Bridging Gaps in Induced Seismicity Hazard Forecasting in Alberta, Canada

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Prior Evidence for Geological Susceptibilities: Spatial Biases

- Induced earthquakes locations in central Alberta have shown a spatial correspondence with carbonate reef margins.

- Induced earthquake locations have shown a spatial correspondence with relatively higher Duvernay formation overpressure.

After Eaton & Schultz, 2018
Prior Evidence for Geological Susceptibilities: IS Rate Models

- Prior study examined operational effects on HF IS in Kaybob Duvernay [Schultz et al., 2018].
- Decent linear fit. Noted systematic biases above or below best fit line.
- Systematic biases not strongly pronounced in single cluster/pad Σ fits.
- Significant improvement to goodness of fit ($R^2 = 0.96$) if only seismogenic wells are considered.
- Suggests presence of spatial biases.
Understanding Geological Susceptibility

- What is the meaning of spatial biases?
- Can’t be operational, stimulation volume accounts for the rate.
- Only geological factors remain.
- Likely the result of the probabilistic intersection of all contributing factors.
- Basin-wide estimate of this likelihood in viable HF plays is < 0.3% [Atkinson et al., 2016; Skoumal et al., 2015].
Quantifying Geological Susceptibility: 
*Input Geological Features*

- Can $\delta$ be quantified spatially?
- What factors contribute to it?
  - Tectonic
  - Geomechanical
  - Hydrological
- What factors are publicly available?
- Collect all and see what the machine comes up with.
Quantifying Geological Susceptibility: 
Identifying IS
Spatiotemporal Association Filter
Spatiotemporal Association Filter
Quantifying Geological Susceptibility: Binary Classification Problem
Geological Susceptibility Model

- Quantifies the likelihood of encountering an earthquake if a well is drilled in a given region.
- Allows for extrapolation to regions as of yet undrilled.
Geological Susceptibility Model

- Allows for extrapolation to regions as of yet undrilled.

- Appears to be producing geologically intuitive results: previously identified proxies are still important.

- Proximity to basement is the most important, similar to consensus and other regions [Skoumal et al., 2018].
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Appears to be producing statistically robust results.

AUROC is better than random guessing (0.87).
Summary

- Spatial biases in a $\Sigma$ GR-FMD model account for 96% of variability in the IS rate.
- Model appears to be performing better than just guessing.
- Modelled weights to proxies makes intuitive sense.
- New $\delta$ parameter suggested to account for spatial biases, interpreted as the geological susceptibility to IS. Can be estimated by machine learning methods.
- Proposed model could help bridge knowledge gap for forecasting IS hazard.
*The Geological Susceptibility of Induced Earthquakes.*
Thank you
Seismicity in the WCSB is sparse and relatively quiescent.

Long-lasting clusters have been recognized.

Three clusters account for the majority of Albertan seismicity: RMHSZ, BrC, CLS.

CLS is known to be related to HF of the Duvernay Formation [Schultz et al., 2017].
Statistical Tests:
Kolmogorov-Smirnov & Mann-Whitney U test

Volume

Rate

Pressure
Bootstrap Resampling

- Repeat KS & MW tests for $10^5$ trials.
- Randomly remove 10% of pads.
- Randomly flip seismogenic association state of 1% of pads.
- Compute distribution of test p-values (blue).

- Areas shaded orange indicate statistical significance.
- Reconfirms prior result is robust, and gives a sense of sensitivity to missed associations.
- Seismogenic pads tend to be higher volume operations in the Kaybob Duvernay.
$\Sigma$ GR-FMD Fit

$\quad b \ 0.90 \pm 0.03$

$\quad Mc \ 1.30$

$\quad N \ 1080$

$\quad R^2 \ 0.990$

![Graph a)](image1)

![Graph b)](image2)

$R$ for $b$-value

$b$-value

$\Sigma \ -2.0 \pm 0.1$

$R$ for Seismic Index

Seismic Index