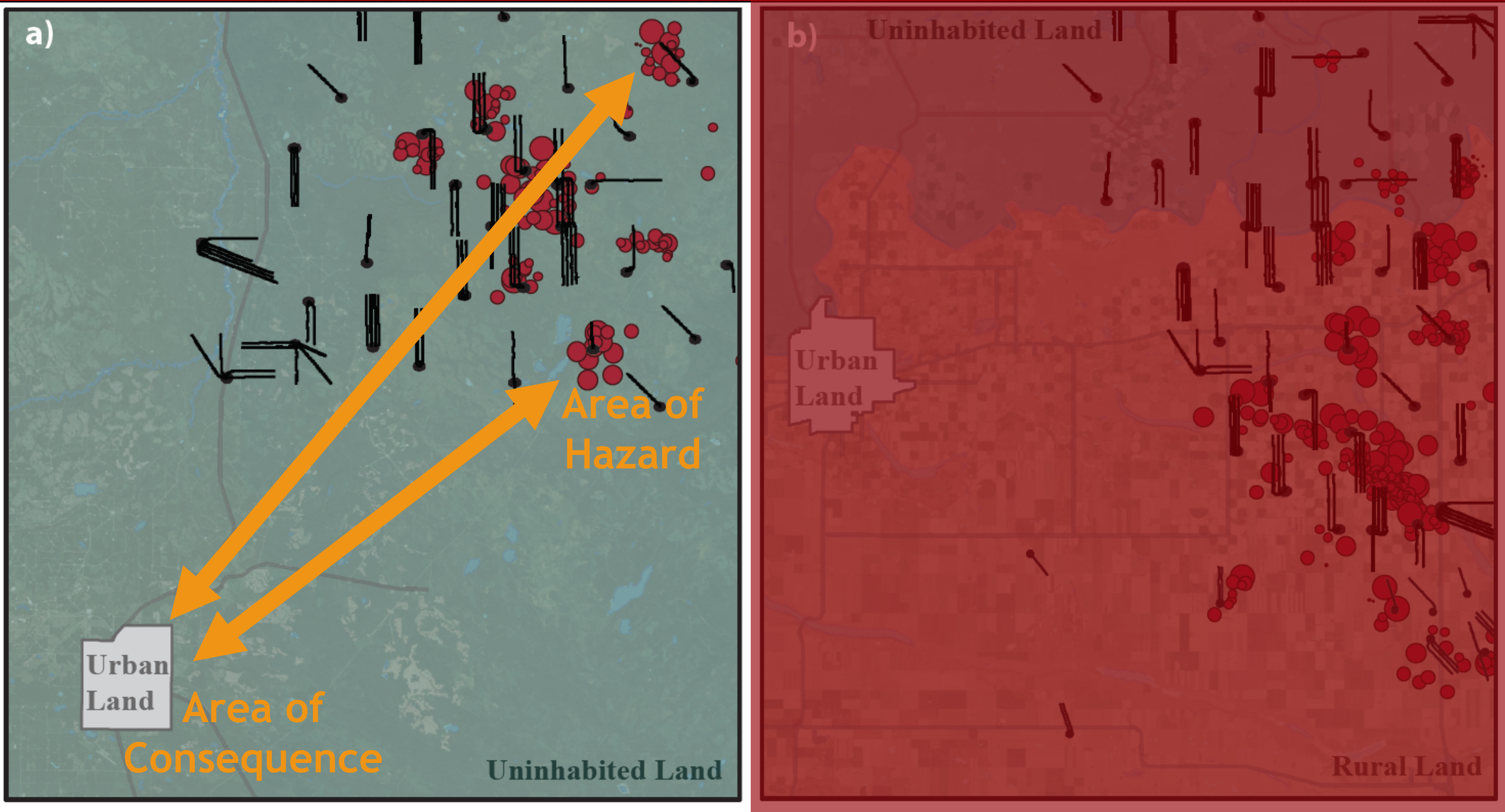
- Compute ground motion parameters as a function of earthquake distance, depth, site amplification, and magnitude.
- Some exist now that are adequate for understanding HF IS.



Earthquake Event Scenarios

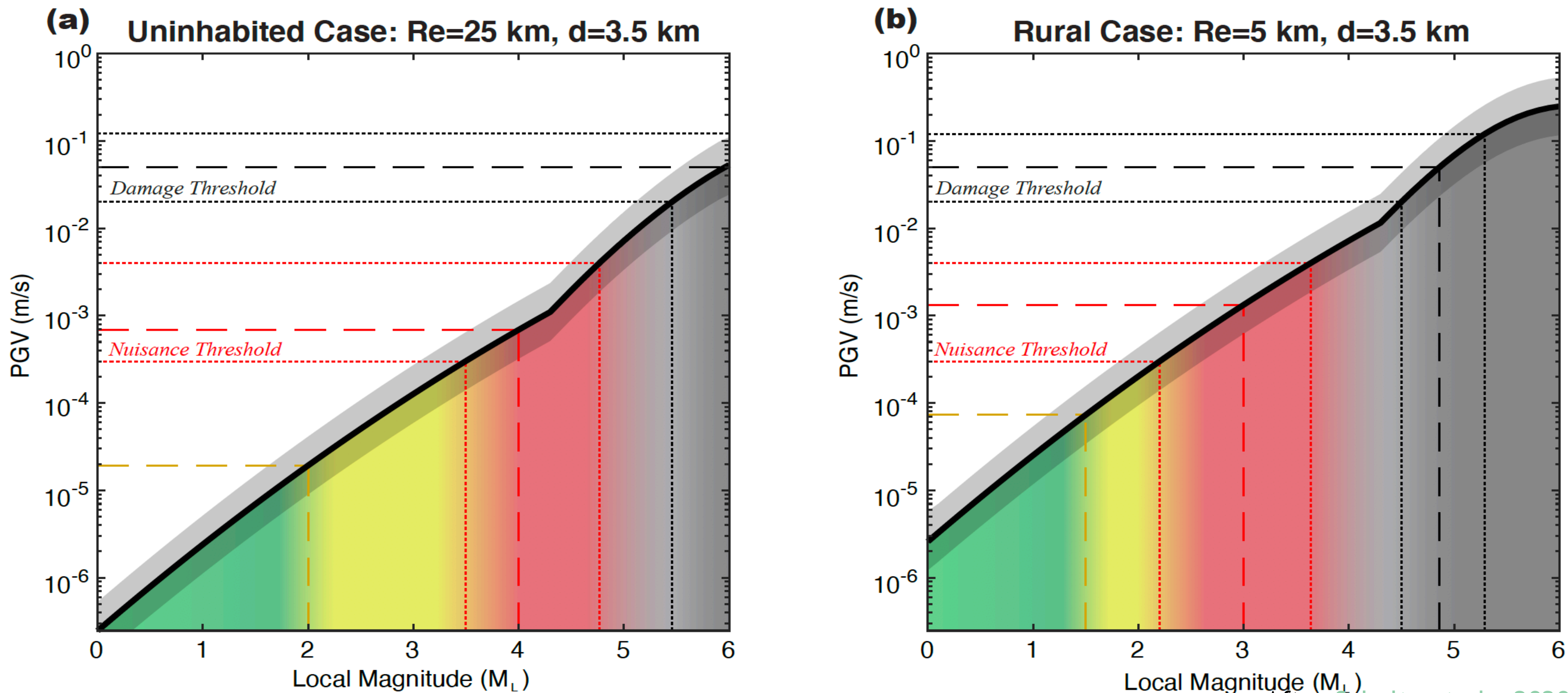


Earthquake Event Scenarios



Simple Traffic Light Analysis (PGV)

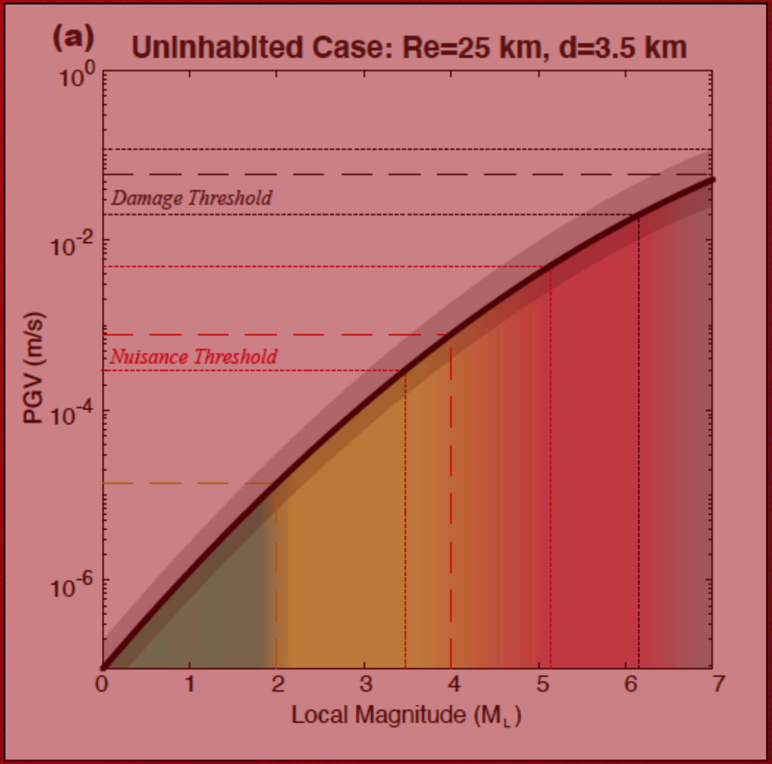
- Simple translation of expected nuisance or damage thresholds into magnitudes.



After Schultz et al., 2020a

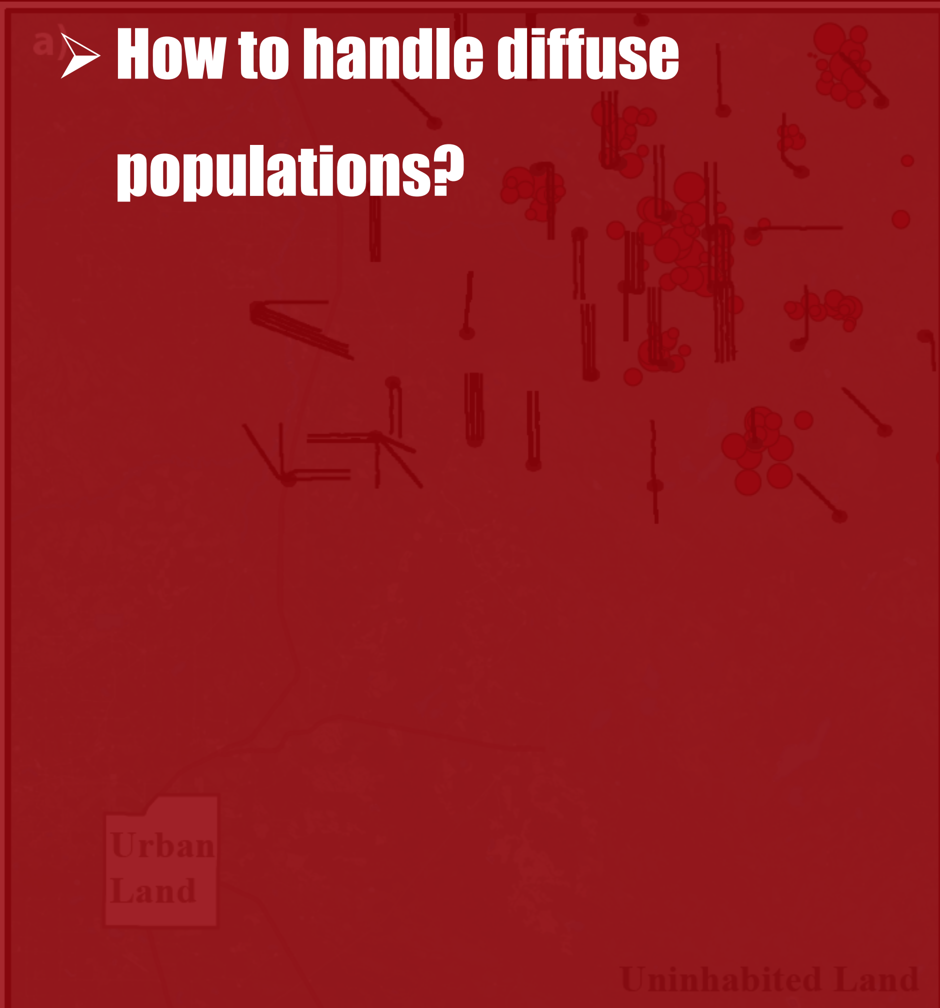
Criticisms of Simple Approach

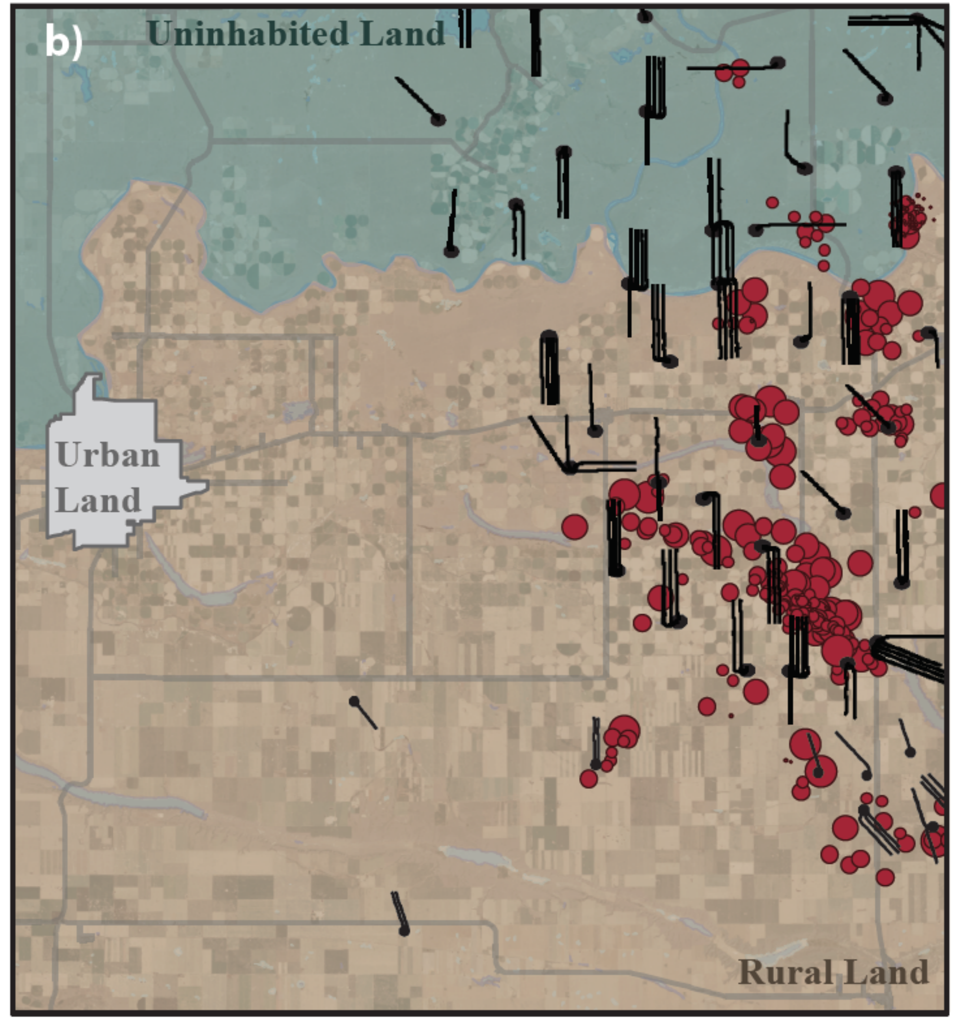
- Only works for simple, uninhabited, or single area-of-concern cases.
- Only considers a single event, not run-away cases that grow past the red-light threshold.
- Ignores statistics of error and ground motion variabilities.
- ***Doesn't quantify risk!***



Realistic Earthquake Event Scenarios

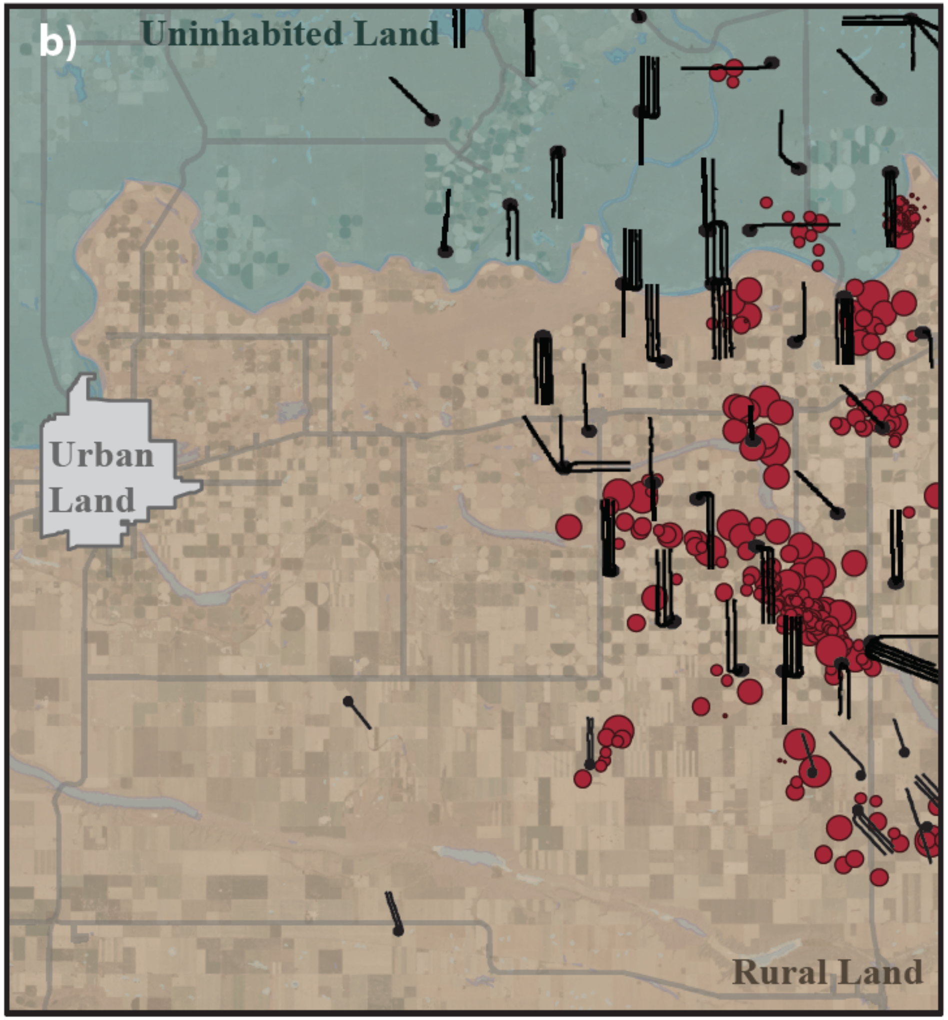
- How to handle diffuse populations?





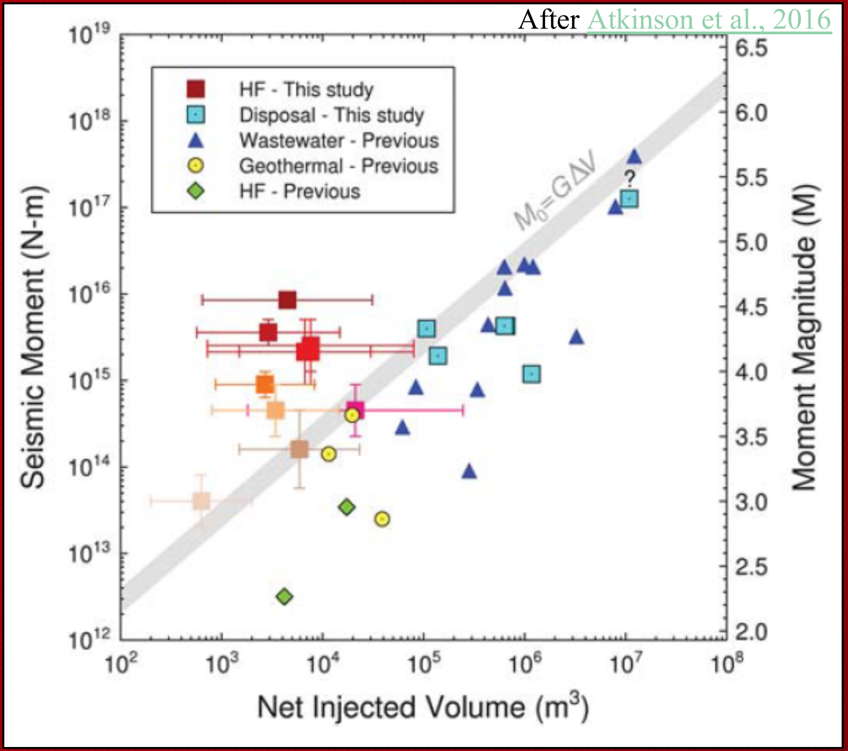
Realistic Earthquake Event Scenarios

- How to handle diffuse populations?
- Pull in government census information on population density.
- Invert data for a statistical expectation value of epicentral distance to a household.



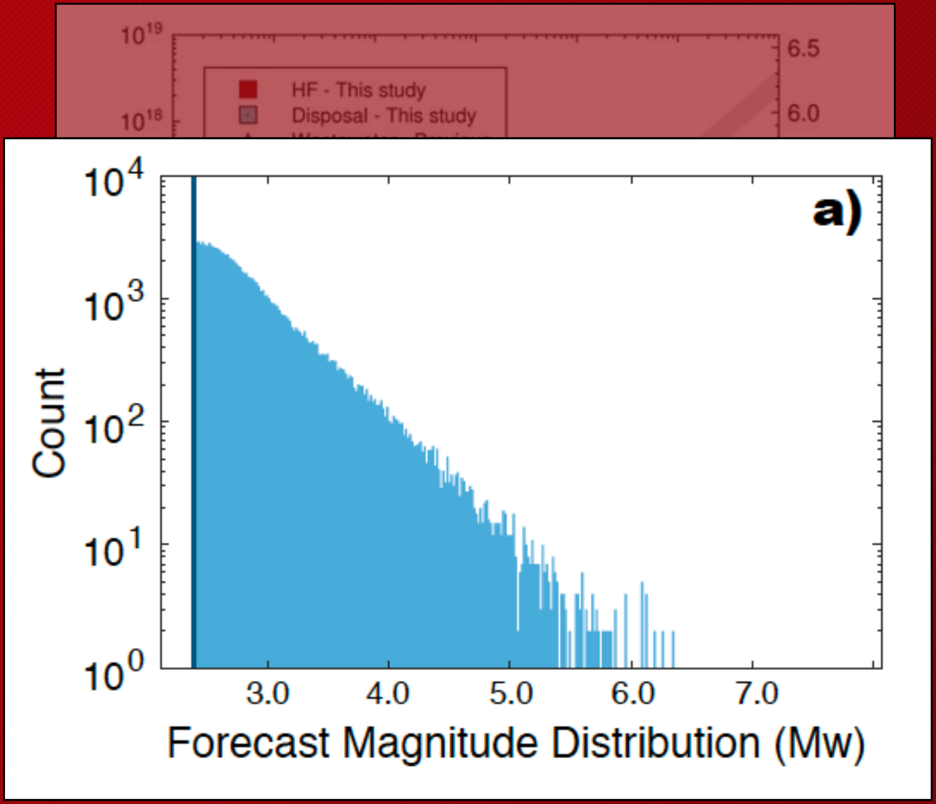
Accounting for Variability: *Run Away Earthquakes*

- How to handle multiple earthquake Mmax?
- No stimulation volume control on Mmax…



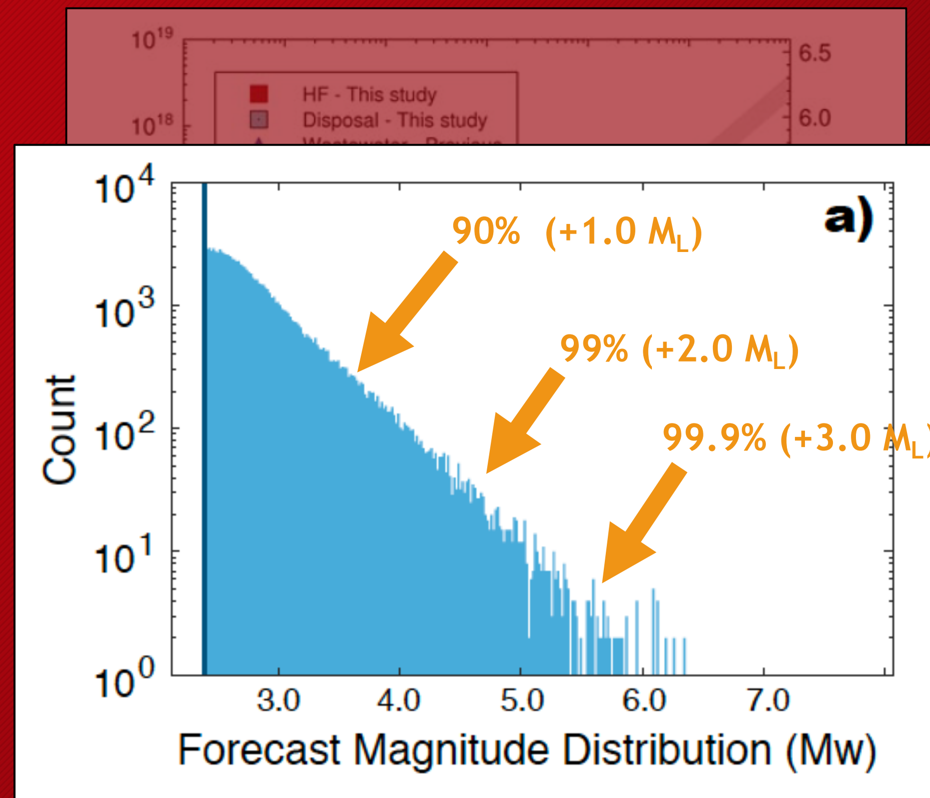
Accounting for Variability: *Run Away Earthquakes*

- No stimulation volume control on Mmax...
- Treat earthquakes like tectonic ones.
- Use GR-FMD to estimate Mmax statistically, given a red-light event.
- Use event counts: 90% occur during stimulation.



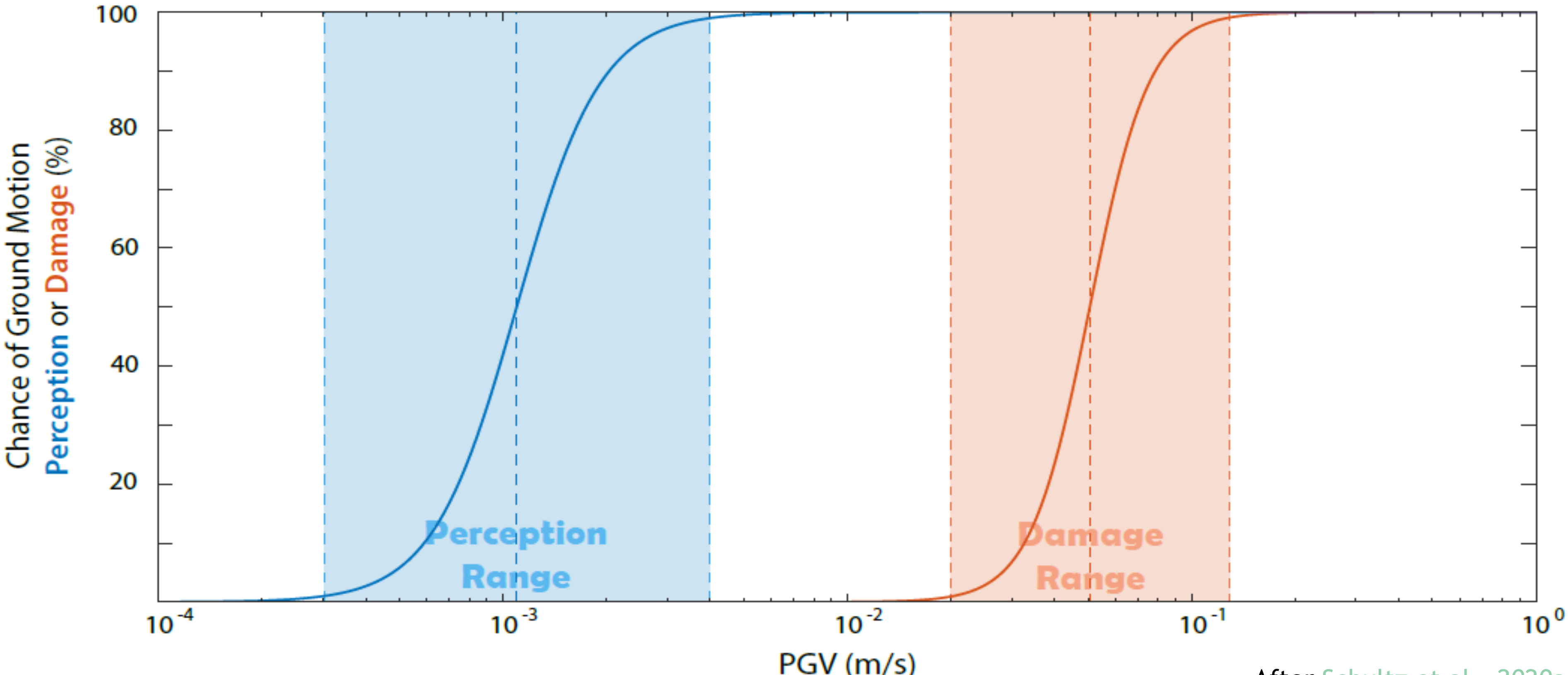
Accounting for Variability: *Run Away Earthquakes*

- Use GR-FMD to estimate Mmax statistically, given a red-light event.
- Use event counts: 90% occur during stimulation.
- Yellow-light threshold should be two magnitude units less than red-light.



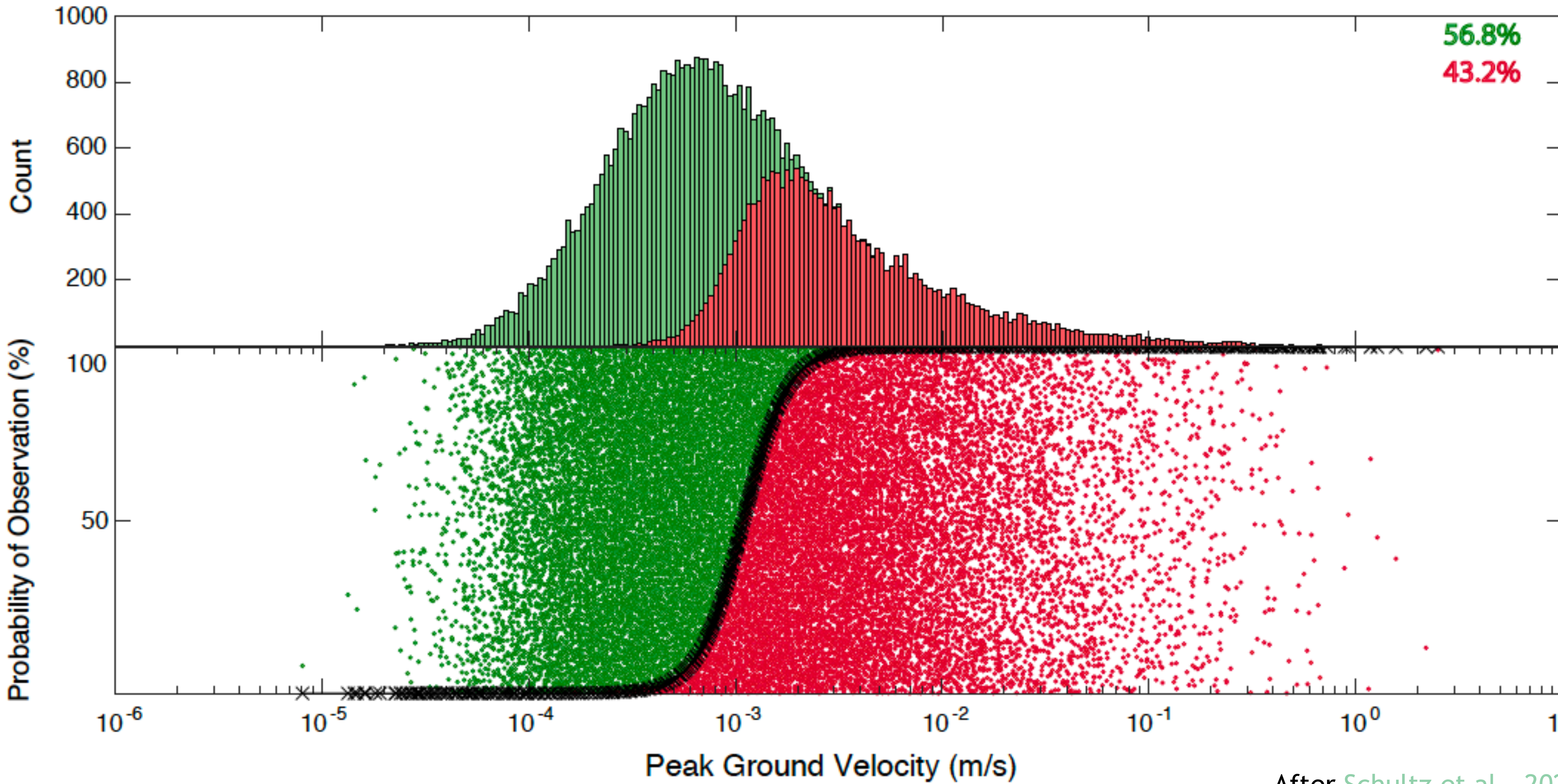
Accounting for Variability: *Ground Shaking Response Functions*

- Use empirical ranges to simulate damage or nuisance actualizations (fragility functions & nuisance functions).



After Schultz et al., 2020a

Quantifying Risk



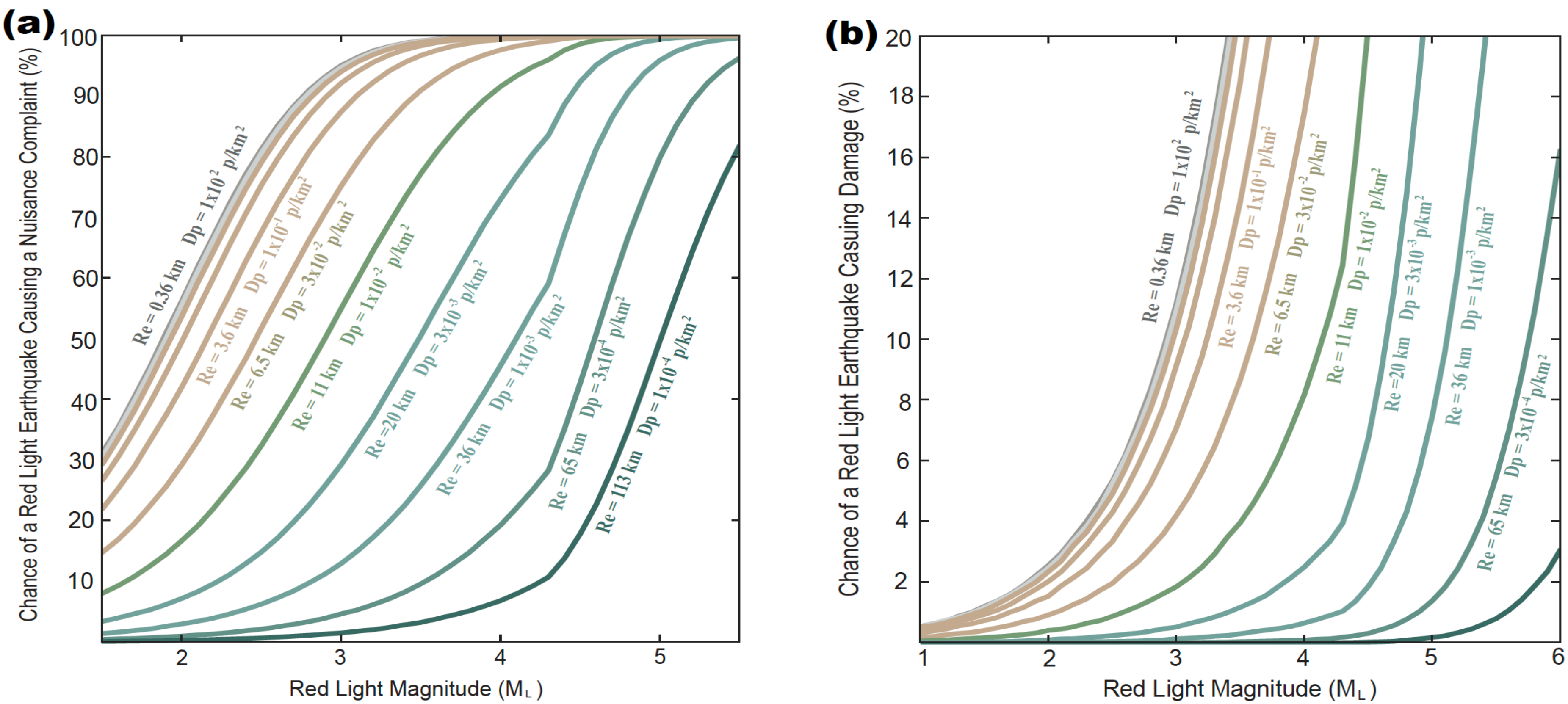
After Schultz et al., 2020a

Review: Quantifying Risk

- Assume a red-light event occurs.
- Build a distribution of possible Mmax.
- Estimate ground motions of all possible events, respecting variance.
- Randomly determine damage or nuisance actualizations.
- Ratio of actualized nuisance/damage to all possible cases estimates risk.
- *Try simulate some synthetic examples!*

Risk Curves

- Strongly dependent on population density.
- At high population densities, curves begin to "stack."



After Schultz et al., 2020a

Advantages to Risk Curve Approach

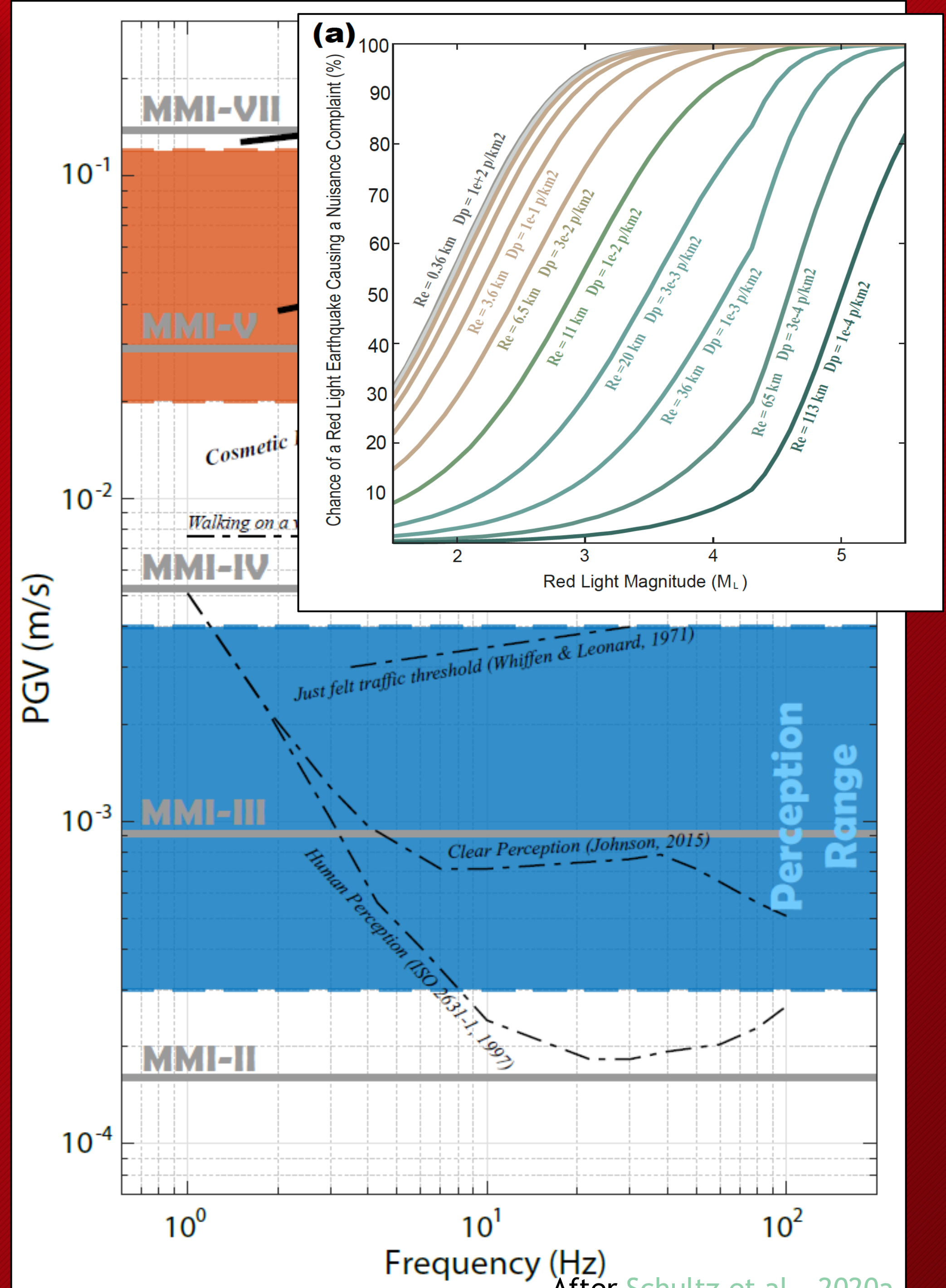
- Quantifies risk, simply.
- Applicable to a risk-matrix approach (ISO 9001:2015).
- Decisions can be made in a risk-management language.
- Can be updated with economic models to quantify loss (in $$).

		Consequence				
		Insignificant	Minor	Moderate	Major	Severe
Likelihood	Almost certain	Medium	High	High	Extreme	Extreme
	Likely	Medium	Medium	High	Extreme	Extreme
	Possible	Low	Medium	Medium	High	Extreme
	Unlikely	Low	Low	Medium	High	High
	Rare	Low	Low	Low	Medium	High

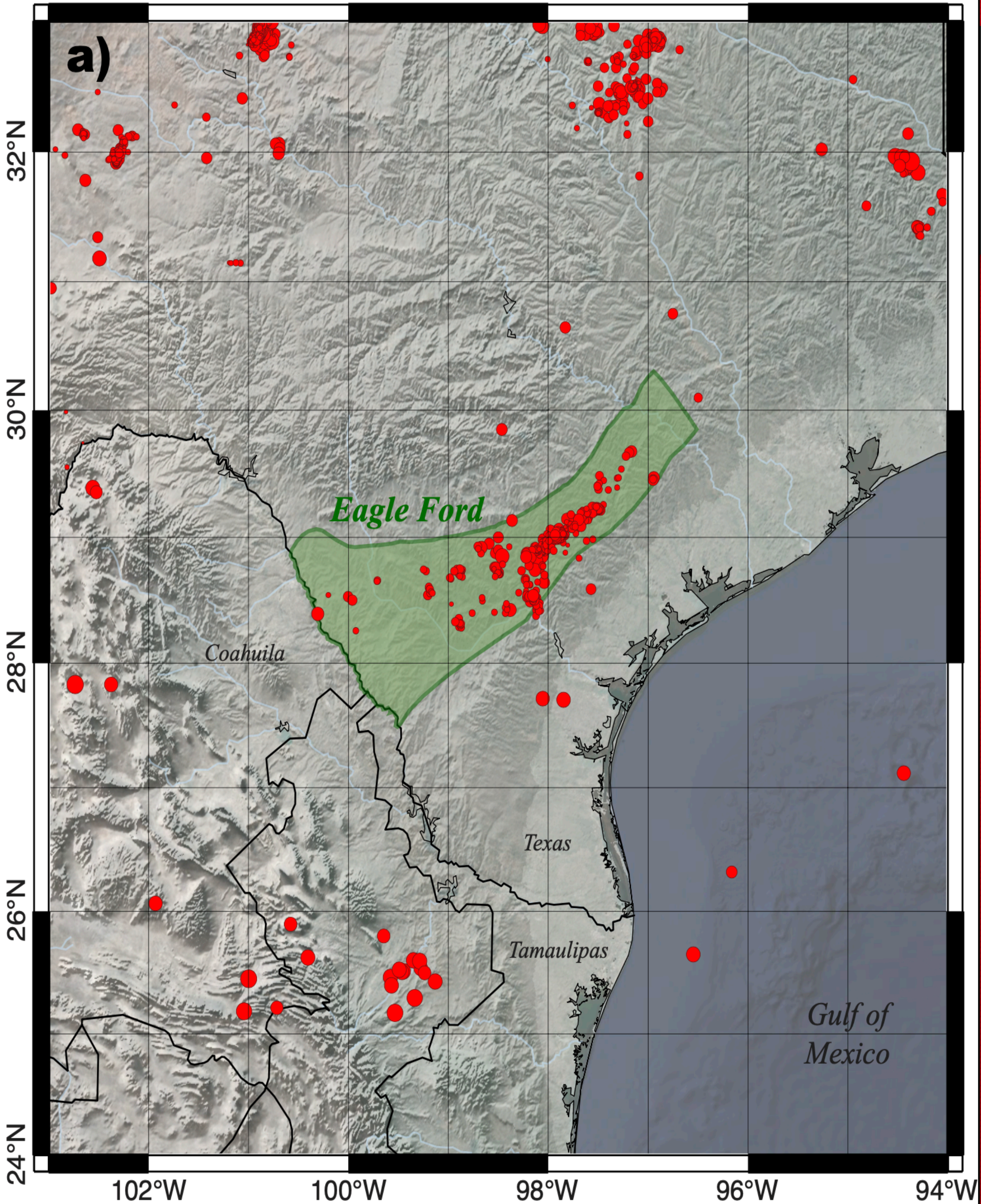
- *Provides some direct insight into how to performance manage HF IS too!*

Red-light Choice?

- Probabilistic, risk-informed approach.
- Forecast the run-away EQs trailing well shut-in.
- Red-lights could be tied to ‘nuisance’ and damage GM.
- Prior method is 0-D, generalize for 2-D.

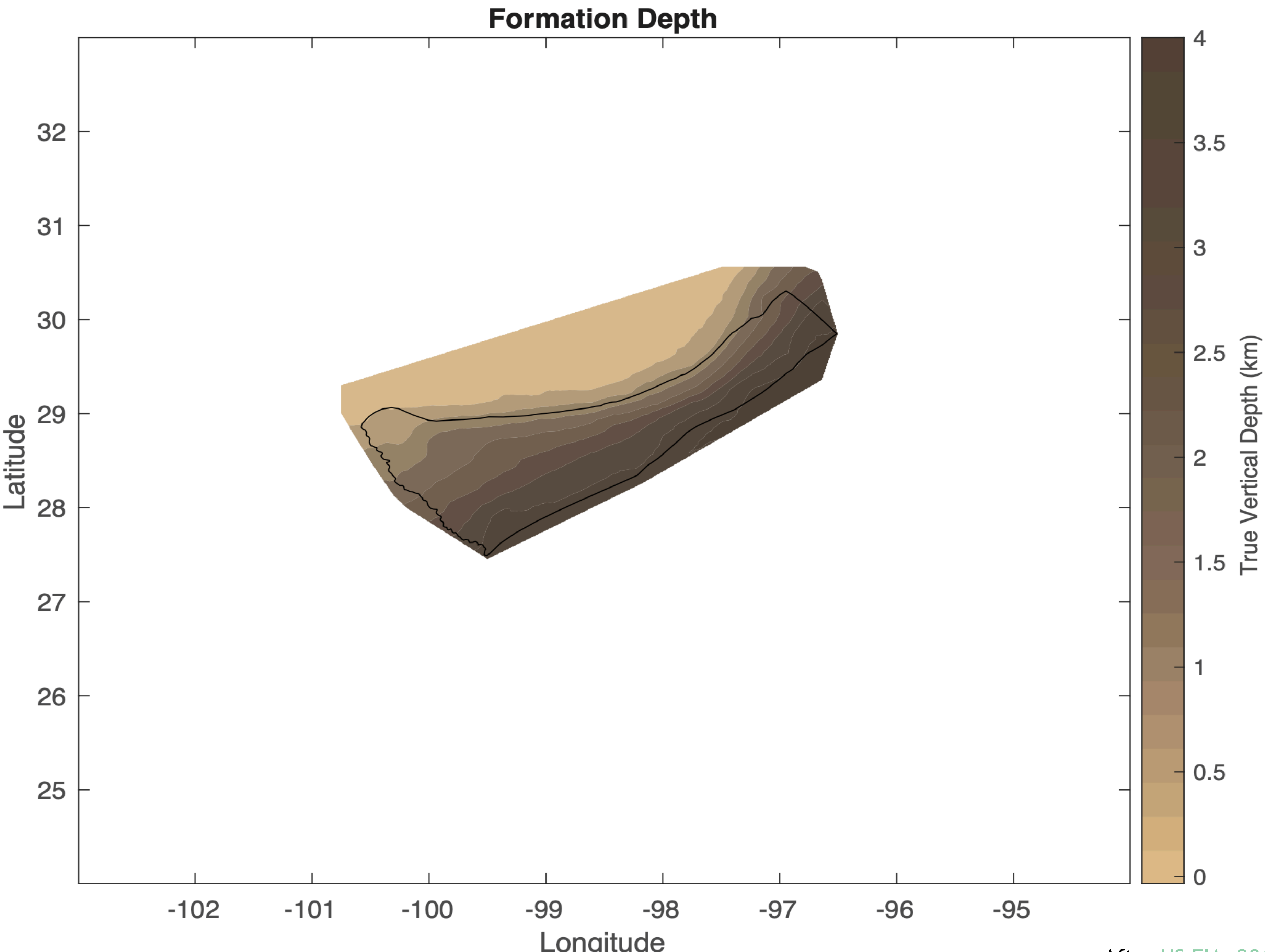


After Schultz et al., 2020a

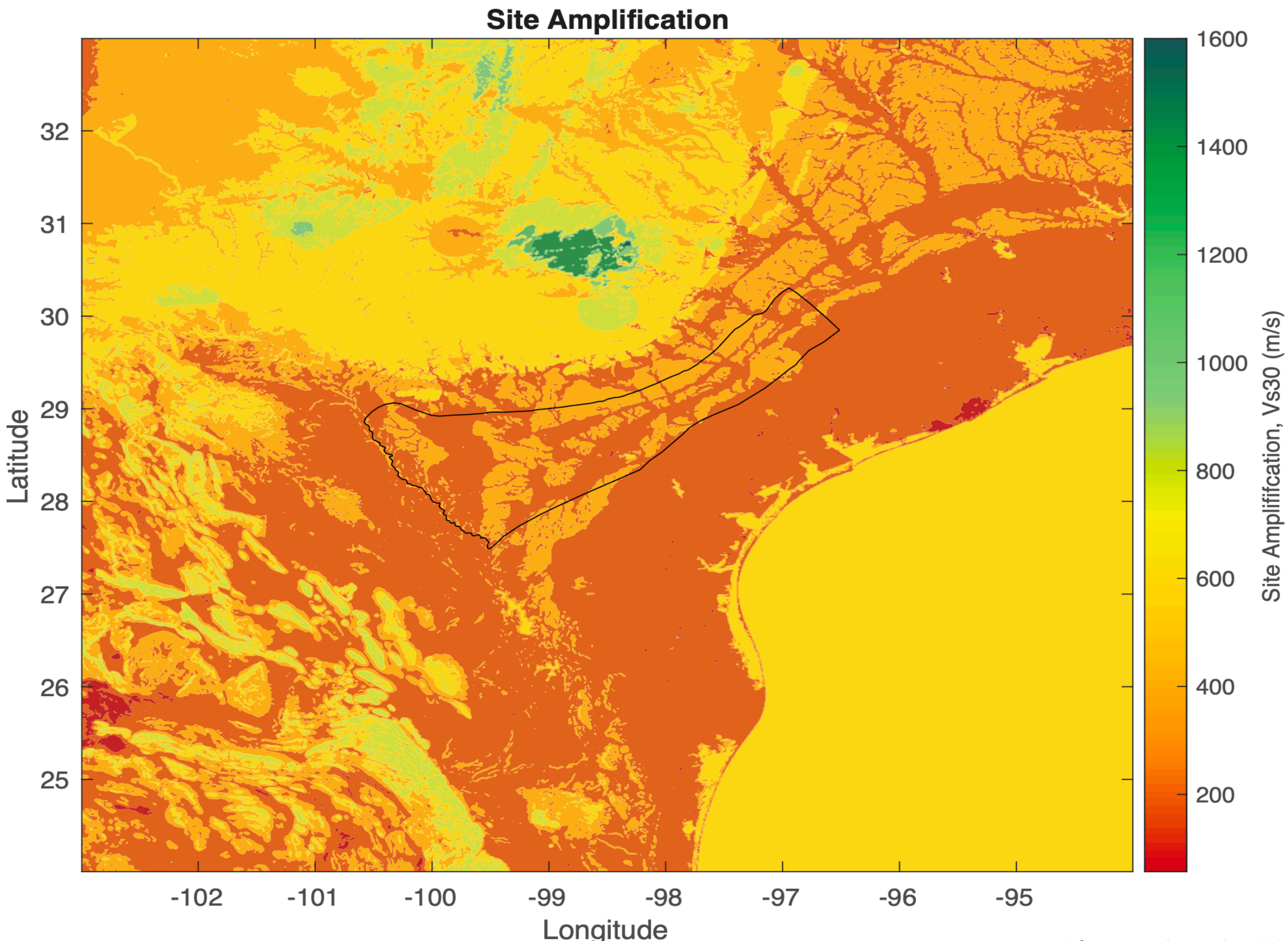


Eagle Ford

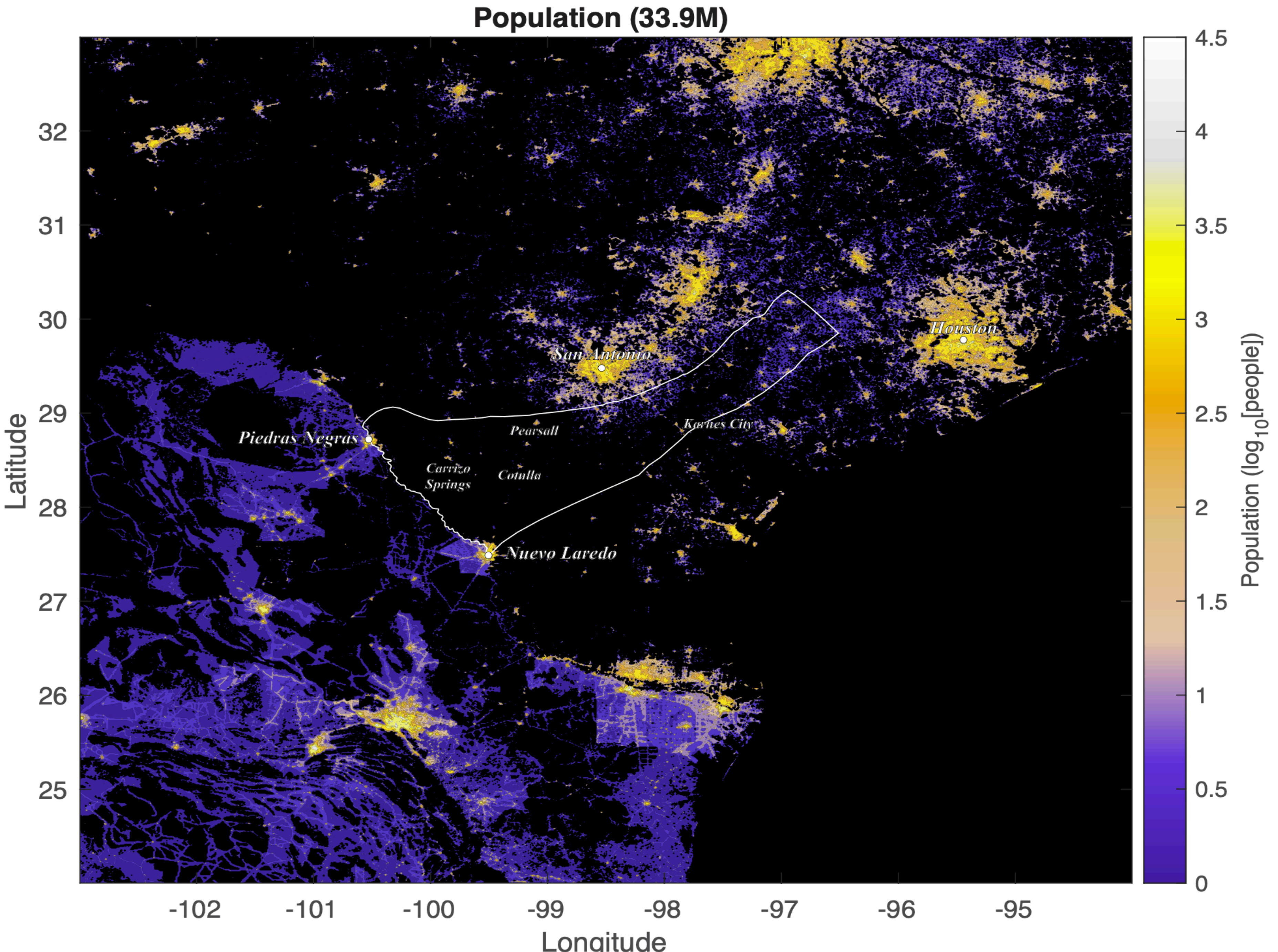
- Seismicity has been linked to HF operations
- Hosted the largest HF IS (4.0 Mw) in the USA.
- Slender shape transitions through differing populations.
- Ideal case to test TLP red-light approach.



After US EIA, 2014



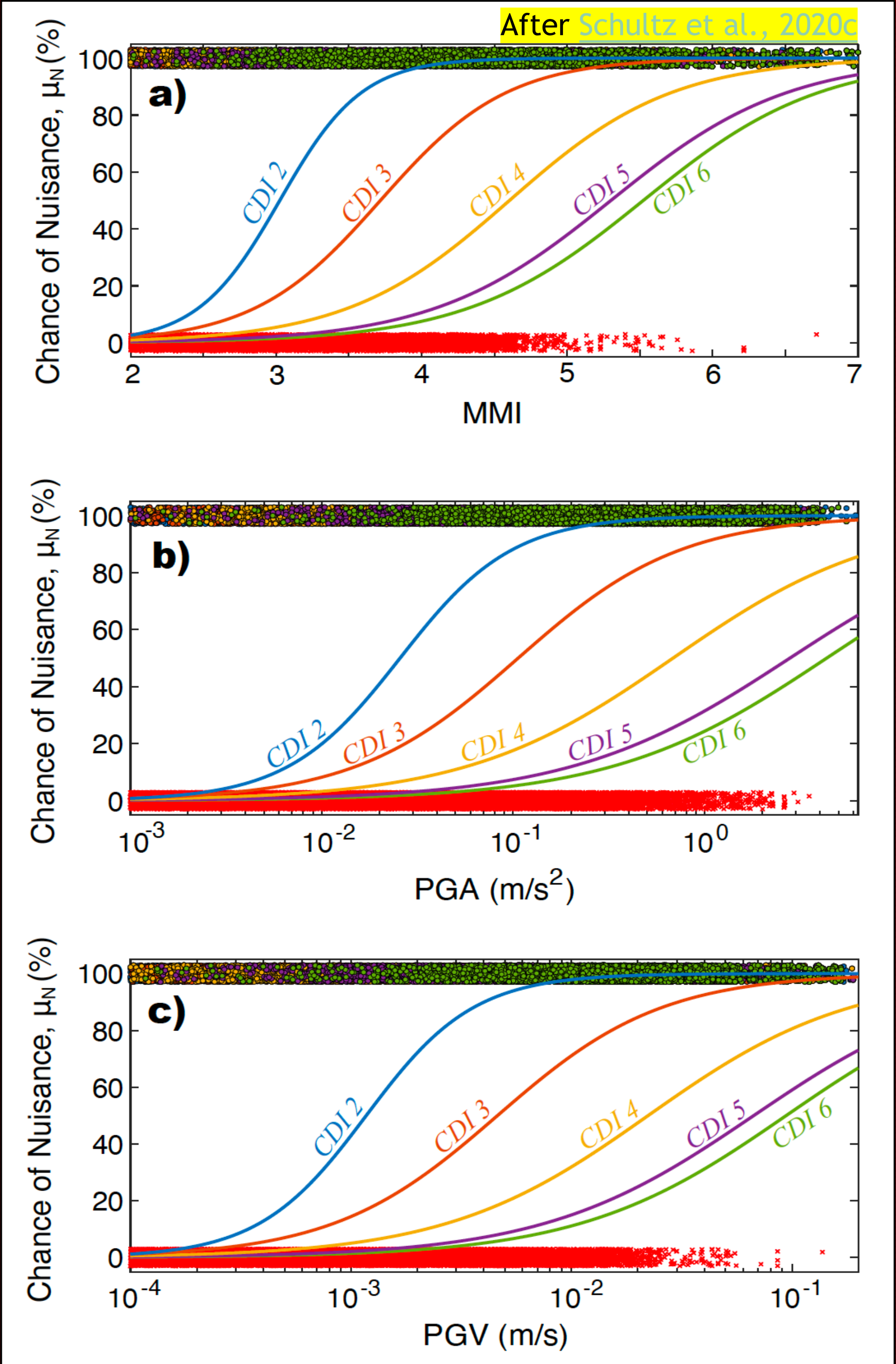
After Heath et al., 2020



After Rose et al., 2019

Nuisance Functions

- Given a GM, estimate the likelihood of being felt.
- CDI (2-6) quantifies various degrees of felt thresholds.
- Subjective criteria: Just felt, exciting, somewhat frightening, frightening, extremely frightening.
- Focus on CDI 3.



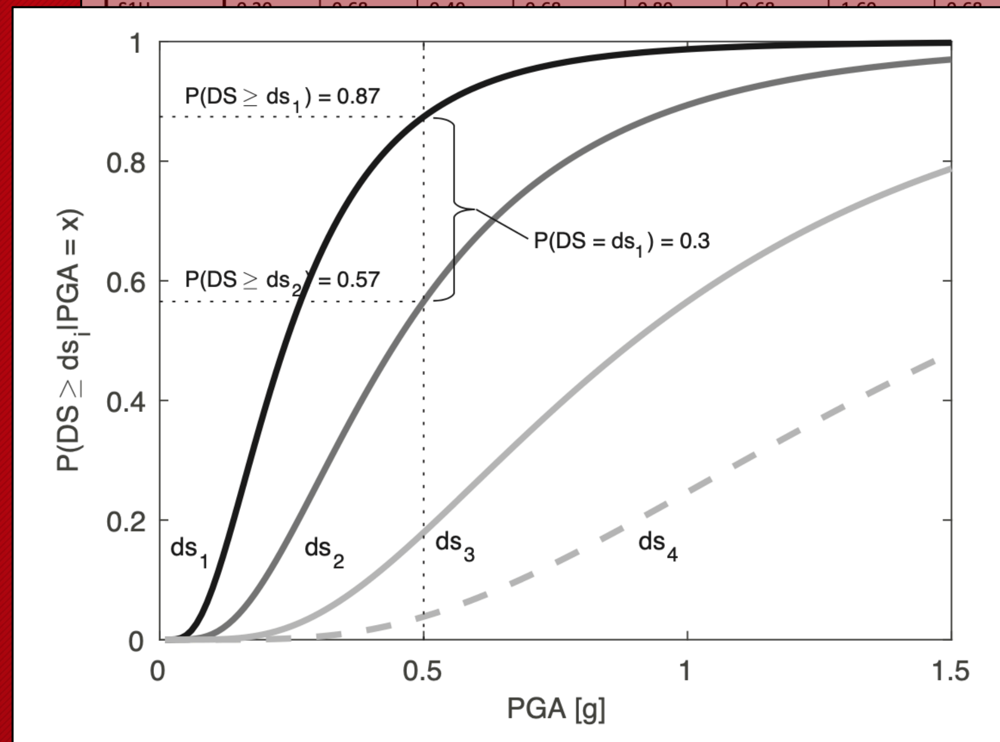
Fragility Functions

- Given a GM, estimate the likelihood of damage.
- DS (1-4) quantifies various degrees of damage.
- Damage criteria: slight/minor, moderate, extensive, complete.
- Focus on DS 1, using pre-code fragility functions.

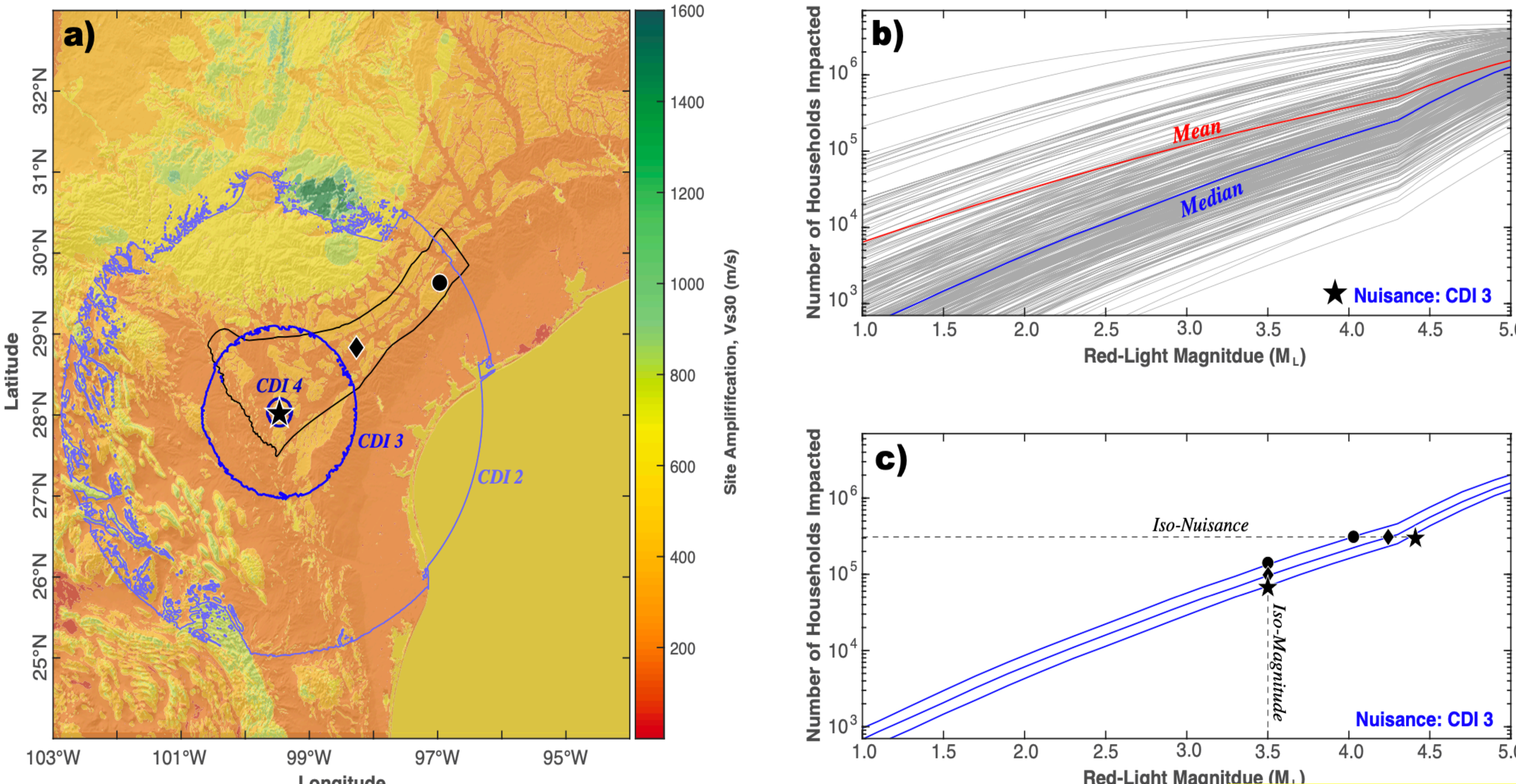
Table 5.13d Nonstructural Acceleration-Sensitive Fragility Curve Parameters - Pre-Code Seismic Design Level

After FEMA, 2015

Building Type	Median Spectral Acceleration (g) and Logstandard Deviation (Beta)							
	Slight		Moderate		Extensive		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	0.20	0.72	0.40	0.70	0.80	0.67	1.60	0.67
W2	0.20	0.66	0.40	0.67	0.80	0.65	1.60	0.65
S1L	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
S1M	0.20	0.66	0.40	0.68	0.80	0.68	1.60	0.68
PC2M	0.20	0.65	0.40	0.68	0.80	0.68	1.60	0.68
PC2H	0.20	0.66	0.40	0.67	0.80	0.67	1.60	0.67
RM1L	0.20	0.66	0.40	0.67	0.80	0.66	1.60	0.66
RM1M	0.20	0.64	0.40	0.66	0.80	0.65	1.60	0.65
RM2L	0.20	0.66	0.40	0.67	0.80	0.67	1.60	0.67
RM2M	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
RM2H	0.20	0.65	0.40	0.67	0.80	0.67	1.60	0.67
URML	0.20	0.69	0.40	0.65	0.80	0.65	1.60	0.6[illegible]
URMM	0.20	0.64	0.40	0.66	0.80	0.66	1.60	0.66
MH	0.20	0.67	0.40	0.65	0.80	0.65	1.60	0.65

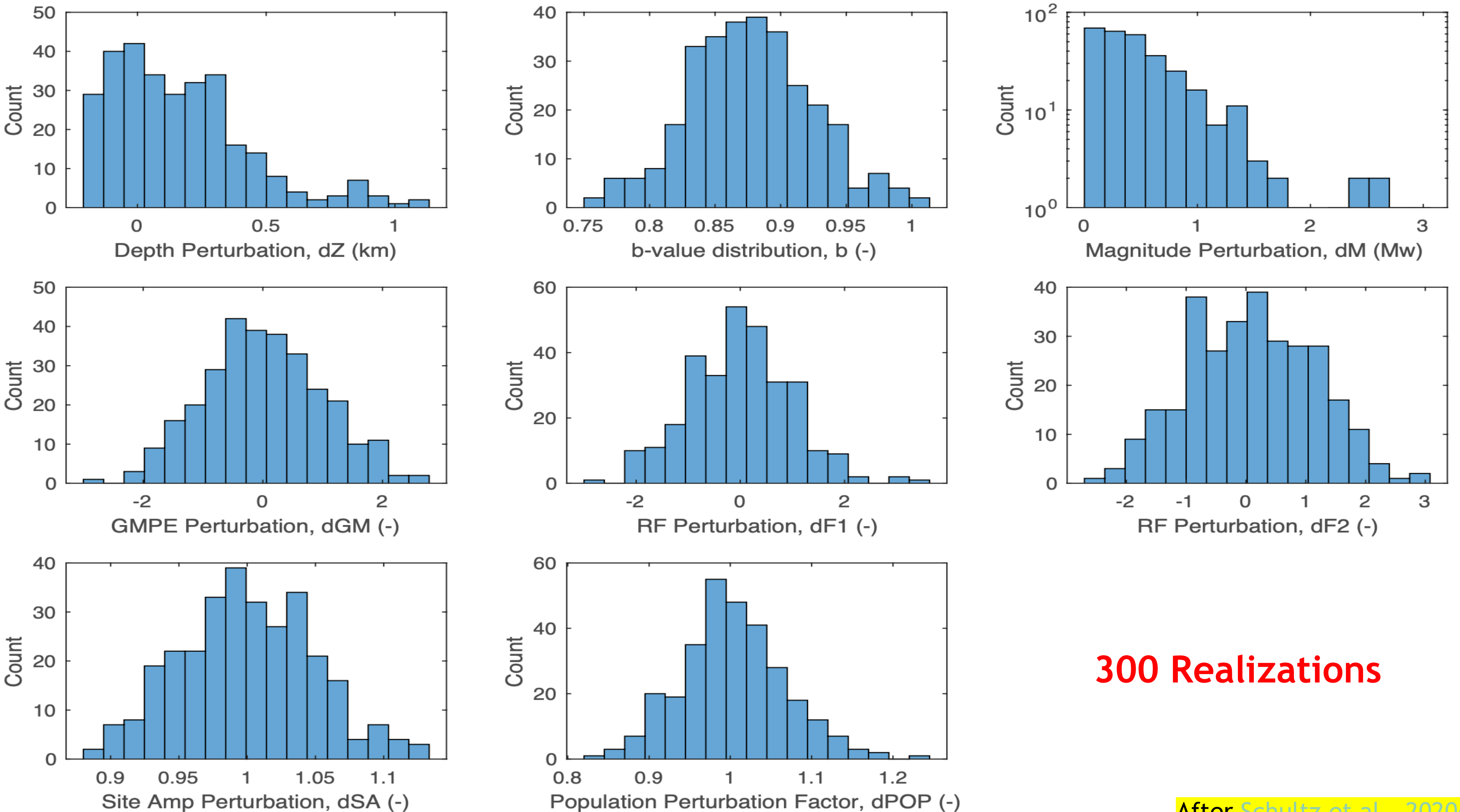


Earthquake Impacts



After Schultz et al., 2020d

Accounting for Variability: *Monte Carlo Perturbations*

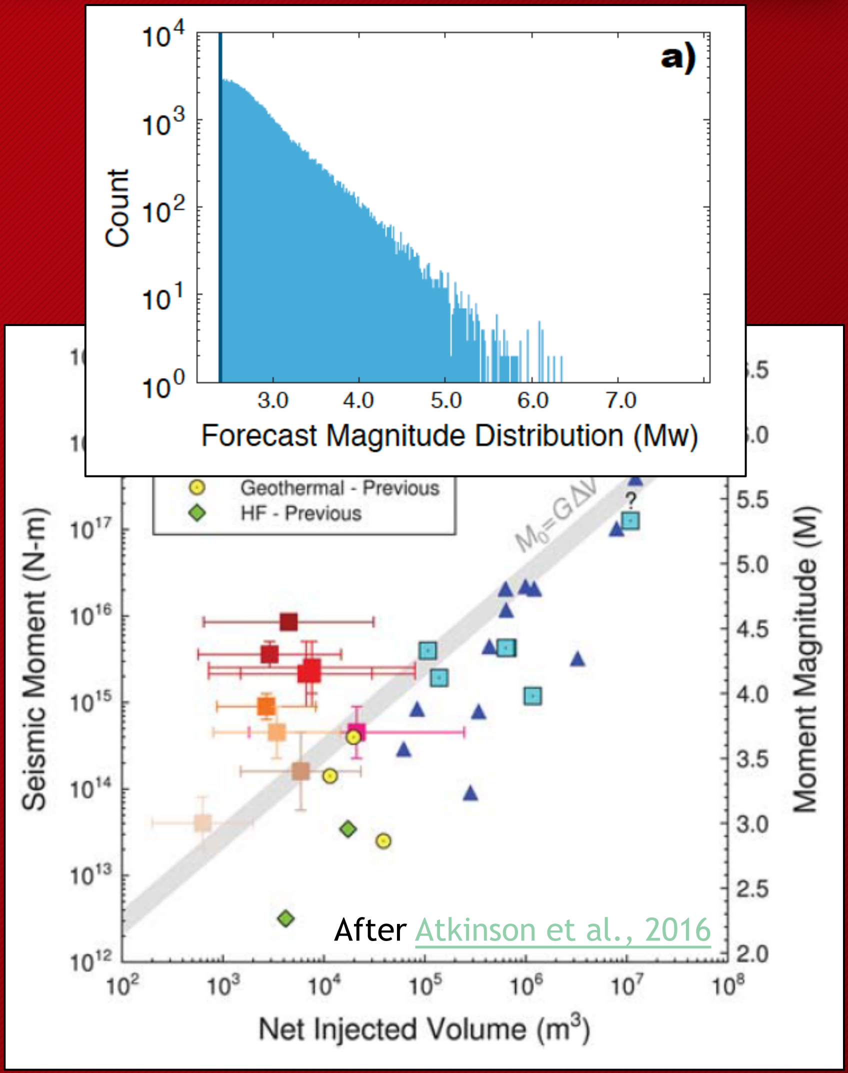


300 Realizations

After Schultz et al., 2020d

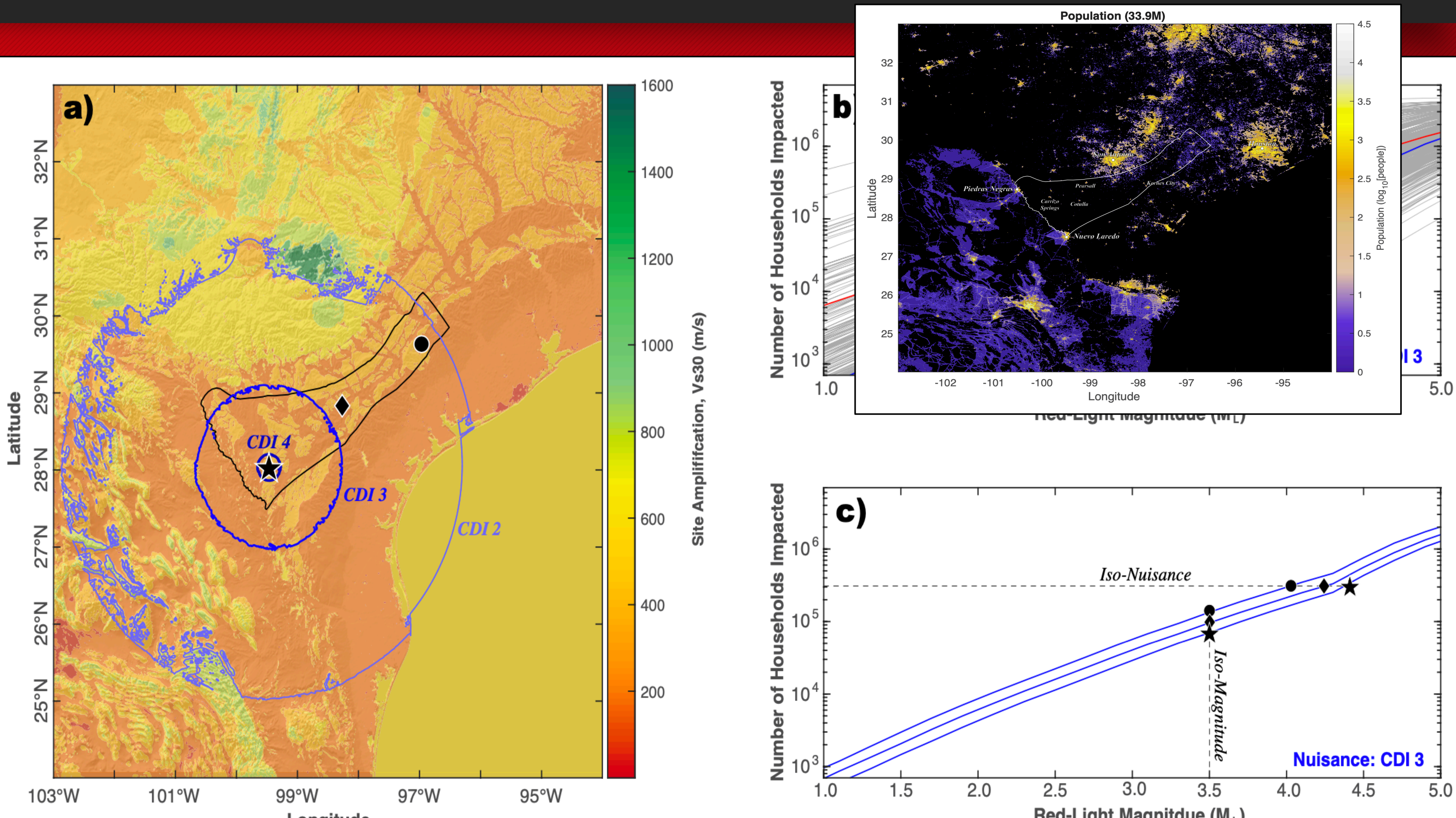
Accounting for Variability:
Run Away Earthquakes

- No stimulation volume control on Mmax…
- Treat earthquakes like tectonic ones.
- Use GR-FMD to estimate Mmax statistically, given a red-light event.
- Use event counts: 80% occur during stimulation.



After Atkinson et al., 2016

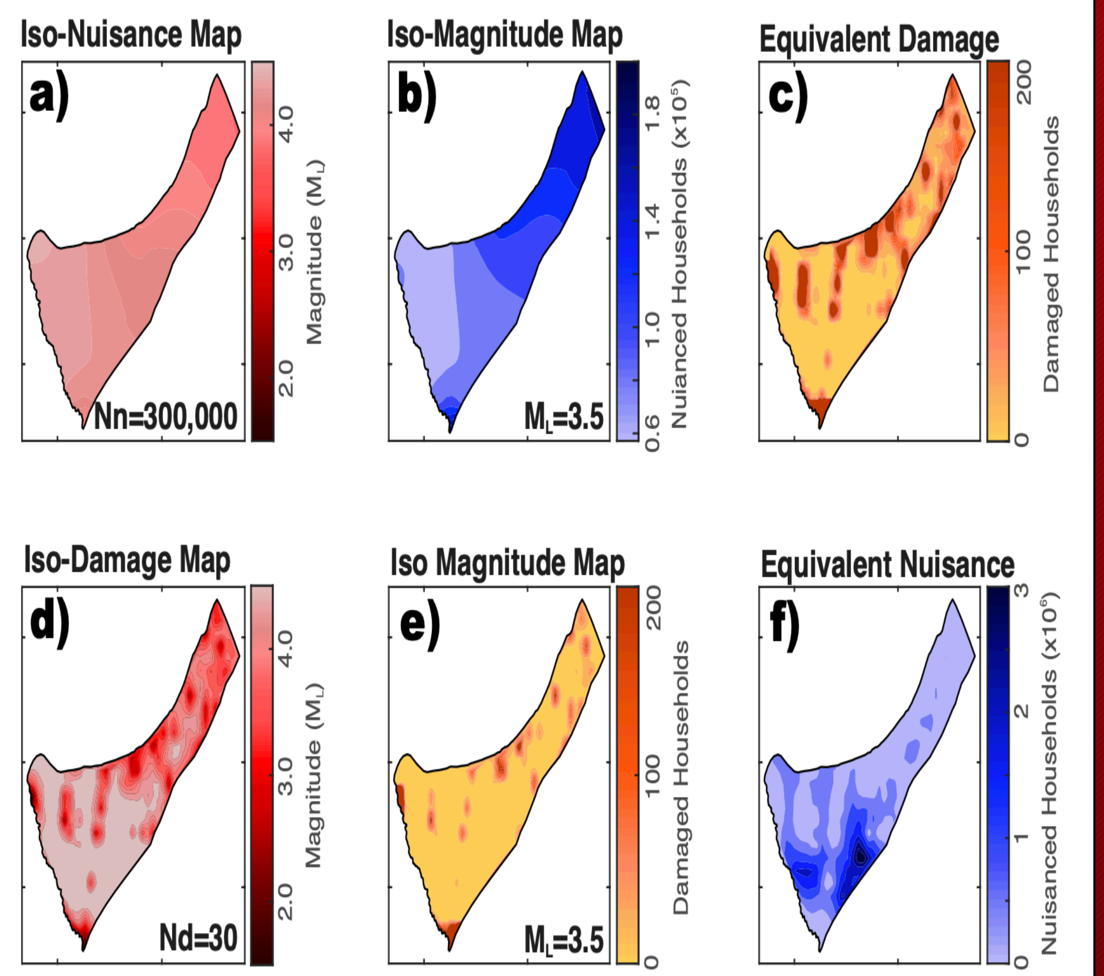
Earthquake Impacts



After Schultz et al., 2020d

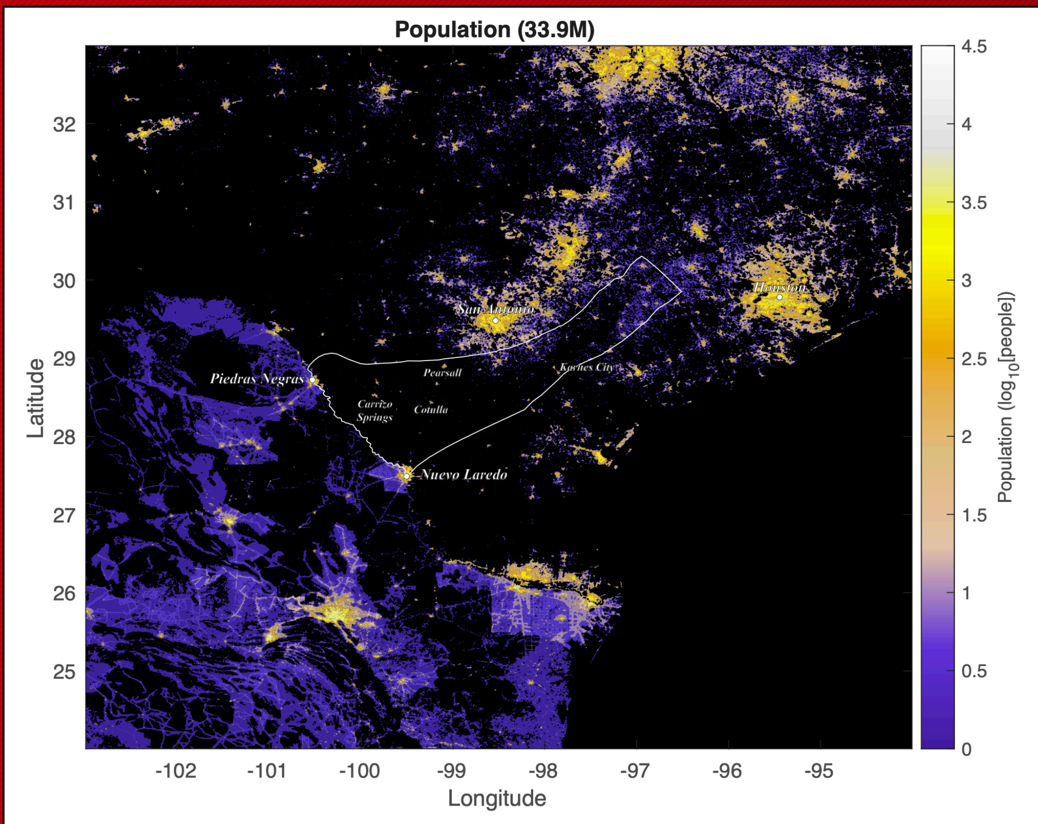
Iso-Risk & Iso-Magnitude Maps

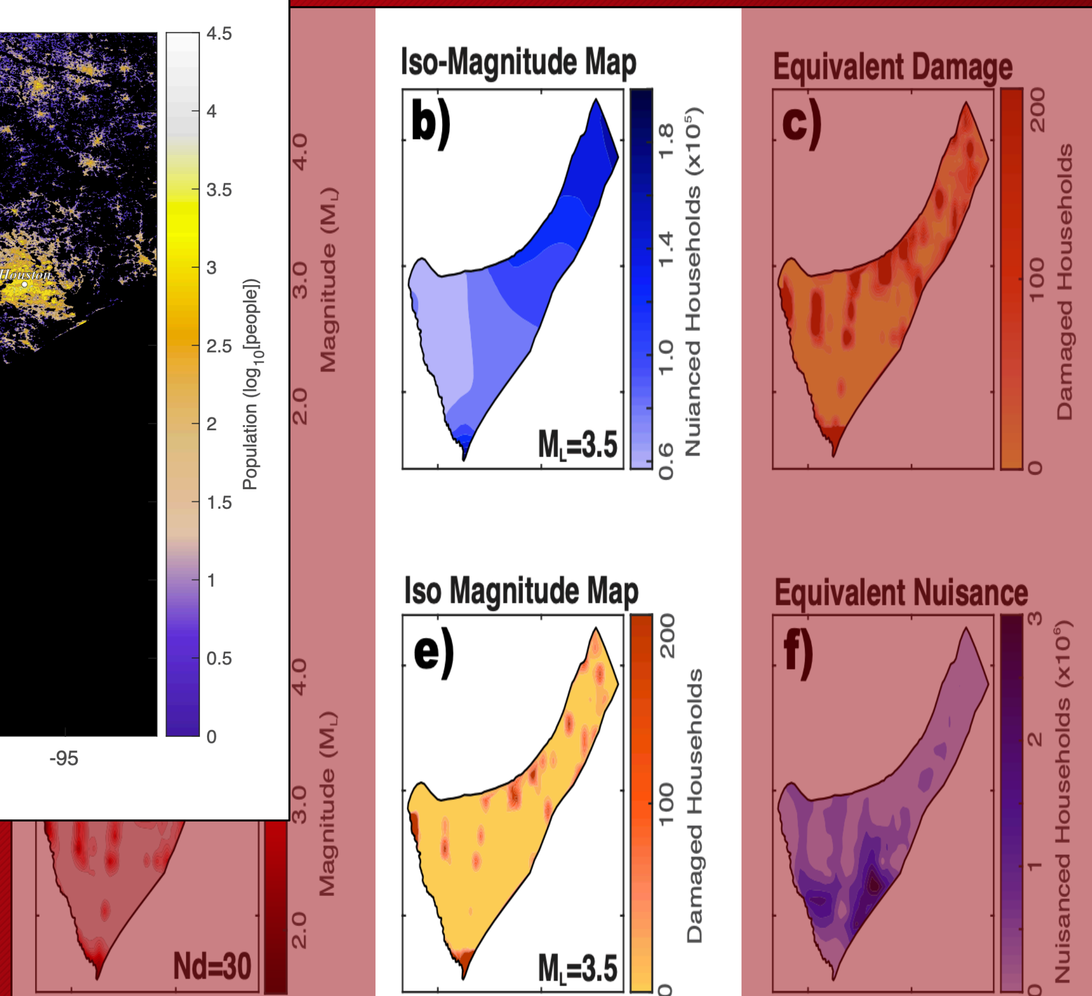
- Heterogeneous nuisance/damage, with a single valued red-light magnitude.
- Long range nuisance, short range damage.
- Magnitude values depend on risk tolerance.



After Schultz et al., 2020d

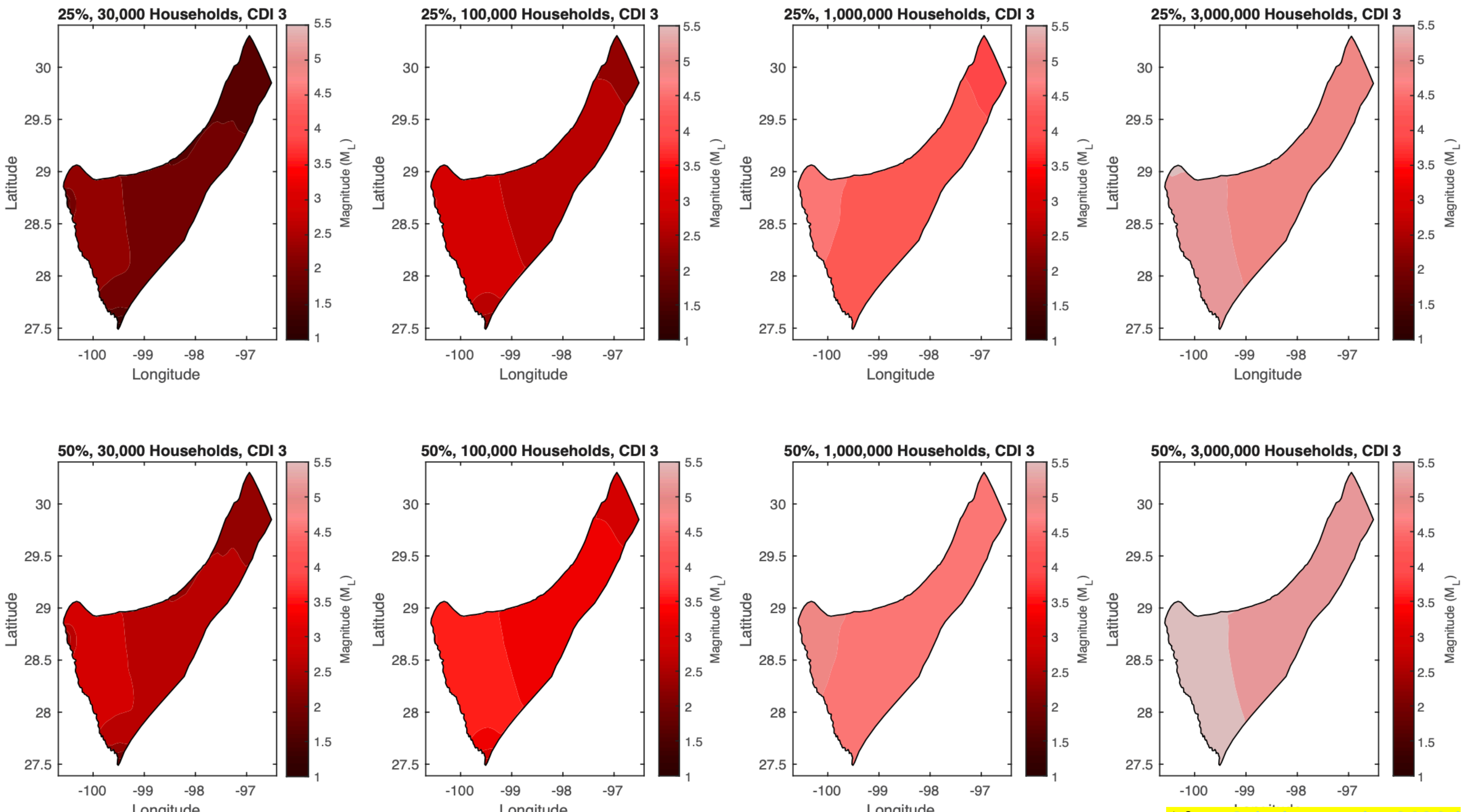
Iso-Risk & Iso-Magnitude Maps





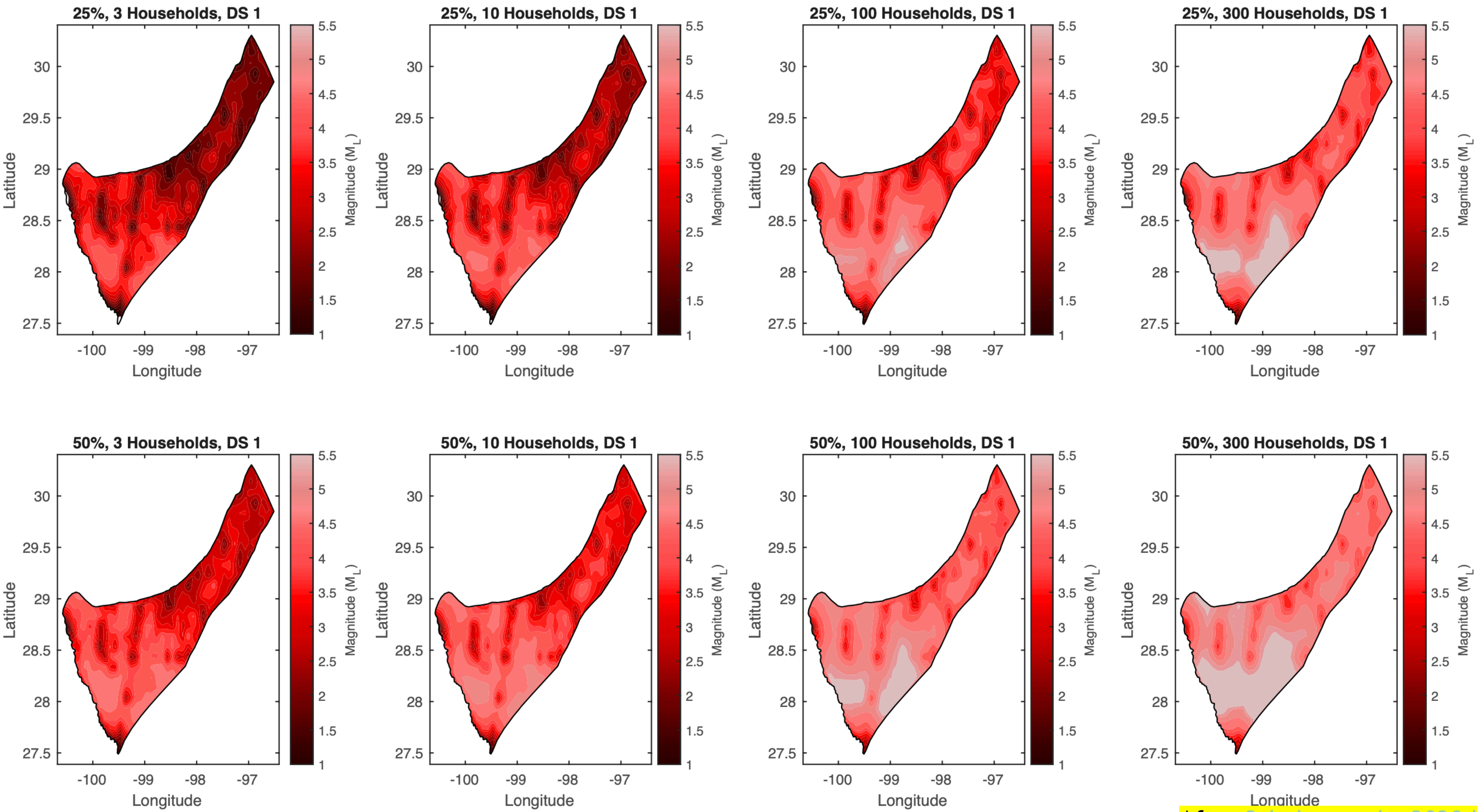
After Schultz et al., 2020d

Iso-Nuisance Maps



After Schultz et al., 2020d

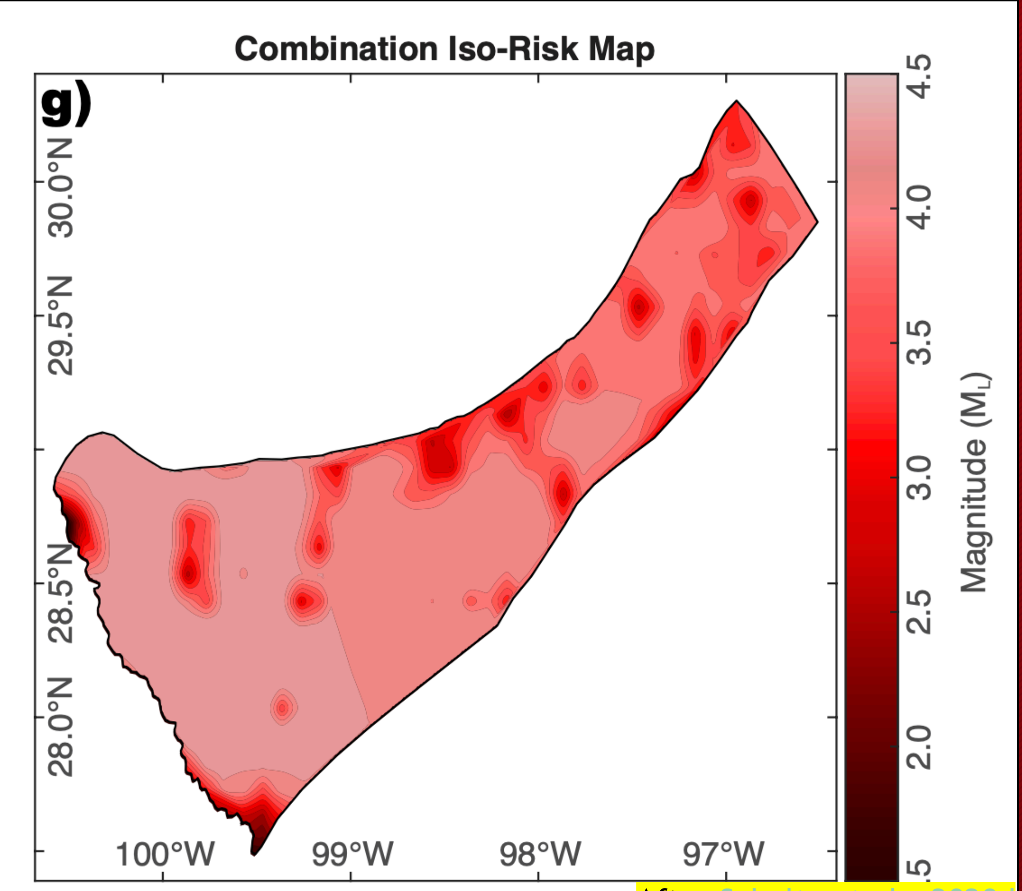
Iso-Damage Maps



After Schultz et al., 2020d

Combination Map

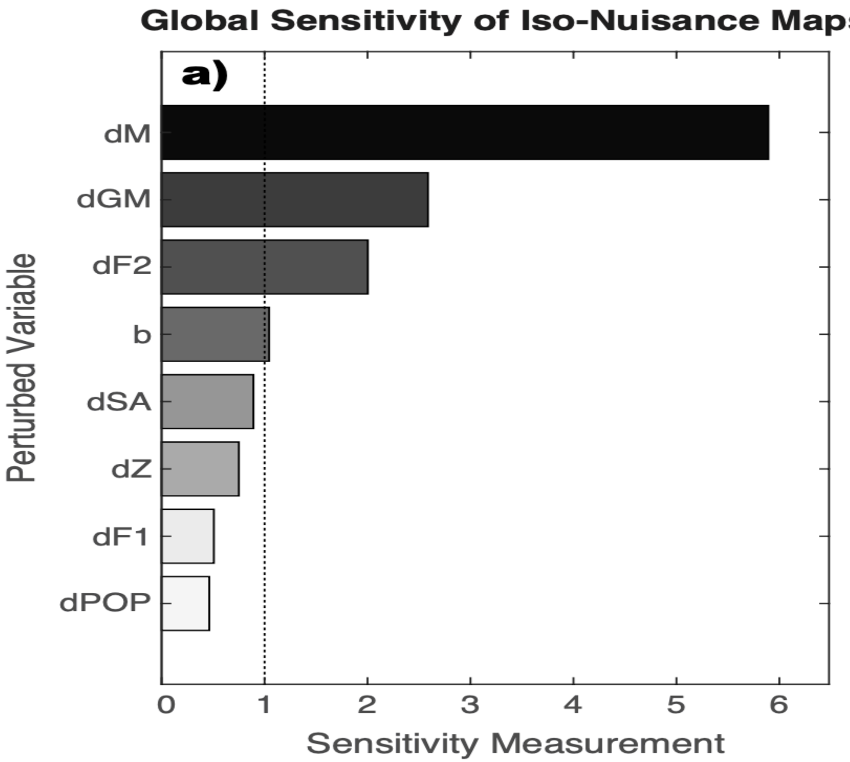
- Satisfy damage/nuisance tolerances by taking the smaller of the two magnitudes.
- Nuisance controls rural M_L, damage controls urban M_L.
- Can be repeated for different tolerances.

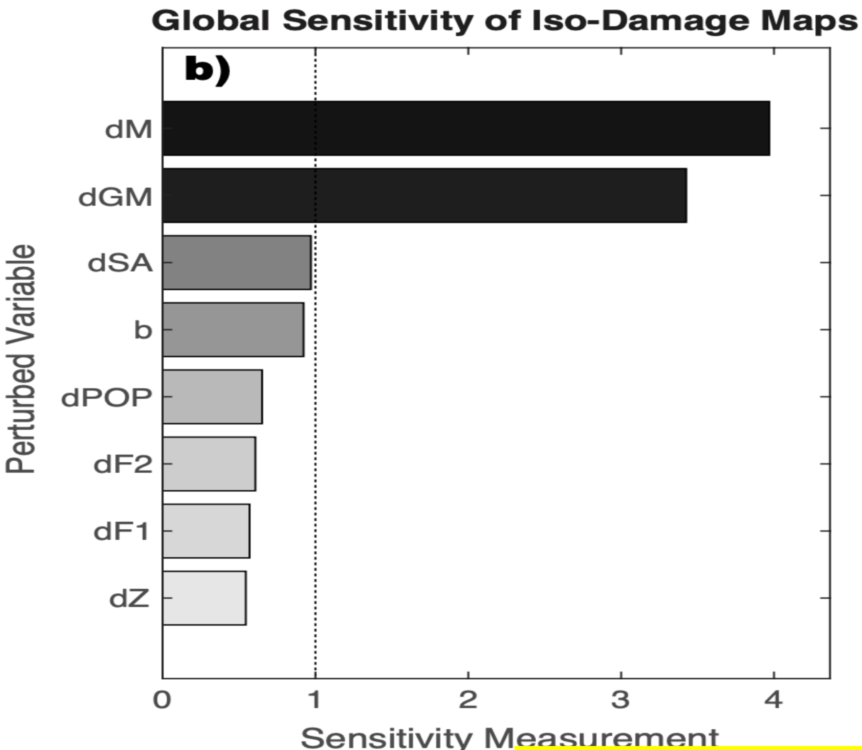


After Schultz et al., 2020d

Understanding Variability: *Perturbation Sensitivity Analysis*

- Test sensitivity of perturbed parameters on iso-risk maps.
- Forecast magnitude #1.
- GMPE variability #2.





After Schultz et al., 2020d

Summary

- ❖Discussed why HF IS occurs: basement-rooted faults, reactivated via pore pressure.
- ❖Presented a method to choose red-light (and yellow) thresholds that reduce risks of HF IS.
- ❖Generalized the method for realistic geospatial databases, using risk tolerances.

Questions?

Schultz, Skoumal, Brudzinski, Eaton, Baptie, & Ellsworth (2020b). ***Hydraulic Fracturing-Induced Seismicity,*** Reviews of Geophysics, doi: 10.1029/2019RG000695.

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