Rates of Induced-Earthquake Activation in Western Canada and Implications for Hazard

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CANADIAN INDUCED SEISMICITY COLLABORATION

Western
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IF A PICTURE IS WORTH A THOUSAND WORDS

A VIDEO IS WORTH

A MILLION

Seismicity and HF wells through time in Western Canada

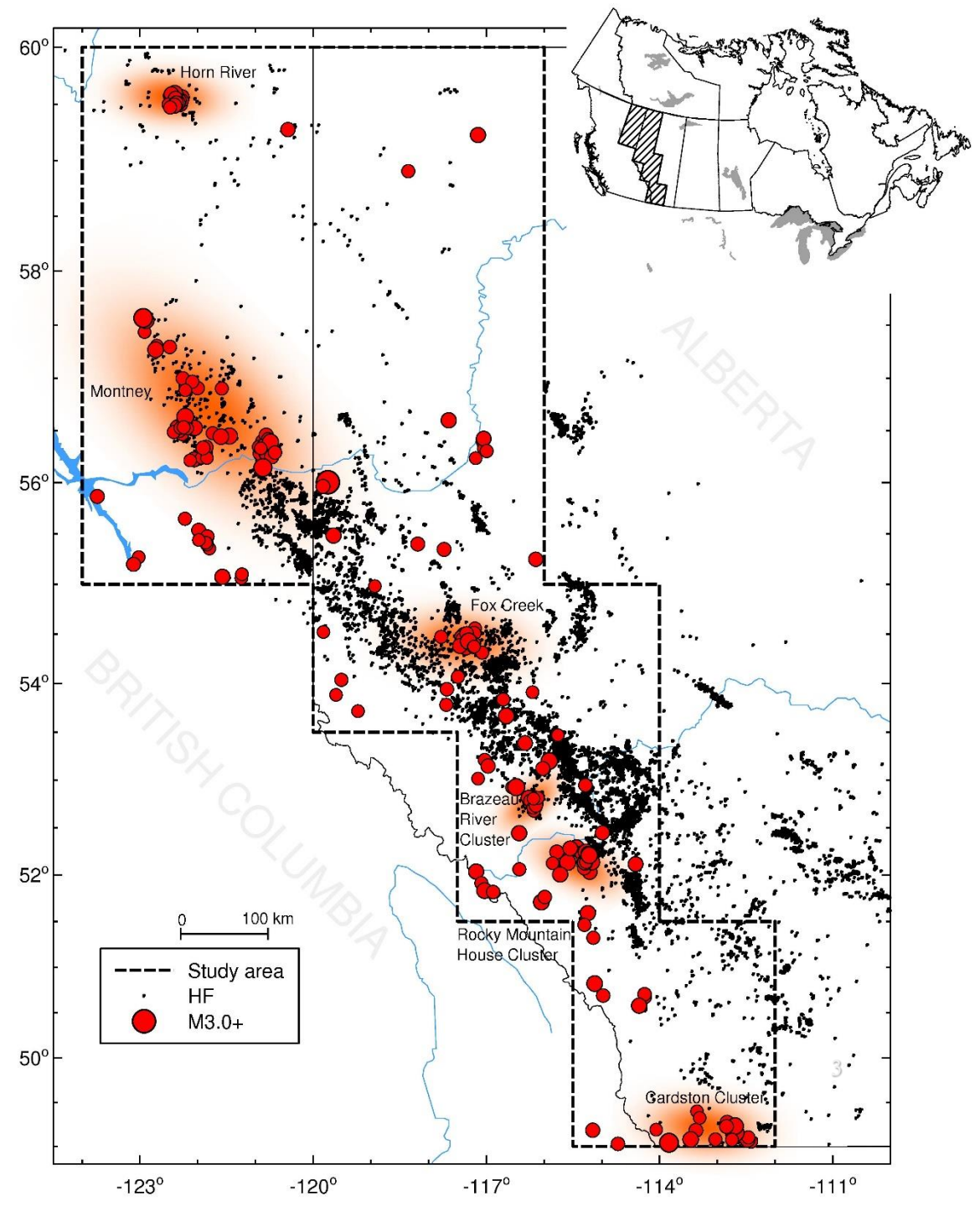
(http://www.inducedseismicity.ca/presentations/)

Induced Seismicity examples in Western Canada

Potential for induced seismicity varies greatly in space

Key the statistical characterization of induced-seismicity potential to areas in space

Seismicity of study region in the Western Canada Sedimentary Basin (WCSB). Events of moment magnitude M≥3 are shown since 1985 (red circles), from the Canadian Composite Seismicity Catalogue www.inducedseismicity.ca). HF wells are shown with black dots. The well-known seismicity clusters are shown with red shaded areas.



Preliminary Statistical Model

$R_h = N_{Hit} / N_{Active}$

probability that operations in a 10-km cell may induce seismicity

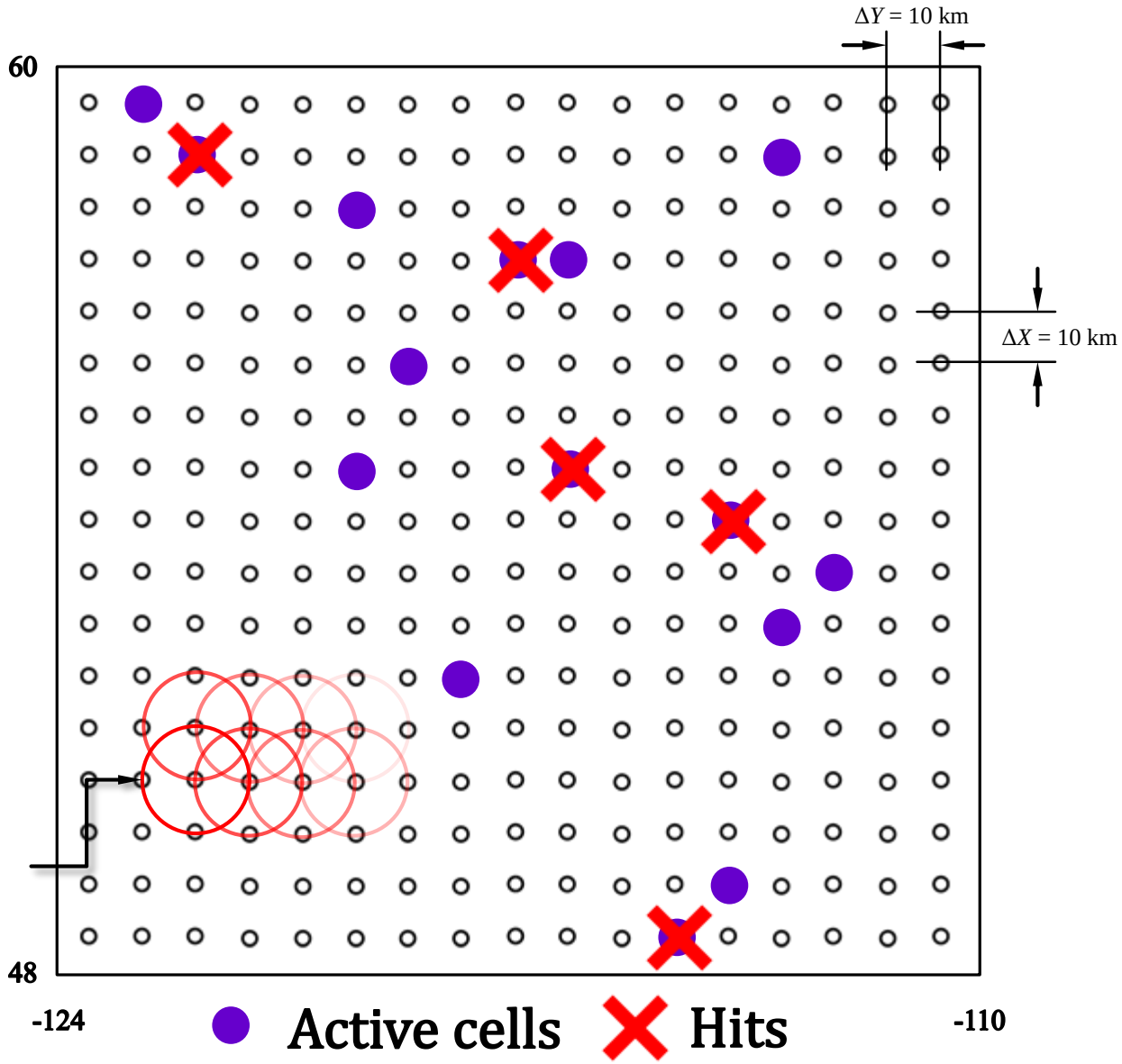
"Hit"

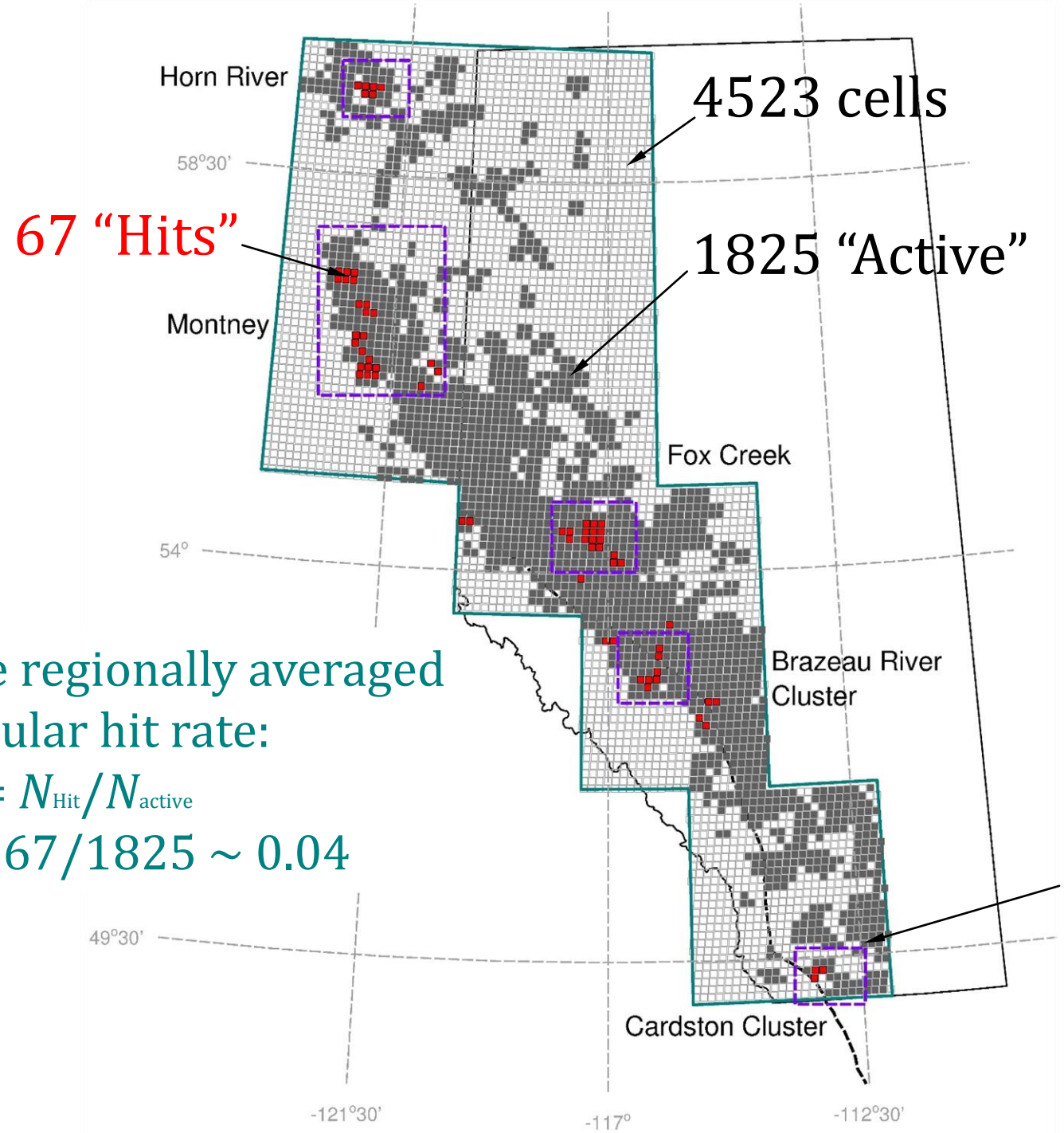
contains at least one event that follows the start date

"Active" or **"Null"**

Every cell that contains at least one *significant energy operation*

Within the cell, we determine whether there has been **any known seismicity** and whether there were **any active oil/gas wells** in the cell





The simple screening methodology is reliably identifying cells having associated events

The regionally averaged cellular hit rate:

$R_h = N_{Hit}/N_{active}$

$= 67/1825 \sim 0.04$

associated with HF wells from more detailed site-specific studies

Could the observed correlation (67 hit cells) be obtained by random chance?

Randomly-distributed events

The degree of correlation: **0 times in 1500 trials**

[5 95]th percentile: [11 33] /1825 = [0.01 0.02]

At least 34(=67–33) cells are actually hits at 95% confidence level (i.e., above and beyond those expected by random chance)

seismicity is so clearly clustered

{ hydraulic fracturing just happens to coincide with areas that are prone to seismicity }

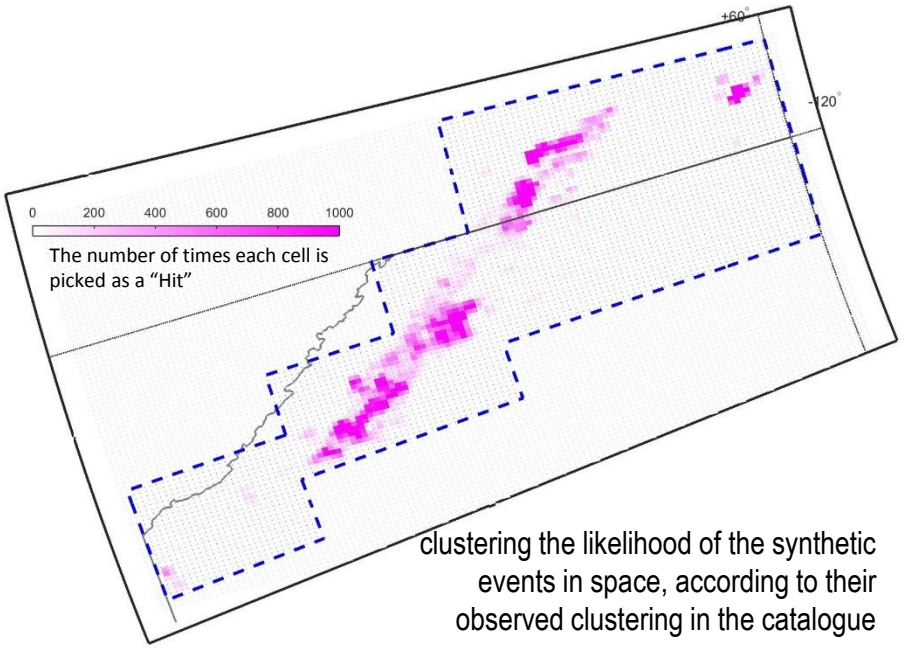
Clustered Analysis – smoothed seismicity

The degree of correlation: **2 times in 1500 trials**

[5 95]th percentile: [20 48]/1825 = [0.01 0.03]

At least 19(=67–48) cells are actually hits at 95% confidence level (i.e., above and beyond those expected by random chance)

1500 independent simulations of the regional seismicity pattern (1985-2015) – 270 **M**≥3.0



clustering the likelihood of the synthetic events in space, according to their observed clustering in the catalogue

→ the occurrence rate of events in a short time window following HF treatments is *too high to be coincidental*

Other Possible Causes of the Correlation

To test the hypothesis that disposal wells are involved in triggering the seismicity, we identified all disposal wells within each of the **67 hit cells**.

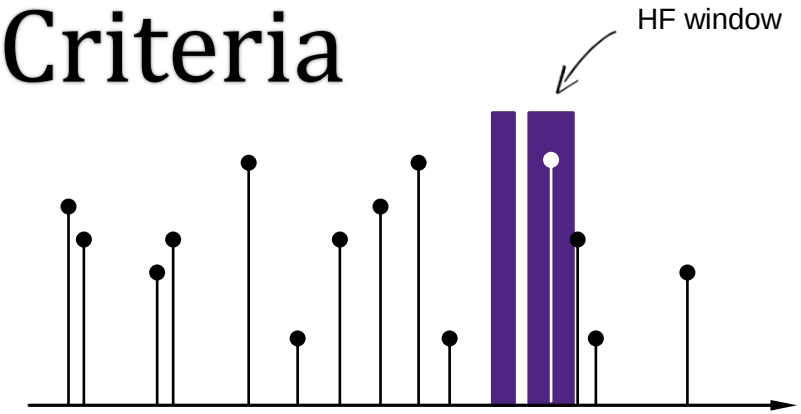
- **34** (out of 67) hit cells: **no proximate disposal well** with *significant activity* that pre-dates the seismicity (minimum disposal volume, prior to seismicity initiation, is at least as large as that involved in typical HF operations in the area).
  - there is still the possibility that the association with the HF well could be *coincidental*.
- **33** (out of 67) **ambiguous** cases for which a disposal well might play some role.

HF *or* D *or* HF+D *or* Production *or* Tectonic?

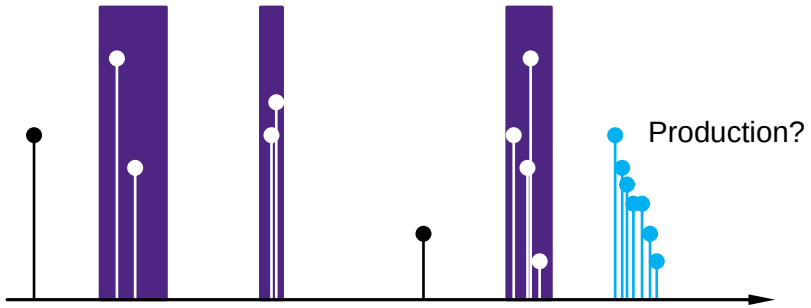
Additional diagnostic criteria …

Diagnostic Criteria

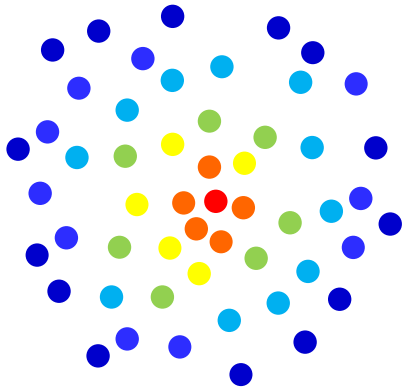
1 Occurrence of similar sequences in the area, pre-dating the HF activity (*earthquakes occur regularly*)



2 Abrupt continuation or stoppage of a sequence (*less diagnostic for disposal*)



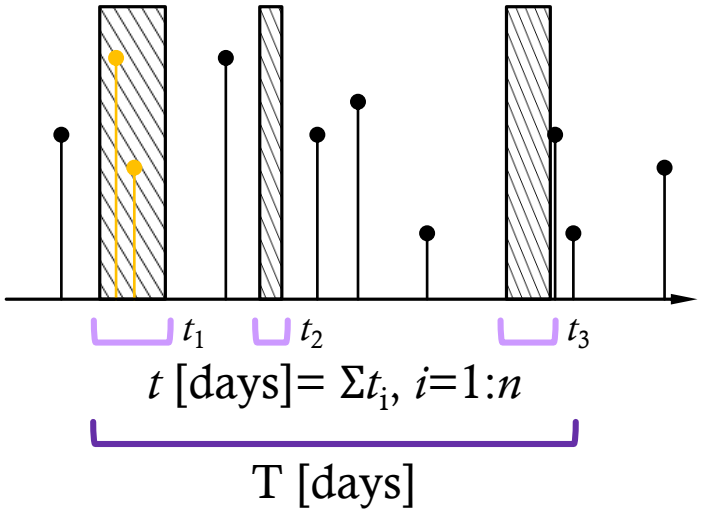
3 Sequence featuring increasing distance from well with time (*fluid pressure will diffuse to greater distances with increasing time*)



Discrimination Ratio (DR)

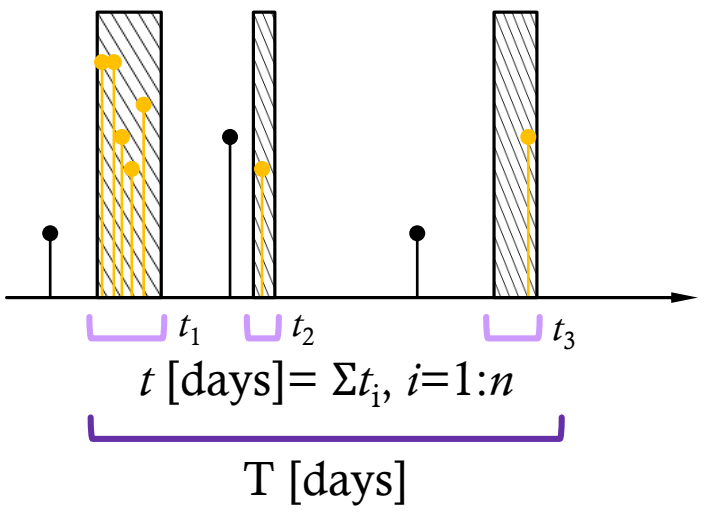
characterizing the degree of event clustering within HF windows

Randomly distributed events



events occurred sporadically in both space and time and some coincidental association may exist

HF-associated



events occurred mostly within HF windows and tightly correlated in time with HF operations

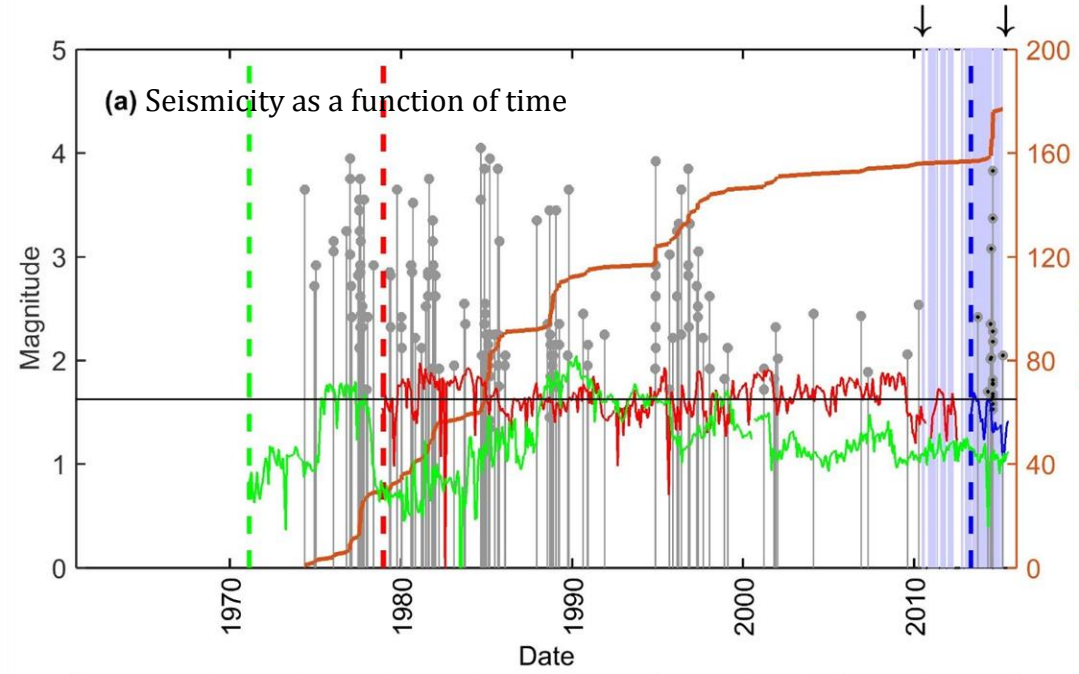
Discrimination Ratio (DR)

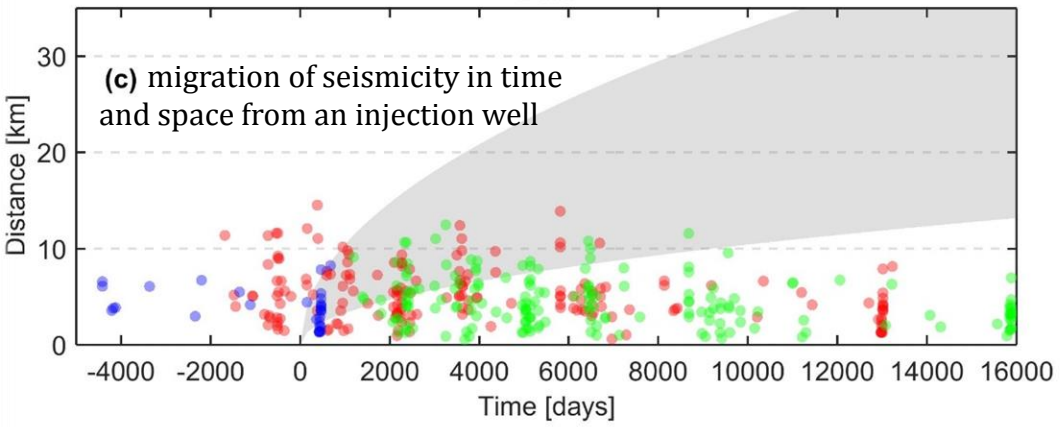
$$DR = \frac{n/N}{t/T}$$

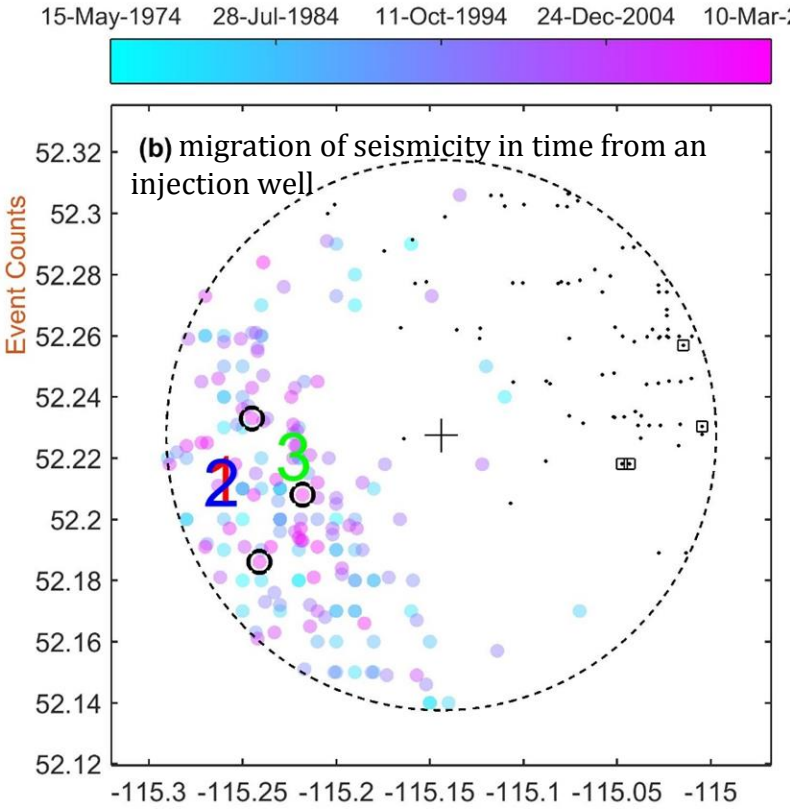
n/N: fraction of events meeting the HF criterion

t/T: fraction of time that was covered by HF windows

- For ***randomly-distributed events***, DR~1; we will get approximately the same fraction of events within HF windows as the fraction of time covered by HF windows.
- For ***clustered events***, DR will increase with increasing clustering in HF windows, as the number of events meeting the HF temporal criterion increases, while the denominator is constant.







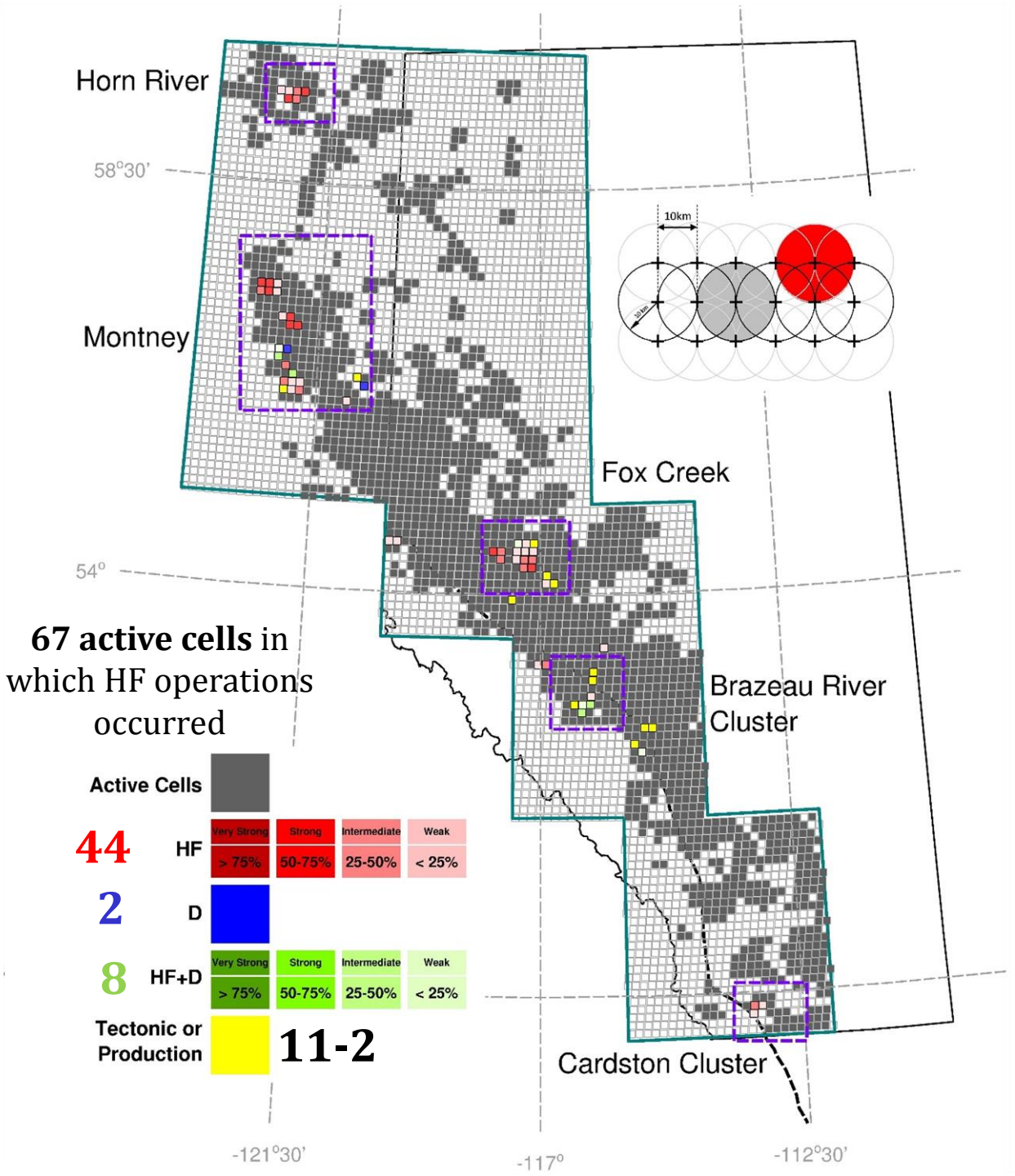
Total window length [days]: 1773
Time covered by HF [days]: 1640
Total number of events: 21
No. of events passing HF criteria: 21
DISCRIM Ratio = 1.000/0.925 = 1.1
$5,75,95^{th}$ = 0.88, 1.030, 1.08, μ = 1.030

The confidence of the association with hydraulic fracturing and disposal in each hit cell

$$L = (DR - \mu)/DR$$

DR is the value of the discrimination ratio as calculated from the observations in a cell

μ is the mean value of DR that is expected by random chance

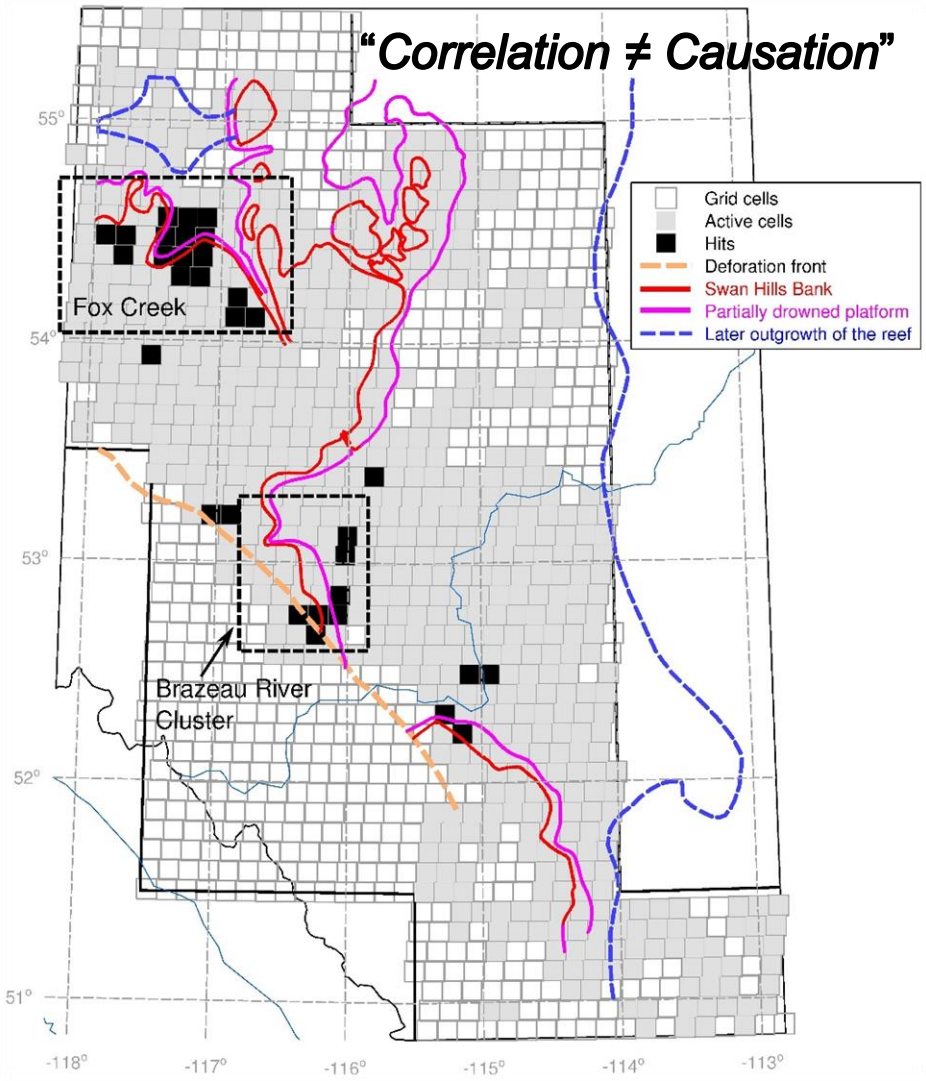


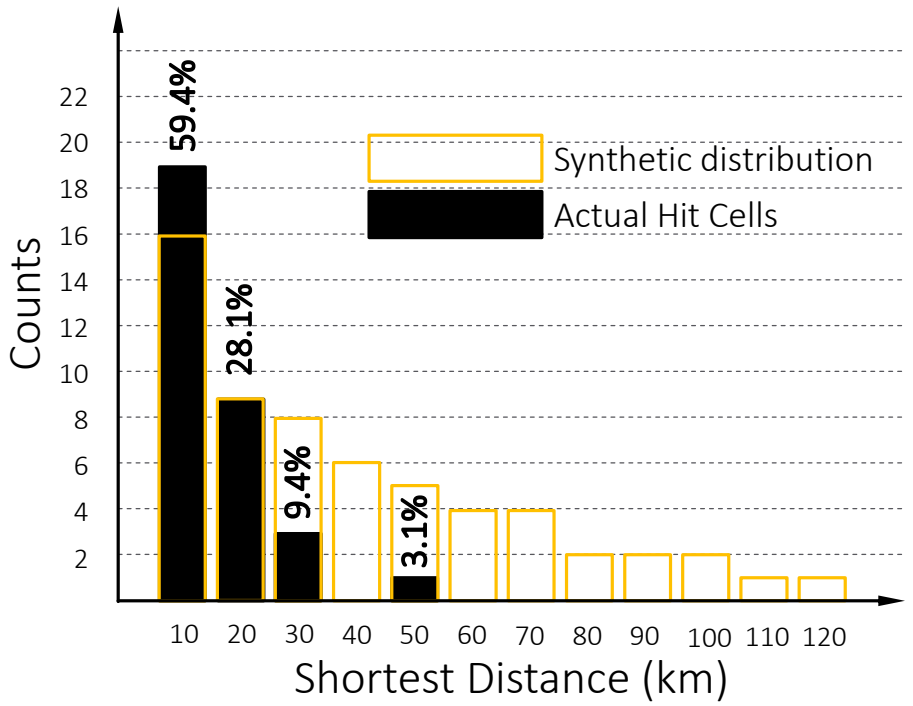
Probabilistic Indicators of the Likelihood of future Induced Events

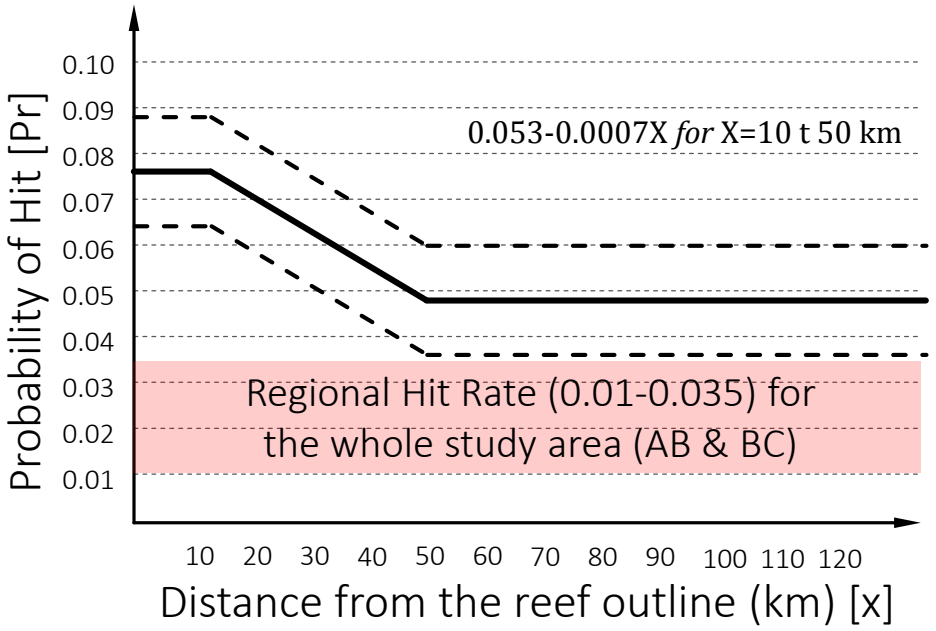
- The recent earthquake rate changes in WCSB are highly correlated with HF wells, in a way that is highly **unlikely to be coincidental**.
- It is apparent that in some areas the rate is significantly *higher* than average, while in others it is *lower*.
- Studying variability of the association rates is a *multivariate analysis* → new information will affect the *a priori* distribution for each variable → modify the **induced event probability**.
- Factors that may affect the likelihood of induced seismicity include the *geologic setting*, *poroelastic properties*, *the presence of faults and fractures*, and *operational parameters* such as pressure, pumping rates, and total volumes injected or extracted.
- EXAMPLE: It has been noted that *confirmed cases of induced earthquakes* in central Alberta are focused in *a narrow band* along the margins of the **Swan Hills Formation** (Schultz et al. 2016). The association is likely due to

  (1) reef nucleation preference for faulted basement areas and/or

  (2) enhanced permeability/porosity from diagenesis







$R_h = N_{Hit}/N_{Active}$ = 32/673 = 0.048 > [0.01-0.035] the upper range of the regional hit rate (whole study area)

→ proximity to the reefs results in a greater likelihood of induced seismicity

Conclusions

- For the geological setting and operational parameters in the WCSB, the likelihood that hydraulic fracture operations in an area of 10 km radius will be associated with M≥ 3 earthquakes is **0.010** to **0.035** (~= the overall "non-normalized" cellular rate), at the 95th percentile confidence limit. This is the likelihood *averaged over the entire region*. In some areas the rate is significantly higher than average, while in others it is lower.
- The proximity of a nearby disposal well *increases* the likelihood that HF operations will be associated with seismicity.
- Proximity to the *Swan Hills Formation* (a proxy for likely existence of basement controlled faults) is associated with increased seismogenic potential of HF operations. Specifically, the hit rate is higher for cells within 10-20 km of the reef edge as denoted by the Swan Hills Formation.

Thank you