Natural Resources Canada | Ressources naturelles Canada

An Update of Induced Seismicity Research Results and their Regulatory Implications

Honn Kao

Geological Survey of Canada, Natural Resources Canada

September 20, 2022, at CAPP Induced Seismicity Meeting

Canada

Acknowledgements

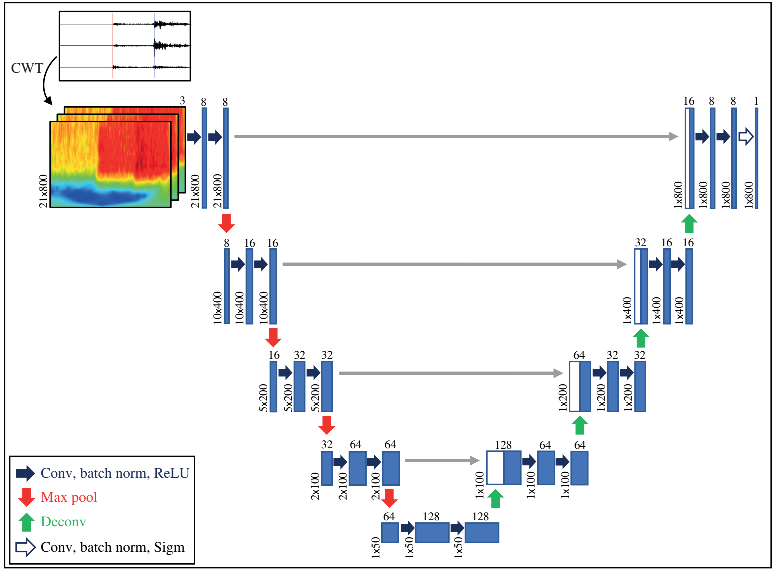
- Team members: *Ali Babaie Mahani, Ramin Dokht, Dawei Gao, Chet Goerzen, Adebayo Ojo, Fengzhou Tan, Ryan Visser, Bei Wang, Hongyu Yu, Jianlong Yuan.*
- Admin and general supports from the *Induced Seismicity Research Project, Environmental Geoscience Program of NRCan*, and *U. of Victoria*.
- Financial and logistic supports from *Geoscience BC* and *BCOGC*
- Collaborations with *BCOGC, McGill U., Ruhr-Universität Bochum, U. of Calgary*, and *U. of Alberta*.
- Fieldwork supports from *CAPP members.*

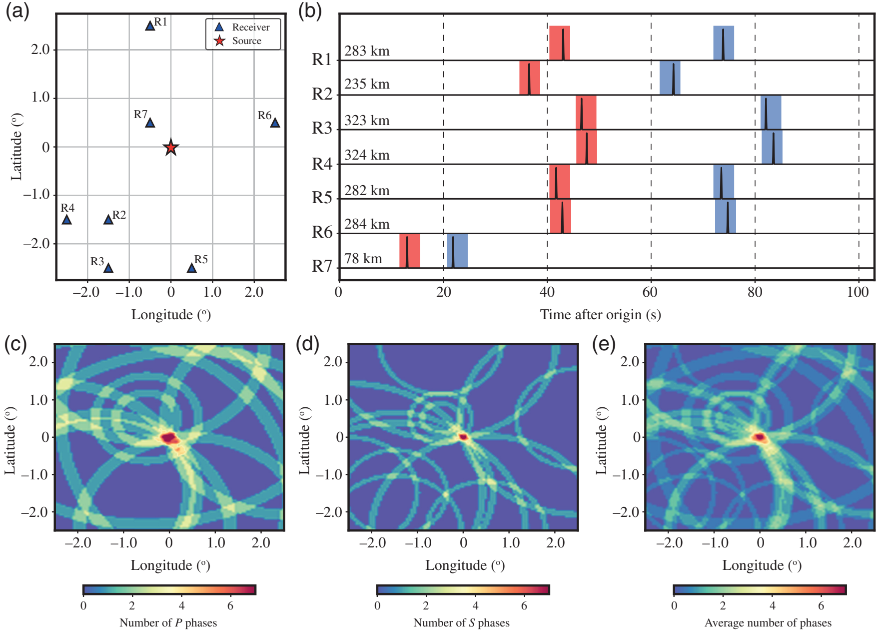
Outlines

- New methods for improved earthquake location and depth ➔ Comprehensive IIE catalogues
- Source characteristics of IIE in western Canada
  - Case study 1: Long-term WD-induced Musreau Lake sequence
  - Case study 2: Revisit of the 2015 HF-induced sequence
- Controlling factors of Montney IIE seismogenesis

Combining Deep Learning and Source Scanning

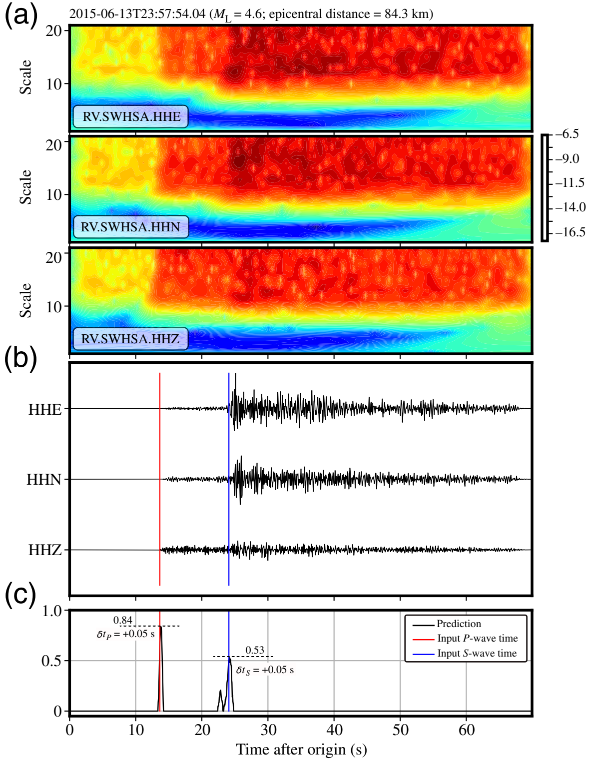
Fast, Automatic, and Accurate Location for Small Seismic Events

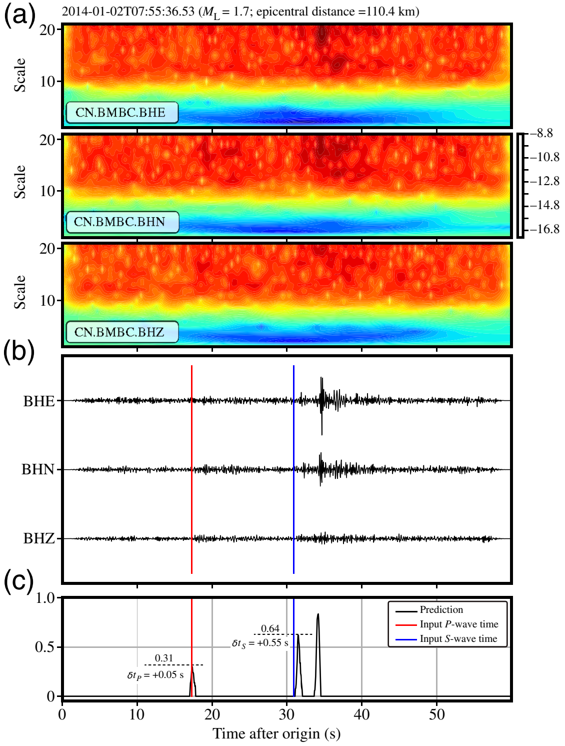


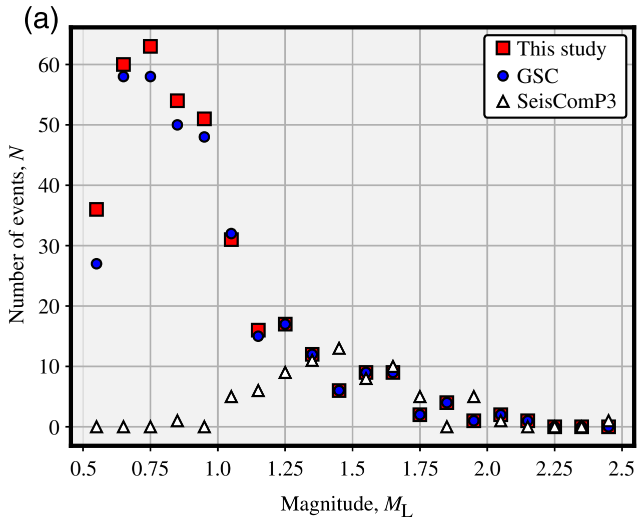


Dokht et al. (2018, SRL); *Dokht et al.* (2022, BSSA)

Fast, Automatic, and Accurate







Dokht et al. (2022, BSSA)

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2018JB017050

Seismicity-Scanning Based on Navigated Automatic Phase-Picking

Fengzhou Tan[1,2], Honn Kao[1,2], Edwin Nissen[1], and David Eaton[3]

[1]School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada, [2]Geological Survey of Canada, Pacific Geoscience Centre, Sidney, British Columbia, Canada, [3]Department of Geoscience, University of Calgary, Calgary, Alberta, Canada

Key Points:
- We take a cocktail approach combining merits of three different techniques to delineate complex spatiotemporal distribution of seismicity
- This new method, named Seismicity-Scanning based on

S-SNAP: automatic location method for events clustered in both time and space.

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2020JB019430

Depth-Scanning Algorithm: Accurate, Automatic, and Efficient Determination of Focal Depths for Local and Regional Earthquakes

Jianlong Yuan[1,2,3], Honn Kao[2,4], and Jiashun Yu[1,3]

[1]State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (Chengdu University of Technology), Chengdu, Sichuan, China, [2]Pacific Geoscience Centre, Geological Survey of Canada, Sidney, British Columbia, Canada, [3]College of Geophysics, Chengdu University of Technology, Chengdu, Sichuan, China, [4]School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada

Key Points:
- We propose an innovative method that systematically scans seismograms recorded at local and/or regional distances to determine the precise source depth
- This new method, named "Depth-Scanning Algorithm," is designed specifically to be free from human intervention

DSA: accurately determine earthquake depths with poor station coverage.

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2020JB019714

Optimization of the Match-Filtering Method for Robust Repeating Earthquake Detection: The Multisegment Cross-Correlation Approach

Dawei Gao[1,2] and Honn Kao[1,2]

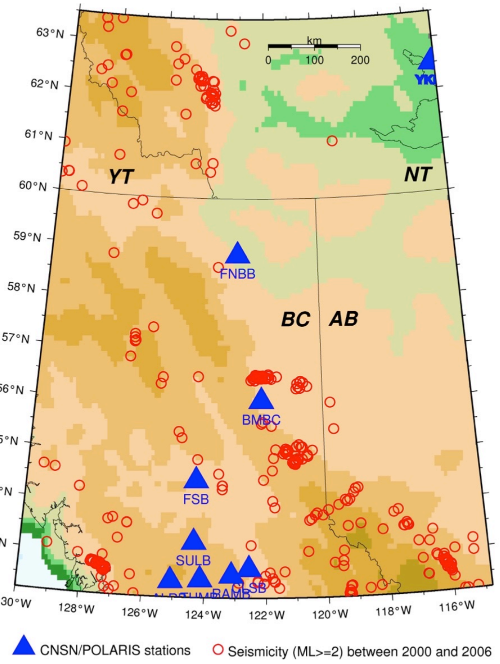
[1]School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada, [2]Pacific Geoscience Centre, Geological Survey of Canada, Sydney, British Columbia, Canada

Key Points:
- Selecting a proper template window length and an optimal filter is of great importance in optimizing the match-filtering method
- High cross-correlation coefficients obtained by conventional match-filtering do not necessarily

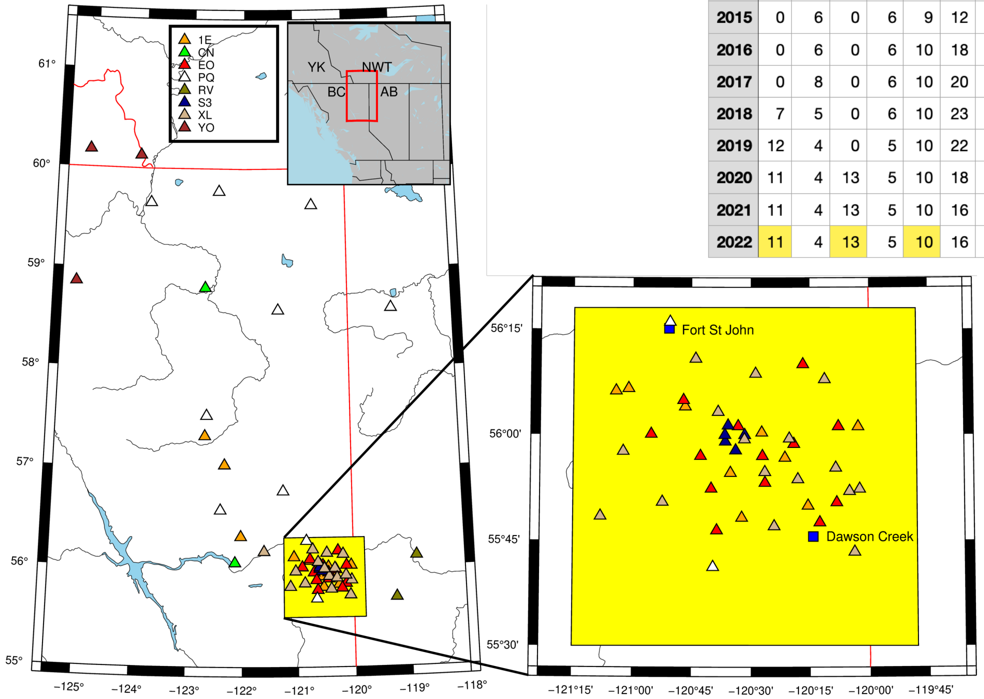
MFMC: match-filtering with multisegment cross-correlation to detect repeating earthquakes.

Improved Seismic Monitoring of IIE in Western Canada

Year	1E	CN	EO	NY	PQ	RV	TD	XL	Y5	YO	S3	Total
2013	0	7	0	6	6	1	1	0	0	0	0	21
2014	0	7	0	6	8	12	1	0	1	0	0	35
2015	0	6	0	6	9	12	1	0	1	0	0	35
2016	0	6	0	6	10	18	1	0	1	4	0	46
2017	0	8	0	6	10	20	1	8	1	4	0	58
2018	7	5	0	6	10	23	1	9	1	4	0	66
2019	12	4	0	5	10	22	1	16	1	4	0	75
2020	11	4	13	5	10	18	1	17	1	4	0	84
2021	11	4	13	5	10	16	1	16	1	4	5	86
2022	11	4	13	5	10	16	1	16	1	4	5	86



Seismicity and seismic network in 2006



Regional and local seismic networks in 2022

Comprehensive IIE Catalogues

Natural Resources Canada / Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8705

A comprehensive earthquake catalogue for southwestern Alberta, between 2004 and 2015

G.D. Huang, H. Kao, and Y.J. Gu

2020

Canada

Natural Resources Canada / Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8718

A comprehensive earthquake catalogue for the Fort St. John–Dawson Creek region, British Columbia, 2017–2018

R. Visser, H. Kao, B. Smith, C. Goerzen, B. Kontou, R.M.H. Dokht, J. Hutchinson, F. Tan, and A. Babaie Mahani

2020

Canada

Natural Resources Canada / Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8831

A comprehensive earthquake catalogue for northeastern British Columbia: the northern Montney trend from 2017 to 2020 and the Kiskatinaw seismic monitoring and mitigation area from 2019 to 2020

R. Visser, H. Kao, R.M.H. Dokht, A.B. Mahani, and S. Venables

2021

Canada

Natural Resources Canada / Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8825

An earthquake catalogue for seismic events in the Norman Wells region of the central Mackenzie Valley, Northwest Territories, using waveform data from local seismic stations

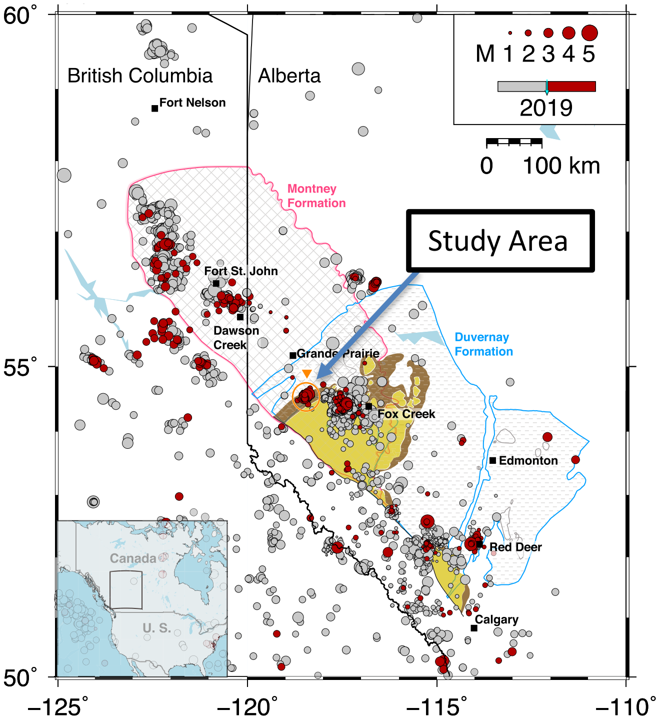
A.M. Farahbod, H. Kao, and D.B. Snyder

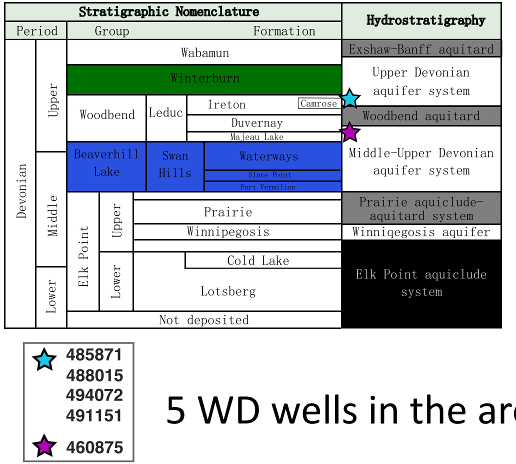
2021

Canada

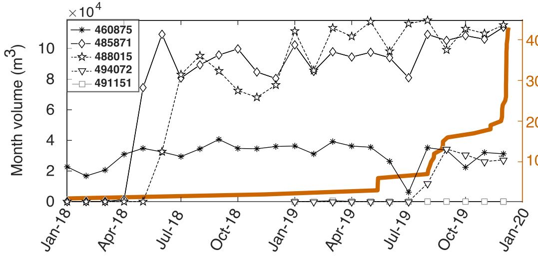
All IIE catalogues are published as Geological Survey of Canada (GSC) Open File Reports, freely available at NRCan's GEOSCAN database (https://geoscan.nrcan.gc.ca).
Daily earthquake catalogues are provided to BCOGC for regulatory purposes.

WD-induced Musreau Lake IIE Sequence

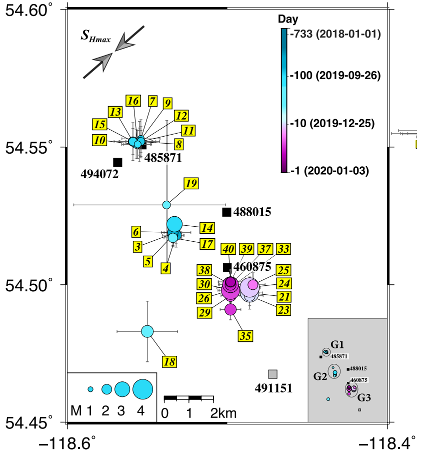




5 WD wells in the area

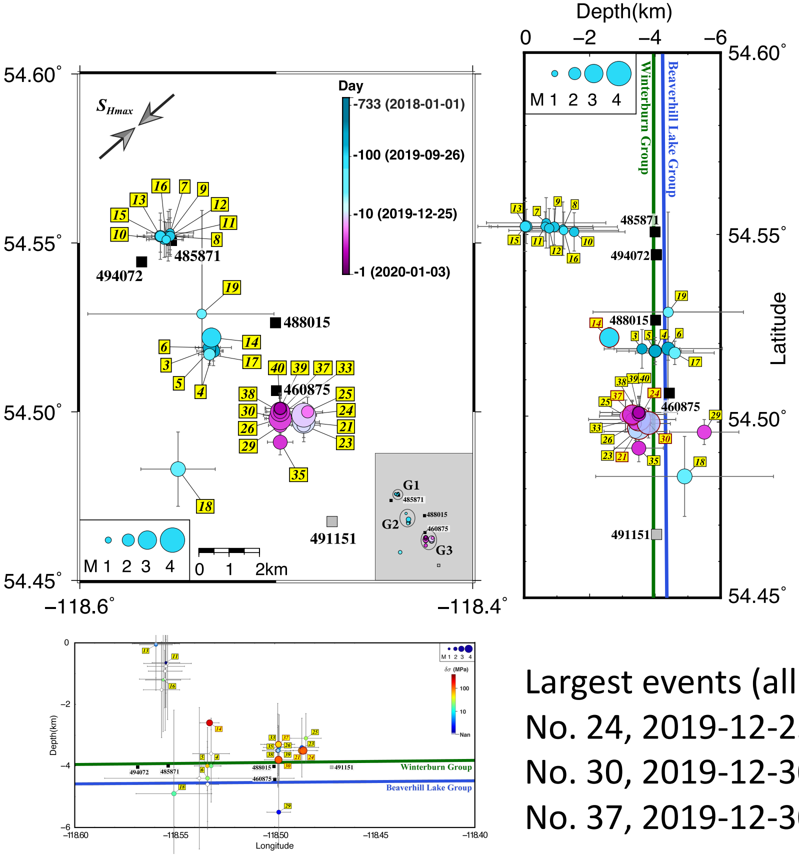


WD started in 2000 (<10^4 m^3/month), reached ~10^5 m^3/month in May 2018



Three main groups:
G1 and G2: May – Sep 2019
G3: Dec 2019

Yu et al. (2021, GRL)



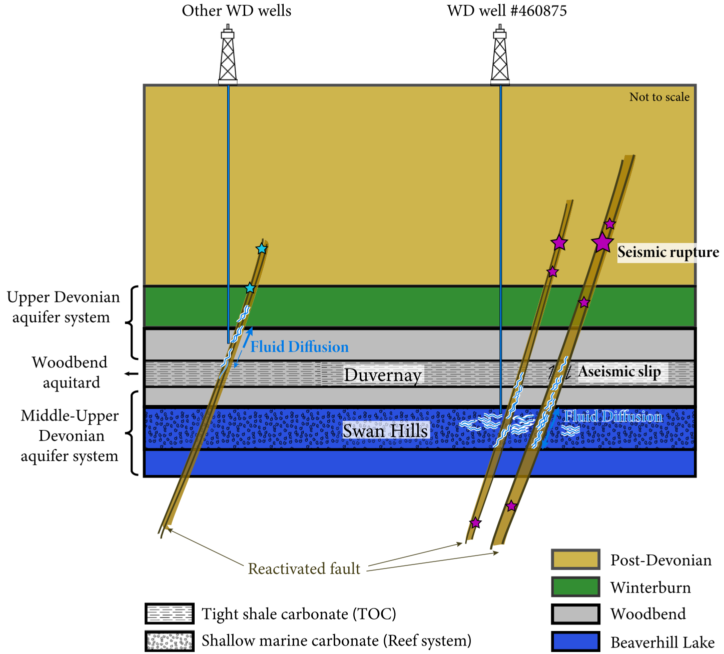
Largest events (all in G3):

No. 24, 2019-12-25 M_L 3.9

No. 30, 2019-12-30, M_L 3.7

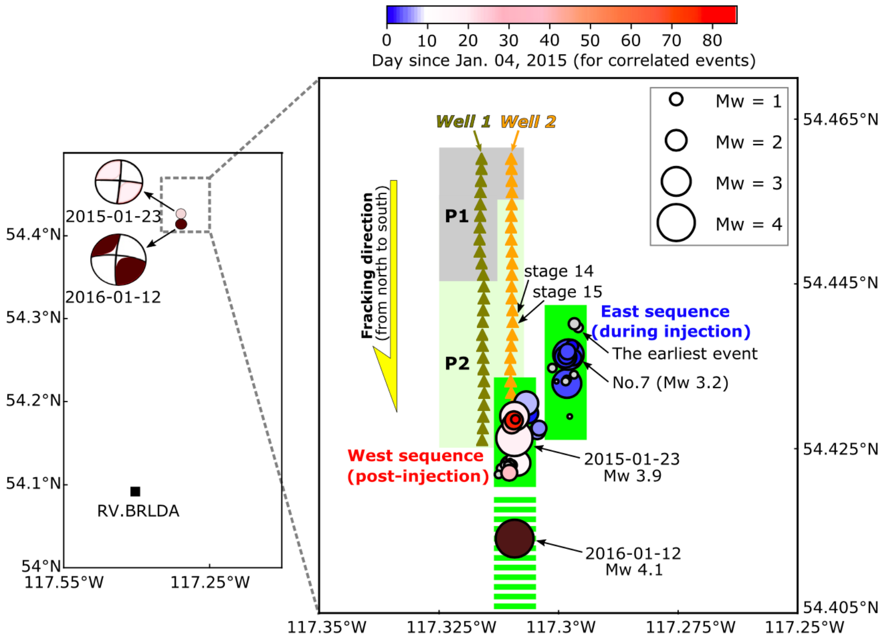
No. 37, 2019-12-30, M_L 3.2

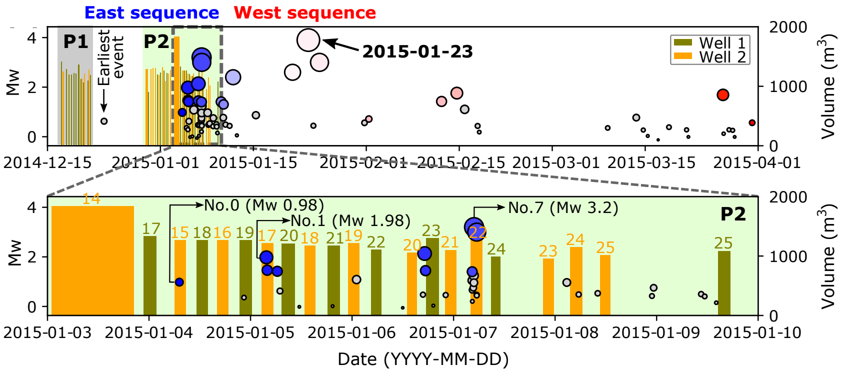
Yu et al. (2021, GRL)



- IIE can occur at deeper or shallower depths depending on local geological/hydrological settings
- From seismic quiescence to surged activity after decades of WD

Revisit the 2015 Fox Creek Earthquake Sequence



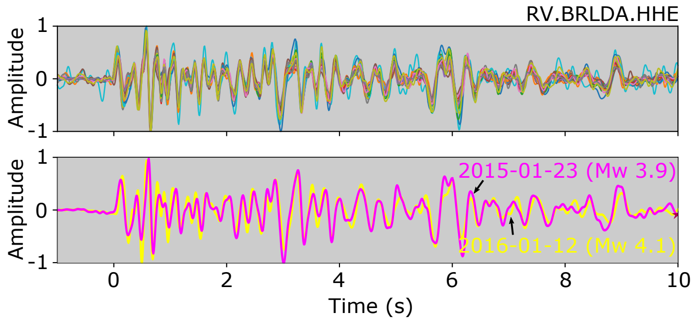


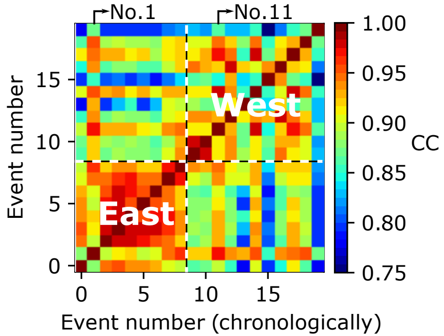
- HF started on 2014-12-17, ended on 2015-01-09
- P1 = Dec 17-21, 2014; P2 = Dec 29 2014 – Jan 09, 2015
- First IIE occurred ~2 days after P1 was finished, but most events occurred during later days of P2
- East sequence occurred earlier, but located farther from the injection, than the west sequence
- The largest event (Mw 3.9) occurred on 2015-01-23, ~2 weeks after P2 completion
- About one year later, another Mw4.1 event occurred along a neighboring segment to the south

Gao et al. (2022, GRL)

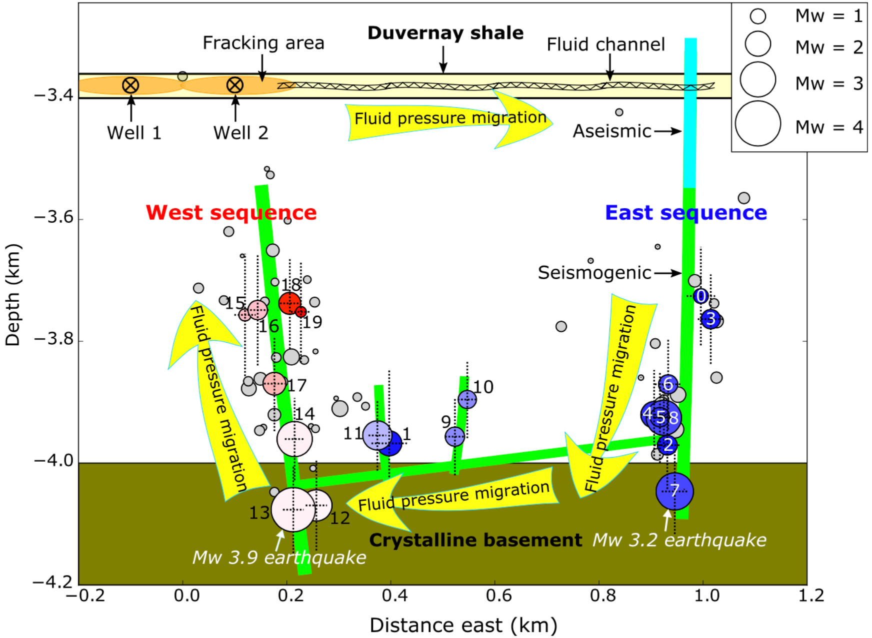
Waveforms are similar, but not identical

➔ Not repeating earthquakes, but migrating spatially





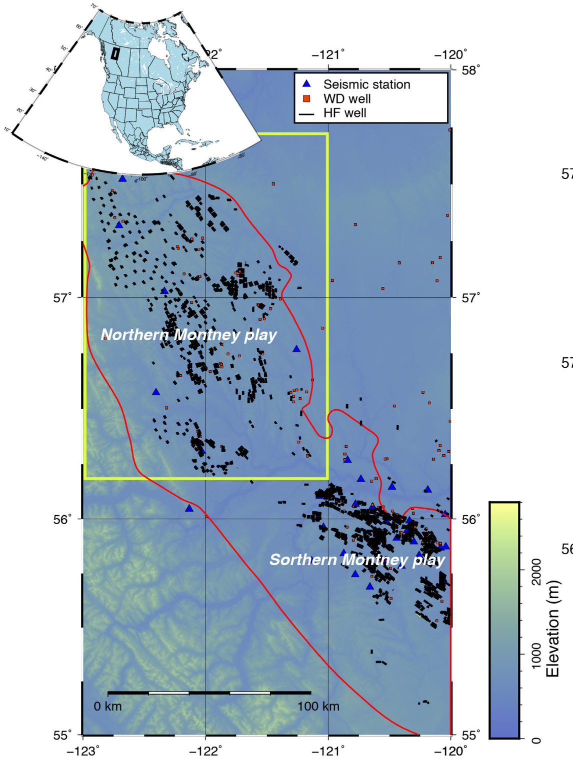
Waveform similarity analysis indicates the clear difference between east and west sequences.

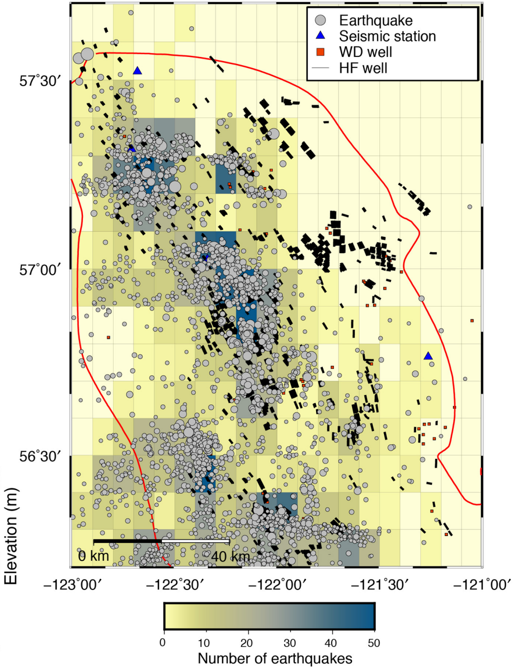


- IIE sequence shows a complex 3D pattern: outward ➔ downward ➔ inward ➔ upward
- This pattern highlights the significance of **geological and hydrogeological networks** in facilitating fluid pressure migration and IIE seismogenesis.

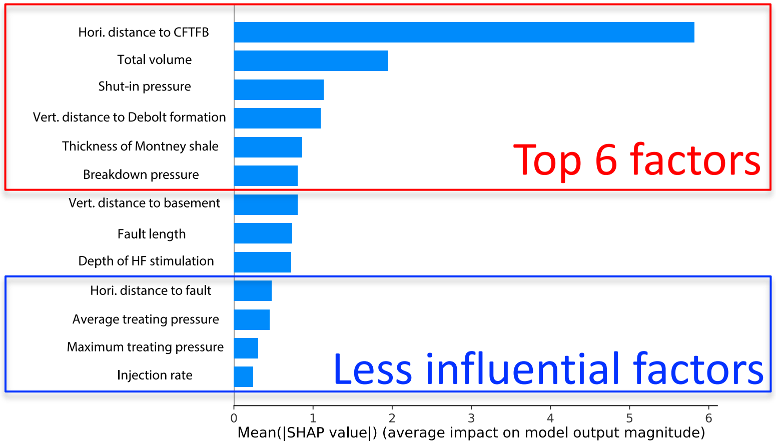
Gao et al. (2022, GRL)

Controlling Factors of IIE in Northern Montney



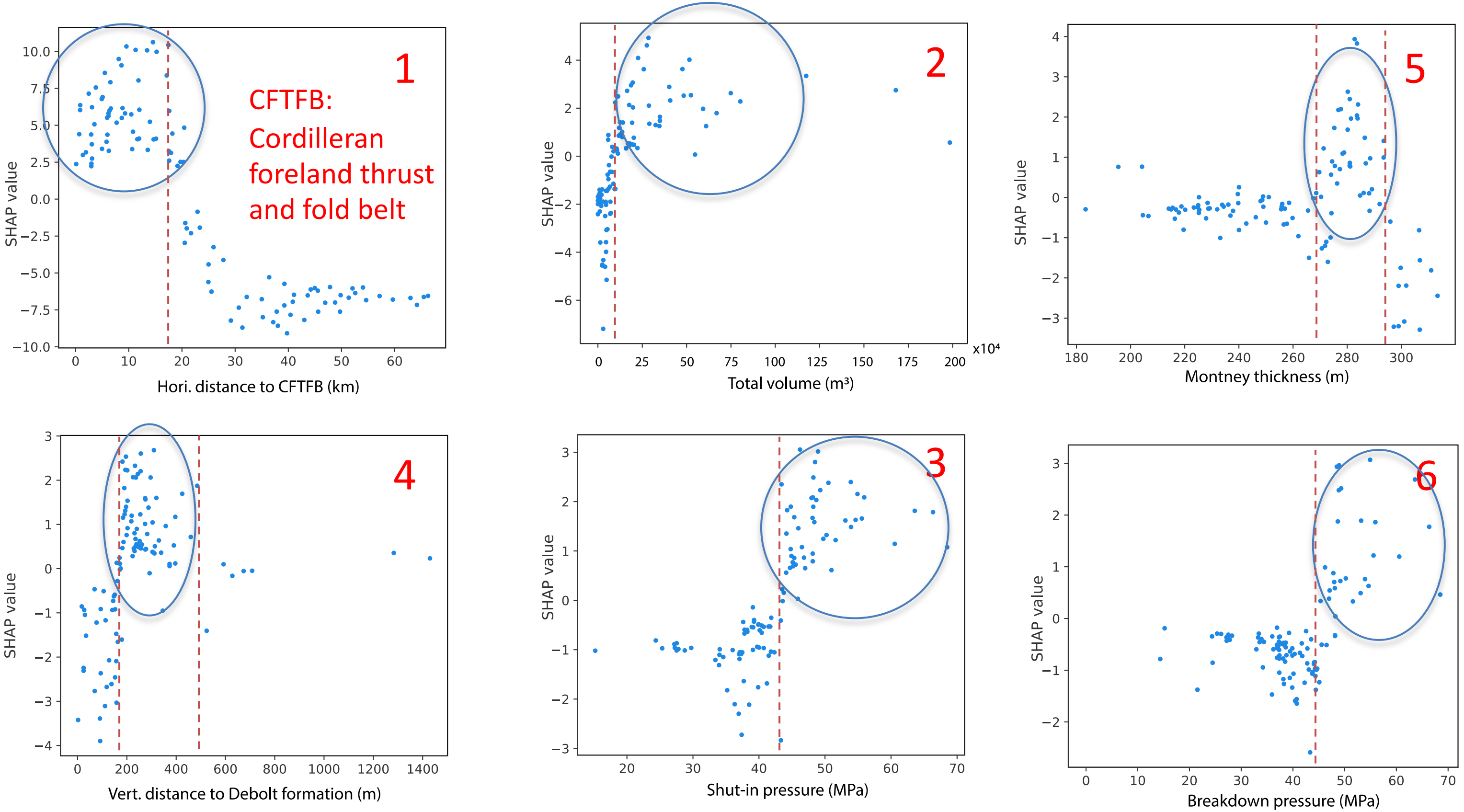


- Extreme Gradient Boosting (XGBoost) machine-learning algorithm
- 6 geological factors and 7 operational factors
- Use Shapley Additive Explanations (SHAP) values to quantitatively interpret the results



Wang et al. (2022, SRL)

SHAP Values of the Top 6 Factors Controlling IIE in NMP

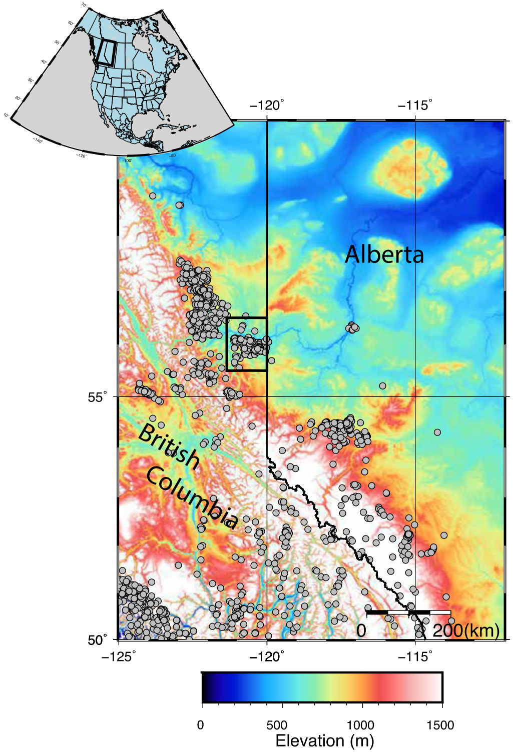


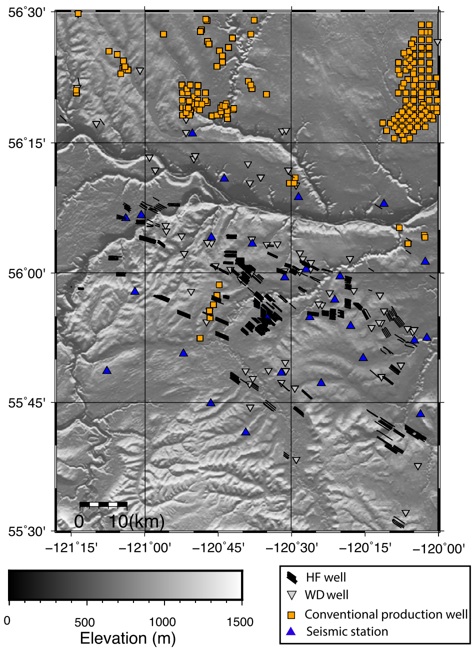
Natural Resources Canada | Ressources naturelles Canada

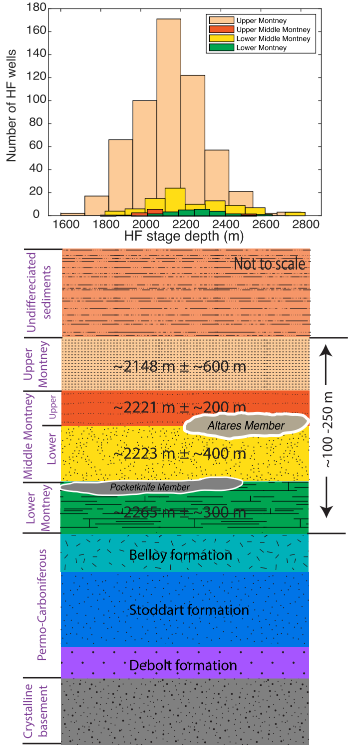
Wang et al. (2022, SRL)

Canada

Controlling Factors of IIE in Southern Montney



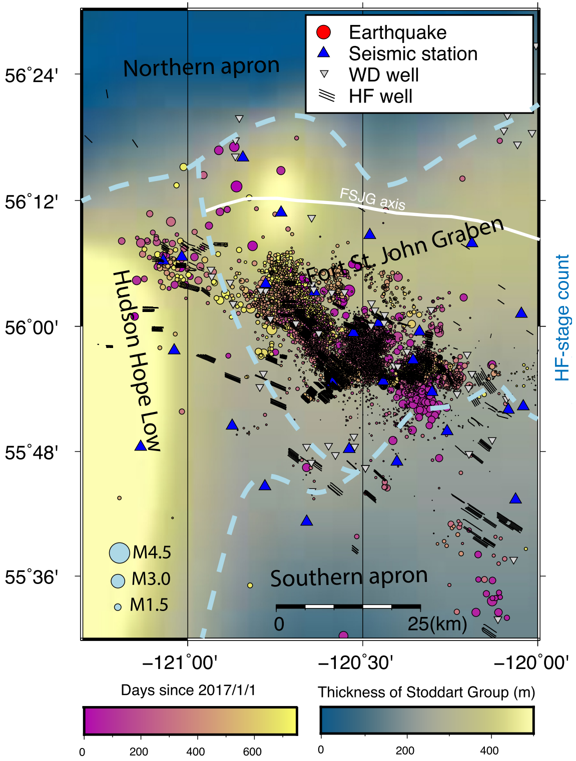


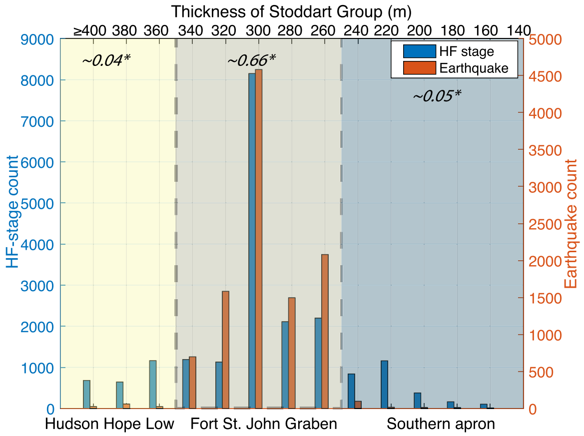


- IIE distribution is not always quantitatively correlated with the distribution of injection wells.
- No. of HF wells targeting UM >> those targeting others

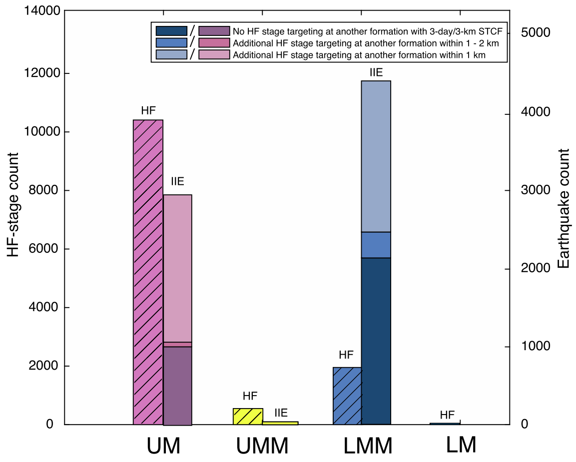
Wang et al. (2022, EPSL)

Injection wells and local seismicity (2017–2018) in Southern Montney





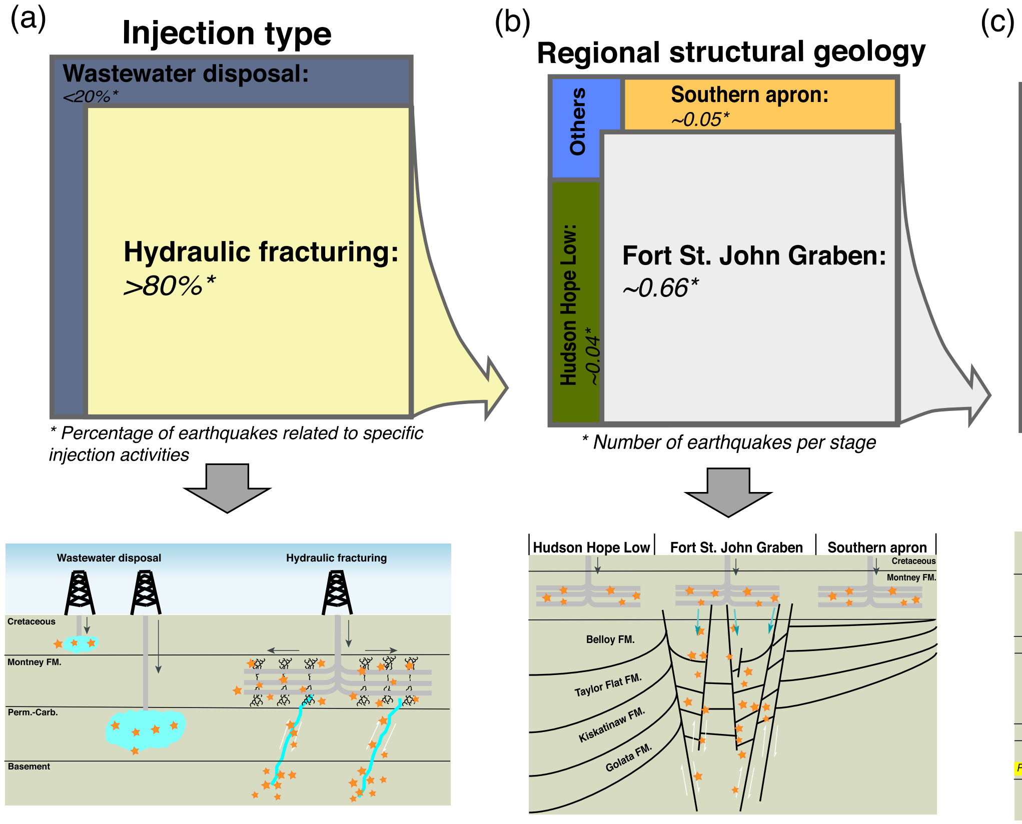
The number within each column indicates the number of eathquake per HF stage



- HF wells inside FSJG had more IIE per stage than those in HHL and southern apron

- HF stages targeting LMM generated more IIE than those targeting UM, UMM or LM.

Wang et al. (2022, EPSL)

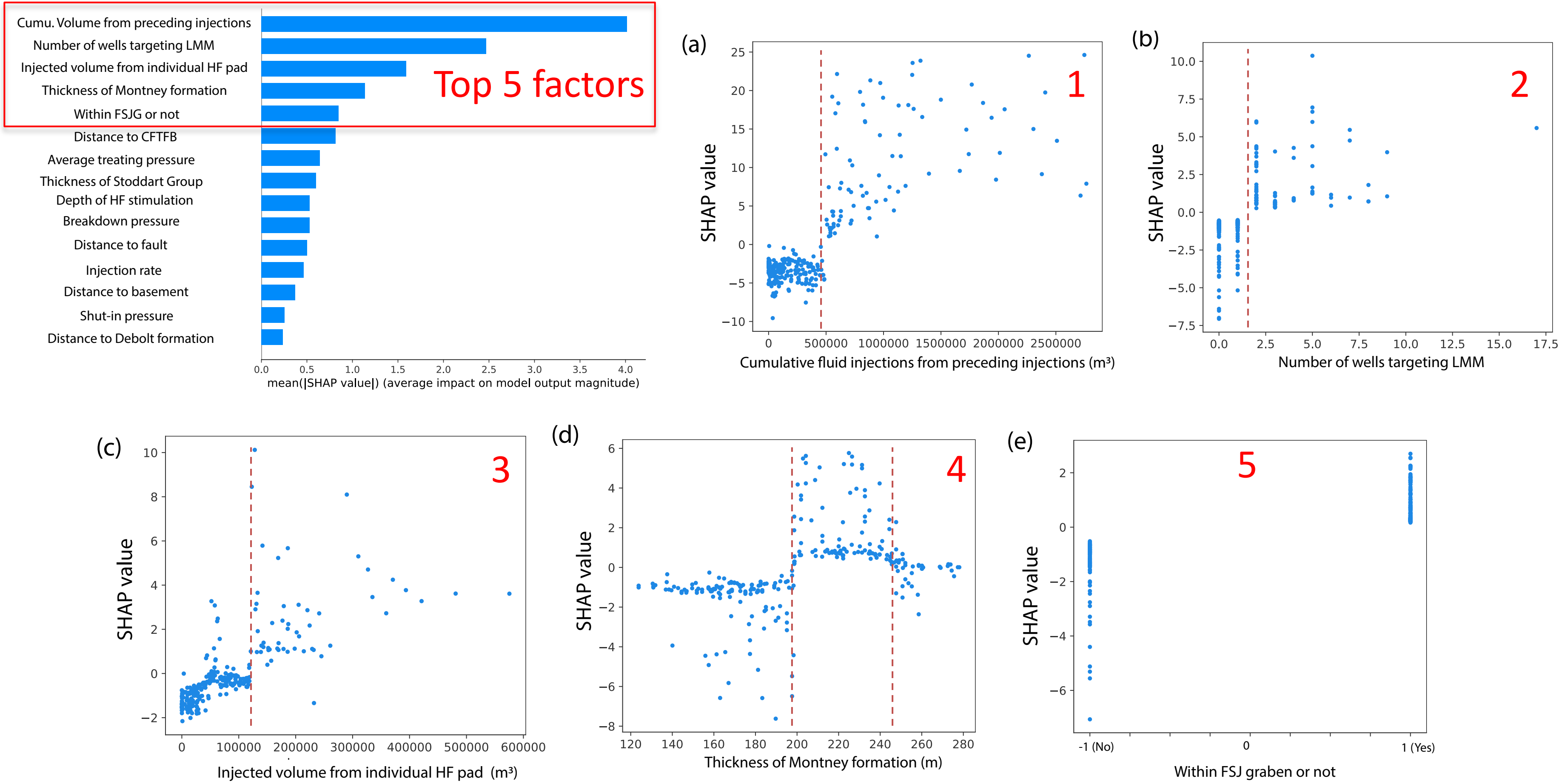


HF > WD

Within FSJG > Outside

Targeting LMM > Others

Wang et al. (2022, EPSL)



Wang et al. (2022, submitted)

Conclusions

- Improved methodology and machine-learning algorithms have provided new approaches to study IIE and their source characteristics
- Decade-long wastewater injections can eventually reactivate regional/local fault systems in seismically quiet areas (e.g., the 2018-2019 Musreau Lake sequence)
- IIE can be shallower or deeper than injection depth, depending on the local geological and hydrological settings
- IIE migration can show a complex 3D pattern that is closely linked to the existence of hydraulic conduits and aseismic slip (e.g., the 2015 Fox Creek sequence)
- Different top controlling factors for different regions
- NMP: distance to CFTFB (geological), total injected volume (operational), shut-in pressure (operational), and Montney thickness (geological)
- SMP: Injected volume (operational), number of wells targeting LMM (geological and operational), Montney thickness (geological) and within FSJG (geological)

Questions?

- Contact Info:

Honn Kao

Geological Survey of Canada, NRCan

honn.kao@nrcan-rncan.gc.ca