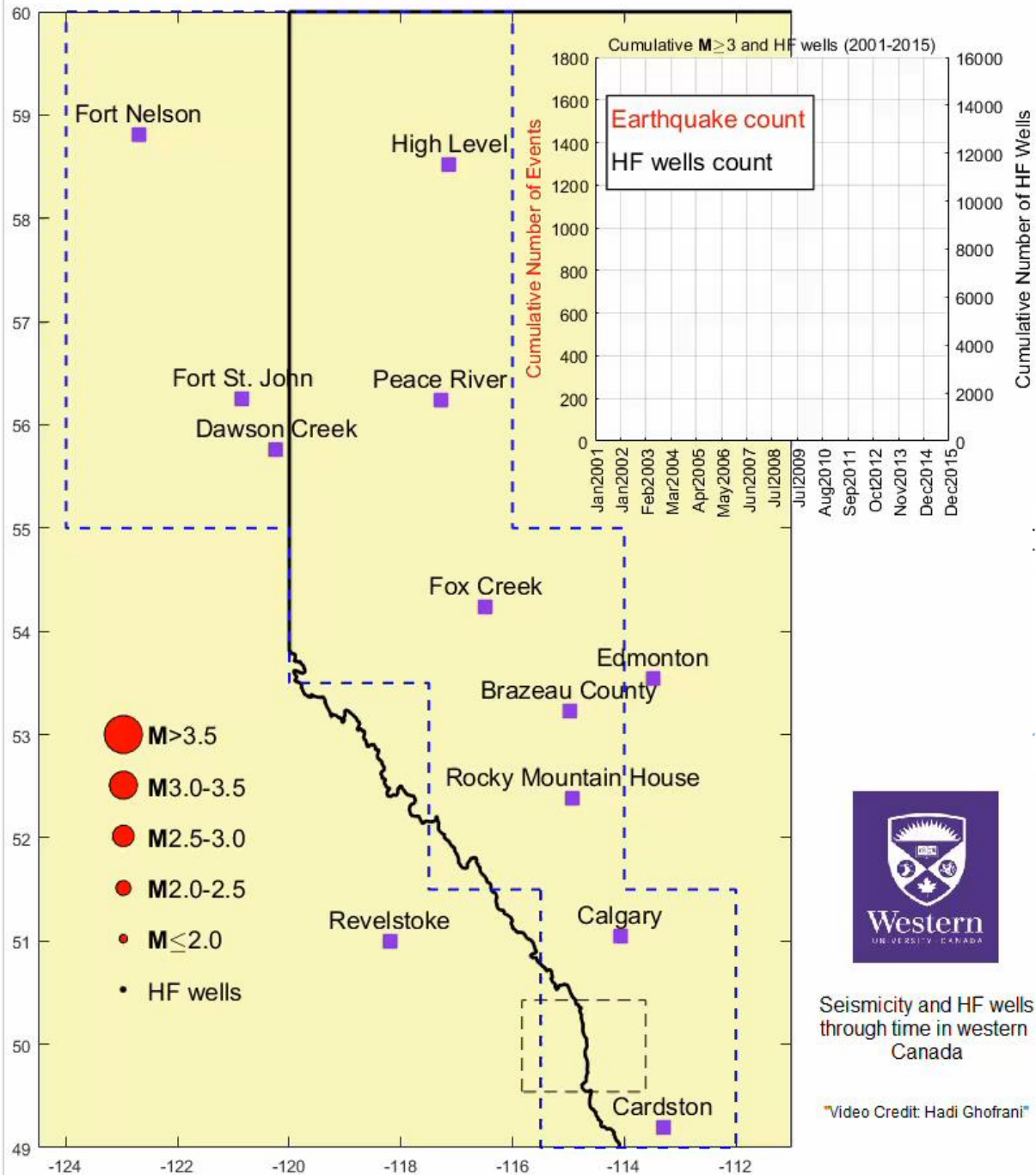


Rates of Induced- Earthquake Activation in Western Canada and Implications for Hazard

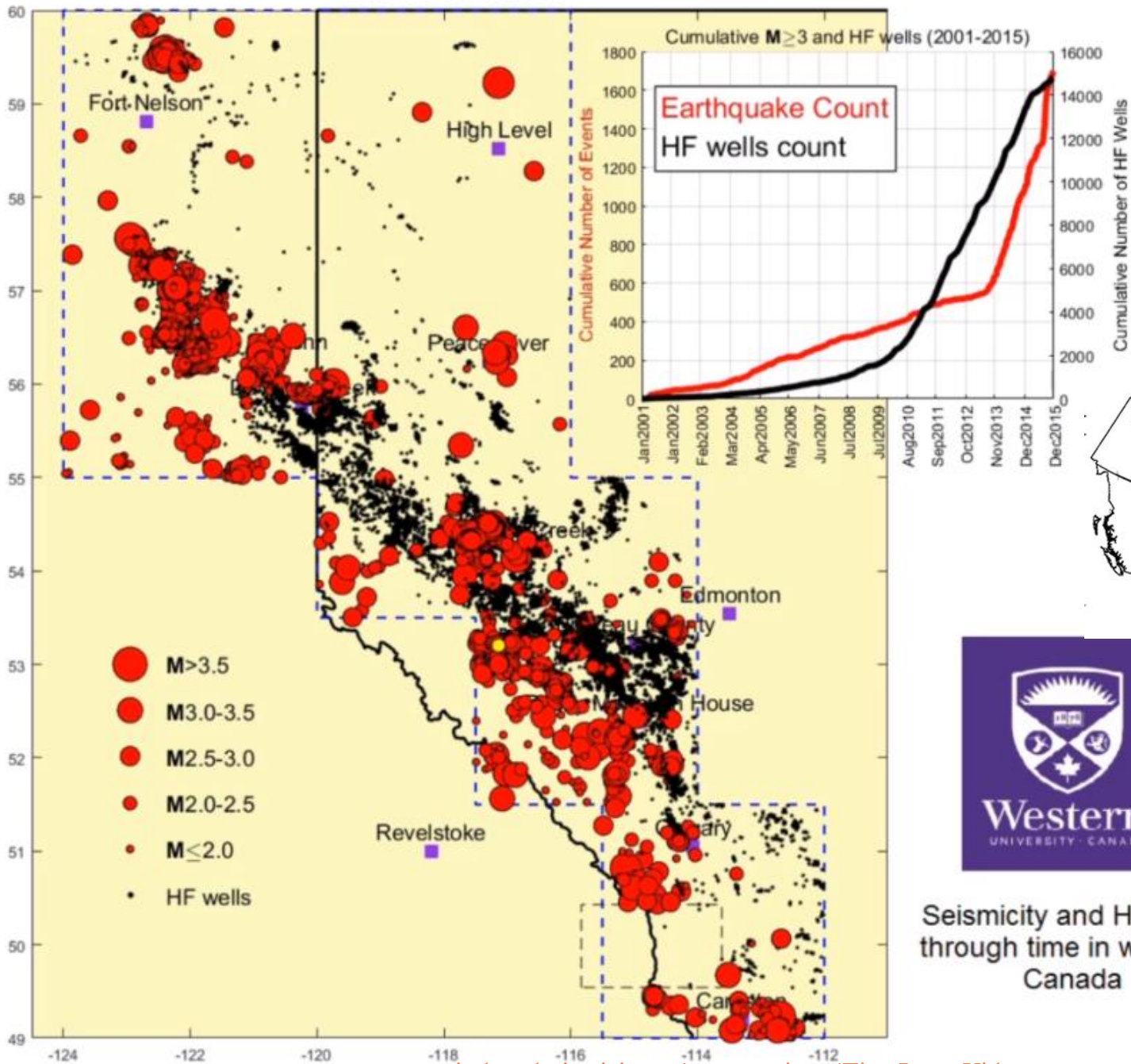
Hadi Ghofrani *and* Gail M. Atkinson

CANADIAN INDUCED SEISMICITY COLLABORATION





29-Dec-2015



Seismicity and HF wells through time in western Canada

Statistical model of relationship between hydraulic fracture wells (HF wells) and seismicity

Divide region into grid of overlapping cells, each of 10 km radius

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

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

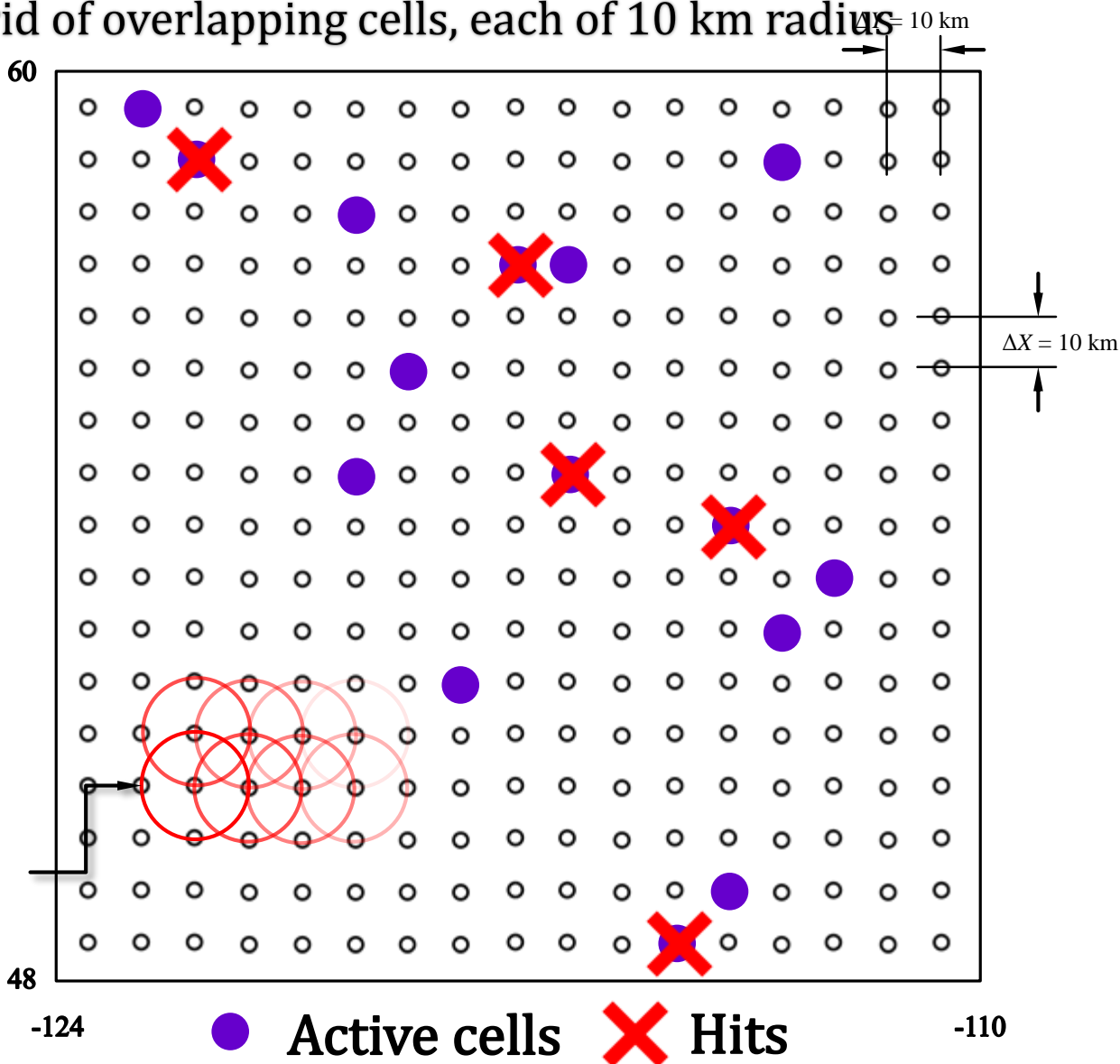
“Hit”

contains at least one $M > 3$ that follows HF well within 3 months

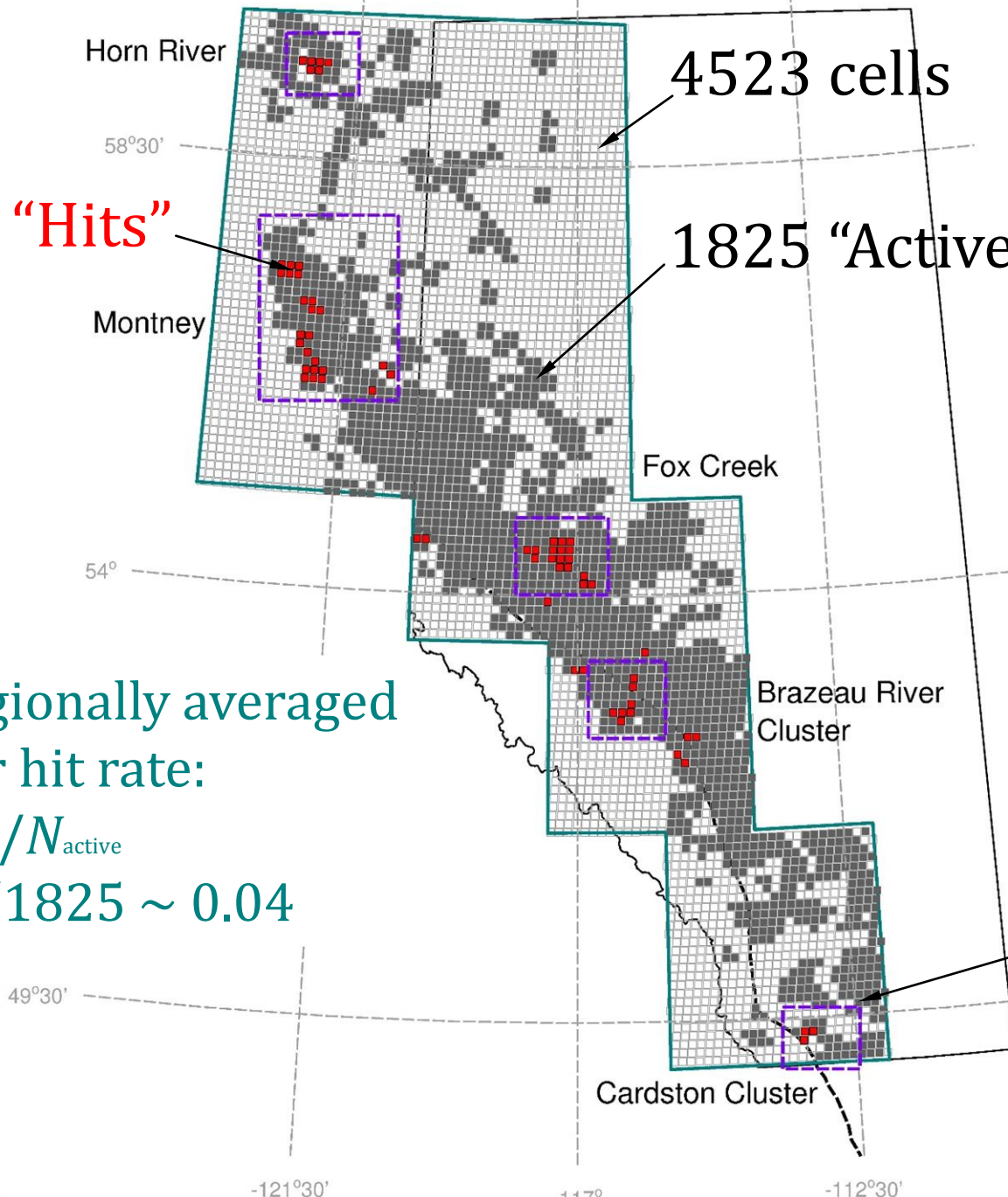
“Active” or “Null”

Every cell that contains at least one HF well

Within the cell, we determine whether there has been **any seismicity** and whether there were **any HF wells** in the cell



67 "Hits"



4523 cells

1825 "Active"

The screening methodology identifies cells having associated events

The regionally averaged cellular hit rate:

$$R_h = N_{\text{Hit}} / N_{\text{active}} = 67 / 1825 \sim 0.04$$

associated with HF wells from more detailed site-specific studies

How many of the hits (**67 hit cells of 1825 active cells**) might be obtained by random chance?

Randomly-distributed events

[5 95]th percentile: [11 33] /1825

At least **34**(=67–33) cells are actually hits at 95% confidence level

What if we use spatially-clustered model?

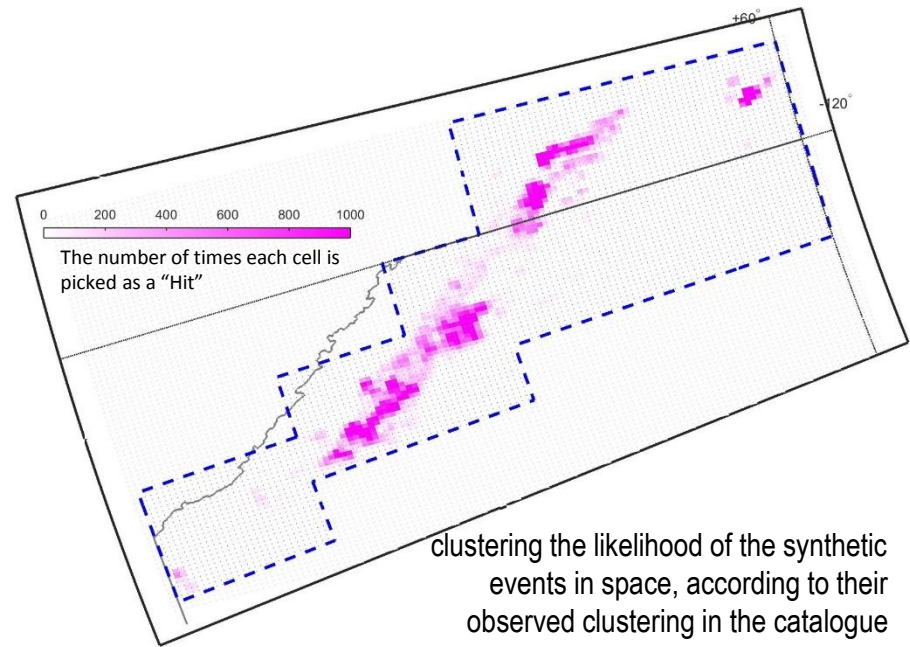
{ hydraulic fracturing just happens to coincide with areas that are prone to seismicity? }

Clustered Analysis – smoothed seismicity

[5 95]th percentile: [20 48]/1825

At least **19**(=67–48) cells are actually hits at 95% confidence level

1500 independent simulations of the regional seismicity pattern (1985-2015) – 270 $M \geq 3.0$



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

So we have clear correlation with HF wells - but maybe nearby disposal wells are to blame?

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).
- ◆ **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?

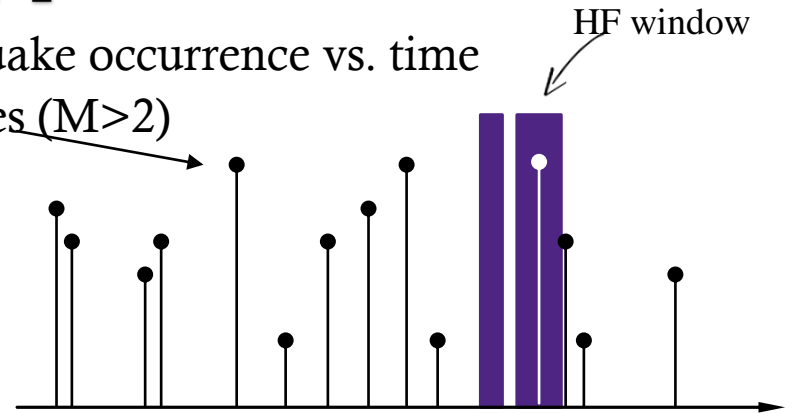
Evaluate role of various factors using additional diagnostic criteria

...

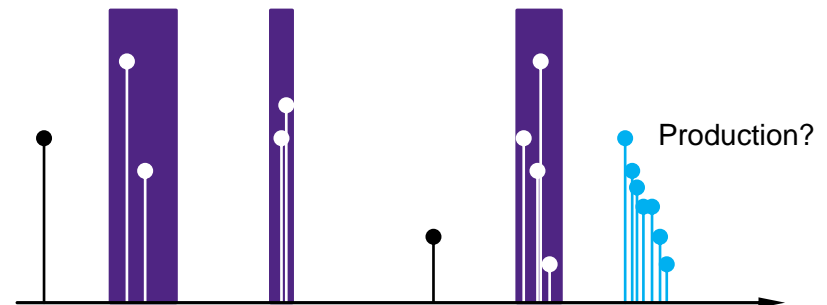
Diagnostic Criteria applied to hit cells

Figure shows earthquake occurrence vs. time
Earthquakes (M>2)

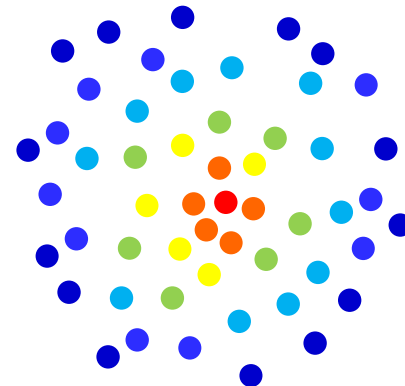
1 Occurrence of similar sequences in the area, pre-dating the HF activity (*earthquakes occur regularly*)



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



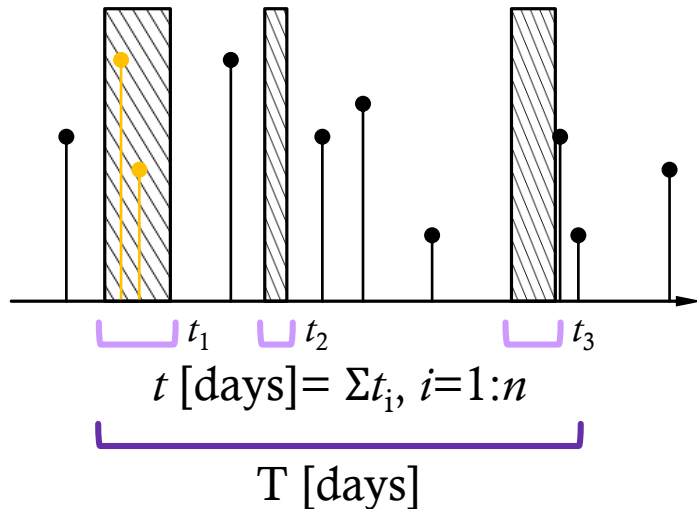
3 Sequence featuring increasing distance from well with time (*fluid pressure will diffuse to greater distances with increasing time – best for disposal wells*)



Discrimination Ratio (DR)

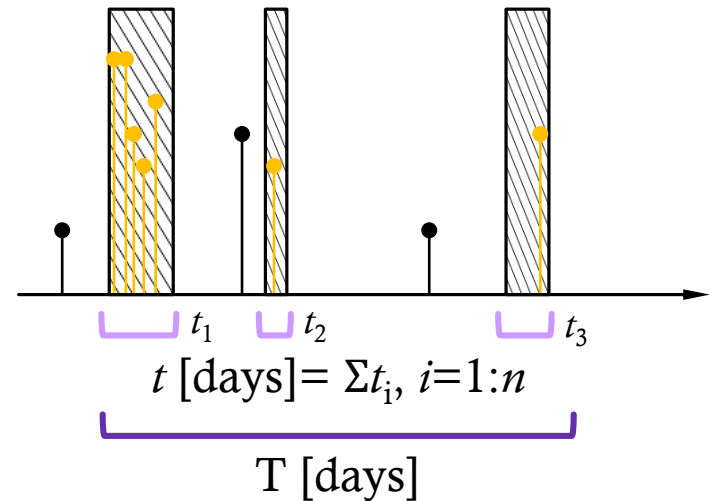
-characterizes the degree of event clustering within HF windows

Randomly distributed events



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

HF-associated



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

Discrimination Ratio (DR)

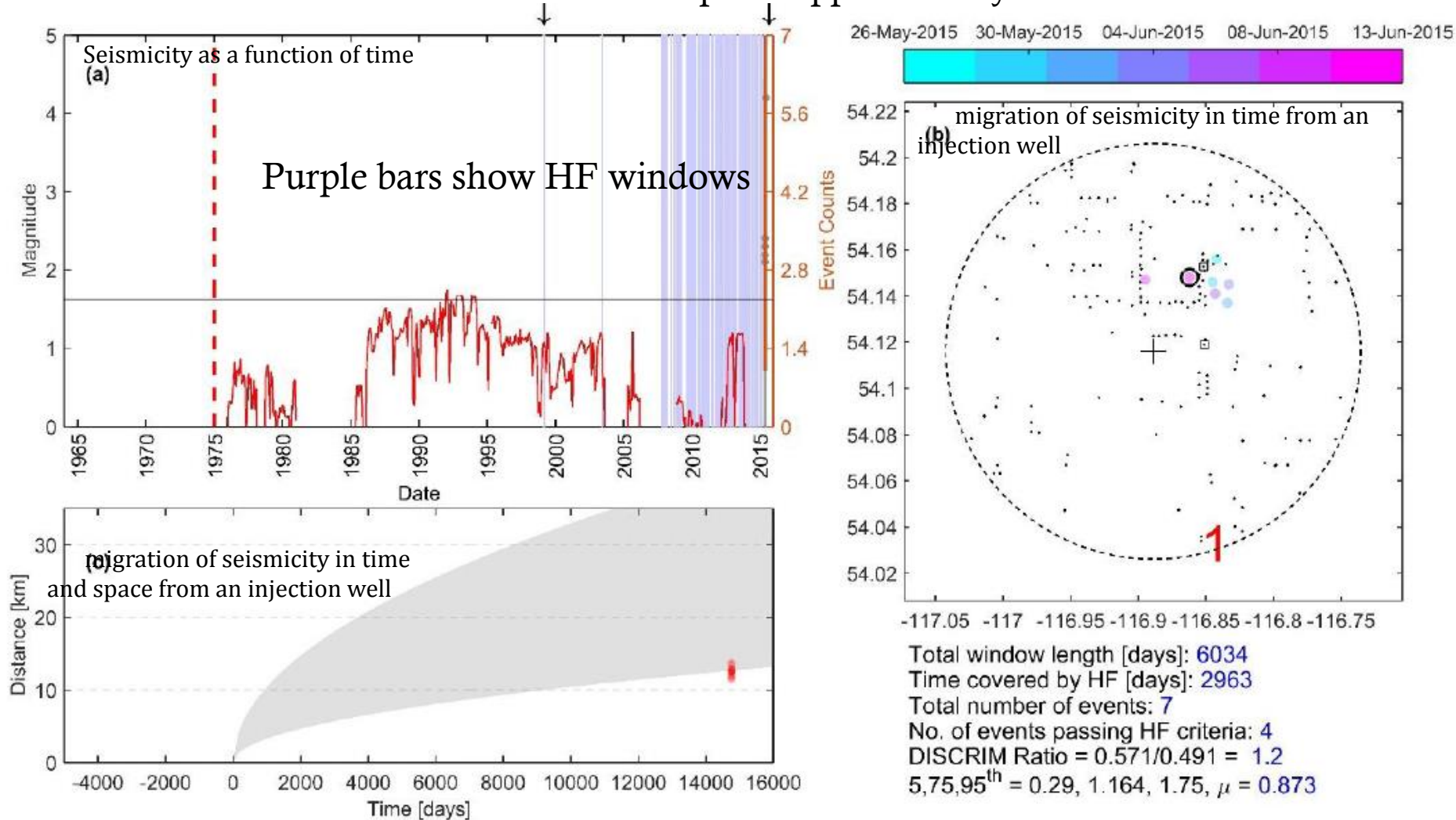
$$DR = \frac{n/N}{t/T}$$

fraction of events meeting the HF criterion
fraction of time that was covered by HF windows

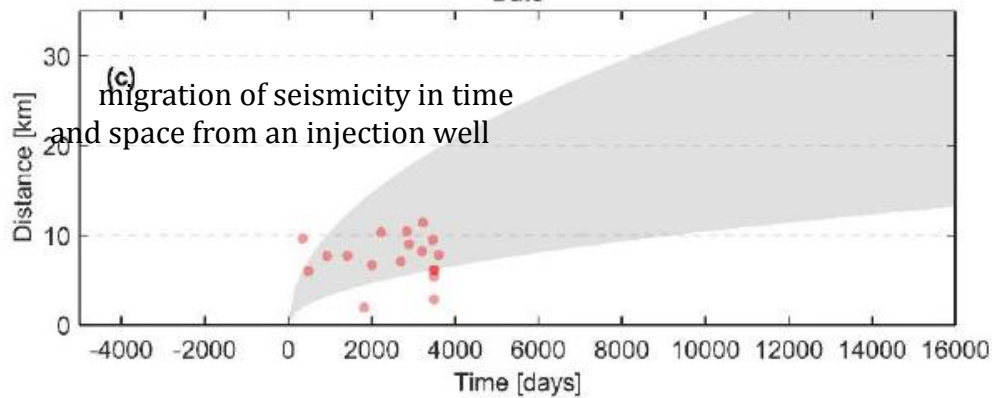
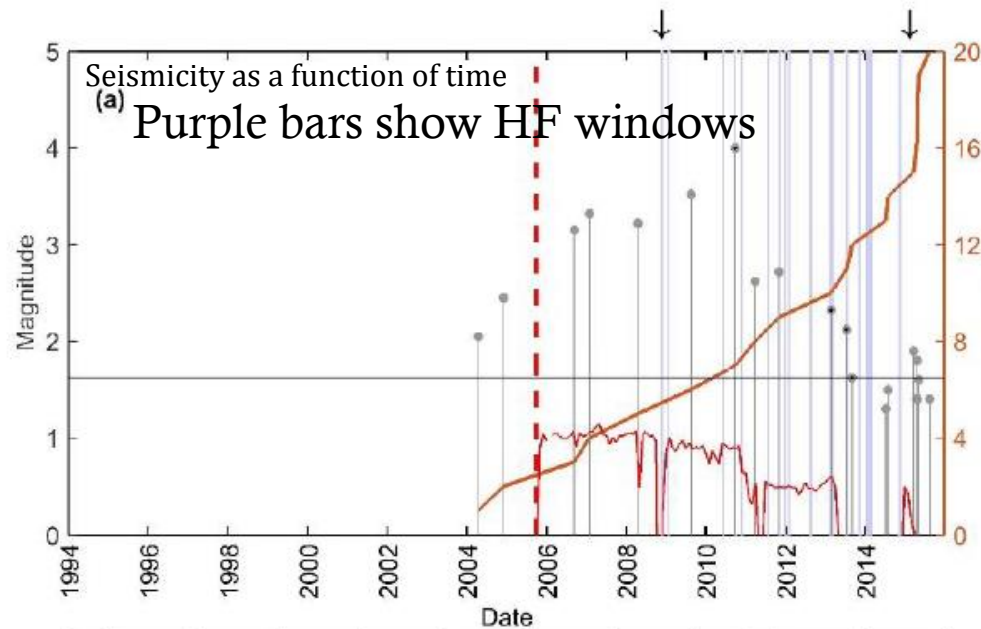
- ◆ For *randomly-distributed events*, $DR \sim 1$; we will get approximately the same fraction of events within HF windows as the fraction of time covered by HF windows.
- ◆ For *clustered events*, DR will increase with increasing clustering in HF windows, as the number of events meeting the HF temporal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

Examine DR for each hit cell: use Monte Carlo simulation to determine whether DR falls within the range that might be expected by chance).

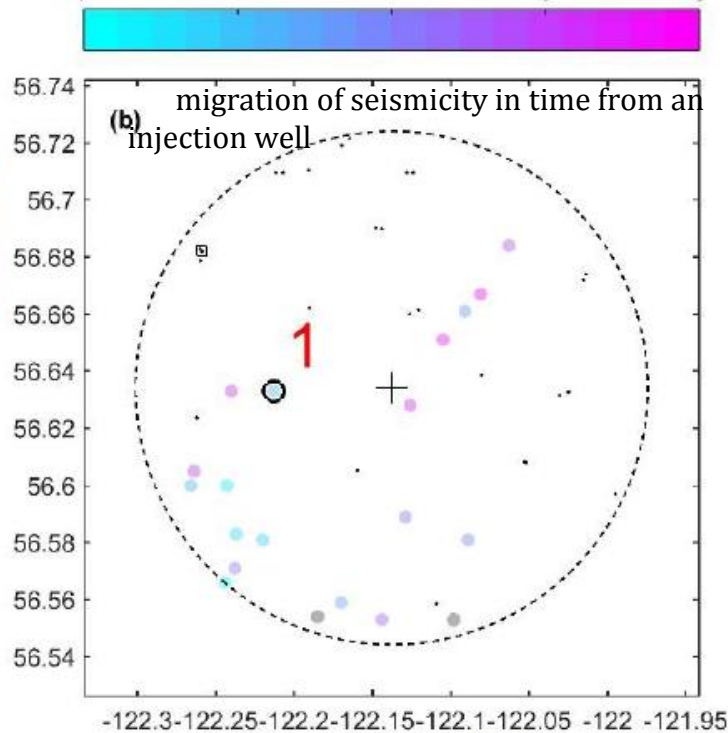
Also examine whether association with disposal appears likely.



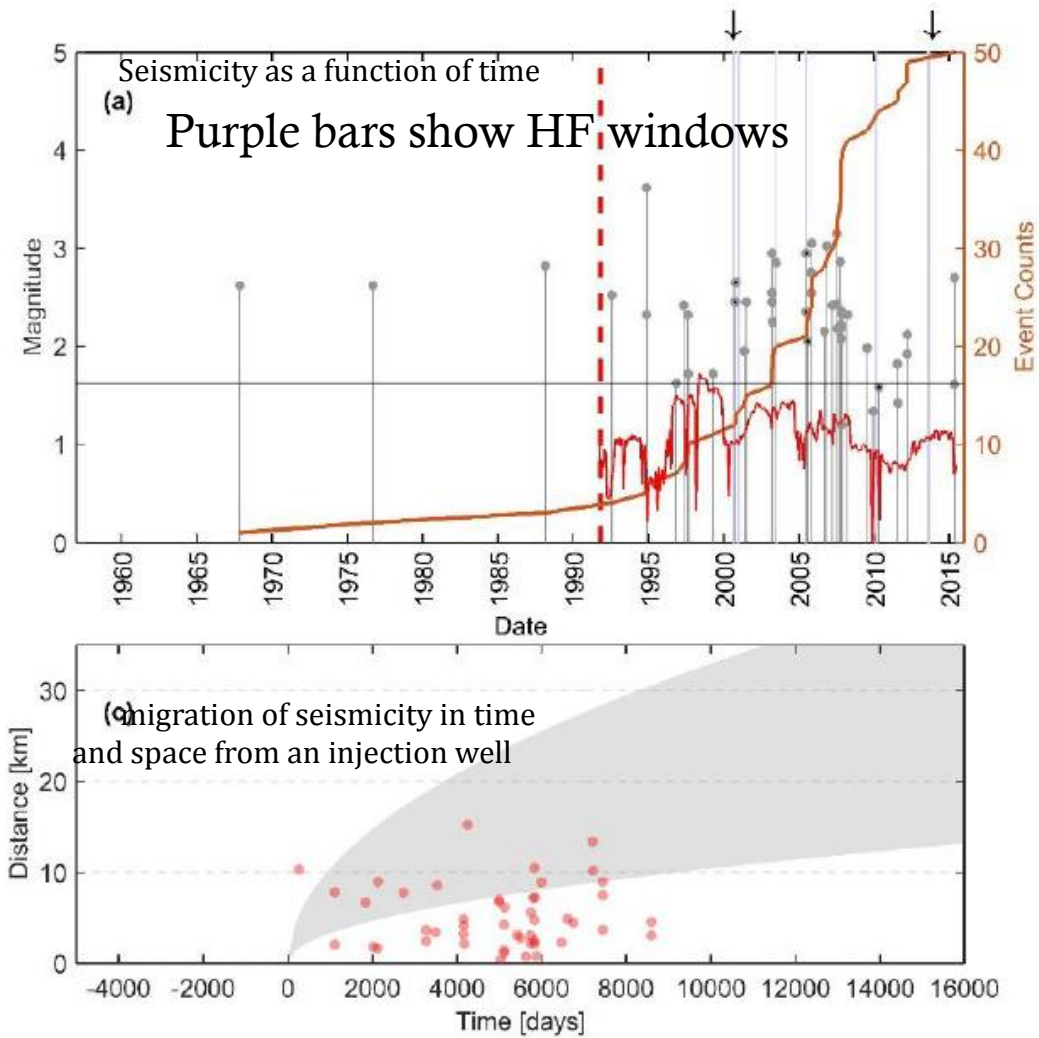
This cell is classed as HF-associated (high DR)



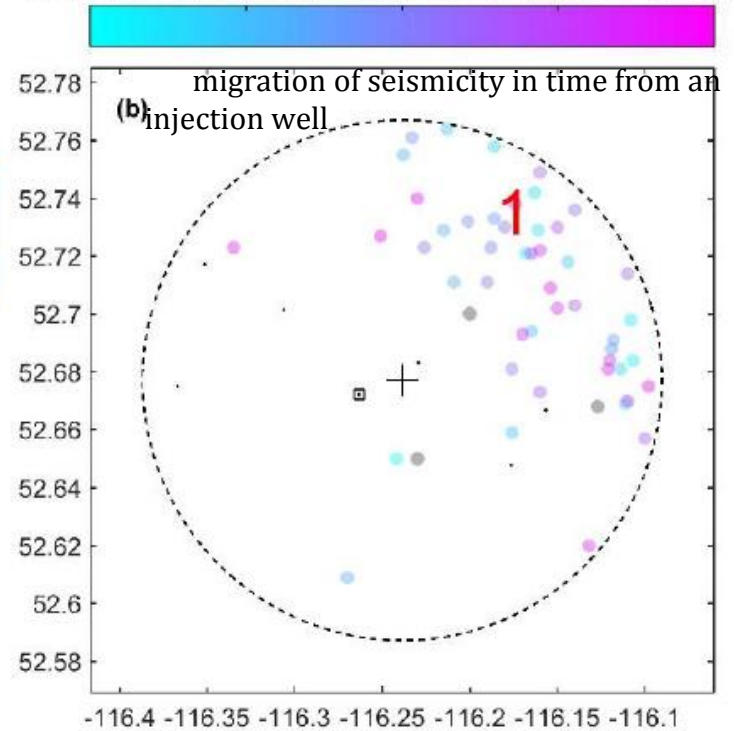
10-Sep-2006 03-Dec-2008 27-Feb-2011 23-May-2013 17-Aug-2015



This cell is classed as disposal-associated



19-Jul-1992 31-Mar-1998 11-Dec-2003 22-Aug-2009 05-May-2015



This cell is classed as HF+D-associated

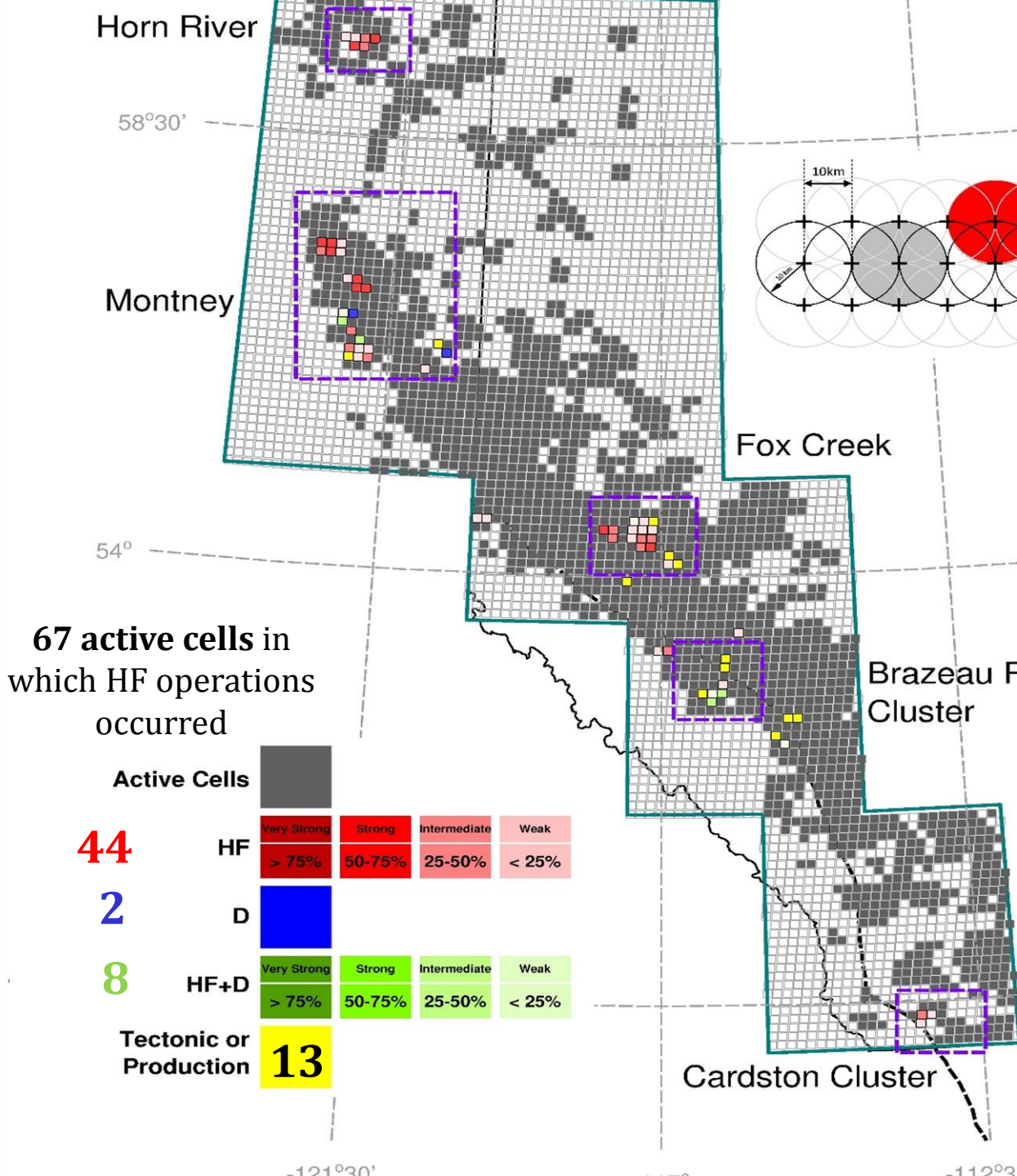
The confidence of the association with hydraulic fracturing and disposal in each hit cell

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

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

Cells colour-coded based on strength of association



Conclusions

- ◆ The likelihood that hydraulic fracture operations in an area of 10 km radius will be associated with $M \geq 3$ earthquakes is **0.010** to **0.035** at the 95th percentile confidence limit (*averaged over the Western Canada Sedimentary Basin*).
- ◆ The **proximity of a nearby disposal well** *increases* the likelihood that HF operations will be associated with seismicity.
- ◆ Likelihood function can be modified for specific geologic or operational factors.

*Thank
you*