AER/AGS Open File Report 2019-12

Preliminary Overview of the 2018 and 2019 Earthquakes near Red Deer, Alberta

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Executive Summary

The occurrence of two felt seismic events near Red Deer in March 2018 and March 2019 has recently spurred the Alberta Geological Survey (AGS) to review earthquakes in central Alberta, outside of the Alberta Energy Regulator's Subsurface Order No. 2 for the Fox Creek region. Multiple analyses of collected seismic data in the Duvernay East Shale Basin (ESB) area have produced a better understanding of the seismotectonic conditions of the Duvernay. This report outlines a high-level description of these findings.

- A M_L 3.13 earthquake was recognized on March 19, 2018 near Red Deer. The shaking from the event was felt by some.
- A M_L 4.18 earthquake was recognized on March 4, 2019 near Red Deer. The shaking from the event was felt by many. Complaints of damage from the event were received as well.
- A nearby operator installed a seismic network and shared their data with the AGS.
- Analysis of data suggested that the M_L 3.13 and 4.18 events were induced, and that other smaller clusters of events (up to M_L 2.0) were also induced in the Duvernay ESB.
- A historical analysis of all nearby seismological data in the Duvernay ESB discovered an additional well which caused earthquakes (up to M_L 2.59) in the Duvernay ESB during September of 2014.
- Examination of well log records to identify new proxies of fluid flow (thought to indicate susceptibility to induced earthquakes) suffered from sparse well control at suitable depths.
- The modelled geological susceptibility of induced earthquakes in the Duvernay has been updated to include these new events and a new geological proxy related to distance from the Leduc Reef margins.

More in-depth and rigorous work is currently in progress. For full scientific rigor, the detailed results of the seismological work are being prepared for submission to a peer-reviewed journal (Schultz and Wang, in progress).

1 Introduction

A notable increase in the number of earthquakes attributable to petroleum resource development has been observed within the Western Canadian Sedimentary Basin (WCSB)(Wetmiller, 1986; Baranova et al., 1999; Schultz et al., 2014; Atkinson et al., 2016). In particular, hydraulic fracturing has contributed most significantly to the apparent rate change in the past few years (Schultz et al., 2017; 2018). Despite the regionally pronounced change in earthquake rate and hazard (Ghofrani et al., 2019), only a small proportion of the total wells within the WCSB exhibit induced earthquakes (Atkinson et al., 2016).

Within Alberta, the majority of recent induced earthquake activity has been focused on areas of Duvernay Formation development near Fox Creek (Schultz et al., 2017; 2018) and has been managed via a traffic light protocol (TLP) (Alberta Energy Regulator, 2015). However, recent events (19 March 2018 and 4 March 2019) were large enough (M_L 3.13 and M_L 4.18) to be felt by nearby residents in the City of Red Deer, who were between 4–10 km away. The observation of these events in a typically seismically quiescent region was suspicious, considering the recent development of the Duvernay East Shale Basin (ESB). Because deployments of seismic monitoring stations in the province (Figure 1) have been skewed to more seismically active areas (Schultz and Stern, 2015), assessing the induced status of this cluster based solely on data from those areas was impossible. Instead, the operator of the well in question deployed a passive seismic monitoring network (Figure 2) to more thoroughly address the issue. The data were shared with the Alberta Geological Survey (AGS) and prompted several follow-up analyses.

In this report, we outline the workflow and learnings developed from data recorded by the AGS seismic monitoring network and data shared by industry. We find a handful of new clusters near Red Deer that are confirmed as induced – at least two of which were large enough to be felt by people nearby. From this, a historical analysis found one more ESB seismic event closer to the Rocky Mountains in 2014. We use learnings from other hydraulic fracturing induced seismicity case studies to search for geological conditions responsible for these earthquakes. Based on these new learnings we produce a more complete version of the geological susceptibility model developed by Pawley et al. (2018).

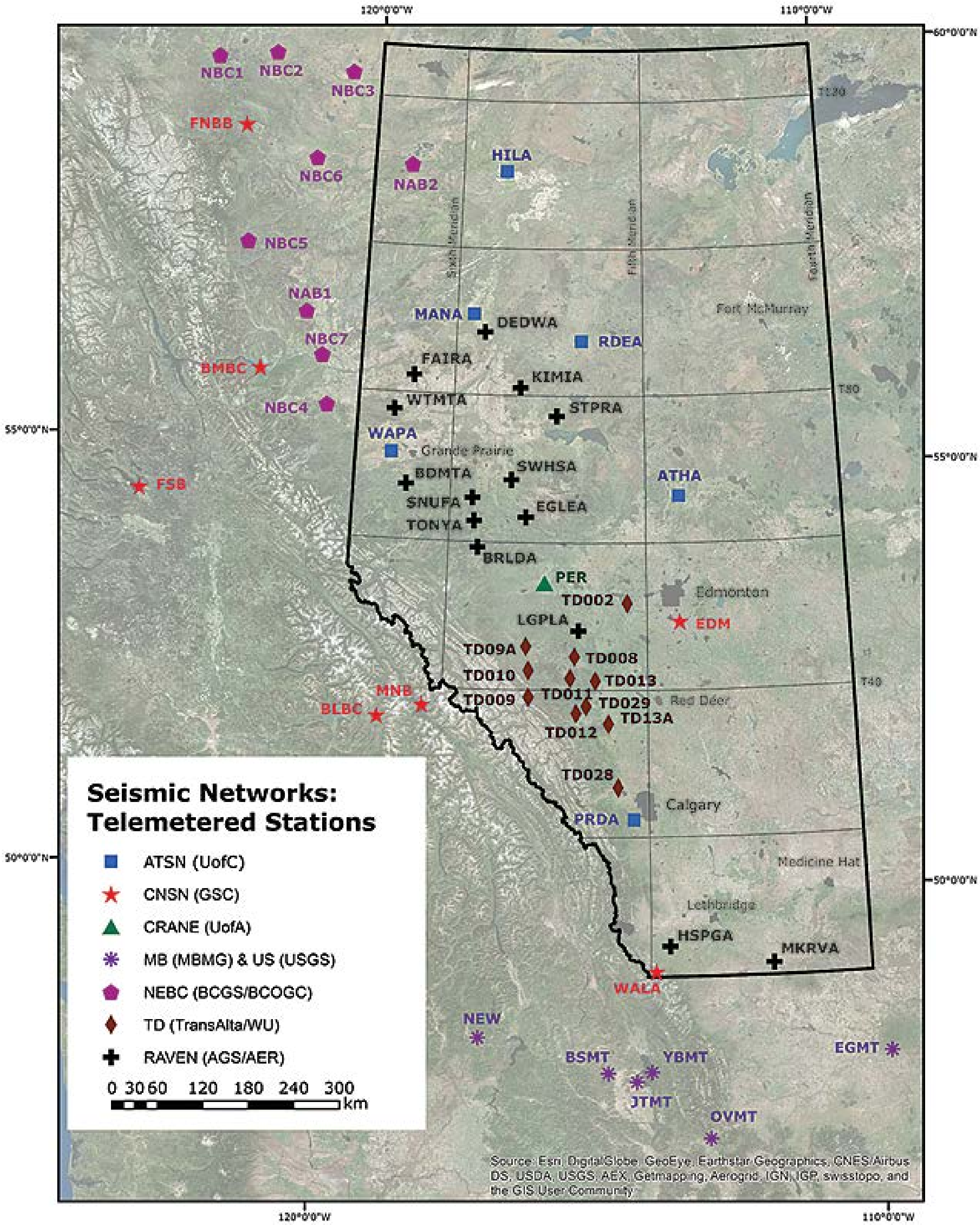

Figure 1. Map of passive seismic stations used for earthquake cataloguing in Alberta.

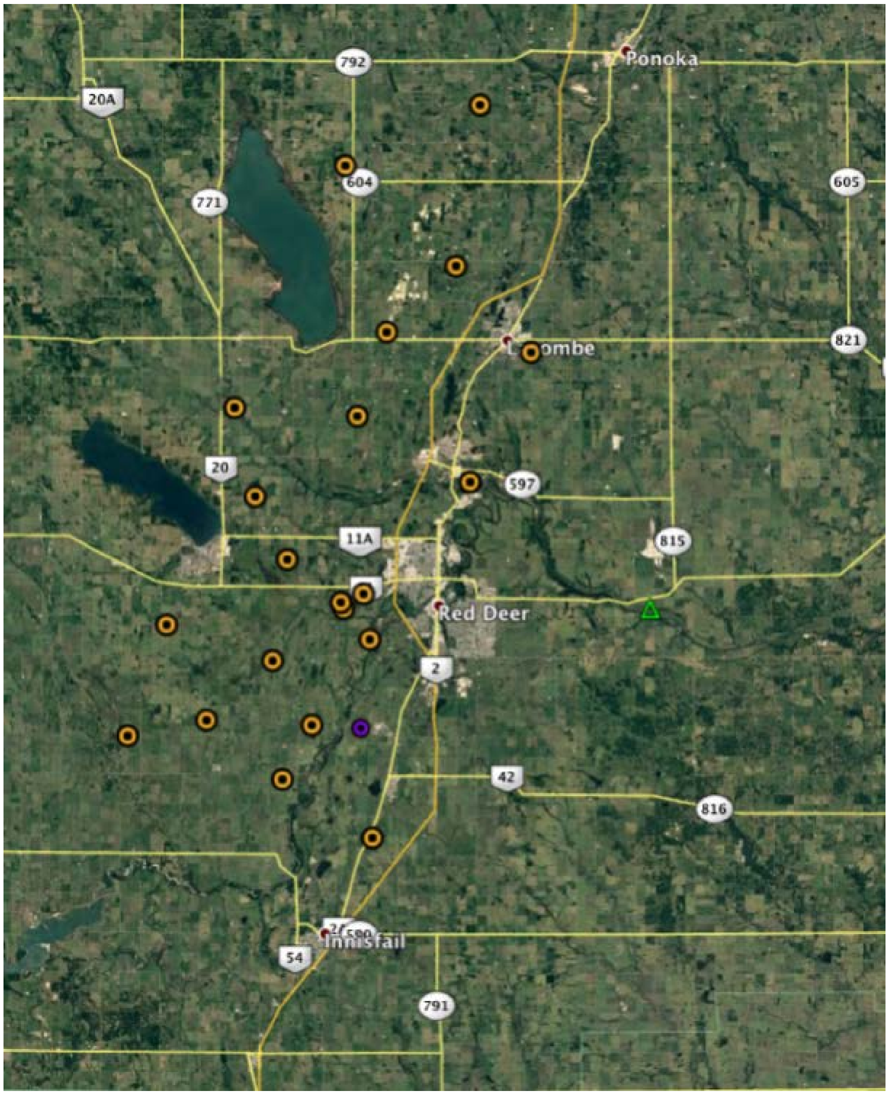

Figure 2. Map showing the locations of passive seismic station used in East Shale Basin analysis. Green triangle is an offline station from the University of Alberta, purple circle is a newly installed Alberta Geological Survey RAVEN station, and the orange circles are the stations installed by operators that provided their data. Background satellite imagery and road network provides geographic context.

2 Seismological Analysis

In this section we describe the high-level seismological analysis conducted to understand the recent events occurring in the Duvernay ESB area. The detailed results and implications of this seismological analysis are to be elaborated on in a future peer-reviewed study (Schultz and Wang, in progress).

Earthquakes throughout the province are routinely catalogued by the AGS (Stern et al., 2013). In this report, we consider historical events in the Duvernay Willesden Green and ESB areas starting in 2006 through March 2019 (Figure 3). We refine the AGS catalogue within this time period acquired by the regional network (Figure 1) and supplement it with industry data (Figure 2). This supplemental dataset provides an excellent basis to understand the seismogenic potential for induced earthquakes in the Duvernay ESB—this could not have been confidently accomplished otherwise.

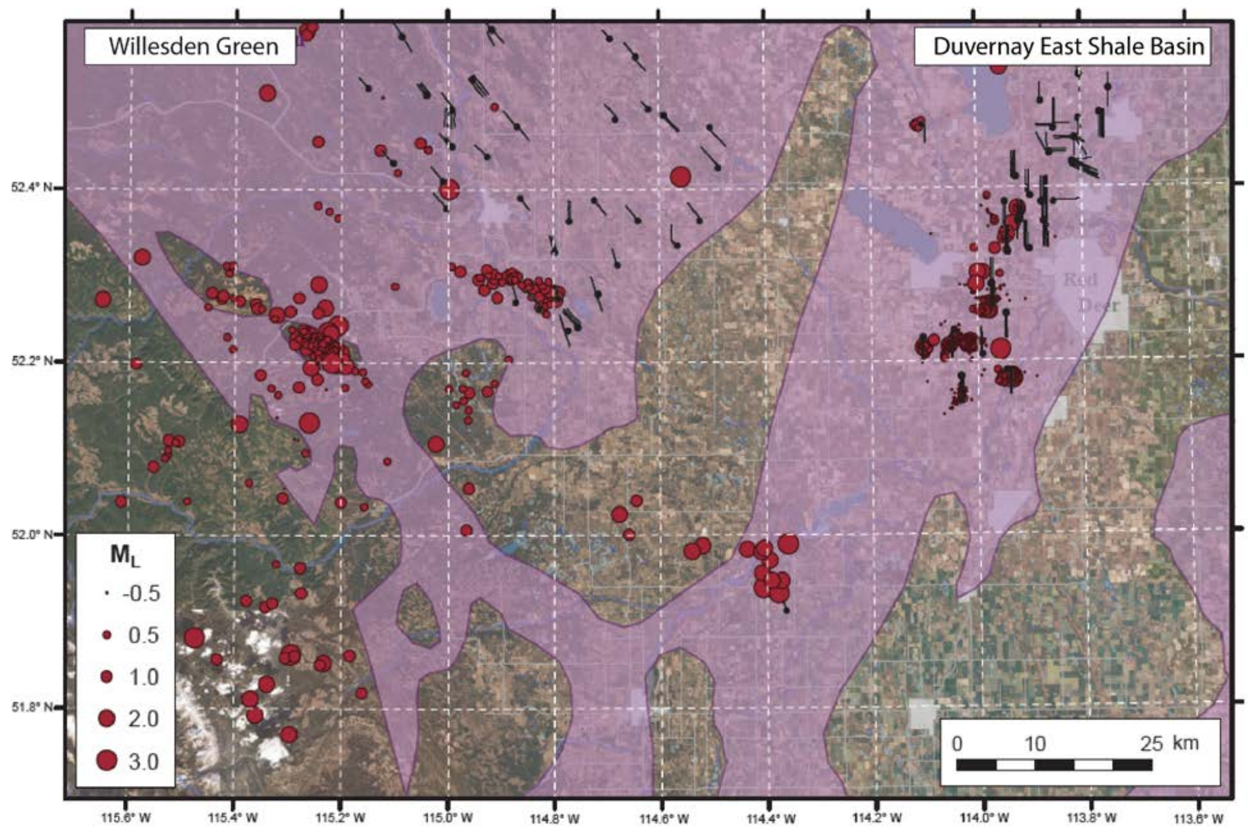

Figure 3. Map of seismicity in the Duvernay East Shale Basin and Willesden Green areas. Plotted are earthquakes from 2006 to March 2019 (red circles, scaled by magnitude), Duvernay hydraulic fracturing wells (black tadpoles), extent of the Duvernay Formation (purple area), and nearby towns (gray area). Earthquakes from the catalogue include all earthquakes with a hypocentre at a depth of 3 km or greater. Earthquake hypocentres are deeper within the western part of the map area; all noise considered to result from mining blasts were removed from the analyses.

Using a workflow similar to previous studies (Schultz et al., 2017; 2018), numerous events in this refined/supplemented catalogue were found to be associated with contemporaneous hydraulic fracturing completions. Many of the events in the Willesden Green area are likely induced by ongoing secondary recovery operations (Wetmiller, 1986; Baranova et al., 1999). On the other hand, many Duvernay ESB clusters are associated with hydraulic fracturing (Figure 4). Correlation between hydraulic fracturing operations and earthquake cluster timing was ascertained using statistical tests (Schultz and Telesca, 2018).

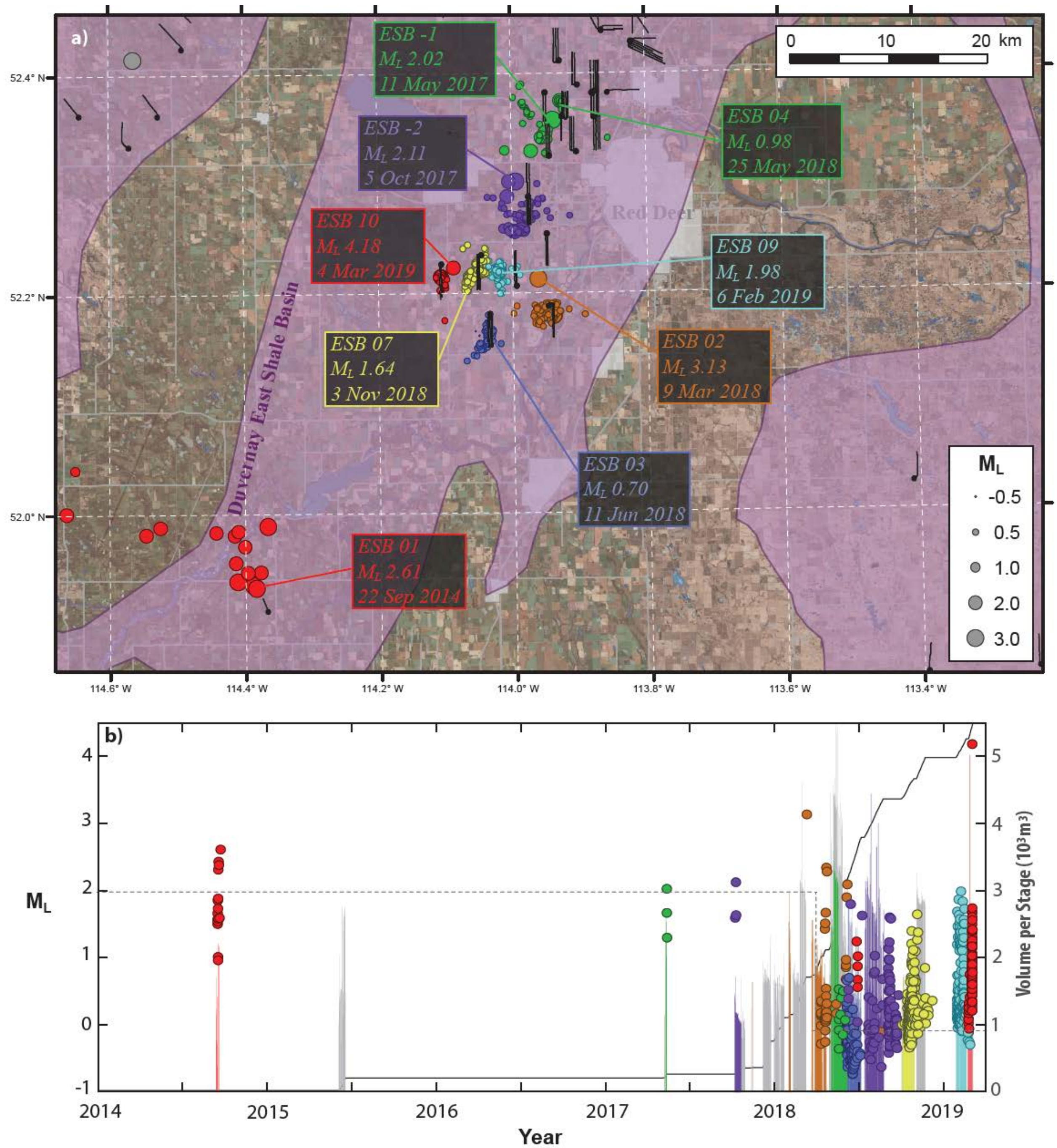

Figure 4. Seismicity in the Duvernay East Shale Basin near Red Deer. a) Map of earthquakes from 2006 through March 2019 (circles scaled by magnitude), Duvernay hydraulic fracturing wells(tadpoles), extent of the Duvernay Formation (purple areas), and nearby towns (gray areas). b) Timeline of earthquake magnitudes (circles) compared against volumes in stage completions (gray area) and fraction of cumulative volume used (black line). An observation of sudden, small magnitude earthquakes starting in early 2018 was possible because of the supplemental operator data. Hydraulic fracturing wells and earthquakes are colour coded by their associations in both panels.

Specifically, at least thirteen new clusters of induced earthquakes are recognized. The majority of these events would have remained undetected on the regional network (approximate detection threshold of M_L 2.0). In fact, the observation of clusters in early 2018 (during the acquisition of the supplemental data) allows for the association of previous seismicity in the region with prior hydraulic fracturing operations. For example, the M_L 3.13 event of 19 March 2018 (before the acquisition of supplemental data) likely was induced, as indicated by similarity in both timing and waveform to events in the nearby cluster (Figure 5). Most notable of this historical analysis, a case of induced earthquakes is recognized in the southwest corner of the Duvernay ESB in the fall of 2014. Preliminary analysis of this 2014 cluster appears to have similar characteristics to those observed near Fox Creek, in terms of total stimulation volume (per well) versus earthquake productivities. On the other hand, events near Red Deer appear to be related to higher volume-per-pad stimulations (Figure 4), which suggests a lower seismogenic index (i.e., less geological susceptibility) in these cases; however, more data will be required to make a more definitive assertion here.

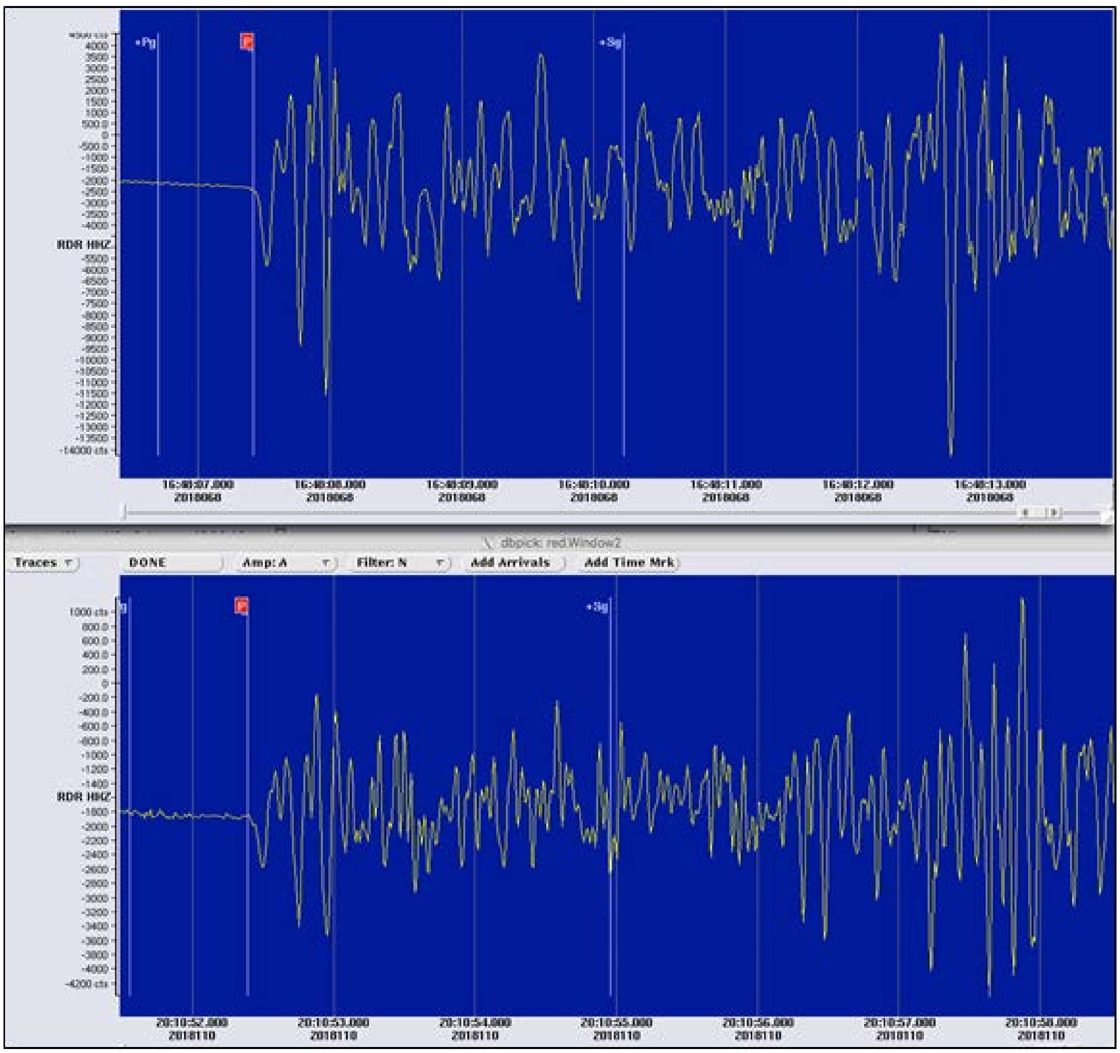

Figure 5. Waveform similarity of the M_L 3.13 to another nearby induced event. Top panel shows the P-wave arrival of the M_L 3.13 event on the vertical component. The bottom panel shows the P-wave arrival of the nearby M_L 2.34 event. Analogous motions are noted in the first several seconds after the P-wave arrival, suggesting similar location and fault motion.

Overall, the occurrence of seismicity in the Duvernay ESB, and its confirmation as induced events, places confidence in the seismogenic potential of this portion of the basin to cause events. Events in this region have been observed with magnitudes as large as M_L 4.18, with numerous other cases as large as M_L 2.0. Based on these findings we further consider the implications of this observation.

3 Well Log Analysis

Given the propensity for induced seismicity within the Duvernay ESB area, our next steps were to better understand why this region may be susceptible to these events through comparisons to other regions where geological proxies for seismogenic potential have been identified. For example, it was found that hydraulic fracturing induced earthquakes near Cardston were related to fluid flow along faults (Galloway et al., 2018). The presence of fluid flow along faults caused sporadic dissolution of Wabamun Group anhydrite, thinning these strata and eventually causing karst collapse contemporaneous with the deposition of the shales of the Exshaw Formation. A corollary to this dissolution is that areas of locally overthickened Exshaw Formation shale were spatially associated with geological conditions leading to increased seismogenic potential. Along this line of inquiry, we searched for anomalous thinning of anhydrite (in formations proximal to the Duvernay Formation within the stratigraphic succession) using available well log data. Unfortunately, well logs with depths penetrating formations with potential for anhydrite underlying the Duvernay are quite scarce. Instead, the thickness of the overlying Stettler Formation of the Wabamun Group (Figure 6) was used as a potential proxy to identify regions, which may deviate from the regional trend of anhydrite thickness, and coincide with hydraulic fracturing induced earthquake cases.

Despite the concession to instead use the better sampled Stettler Formation, this analysis did not yield spatial trends which were obviously related to earthquake locations. Likely this is still related to inadequate spatial resolution as a result of poorer sampling, if a relationship indeed exists.

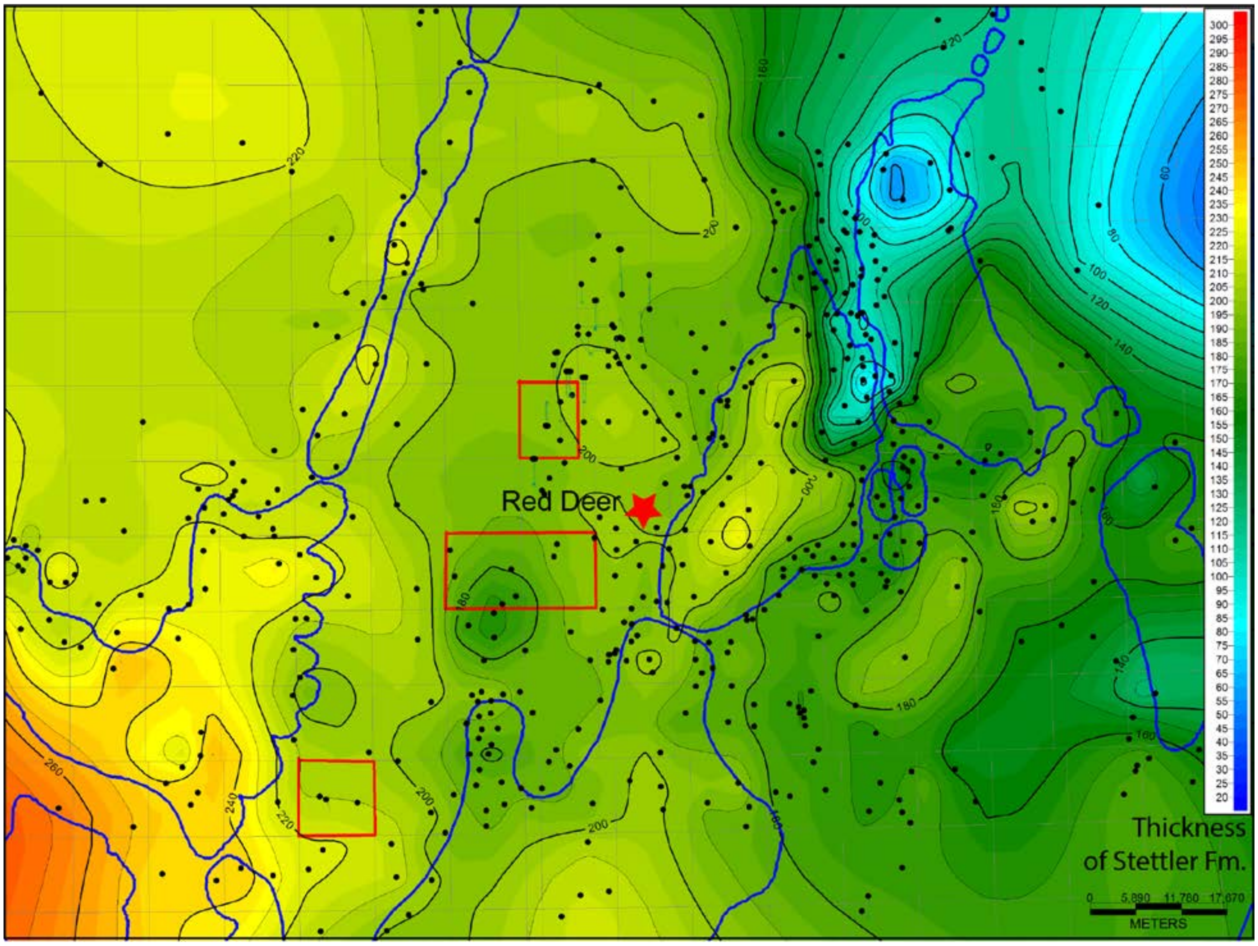

Figure 6. Map of Stettler Formation thickness (comprising predominantly anhydrite). Thicknesses from individual well logs (black dots) were interpolated (coloured area) to infer potential trends that indicate a geological susceptibility to induced earthquakes. Locations of the Leduc Formation reef margins (blue lines), areas experiencing induced earthquakes (red boxes), and the City of Red Deer (red star) are also shown.

4 Updates to the Geological Susceptibility Model

The occurrence of new earthquakes in the Duvernay ESB and Fox Creek areas provide new data and an opportunity to update the susceptibility model for induced seismic events. Originally, the geological susceptibility approach (Pawley et al., 2018) utilized a machine learning algorithm to predict which areas may be more prone to experiencing earthquakes. This model was based on associations of which injection wells did and did not cause earthquakes, coupled with the best available information on underlying geological features. This approach is being continually refined as many of the underlying features are incompletely known, new earthquake clusters continue to occur, the play continues to be developed, and our understanding of the triggering mechanisms of these earthquakes grows.

A versioning approach was adopted to update the geological susceptibility model, due to the addition of new data to inform the model (Schultz and Pawley, 2019). Updates to the model include: (i) new wells developed in the years since the first version of the model, (ii) newly identified clusters of induced earthquakes in the Fox Creek and ESB areas, and (iii) a new geological feature using the Leduc Formation reef edges analogous to prior work (Schultz et al., 2016). Full details of the changes and results are discussed in Schultz and Pawley (2019) and shown in Figure 7.

Overall, the versioning approach has allowed for the incorporation of the new Duvernay ESB events into the geological susceptibility model. The new version appears to more faithfully represent the Duvernay ESB cases that were previously unencountered. New to this version, the geological susceptibility model now appears to extrapolate more strongly to regions nearby the margins of the Leduc reefs (Figure 7), which could be important for future development of the play. Similar to seismological analysis of the Duvernay ESB, the susceptibility model still predicts a low (but non-zero) likelihood of events in this region. The interpretation of this is that large enough volumes used during hydraulic fracturing stimulations can allow for moderately seismogenic regions to produce felt events.

a) b)

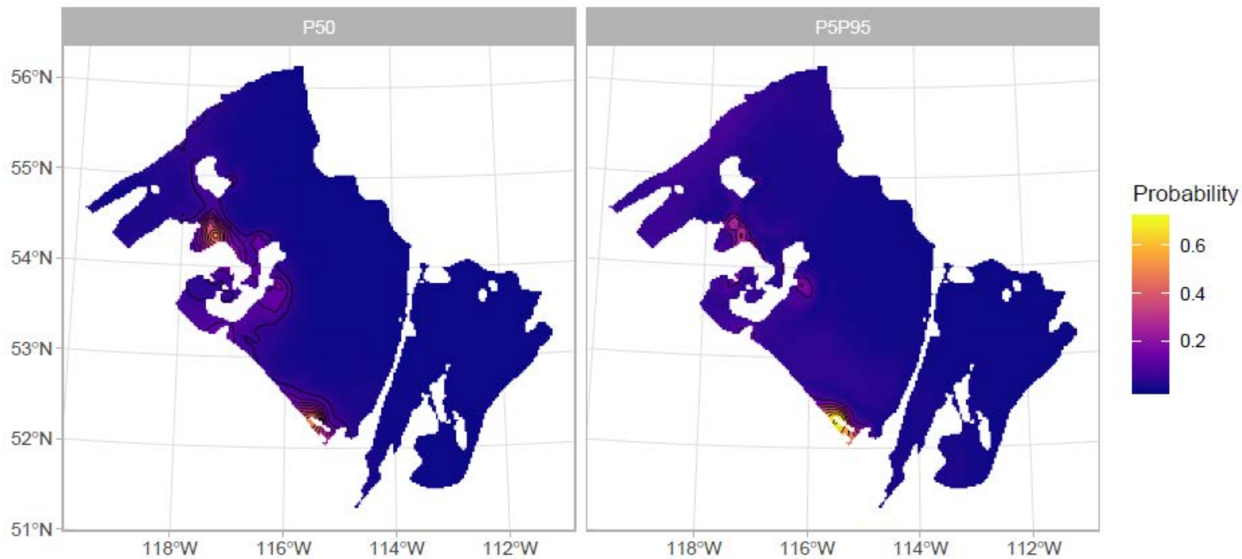

Figure 7. Seismogenic activation potential from the current geological susceptibility model (Schultz and Pawley, 2019). a) Median model values. b) Error in the model (difference between 5 and 95 percentiles).

5 Conclusions

In conclusion, this report outlines the developed learnings from the newly emerging cluster of earthquakes in the Duvernay ESB. Analysis of data suggested that the M_L 3.13 and 4.18 events were induced, and that other smaller clusters of events (up to ML 2.0) in the Duvernay ESB were also induced. A historical analysis also revealed a previously unidentified case of induced seismicity in 2014. These seismological results are being prepared for submission to a peer-reviewed journal (Schultz and Wang., in progress).

Attempts to define new geological features based on inferred hydrological concepts were hampered by sparse data. However, the geological susceptibility model was successfully updated to reflect the new information gained from this work, including new training data and one new geological feature. Detailed results of this work are published in an AGS OFR (Schultz and Pawley, 2019).

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