Determination of factors controlling geological susceptibility to induced seismicity in the Montney Formation based on machine learning approach

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Introduction

- A significant increase in the seismicity rate in western Canada in recent years has been associated with the development of unconventional oil and gas reserves, including hydraulic fracturing[1] and saltwater disposal[2]. Because of incomplete understanding of the underlying spatio-temporal distribution, induced seismicity is a subject of extensive academic research[3,4,5].
- Incomplete information and lack of continuous data both hinder a full understanding of the seismicity distribution, which is potentially linked to seismic hazard in WCSB[6]. Understanding the mechanisms controlling the geological susceptibility to induced earthquakes is crucial for the seismic hazard assessment as well as seismic risk mitigation. Additionally, it is still not well understood, why most hydraulic fracturing and wastewater disposal operations are not triggering higher-magnitude earthquakes[3].
- We present the analysis of factors controlling the occurrence of induced seismicity in the Montney formation using a machine learning approach. Two supervised algorithms – **Decision Tree** and **Random Forest** were used to indicate the characteristics that have the greatest influence on the geological susceptibility. In addition, geological susceptibility maps for each Montney unit were presented. Similar methodology was introduced by Pawley et al., who analyzed the susceptibility in the Duvernay formation[7].
- Data used in this study were compiled from publicly available sources: geoSCOUT, BCOGC, AER databases as well as the Canadian Induced Seismicity Collaboration earthquake catalogue.

Methodology & Data

Project steps:

1. data collection and preparation
2. labelling wells as seismogenic/nonseismogenic (binary classification)
3. algorithm development
4. feature importance analysis
5. geological susceptibility analysis

- 6315 hydraulic fracturing wells drilled into the Montney in British Columbia and Alberta provinces were analyzed.
- Earthquake data were sourced from the Canadian Induced Seismicity Collaboration website and included the seismic events registered before 04/27/2019.

Table 1 Numbers and percentages of seismogenic and non-seismogenic wells according to Montney unit associated with > M2.5 induced events.

d	Montney unit	Seismogenic		Non-seismogenic	
		Number	%	Number	%
0-0.33	Upper	23	0.68	3354	99.32
0.34-0.66	Middle	12	0.5	2408	99.5
0.67-1	Lower	5	0.97	513	99.03

Labels:

- Wells seismogenic / non-seismogenic M>2.5, <5km, up to 3 months after HF operations

Features:

- Formation pressure
- SHmax azimuth
- Distance to Cordilleran Disturbed Thrust and Fold Belt
- Distance to lineaments
- Formation tops (Debolt, Precambrian basement)
- Depth Factor:

$$d = \frac{Z_w - Z_t}{Z_{th}} \quad (1)$$

Z_w - true vertical depth (TVD) of the well;
Z_t - top of the Montney in the location of the well;
Z_{th}- thickness of the Montney in the location of the well.

Geological susceptibility

Input parameters → **Logistic regression model** *Train set 75% / test set 25% Stratified Random shuffling (100 shuffles)* → **Probabilities extraction** *For each Montney unit based on depth factor* → **Probabilities interpolation** *Min-max normalization:*

$$v' = \frac{v_w - \min(V)}{\max(V) - \min(V)} \quad (2)$$

- ❑ Levels of seismogenic susceptibility vary across the all units in the N part of the formation
- ❑ Susceptibility increasing towards the N direction
- ❑ Lower Montney - higher levels of susceptibility

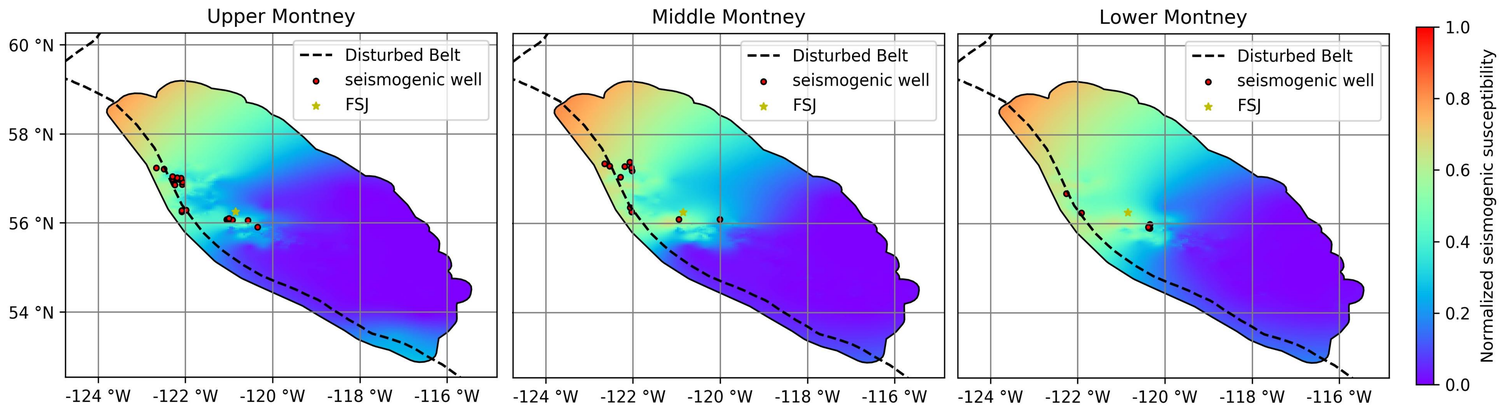

Figure 2 Normalized geological susceptibility to induced seismicity in Upper, Middle and Lower Montney.

Conclusions

- Our analysis revealed that 3 types of features exert the greatest influence on the geological susceptibility to induced seismicity in the Montney Formation:
  (1) tectonic setting (distance to Cordilleran Thrust and Fold Belt and lineaments;
  (2) vertical distance to basements / geomechanical basements (Precambrian basement, Debolt formation);
  (3) depth of the injection relative to the Montney top - which correlates with the specific Montney interval stimulated during HF;
- Our observations confirm several current hypotheses about the factors influencing induced seismicity.
- Depth factor confirms the current hypothesis about the higher susceptibility for induced seismicity in the Lower Montney, comparing to Upper and Middle units
- Geological susceptibility varies within the Upper, Middle and Lower Montney, however the differences are noticeable mainly in the N part.
- The Lower Montney was indicated as the most prone to high-magnitude seismic activity in N part. Distinctive, higher seismogenic susceptibility comparing to other units was also observed in the Upper Montney interval located in the SW part.

Feature importance – Decision Tree and Random Forest

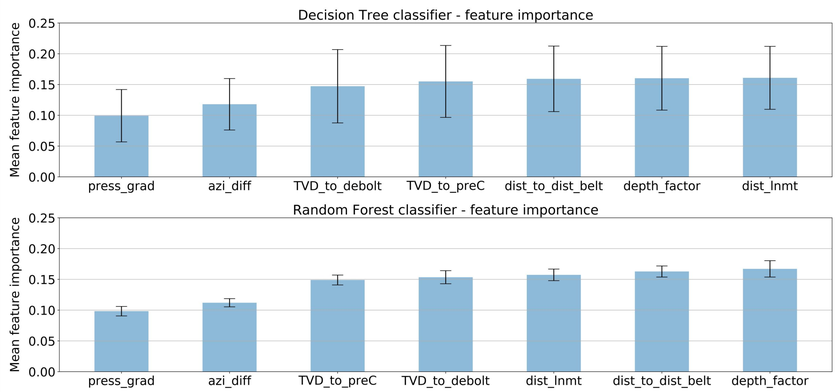

Figure 1 Feature importance calculated using Decision Tree (above) and Random Forest (below) classifiers. Results are presented in the ascending order to the right: pressure gradient (*press_grad*), SHmax azimuth variance (azi diff), vertical distance from the well to Precambrian basement and Debolt Formation (*TVD_to_preC* and *TVD_to_debolt*, respectively), distance to lineaments (*dist_lnmt*), distance to the Disturbed Thrust and Fold Belt (*dist_to_dist_belt*), *depth_factor*.

- ❑ The most important features:
  distance to lineaments and the Disturbed Belt, depth factor, vertical distances to the Debolt Formation and the Precambrian basement.
- ❑ Results confirm hypotheses about the importance of tectonic setting of the well
- ❑ High importance of the depth factor potentially indicates the higher seismic risk in the Lower Montney
- ❑ Pore pressure and SHmax azimuth with respect to regional stress does not seem to influence the geological susceptibility
- ❑ Random Forest indicates the same set of features with similar feature importance values. At the same time, Random Forest expressed significant decrease of standard deviation, which suggest the higher accuracy of the results

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