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Key Insights Gained from Induced Seismicity Monitoring in North American Shale Plays

Adam Baig, Ben Witten

Why Monitor?

- How much more can we do to understand the subsurface?
- How can we better mitigate the risks associated induced seismicity?
- How can we form better regulatory controls and communicate to stake holders?

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KEY INSIGHTS FROM INDUCED SEISMIC MONITORING IN CANADA AND THE USA

1. Understanding the nature of induced seismicity is key to managing it
2. Recording seismic network controls data usage
3. It is important to get event magnitudes right
4. Ground motions should play a role in regulatory protocols
5. Real-time induced seismicity risk management is possible but…

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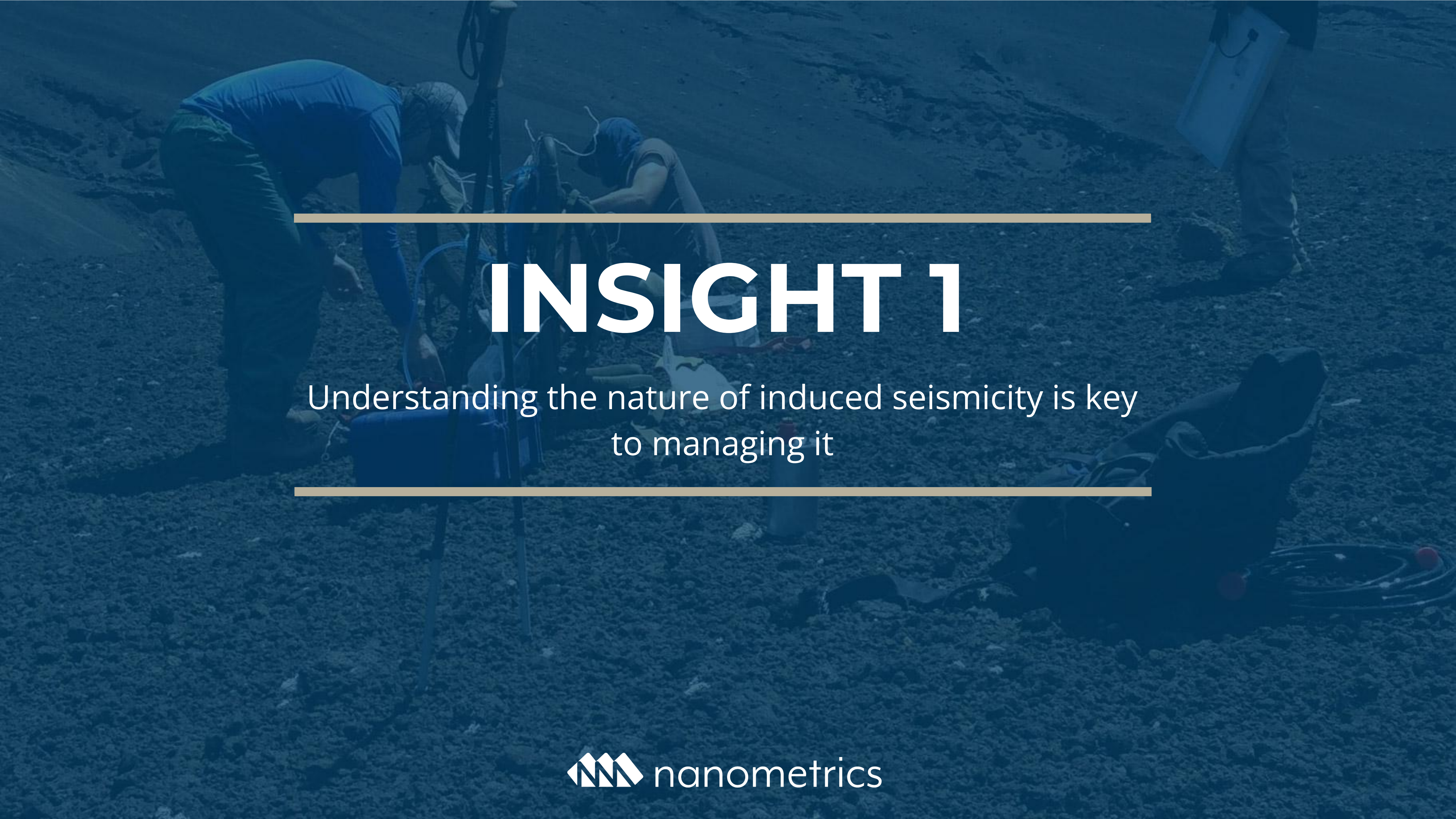

INSIGHT 1

Understanding the nature of induced seismicity is key to managing it

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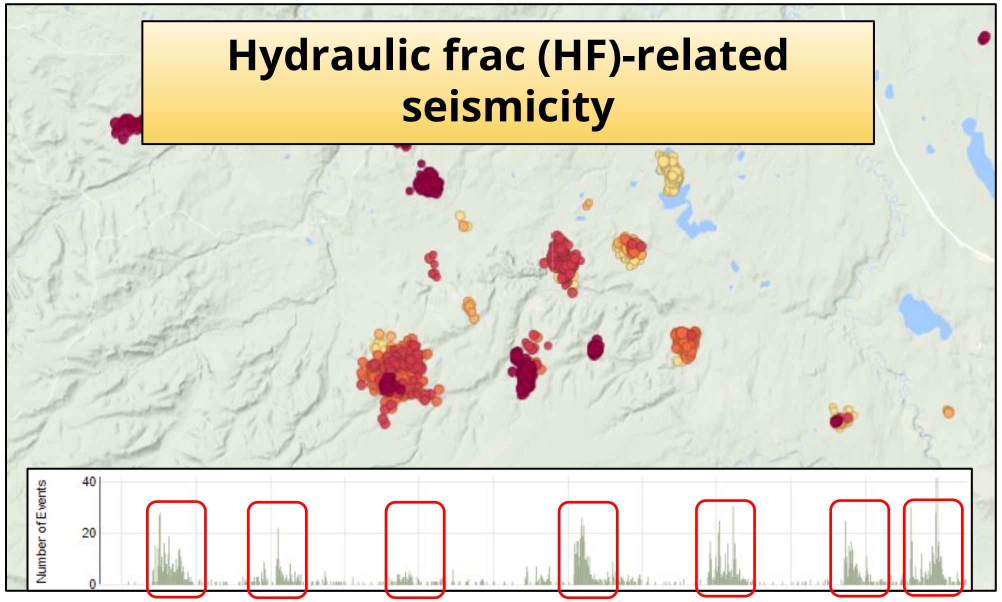
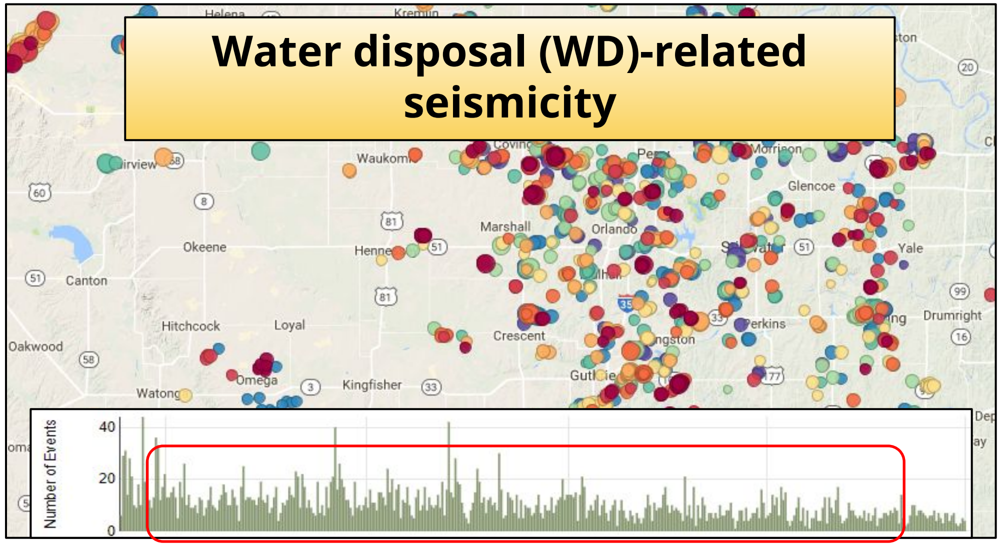
INDUCED SEISMICITY ATTRIBUTES

1. Strong temporal and spatial correlation with HF operations*
2. Follows Gutenberg-Richter frequency-magnitude relationship with b-value ~1
3. No baseline seismicity
4. Seismicity uncorrelated with frac stage times*
5. Seismicity diminishes within hours or days following operation completion*
6. Presence of positive magnitude events

*Attributes that do not apply to the waste water disposal-related induced seismicity





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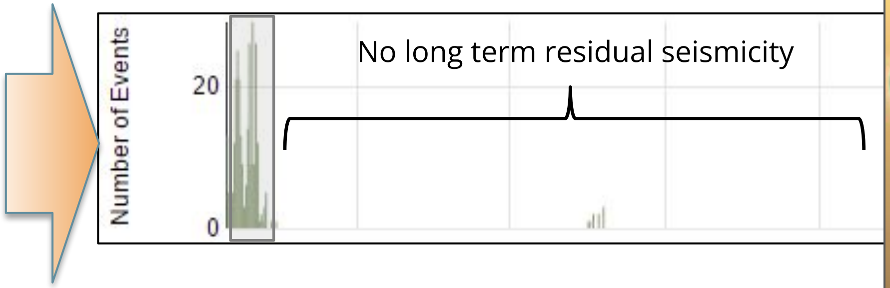
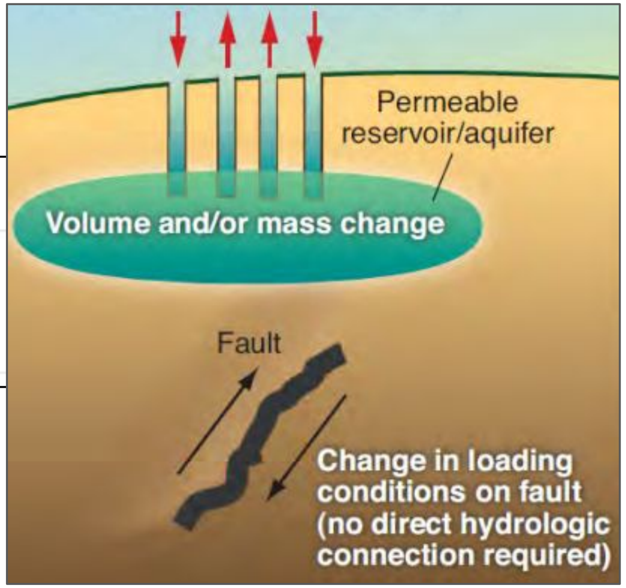
INDUCED SEISMICITY ACTIVATION MECHANISMS

1. Stress transfer (fast process)

- Triggered by stress changes due to HF fluid injection
- Critically-stressed optimally-oriented faults
- Seismicity diminishes quickly after the stresses due to HF operations have subsided
- **Predominant in HF-induced seismicity**



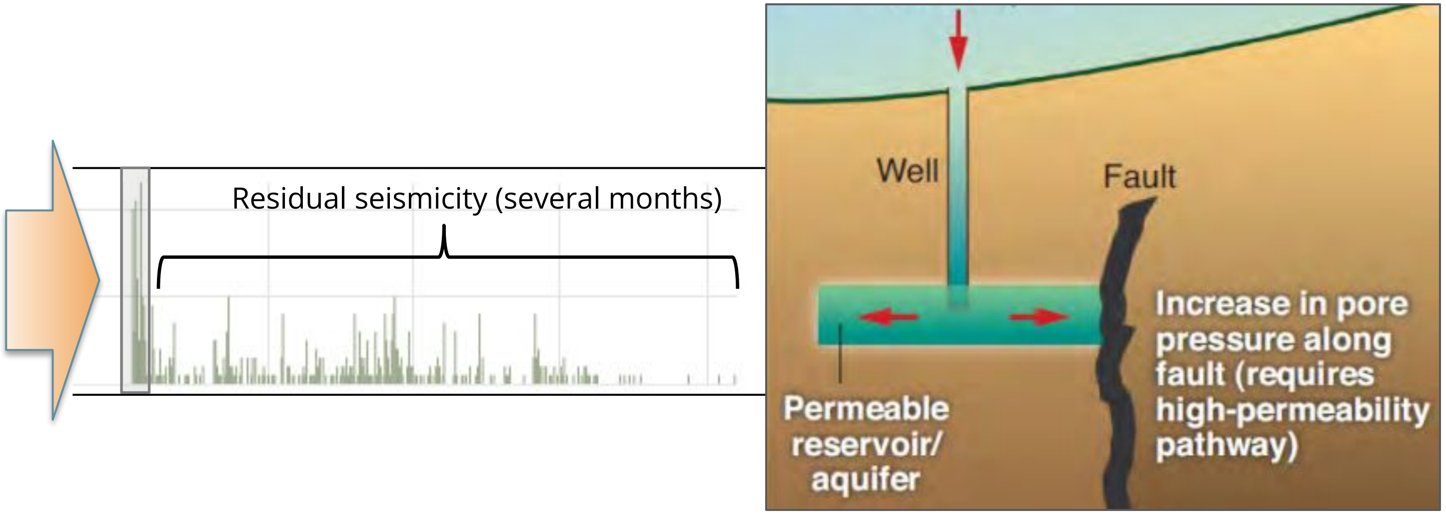


(Ellsworth, 2013)

INDUCED SEISMICITY ACTIVATION MECHANISMS

1. Fluid/pressure diffusion (slow process)

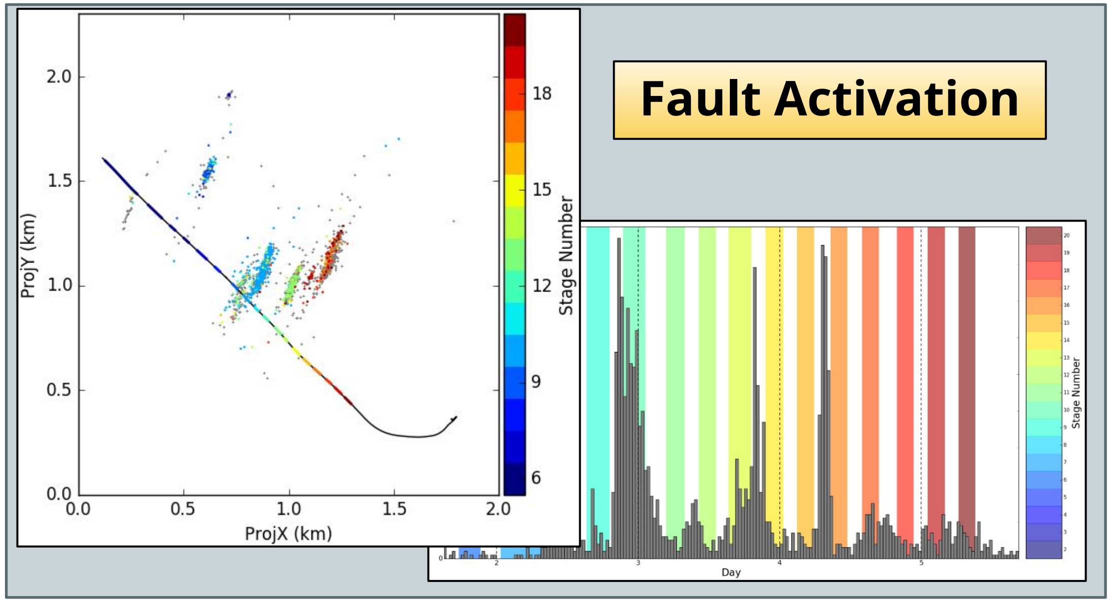
- Hydrological link between the hydraulic fractures and fault
- Fault closer and pressurized
- Residual seismicity
- **Predominant in WD-induced seismicity**

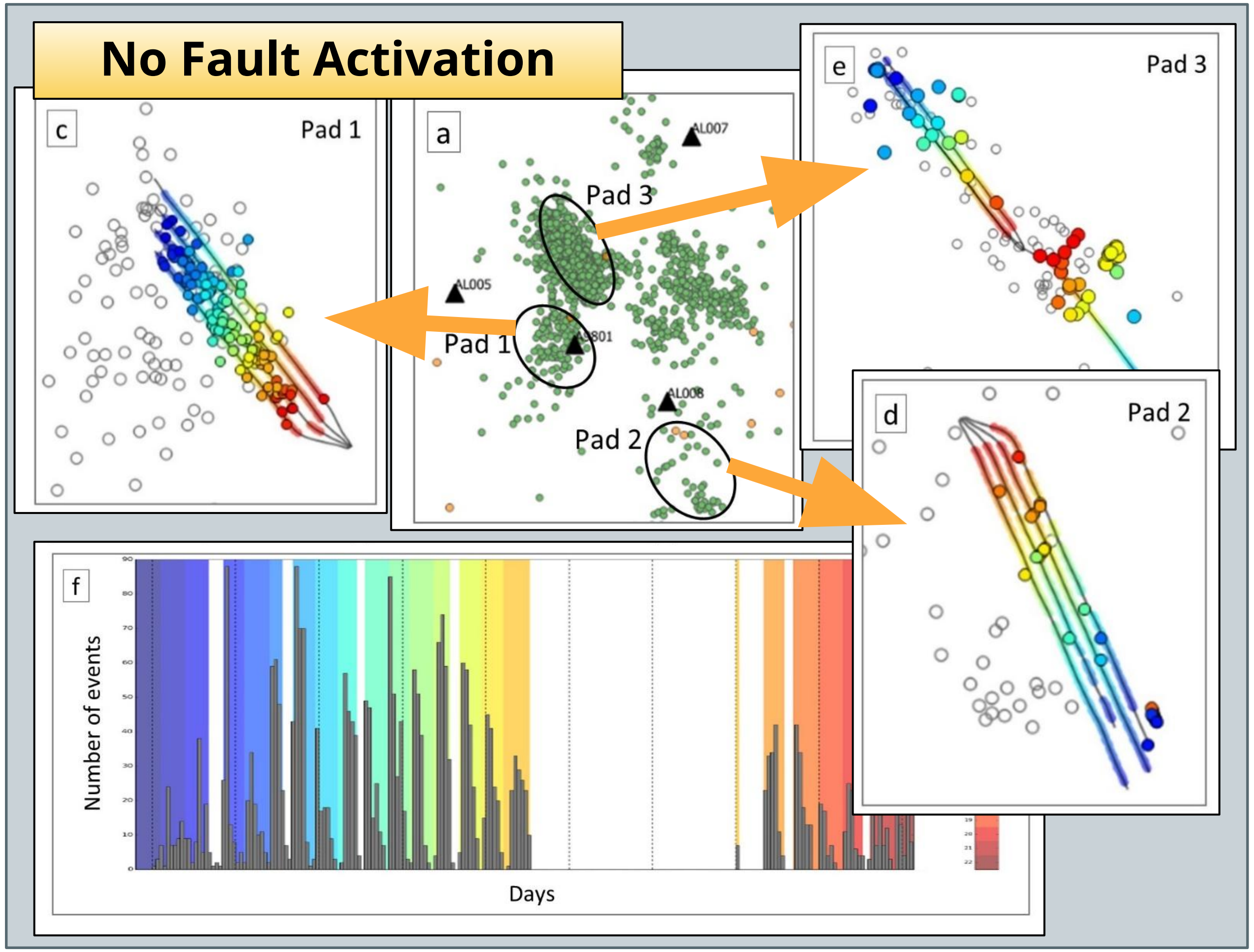


(Ellsworth, 2013)

NOT ALL IS RELATED TO FAULT ACTIVATION

- Not all detected seismicity is fault activation
- High-resolution data potentially changes the interpretation
- Seismicity can be related to activation of secondary fracture networks
- Not capable of producing a large events





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INSIGHT 2

Recording seismic network controls data usage

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RECORDING NETWORK GOVERNS DATA USAGE

	Public Networks	Regional (Subscriber) Arrays	Private Local Arrays	Microseismic Arrays
Coverage	National/state-wide	Shale play regions	Single or multiple pads	Single pad
Station Spacing	10s or 100s of km	10s of km	2-5 km	10s of m
Magnitude of completeness (Mc)	~M 1.5 to 2.5	~M 0.7 to M1.8	~M -0.3 to 0.7	~M -2.0 to -0.3
Location Uncertainty	2 to 10s of km	500 m to 1.5 km	80 m to 300 m	< 30m
Instrumentation	Seismometer, Accelerometer			Geophone
Purpose relative to induced seismicity	**Is there induced seismicity?**	**Characterize IS and comply with regulations**	**Actively manage and mitigate IS risk**	Estimate effectiveness of stimulation design and well spacing

ex. OGS, Texnet, USGS, OhioSeis

Increasing monitoring resolution and cost

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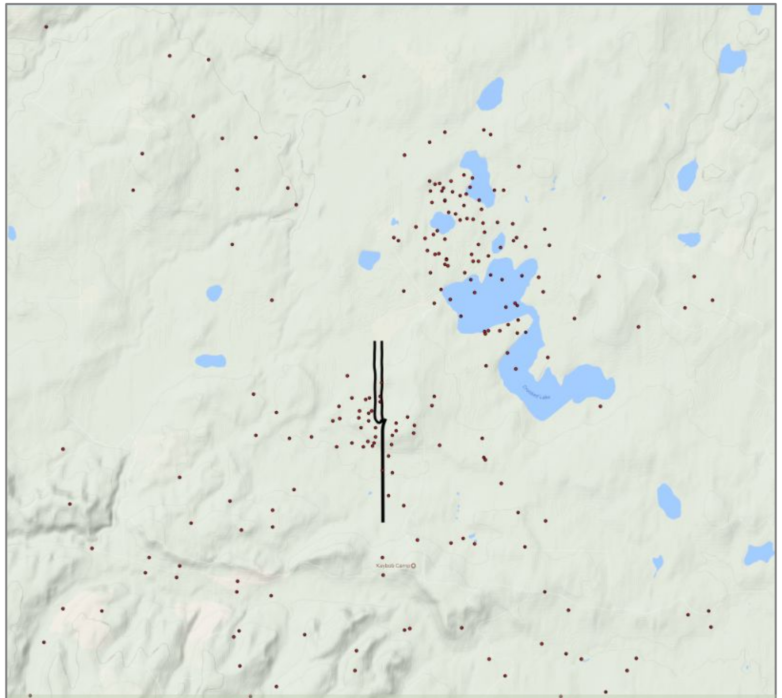
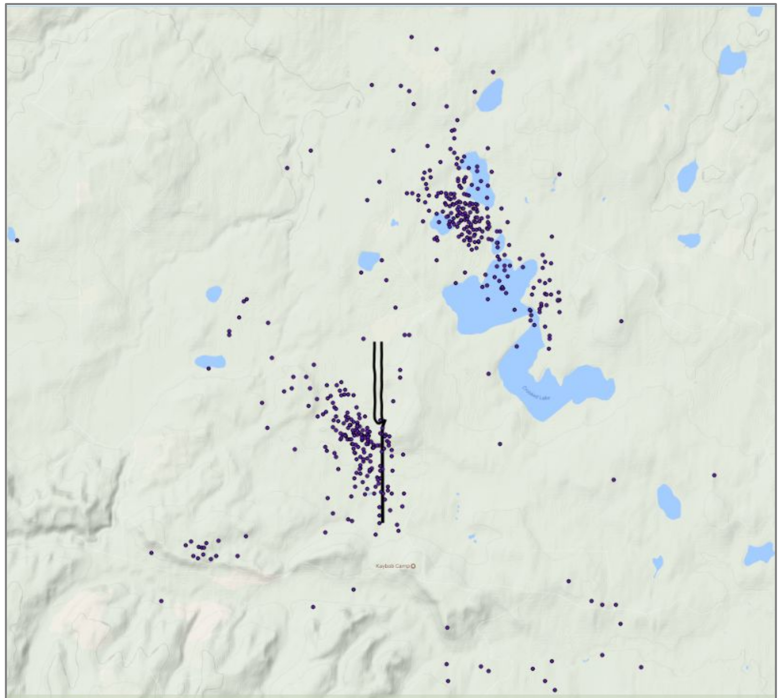
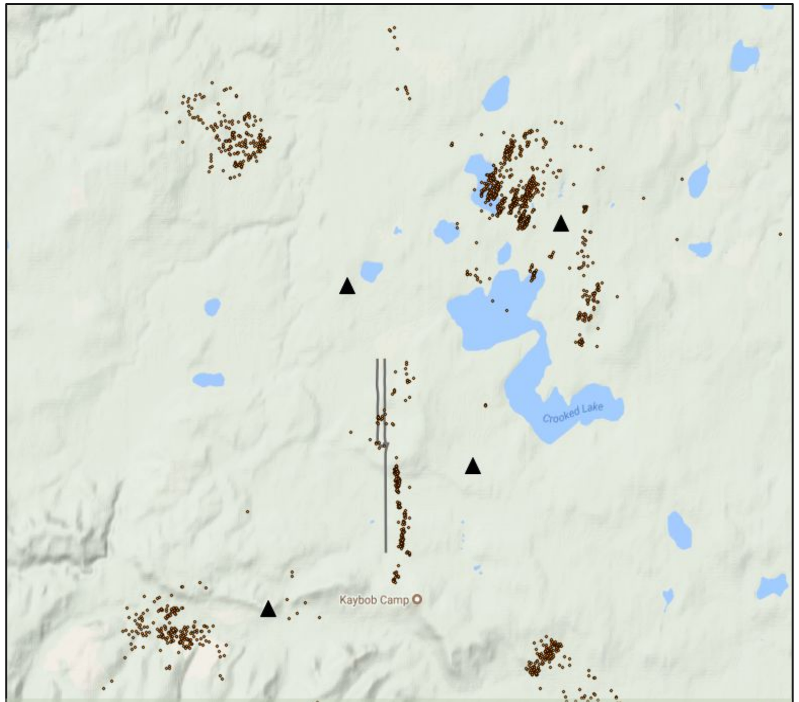
SEISMIC NETWORK PERFORMANCE COMPARISON



- ~300 recorded events (Mc of 2.3)
- Diffuse cloud of events



- ~900 detected events (Mc of 1.1)
- Clustering of seismicity more apparent



- ~2500 detected events (Mc of 0.6)
- Delineate faults and small scale features

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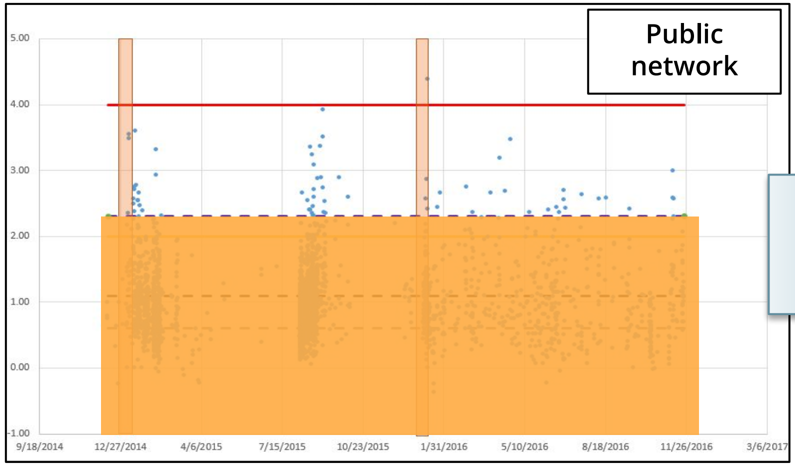
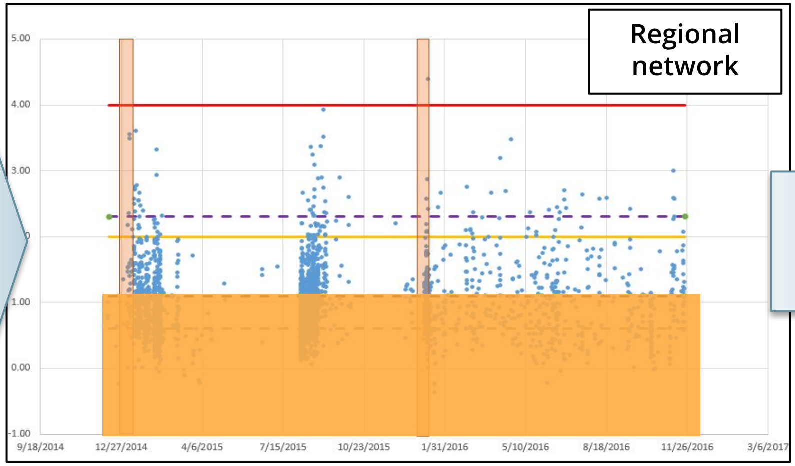
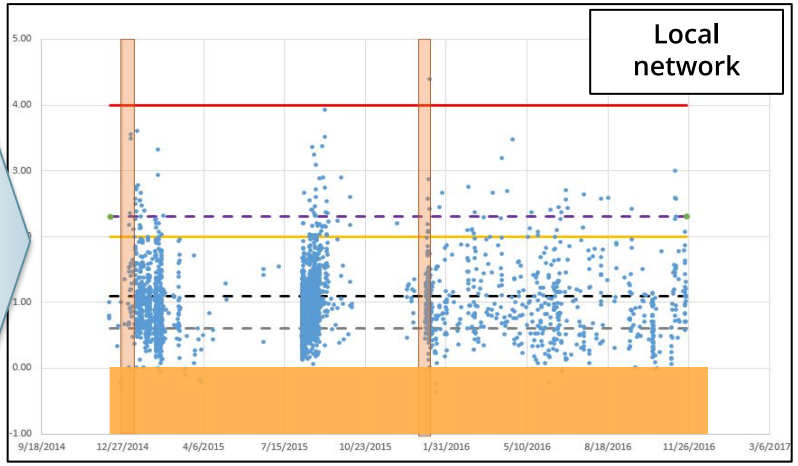
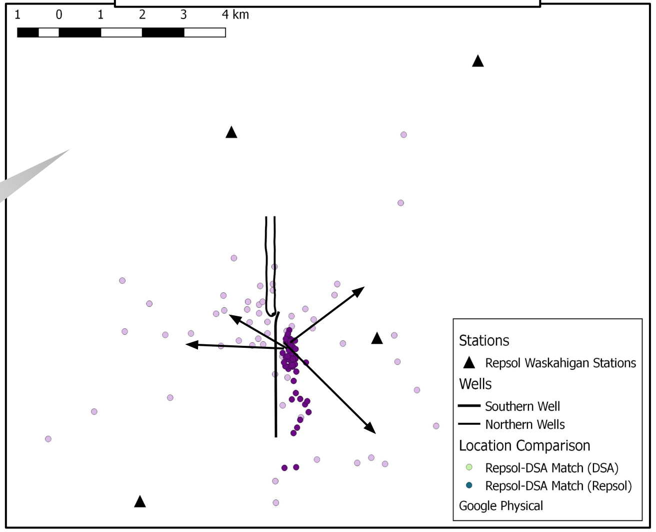
LOCATION UNCERTAINTY AND DETECTION SENSITIVITY COMPARISON





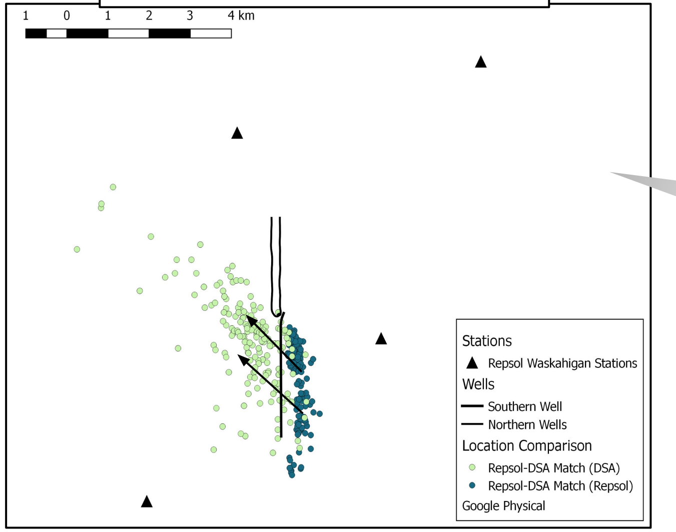


Local vs public catalog



Average event location shift of 2.7 km

Local vs regional catalog



Average event location shift of 1.5 km

INSIGHT 3

It is important to get event magnitudes right

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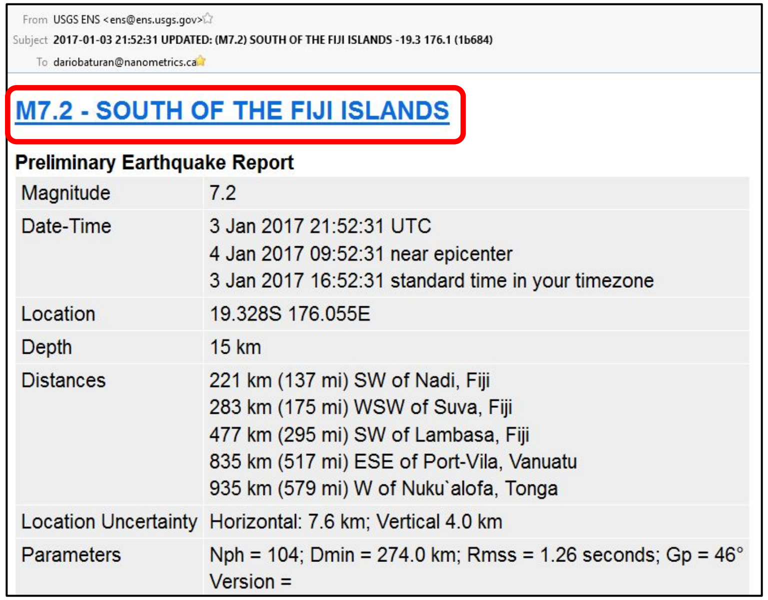
MAGNITUDES ARE IMPORTANT AND COMPLICATED

- Single most important source parameter
- Regulatory traffic-light protocols are based on staged magnitude thresholds
- Operational shutdown thresholds examples:
- Ohio (ODNR): M2.5
- Oklahoma (OCC): M3.5
- British Columbia (BCER): M4.0
- Alberta (AER): M4.0
- Magnitude uncertainty is a known earthquake seismology problem



From USGS ENS <ens@ens.usgs.gov>
Subject 2017-01-03 21:52:31 UPDATED: (M7.2) SOUTH OF THE FIJI ISLANDS -19.3 176.1 (1b684)
To dariobaturan@nanometrics.ca

M7.2 - SOUTH OF THE FIJI ISLANDS

Preliminary Earthquake Report

Magnitude	7.2
Date-Time	3 Jan 2017 21:52:31 UTC 4 Jan 2017 09:52:31 near epicenter 3 Jan 2017 16:52:31 standard time in your timezone
Location	19.328S 176.055E
Depth	15 km
Distances	221 km (137 mi) SW of Nadi, Fiji 283 km (175 mi) WSW of Suva, Fiji 477 km (295 mi) SW of Lambasa, Fiji 835 km (517 mi) ESE of Port-Vila, Vanuatu 935 km (579 mi) W of Nuku`alofa, Tonga
Location Uncertainty	Horizontal: 7.6 km; Vertical 4.0 km
Parameters	Nph = 104; Dmin = 274.0 km; Rmss = 1.26 seconds; Gp = 46° Version =

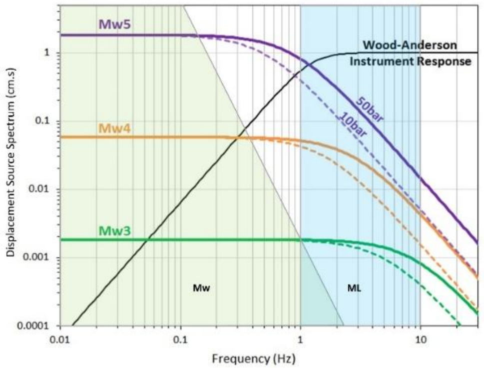
Discrepancy observed in reported magnitudes - Which magnitude is correct?

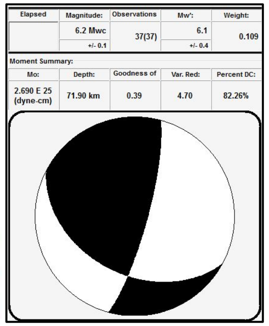
Earthquake (time)	NRCan M_L	Calibrated M_L	USGS NEIC mb	Spectral Fitting M_W	PGC RMT M_W
23/01/2015 06:49:19	4.4	3.9	3.9	4.0	3.7

WHY DON'T MAGNITUDES AGREE AND WHAT TO DO ABOUT IT?

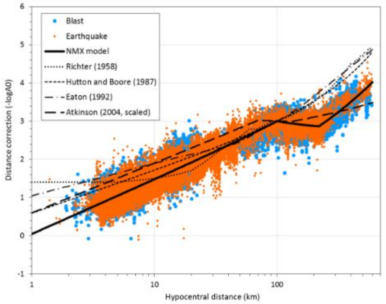
1

Different magnitude scales





Uncalibrated magnitude equations



$$M_L = \log(A) - \log A_0 + S$$

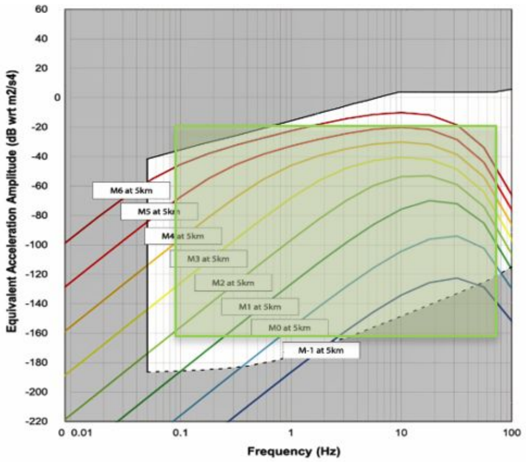
Logarithm of peak motion — Distance correction — Site correction

2

3

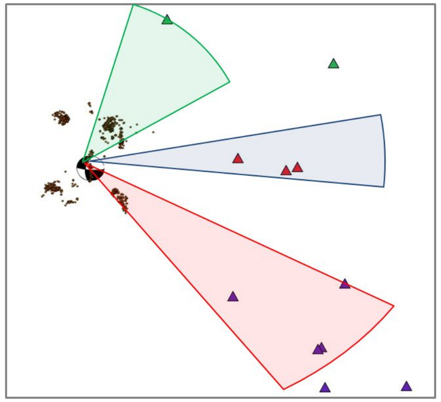
Inadequate instrumentation

- strong motion
- earthquake seismology
- microseismic monitoring



Differences in recording networks

- radiation pattern
- distance range
- site amplification



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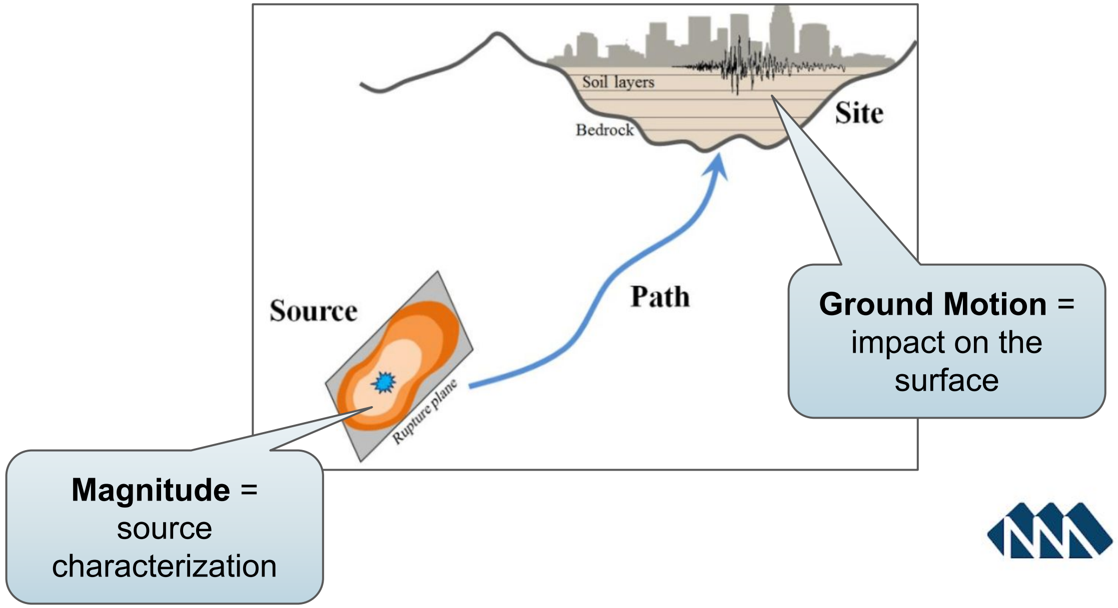
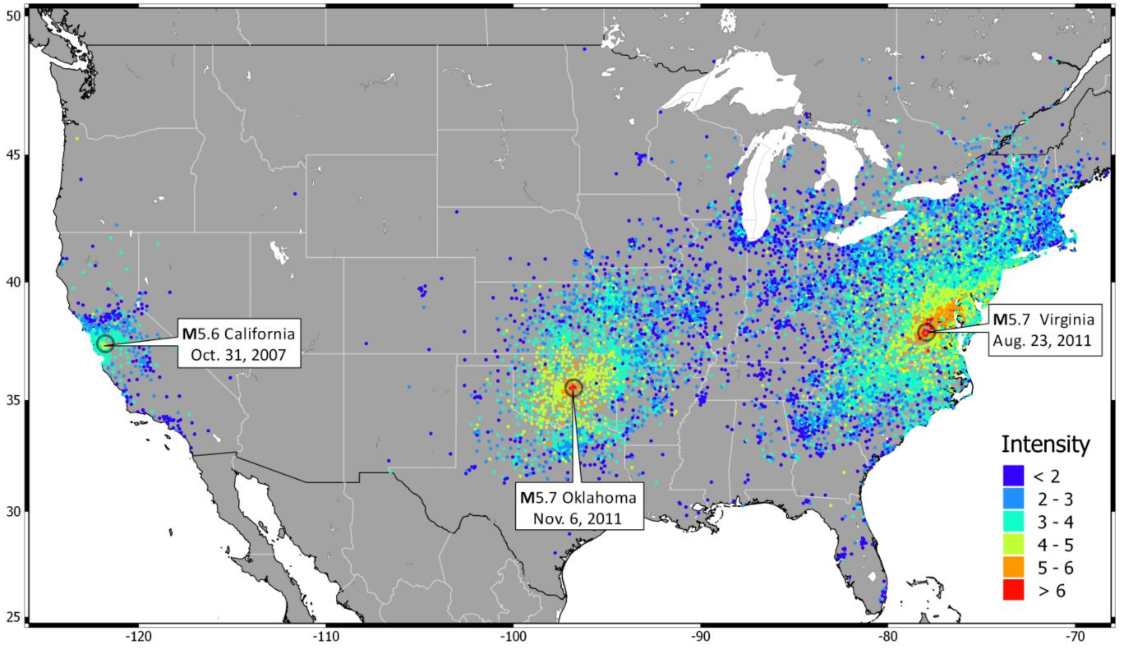
INSIGHT 4

Ground motions should play a role in regulatory protocols

GROUND MOTIONS - IMPORTANCE AND CURRENT USE

- Magnitudes do not tell the whole story
- “Not every M5.0 has the same impact”
- Measure effect or impact of earthquakes on sites of interest
- Used for evaluation of seismic hazard and design spectrum in building codes
- Related to shaking perception and damage estimates





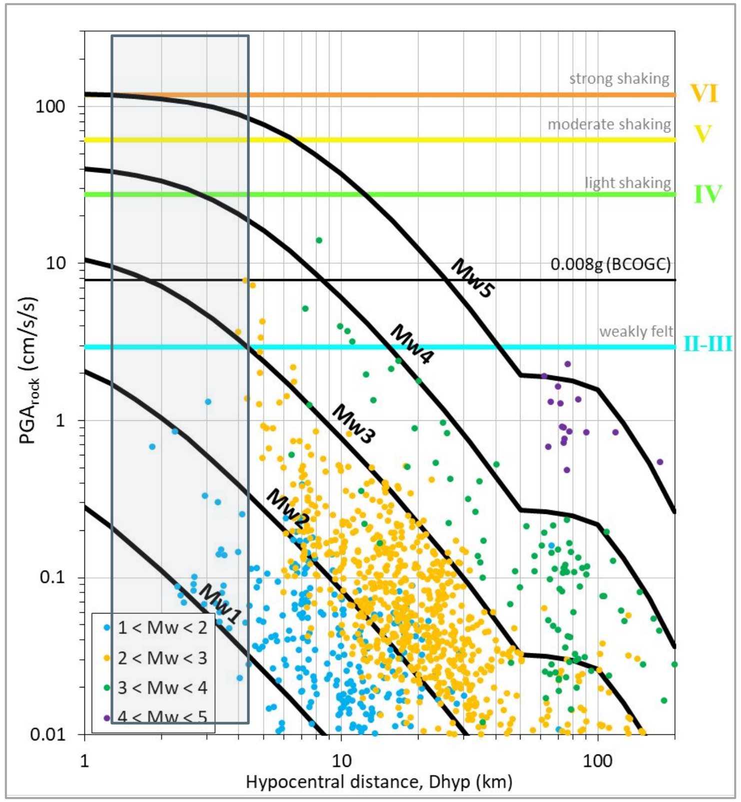
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

GROUND MOTIONS - USE IN REGULATIONS

British Columbia (BCER)

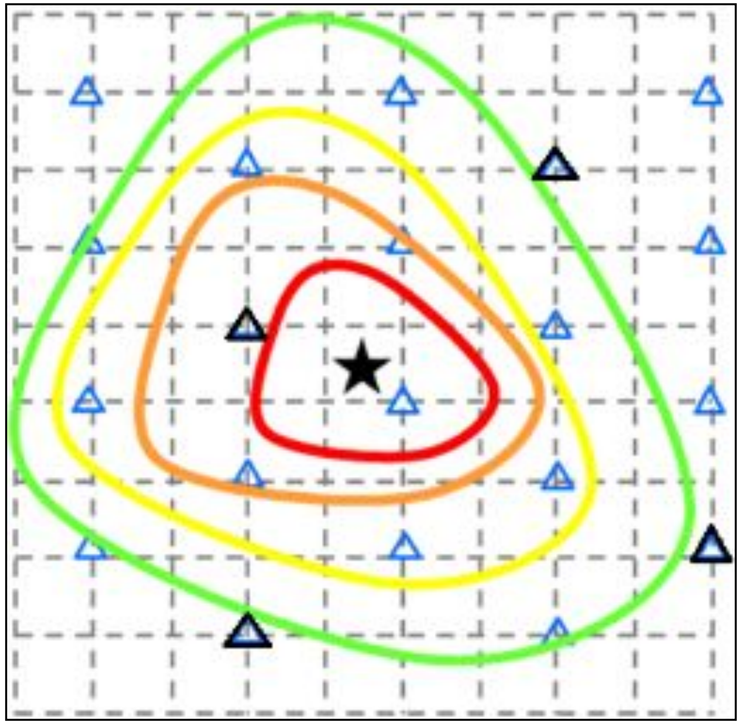
- Single accelerometer within 3 km of active well
- Reporting threshold: 0.008 g (peak ground acceleration)
- Ground motion data not used to drive a traffic light protocol (TLP)
- Used to calibrate attenuation models where the seismic hazard is the highest



GROUND MOTIONS - USE IN REGULATIONS

Role of ground motions in traffic light protocols?

- Potentially combine with magnitudes to relate threshold to earthquake impact
- What threshold should be used?
- How far from the epicenter?
- Recorded or predicted?



INSIGHT 5

Real-time induced seismicity risk management is possible but...

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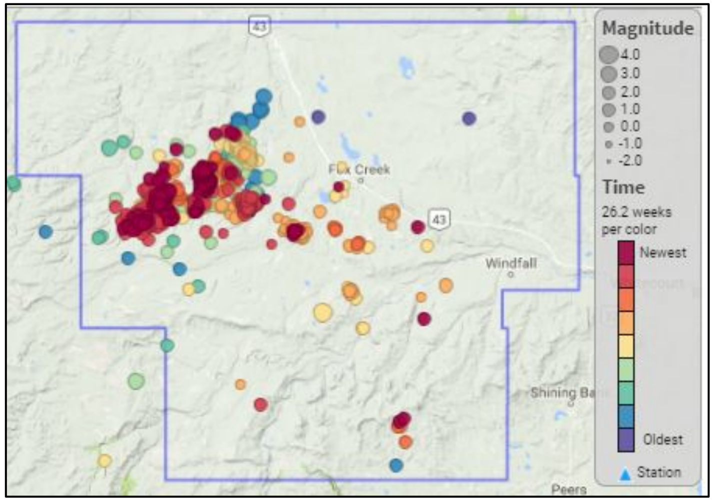
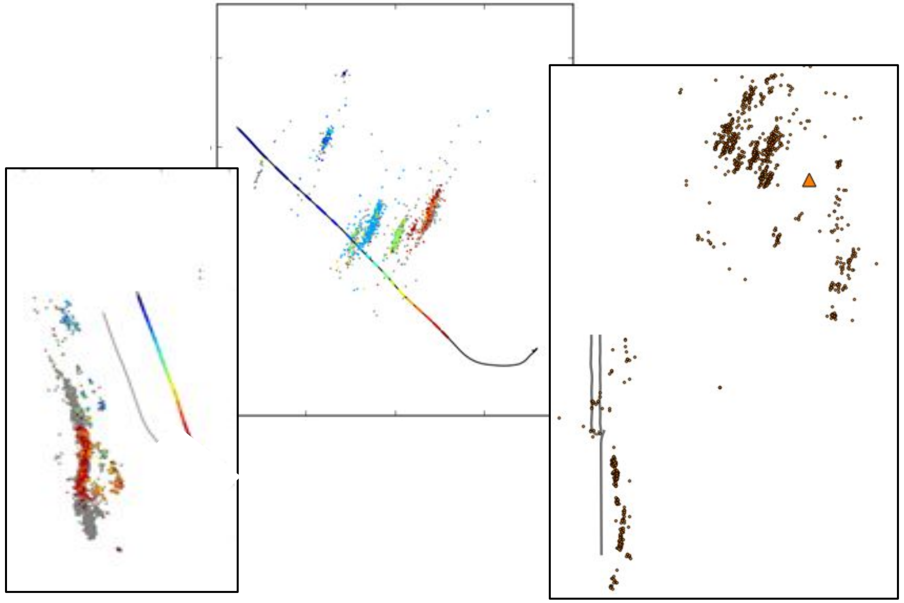
REAL-TIME IS RISK MITIGATION

- O&G-related induced seismicity regions in North America are known
- Relatively unique conditions at each IS-susceptible pad:
  - Fault network size and type
  - Fault orientation relative to the well(s) and regional stress field
  - Stress state
  - Proximity to the well(s)
  - Completion and stimulation design
  - Activation mechanism
- One operator mitigation approach will not work for all
- How do we measure its effectiveness?
- Real-time feedback loop required





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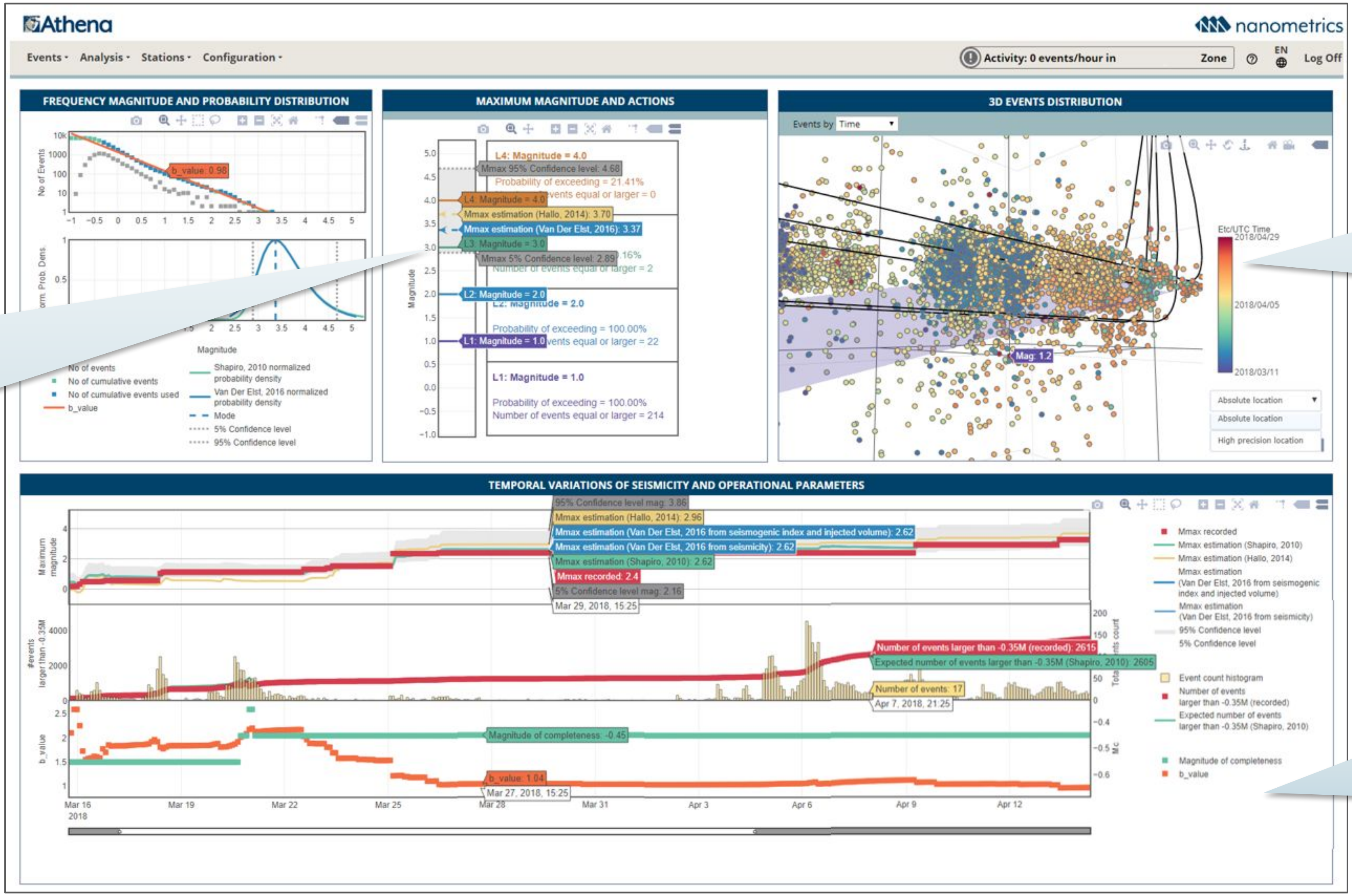
IS RISK MANAGEMENT APPROACH - KEY COMPONENTS

Continuously updated seismicity and Mmax forecasting model



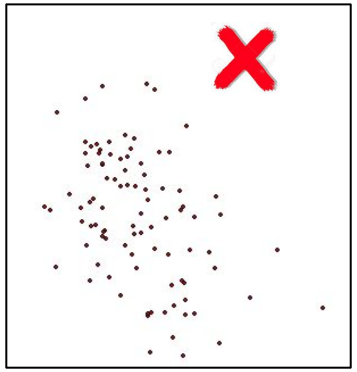
Spatial distribution of seismicity – structure delineation and slip mechanism

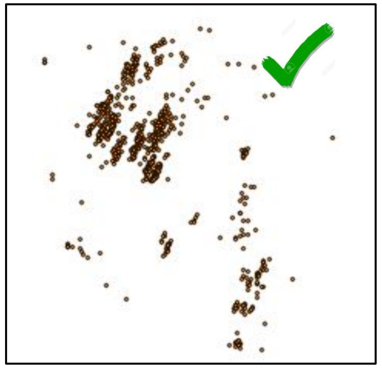
Timeline view of the key parameters and injection data

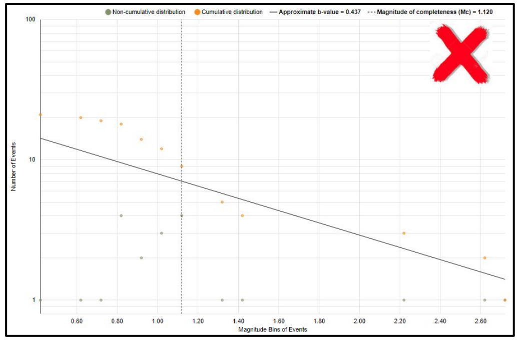
REAL-TIME RISK MITIGATION REQUIREMENTS

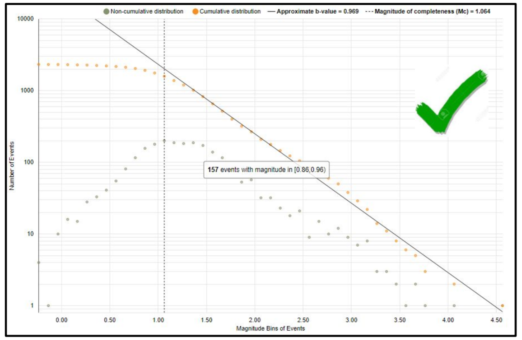
- Published models for induced seismicity forecasting
- Generated using research-grade data sets
- To use forecasting in practice, need to be able to produce:
  - Fast
  - Accurate
  - Complete

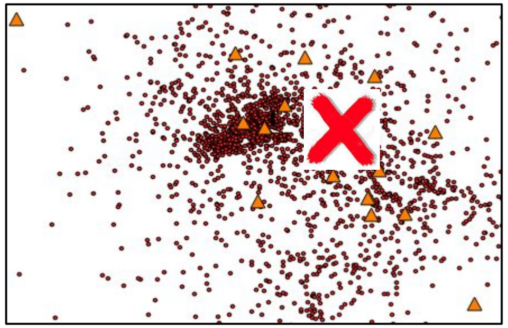
  } Seismic catalogs (lower uncertainty)
- Real-time risk treatment systems are a work in progress BUT
  - High resolution monitoring required
  - Mc well below M0.5
  - High event location accuracy
  - Accurate catalogue level data products
  - Can AI get us sufficient real-time quality?

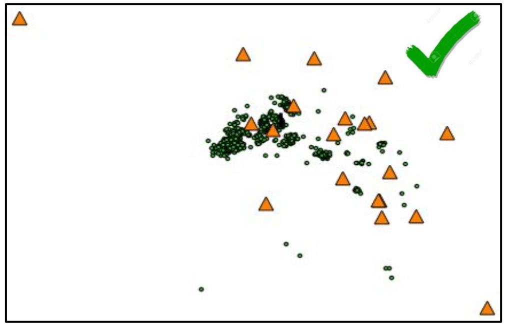












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KEY TAKEAWAYS

- Seismicity has close temporal and spatial correlation to HF operations - not the case with water disposal
- Multiple activation mechanisms observed and high variability in seismic risk
- Data interpretation often changes with monitoring resolution
- Public and private arrays play a complementary role
  - Role for government (regulators), academia, service providers and operators
- All North American traffic light protocols (TLPs) are magnitude-based
  - Standardize magnitude approach to reduce uncertainty
- IS ground motions can potentially enhance TLPs
  - Related to earthquake impact
  - Careful with implementation
- Real-time risk management by operators is possible but…
  - It requires high-resolution monitoring and real-time feedback loop

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THANK YOU

QUESTIONS?
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