AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL067514

Key Points:
- Induced seismicity in Alberta is spatially correlated to a geological formation
- This spatial correlation is highly unlikely to be coincidental
- Correlation is interpreted as a result of geologically biased activation potential

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2

Correspondence to:
R. Schultz,
Ryan.Schultz@aer.ca

Citation:
Schultz, R., H. Corlett, K. Haug, K. Kocon, K. MacCormack, V. Stern, and T. Shipman (2016), Linking fossil reefs with earthquakes: Geologic insight to where induced seismicity occurs in Alberta, *Geophys. Res. Lett.*, *43*, 2534–2542, doi:10.1002/2015GL067514.

Received 19 DEC 2015
Accepted 22 FEB 2016
Accepted article online 26 FEB 2016
Published online 24 MAR 2016

Linking fossil reefs with earthquakes: Geologic insight to where induced seismicity occurs in Alberta

Ryan Schultz[1], Hilary Corlett[1], Kristine Haug[1], Ken Kocon[1], Kelsey MacCormack[1], Virginia Stern[1], and Todd Shipman[1]

[1]Alberta Geological Survey, Edmonton, Alberta, Canada

Abstract Recently, a significant increase in North American, midcontinent earthquakes has been associated with contemporaneous development of petroleum resources. Despite the proliferation of drilling throughout sedimentary basins worldwide, earthquakes are only induced at a small fraction of wells. In this study, we focus on cases of induced seismicity where high-resolution data are available in the central Western Canada Sedimentary Basin. Our regional comparison of induced earthquake depths suggests basement-controlled tectonics. Complementary to these findings, hypocenters of induced seismicity clusters coincide with the margins of Devonian carbonate reefs. We interpret this spatial correspondence as the result of geographically biased activation potential, possibly as a consequence of reef nucleation preference to paleobathymetric highs associated with Precambrian basement tectonics. This finding demonstrates the importance of geologic/tectonic factors to earthquake induction, in addition to industrial operational parameters. In fact, the observation of induced seismicity silhouetting deep fossil reef systems may be a useful tool to identify future regions with increased seismogenic potential.

1. Introduction

In the past several years North America has seen a marked increase in seismicity in stable, intraplate regions. This recent increase in seismicity has been shown to be largely associated with the development of unconventional resources, including wastewater disposal [*Weingarten et al*., 2015] and hydraulic fracturing [*Atkinson et al*., 2016]. In general, the process of anthropogenic alteration of crustal stresses resulting in the triggering of earthquakes is a well-documented phenomenon [*Healy et al*., 1968; *Raleigh et al*., 1976]. For example, during hydraulic fracturing operations small "microseismic" events (<0 M_w) are monitored to evaluate the efficacy of treatment programs intended to increase the permeability of the target reservoir rock [*Maxwell and Cipolla*, 2011]. However, operators have also noted cases where injection of fracturing fluid into larger faults that are favorably oriented for reactivation have induced earthquakes [*Maxwell et al*., 2010; *Wessels et al*., 2011], with some large enough to be felt or recorded on regional seismic networks [*Clarke et al*., 2014; *Friberg et al*., 2014; *Skoumal et al*., 2015; *Schultz et al*., 2015a, 2015b].

Problematic to the understanding of anthropogenic earthquake triggering is their apparent sporadic spatial distribution: often, regions undergoing comparable industrial activity will exhibit vast discrepancies in respondent earthquake rates [*Göbel*, 2015]. Local to the Western Canada Sedimentary Basin (WCSB), there have been well-documented cases of hydraulic fracturing-related [*BC Oil and Gas Commission*, 2012, 2014; *Schultz et al*., 2015a, 2015b], production-related [*Wetmiller*, 1986; *Baranova et al*., 1999], and injection-related [*Horner et al*., 1994; *Schultz et al*., 2014] seismicity (Figure 1a). Despite these case studies, it is still poorly understood why only a small fraction of well operations induce earthquakes, considering the proliferation of industry throughout the WCSB (Figure 1b). Furthermore, contrary to findings in the United States [*Weingarten et al*., 2015], disposal-related seismicity in the WCSB does not appear to be obviously related to high volume or rate. For example, one of the larger volume disposal wells [*Atkinson et al*., 2016] strongly associated with induced seismicity in Alberta [*Schultz et al*., 2014] averages 135 m^3/d with more than 10^6 m^3 of fluid disposed; both of these reported values are below the mean averages and more than an order of magnitude below maximum values for disposal wells in Alberta. To begin addressing these issues, we show that induced seismicity observed in the central WCSB occurs at depths that suggest reactivation of faults within the shallow basement and overlying basal sedimentary strata. Furthermore, our Monte Carlo

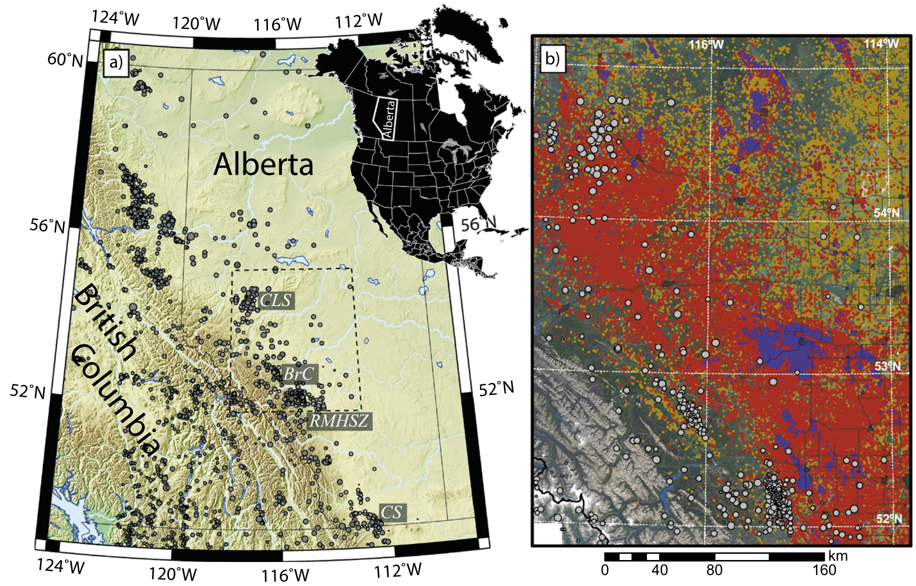

Figure 1. Locations of earthquakes in the WCSB versus locations of industrial activity. (a) The spatial distribution of conventionally located seismicity, both natural and induced (grey circles), in Alberta and British Columbia. Some regions previously associated with induced earthquakes have been labeled; see text for definition of induced earthquake cluster abbreviations. The dashed lines denote study area shown in Figure 1b. (b) The spatial clustering of earthquakes (grey circles) in contrast to nearly ubiquitous 30,000+ hydraulic fracturing wells (red dots), 5000+ disposal/injection wells (blue dots), and 20,000+ conventional production wells (orange dots) in the central WCSB.

simulations suggest that the spatial association between induced earthquakes and fossil reefs in the central WCSB is both statistically significant and most likely noncoincidental. We elaborate on the implications of earthquake-reef association by discussing geologically plausible interpretations to our results, such as the influence of basement faults on reef nucleation and diagenetic overprinting that may allow increased hydraulic communication with surrounding strata or structure. Overall, these results have potential implications for operators, regulators, and research institutions interested in the reduction of hazard related to induced seismicity as they provide first-order geologic considerations explaining why and where induced seismicity occurs at a regional scale.

2. Induced Seismicity in the Central WCSB

Historically, the WCSB has been seismically quiescent with rates in seismicity largely influenced by induced earthquakes [eg., *Atkinson et al.*, 2016]. Our study focuses on the regions of induced seismicity where high-quality data were available. The earliest and most prolific case is the Rocky Mountain House Seismogenic Zone (RMHSZ); this long-standing cluster was previously studied with a local, dense seismic array [*Wetmiller*, 1986] and was shown to be related to poroelastic changes in stress due to gas production in the Strachan D-3A Field [*Baranova et al.*, 1999]. The next long-lasting region of seismic activity is the Brazeau Cluster (BrC), which has been strongly connected with a nearby wastewater disposal well in the Cordel Field [*Schultz et al.*, 2014]. In addition, a transient swarm of earthquakes near the town of Cardston (CS), which were caused by hydraulic fracturing [*Schultz et al.*, 2015b], have been incorporated in our study. One of the most recent series of earthquakes in the central WCSB has been related to a series of hydraulic fracturing operations near Crooked Lake ($CLS_{1\text{-}5}$) [*Schultz et al.*, 2015a]. To date, the CLS continues to be seismically active, with some of the largest magnitude earthquakes associated with hydraulic fracturing ($CLS_{6\text{-}17}$). Lastly, we included the results of the most recent earthquake (9 August 2014 15:28:52 UTC) from the RMHSZ and its aftershock sequence, which is likely the continuation of the declining production-related seismicity in the region.

2.1. Depth Constraints

Within the current body of literature, the most prominent cases of induced seismicity are typically related to preexisting faults in the crystalline basement [*Kim*, 2013; *Friberg et al.*, 2014; *Keranen et al.*, 2014]. In studies

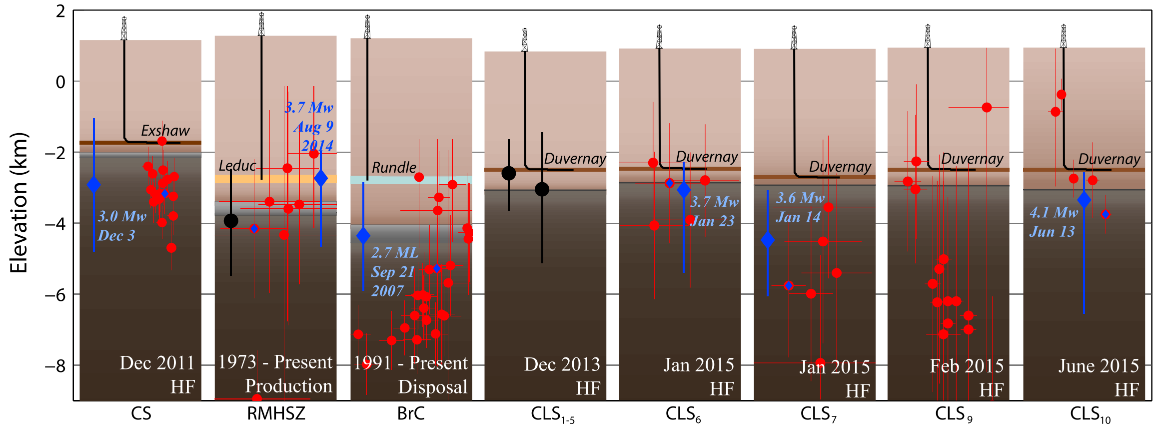

Figure 2. Compiled focal depths of induced earthquakes for various regions in the central WCSB. Stratigraphic columns indicate depth of target formations in relation to the crystalline basement (grey area indicates variability in the Precambrian top) for various source regions, associated induction method, and dates (highlighted at the bottom of individual columns). Earthquake depths are compared for various methods of determination: for double difference (red circles), waveform modeling of individual/beam-averaged seismic events (blue diamonds), and centroid averages of previous studies (black circles). In cases where both double-difference and waveform modeling results are available, the modeled earthquake's hypocenter is indicated (red circle with blue diamond overlaid). In cases where potential structure is observed in double-difference relocations, their depth distribution is plotted against apparent strike angle. Cross-hair span indicates error ellipses to one standard error. Note that horizontal locations of earthquakes and wells do not necessarily reflect their true geometry in relation to each other.

with hypocenters resolved on scales smaller than their faults, planar fault features have been observed trending from basal sedimentary formations where industrial activity takes place into the basement [*Hornbach et al.*, 2015]. In cases of injection-related seismicity, this is understood as the propagation of a high-pressure front, along the permeable damage zone of a mechanically active fault, to a nucleation zone at a point of fault weakness [*Zhang et al.*, 2013; *Segall and Lu*, 2015]. In this study, the locations of these relatively high magnitude earthquakes are constrained using both robust double-difference relocations [*Waldhauser and Ellsworth*, 2000] and waveform modeling [*Dreger*, 2003; *Wang et al.*, 2015b]. Double-difference relocations were determined robustly via a bootstrap process that randomly removes a fraction (10–20%) of the input catalogue before trial inversion [*Efron and Tibshirani*, 1986]. This process is iterated 1000 times so that the hypocenters may be observed as a statistical distribution. In previous studies with limited resolution [*Wetmiller*, 1986; *Schultz et al.*, 2015a], the entire cluster is reduced to a single centroid location, with error estimated from the standard deviation. Figure 2 shows the compilation of these depth constraints in the context of their local stratigraphy, where depths to the Precambrian basement were determined via formation top picks from adjacent wells and then modeled using convergent interpolation. Overall, there is a remarkable consistency among all methodologies, results, and studies throughout the central WCSB [e.g., *Zhang et al.*, 2016]. For example, the comparisons of depth determinations between the waveform-modeled events and the equivalent double-difference relocation agree within error in all cases (Figure 2). Furthermore, we also find that our results from the recent earthquake sequence at the RMHSZ (9 August 2014) agrees with the study of *Wetmiller* [1986], which utilized a dense array to constrain earthquake focal depths. These observations place confidence on the assertion that hypocenters are constrained in the Paleozoic sedimentary units and the shallow crystalline basement.

2.2. Coincidental Earthquake Locations?

The next spatial variable we consider is the lateral extent of induced earthquakes constrained via double-difference relocations. We utilize a spatial correlation as a metric to determine which geological formations are best related to the observed distribution of induced earthquakes. As a result of this analysis, our relocations of seismic clusters show a systematic association with the margins of the regional reef complexes. In fact, the best spatial correlation of earthquakes is in tandem with the Devonian Swan Hills Formation (R^2 0.850), the first/deepest stratigraphic interval containing reefs (Figure 3). Furthermore, we find that the robustly relocated clusters (RMHSZ, BrC, and $CLS_{1\text{-}17}$) are located within a narrow band around these fossil reef margins: no more than 10 km outside and 20 km inside the mapped edges. The extent of the Swan Hills platforms and banks in west central Alberta was most recently mapped using 1315 wells [*Wendte and Uyeno*, 2005] and subsequently updated in this study through the addition of wells along the depicted reef margins.

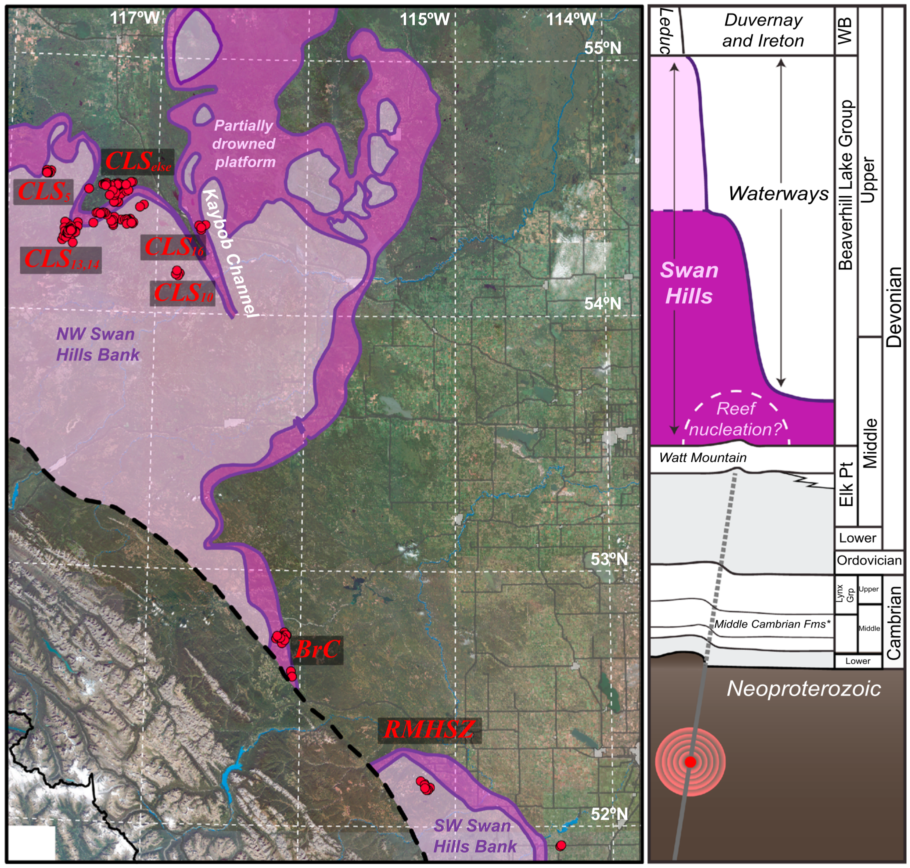

Figure 3. Spatial association of induced earthquakes with Devonian reefs. Epicenters of robustly located, induced earthquake clusters (red circles) are preferentially observed near the edges of the near-basement, Swan Hills Formation (pink/purple contoured area) (modified from *Wendte and Uyeno* [2005]). Black dashed line indicates the extent of the deformation edge of the Rocky Mountains and superimposed grey boxes reference local municipalities. Stratigraphic column describes the geological context of the Swan Hills Formation with respect to the crystalline basement, and the conceptual model relating the reef-rimmed margins of these carbonate platforms/banks to faults and induced seismicity.

To ascertain whether the apparent association between earthquake epicenters and the Swan Hills reef margins is statistically significant or simply a spurious observation, we computed Monte Carlo simulations. To date, the central WCSB has documented 19 sequences of induced earthquakes (RMHSZ, BrC, and $CLS_{1\text{-}17}$) associated with the previously mentioned oil and gas operations (Figure 3). Analogous to observation, our Monte Carlo procedure produces 10^6 randomly generated catalogues of 19 hypothetical induced earthquake clusters. During each iteration, the distances of hypothetical clusters were measured to the nearest Swan Hills Formation reef edge and the range of values was tabulated. The locations of these hypothetical clusters were based on the naïve assumption of random uniformly distributed earthquakes. In the parameters of this simulation we found that the odds of coincidentally inducing earthquakes exclusively in a narrow band around reef edges become vanishingly small ($\ll 10^{-6}$); i.e., the earthquake-reef association is statistically significant and highly likely to be the result of a spatially biased activation potential (Figure 4a).

To further investigate the nature of this biased activation potential, we consider the hypothesis that the spatial distribution of anthropogenic sources of induced seismicity can account for the apparent earthquake-reef association. Within the central WCSB study area, there have been more than 30,000 hydraulic fracturing operations, 5000 disposal/injection wells, and 20,000 conventional production wells documented (Figure 1b). With this information, we update our assumption of a uniformly distributed earthquake density to a more realistic prior distribution according to the kernel density of known conventional production, disposal, and hydraulic fracturing wells. Under these updated assumptions our simulations still recover statistical significance ($<10^{-6}$).

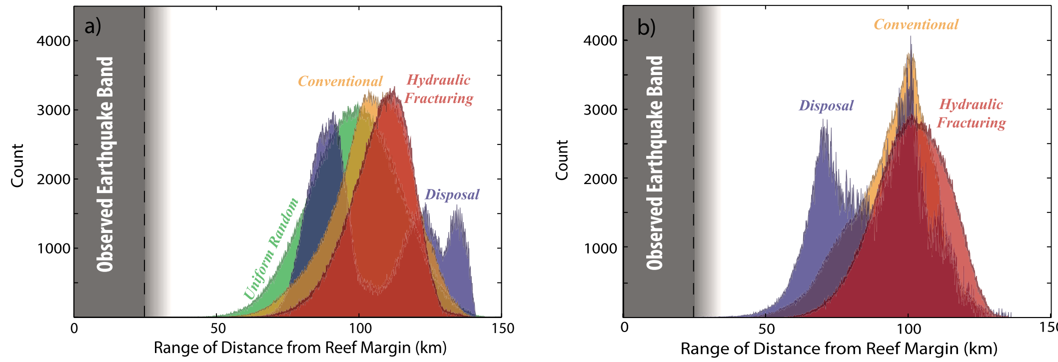

Figure 4. Monte Carlo simulation of earthquake-reef association. (a) Locations of trial earthquake clusters are selected randomly from a uniform distribution and prior distributions based on densities of hydraulic fracturing, disposal, and conventional production wells. In each trial (10^6 iterations) the range of distances from the edges of reefs was determined and compiled into a statistical distribution (labeled, colored area). The narrow band of observed earthquake-reef radial distances (grey area) occurs well into the noncoincidental tail ends of these distributions. (b) Monte Carlo simulations have been repeated, except only wells which are deeper than the sub-Cretaceous unconformity have been utilized in the prior distributions.

Often, cases of induced seismicity are associated with deeper, near-basement operations. Supporting this, hypocenters of induced seismicity in the central WCSB have been observed as restricted to the Paleozoic strata and the shallow basement (Figure 2). However, our previous Monte Carlo simulations implicitly assume that all wells, shallow or deep, have an equal chance of inducing seismicity. In this sense, the observed reef-earthquake association could simply be an artifact of deep wells being preferentially located along the reef margins. To test for potential spatial biases related to depth of operation, our Monte Carlo procedures are again repeated with perturbed kernel densities based on the distribution of wells meeting certain depth criteria. The first depth criterion is based on wells which are deeper than the sub-Cretaceous unconformity [*Peterson and MacCormack*, 2014], which on average occurs at 55% of the depth to basement in the study area. In keeping only wells deeper than this marker formation, we find that all Monte Carlo simulations still expect noncoincidental ($<10^{-5}$) distribution of events near the Swan Hills reef margins (Figure 4b). We continue this line of inquiry with subsequently deeper depth criteria (binned at 5% to basement intervals) to observe the effect on the likelihood of earthquake-reef association (Figure S1 in the supporting information). In these depth-perturbed tests, we find a general trend that coincidentally producing the observed earthquake-reef association becomes more likely with increasingly stringent depth criteria (Figure S2). Specifically, our most skeptical estimates place a confidence greater than 90% that the distribution of disposal or production wells will not result in the clustering of observed seismicity when considering only wells which are greater than 90% depth to basement. Potentially, these higher observational likelihoods from production and disposal are the result of these operations directly accessing the Swan Hills Formation or overlying Leduc Formation as a target reservoir at these deepest stratigraphic intervals. On the other hand, we note that the likelihood of inducing earthquakes exclusively around the margins of the Swan Hills reefs using the hydraulic fracturing kernel density is statistically significant for all depth criteria. Thus, we find that the earthquake-reef association is an unlikely observation even after accounting for the possibility of deeper wells being preferentially located nearby the subsurface reef.

3. Geological Considerations

Within the central WCSB we have shown that production-, disposal-, and hydraulic fracturing-related seismicity in the past four decades have shared two key features. First, the focal depths of robustly located induced earthquake clusters are consistent with the reactivation of preexisting possibly basement-controlled faults. Second, the lateral locations of earthquakes appear to show a statistically significant spatial association with the margins of the lowest stratigraphic interval of large fossil reef structures in the Swan Hills Formation. Furthermore, we have found that it is unlikely that this spatial association is entirely due to the distribution of anthropogenic activities such as hydraulic fracturing, disposal, and conventional production wells. Instead, within this section, we argue that these features may be interpreted as the result of a geologically biased activation potential. To support this argument, we discuss previous evidence that may influence the seismogenic potential including tectonic control on reef nucleation and fault-related diagenetic alteration of Devonian strata.

3.1. Fault-Reef Coupling

Although favorable conditions for reef growth have changed throughout time as the ocean underwent chemical and biological evolution, the nucleation point of many modern and ancient reefs is commonly thought to occur on preexisting bathymetric highs [*James and Wood*, 2010; *James and Jones*, 2016]. For example, modern coral reefs of significant size in the Red Sea and Belize margin coincide almost entirely with fault block edges [*Purdy and Gischler*, 2003; *Purkis et al*., 2012]. Although the physiological requirements for the growth of ancient reefs are not clearly understood, fault-reef coupling analogous to modern coral reefs has been observed in the Devonian of the Canning Basin in Australia, where the Lennard Shelf reef complex initiated on tilted basement blocks [*George et al*., 2009].

Consistent with this reasoning, we have inferred the presence of several near-basement faults in the central WCSB via induced seismicity (Figure 2). Furthermore, these inferred faults are spatially associated with the margins of the Devonian Swan Hills reef complexes (Figure 3) and our Monte Carlo simulations have determined that this spatial association is unlikely to be merely coincidental (Figure 4). Supporting our observations, fault-reef coupling during the Devonian in the WCSB has previously been suggested [*Andrichuk*, 1961; *Klovan*, 1974; *Mountjoy*, 1980; *Moore*, 1989; *Edwards and Brown*, 1999]. At a regional scale, the proximity and alignment of reefs with well-established structurally complex features such as the Peace River Arch supports their association with preexisting structure that may have the propensity for reactivation [*Ross and Eaton*, 1999]. For example, seismic reflection studies and gravity anomaly maps in the central WCSB have inferred cases of basement control on reef nucleation over deep-seated structures [*Eaton et al*., 1995; *Eaton et al*., 1999; *Edwards and Brown*, 1999]. Specific to the Swan Hills Formation, at least two NW-SE trending faults have been previously identified on reflection seismic in the Kaybob and Fox Creek fields adjacent to the deep marine NW-SE trending Kaybob Channel (Figure 3) [*Mountjoy et al*., 1999]. While to date no reef-nucleating basement faults have been published in the areas of the observed seismicity, the above observations support a geologically plausible explanation for the statistically significant association between the Swan Hills Formation and induced earthquakes via basement-controlled faults which may be reactivated by anthropogenic activity.

However, in addition to observations of systematic spatial association, we bring to the reader's attention regions along the Swan Hills reef margins which have remained seismically quiescent to date (Figure 3). While our results have suggested an apparent earthquake preference for these regions, we do not mean to suggest that the entirety of the Swan Hills platform margin has been controlled or is underlain by faults that have the propensity for reactivation. Likely, paleobathymetric highs suitable for reef nucleation were influenced by erosion, depositional architecture, differential compaction, prior reef buildups, or favorable environmental conditions in addition to tectonic controls. In fact, studies have suggested some of these additional controls from the detection of broad antiforms in underlying strata [*Eaton et al*., 1999] or prereef deltaic deposition [*Jansa and Fischbuch*, 1974; *Ferry*, 1989], where the influence of tectonics on these earlier sedimentation patterns is unclear. In addition to these geological complexities, geomechanical and hydrological conditions are also thought to play a role in determining if induced seismicity is expressed. For example, there are likely cases in the study region where the margins of the Swan Hills reefs may be associated with faults that are either poorly oriented for reactivation in today's stress field, or simply lack a viable means to transmit stress perturbations to a zone of fault weakness. We note that higher resolution geophysical surveys would be required to more adequately address this issue.

3.2. Hydraulic Communication via Faults

Given a preexisting, near-failure fault, the geomechanics of seismic event nucleation requires a means of in situ stress change via pore pressure perturbation or poroelastic transmission of stress [*Segall and Lu*, 2015]. In the large majority of cases studied here, injection-related changes in stress due to increased pore pressure have been suspected as the cause of induced earthquakes (CLS and BrC), assuming a conduit of hydraulic communication between the target formation and inferred fault [*Schultz et al*., 2014, 2015a]. Corroborating this story, Devonian reef complexes in the WCSB have undergone postdepositional diagenetic alteration from limestone to dolomite [*Kaufman et al*., 1991; *Machel*, 2004; *Davies and Smith*, 2006], a process that requires significant volumes of Mg-rich fluids. In fact, dolomitization of several reefs has been previously observed proximal to the identified seismic events in the study area [*Duggan et al*., 2001; *Green and Mountjoy*, 2005]. In these cases, deep-seated faults have been suggested as transport conduits of the Mg-enriched fluid necessary for the postdepositional dolomitization. For example, within the Swan Hills Formation in the Simonette Field, a "plume-like" dolomite geobody with a radiogenic signature indicative of basement fluid influence was identified adjacent to faults that intersect the Precambrian [*Duggan et al*., 2001]. This potential for basement related fluid transport supports the plausibility of hydraulic communication between faults and overlying sedimentary strata in the past [*Machel et al*., 2000; *Eccles and Berhane*, 2011], a necessary condition for injection-related induced earthquakes.

3.3. Influence of Dolomitization on Reef Porosity and Permeability

In addition, dolomitization of Devonian limestone strata in the WCSB has the potential for local permeability enhancement and has been an important aspect of successful conventional production in these strata. In Devonian reefs, such as those of the Swan Hills platform, large molds and vugs (centimeter scale) are commonly observed where large reef-building body fossils have been dissolved [*Kaufman et al*., 1991]. Dolomitization of the limestone matrix in the reefs helped to preserve the molds during burial as dolomite is less susceptible to pressure solution [*Sun*, 1995]. Direct replacement of matrix limestone mud to dolomite can result in a substantial (13%) increase in interparticle or intercrystalline porosity, effectively enhancing permeability in dolomitized strata [*Machel*, 2004]. Swan Hills reefs at Rosevear and Hanlan fields have undergone a similar diagenetic history to the CLS study area [*Walls and Burrowes*, 1990; *Saller et al*., 2001] and dolomite reservoirs in these fields are characterized by significantly higher porosities (2–5 times) and permeabilities (2–63 times) than their limestone counterparts [*Saller et al*., 2001; *Atchley et al*., 2008]. Both the Swan Hills Formation platform and the overlying Leduc Formation reefs have been preferentially dolomitized around faults (CLS) and in the vicinity of the induced seismic events [*Duggan et al*., 2001; *Green and Mountjoy*, 2005]. Permeability-enhanced dolomitized strata could allow for greater diffusivity of pore pressure during injection-related operations, thus increasing the likelihood of significant pore pressure perturbations intersecting a critically stressed fault. We note that well-sampled petrophysical surveys would be required to more adequately address this issue.

4. Summary

Overall, the novel finding that induced earthquakes are colocated with fossil reef structures is important as it provides evidence that regional- and local-scale geological factors likely play a role in the nature of induced seismicity. Second, it strengthens two arguments within the context of the central WCSB: (1) reef growth during the Devonian period may have nucleated on elevated structures associated with basement tectonics and (2) Paleozoic and Precambrian strata are likely in hydraulic communication in some of these areas. We speculate that consideration of this result, coupled with extensive mapping of carbonate reef complexes [*Wendte and Uyeno*, 2005], constraints on the ambient regional stress field [*Reiter et al*., 2014], and high-resolution geophysical surveys [*Hope et al*., 1999] could allow for the anticipation of regions with potential for seismic hazard in the WCSB. Operations in the basal sedimentary succession within the vicinity of fossil reef systems in analogous basins may wish to more closely scrutinize the local tectonics with respect to the ambient stress field. And, in cases where nearby critically stressed faults or strata affected by diagenesis are observed or suspected, greater emphasis can be placed on applicable mitigation/diversion strategies. We caution against the overinterpretation of our findings: reef systems tend to nucleate on bathymetric highs in the geologic past, not all of which may be associated with seismogenic faults. We also acknowledge that suitably oriented, critically stressed faults located outside areas of ancient reef growth likely also exist. Overall, these considerations highlight the ongoing need to better understand the interplay between operational parameters such as injection pressure, volume [*McGarr*, 2014], and rate [*Weingarten et al*., 2015] complementary to tectonic parameters also thought to control induced seismicity, e.g., effective proximity to crystalline basement [*Zhang et al*., 2013], and the existence of fault systems in a critically stressed state [*Wang et al*., 2015a]. In conclusion, the finding that induced seismic events are spatially associated with fossil reef structures, which may have nucleated on basement-controlled faults, contributes a new aspect to the discussion of where and why induced seismicity occurs.

Acknowledgments
We would like to thank Dinu Pană for insightful conversations which helped improve the quality of this manuscript as well as the comments from two anonymous reviewers during the revision process. As well, we thank the operators of the seismic networks for their data, including the Regional Alberta Observatory for Earthquake Studies Network [*Alberta Geological Survey* (*Canada*), 2013], the TransAlta Dam Network, the Canadian National Seismic Network, the Canadian Rockies and Alberta Network [*Gu et al*., 1968], and the Alberta Telemetered Seismic Network [*Eaton*, 2014]. These data are routinely analyzed and catalogued at the Alberta Geological Survey [*Stern et al*., 1995]. Robust determinations of hypocentral parameters were performed using double-difference relocation (HypoDD) and waveform modeling (TDMT). Background SPOT6 satellite imagery used in figures was licensed by BlackBridge Geomatics Corp., www.blackbridge.com.

References

Alberta Geological Survey (Canada) (2013), Regional Alberta Seismic Observatory for Earthquake Studies Network, International Federation of Digital Seismograph Networks, Other/Seismic Network, doi:10.7914/SN/RV.

Andrichuk, J. M. (1961), Stratigraphic evidence for tectonic and current control of Upper Devonian reef sedimentation, Duhamel area, Alberta, Canada, *AAPG Bull*., *45*(5), 612–632.

Atchley, S. C., D. M. Cleveland, and L. W. West (2008), A case for renewed development of a mature gas field: The Devonian Swan Hills Formation at Kaybob South field, Alberta, Canada, *Bull. Can. Petrol. Geol*., *56*(2), 165–190, doi:10.2113/gscpgbull.56.2.165.

Atkinson, G. M., et al. (2016), Hydraulic fracturing and seismicity in the Western Canada Sedimentary Basin, *Seismol. Res. Lett*., doi:10.1785/0220150263, in press.

Baranova, V., A. Mustaqeem, and S. Bell (1999), A model for induced seismicity caused by hydrocarbon production in the Western Canada Sedimentary Basin, *Can. J. Earth Sci*., *36*(1), 47–64, doi:10.1139/e98-080.

BC Oil and Gas Commission (2012), Investigation of observed seismicity in the Horn River Basin, 29 pp. [Available at http://www.bcogc.ca/document. aspx?documentID = 1270.]

BC Oil and Gas Commission (2014), Investigation of observed seismicity in the Montney trend, 32 pp. [Available at http://www.bcogc.ca/sites/default/files/documentation/technical-reports/investigation-observed-seismicity-montney-trend.pdf.]

Clarke, H., L. Eisner, P. Styles, and P. Turner (2014), Felt seismicity associated with shale gas hydraulic fracturing: The first documented example in Europe, *Geophys. Res. Lett*., *41*, 8308–8314, doi:10.1002/2014GL062047.

Davies, G. R., and L. B. Smith Jr. (2006), Structurally controlled hydrothermal dolomite reservoir facies: An overview, *AAPG Bull*., *90*, 1641–1690, doi:10.1306/05220605164.

Dreger, D. S. (2003), TDMT_INV: Time Domain seismic Moment Tensor INVersion, in *International Handbook of Earthquake Engineering Seismology*, vol. 81B, 1627 pp., Academic Press, London, U. K.

Duggan, J. P., E. W. Mountjoy, and L. D. Stasiuk (2001), Fault-controlled dolomitization at Swan Hills Simonette oil field (Devonian), deep basin west-central Alberta, Canada, *Sedimentology*, *48*(2), 301–323, doi:10.1046/j.1365-3091.2001.00364.x.

Eaton, D. (2014), Alberta Telemetered Seismograph Network (ATSN): Real-time monitoring of seismicity in northern Alberta, *CSEG Rec*., *39*(3), 30–33.

Eaton, D. W., B. Milkereit, G. M. Ross, E. R. Kanasewich, W. Geis, D. J. Edwards, L. Kelsch, and J. Varsek (1995), Lithoprobe basin-scale seismic profiling in central Alberta: Influence of basement on the sedimentary cover, *Bull. Can. Petrol. Geol*., *43*(1), 65–77.

Eaton, D. W., G. M. Ross, and J. Hope (1999), The rise and fall of a cratonic arch: A regional seismic perspective on the Peace River Arch, Alberta, *Bull. Can. Petrol. Geol*., *47*, 346–361.

Eccles, D. R., and H. Berhane (2011), Geological introduction to lithium-rich formation water with emphasis on the Fox Creek area of west-central Alberta (NTS 83°F and 83°K), Energy Resources Conservation Board, ERCB/AGS Open File Rep. 2011-10, 22 p.

Edwards, D. J., and R. J. Brown (1999), Understanding the influence of Precambrian crystalline basement on Upper Devonian carbonates in central Alberta from a geophysical perspective, *Bull. Can. Petrol. Geol*., *47*(4), 412–438.

Efron, B., and R. Tibshirani (1986), Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy, *Stat. Sci*., *1*(1), 54–75, doi:10.1214/ss/1177013815.

Ferry, R. M. (1989), Beaverhill Lake Group carbonate reservoirs, in *Geophysical Atlas of Western Canadian Hydrocarbon Pools*, edited by N. L. Anderson, L. V. Hills, and D. A. Cederwall, pp. 67–100, Can. Soc. of Explor. Geophys. and Can. Soc. of Petrol. Geol.

Friberg, P. A., G. M. Besana-Ostman, and I. Dricker (2014), Characterization of an earthquake sequence triggered by hydraulic fracturing in Harrison County, Ohio, *Seismol. Res. Lett*., *85*(2), 462, doi:10.1785/0220140127.

George, A. D., N. Chow, and K. M. Trinajstic (2009), Syndepositional fault control on lower Frasnian platform evolution, Lennard Shelf, Canning Basin, Australia, *Geology*, *37*(4), 331–334, doi:10.1130/G25461A.1.

Göbel, T. (2015), A comparison of seismicity rates and fluid-injection operations in Oklahoma and California: Implications for crustal stresses, *Lead. Edge*, *34*(6), 640–648, doi:10.1190/tle34060640.1.

Green, D., and E. Mountjoy (2005), Fault and conduit controlled burial dolomitization of the Devonian west-central Alberta Deep Basin, *Bull. Can. Petrol. Geol*., *53*(2), 101–129.

Gu, Y. J., A. Okeler, L. Shen, and S. Contenti (2011), The Canadian Rockies and Alberta Network (CRANE): New constraints on the Rockies and Western Canada Sedimentary Basin, *Seismol. Res. Lett*., *82*, 575–588, doi:10.1785/gssrl.82.4.575.

Healy, J. T., W. W. Rubey, D. T. Griggs, and C. B. Raleigh (1968), The Denver earthquakes, *Science*, *161*, 1301–1310, doi:10.1126/science.161.3848.1301.

Hope, J., D. W. Eaton, and G. M. Ross (1999), Lithoprobe seismic transect of the Alberta Basin: Compilation and overview, *Bull. Can. Petrol. Geol*., *47*(4), 331–345.

Hornbach, M. J., et al. (2015), Causal factors for seismicity near Azle, Texas, *Nat. Commun*., *6*, 6728, doi:10.1038/ncomms7728.

Horner, R. B., J. E. Barclay, and J. M. MacRae (1994), Earthquakes and hydrocarbon production in the Fort St. John area of northeastern British Columbia, *Can. J. Explor. Geophys*., *30*(1), 39–50.

James, N. E., and R. A. Wood (2010), Reefs and reef mounds, in *Facies Models, 4. Geological Association of Canada*, edited by R. W. Dalrymple and N. P. James, pp. 421–447, St. Johns, Newfoundland.

James, N. P., and B. Jones (2016), Modern reefs, in *Origin of Carbonate Sedimentary Rocks*, pp. 179–191, Wiley, West Sussex.

Jansa, L. F., and N. R. Fischbuch (1974), Evolution of a Middle and Upper Devonian sequence from a clastic coastal plaindeltaic complex into overlying carbonate reef complexes and banks, Sturgeon-Mitsue area, Alberta, *Geol. Surv. Can. Bull*., *234*, 1–105.

Kaufman, J., G. N. Hanson, and W. J. Meyers (1991), Dolomitization of the Devonian Swan Hills Formation, Rosevear Field, Alberta, Canada, *Sedimentology*, *38*(1), 41–66, doi:10.1111/j.1365-3091.1991.tb01854.x.

Keranen, K. M., M. Weingarten, G. A. Abers, B. A. Bekins, and S. Ge (2014), Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection, *Science*, *345*(6195), 448–451, doi:10.1126/science.1255802.

Kim, W. Y. (2013), Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio, *J. Geophys. Res. Solid Earth*, *118*, 3506–3518, doi:10.1002/jgrb.50247.

Klovan, J. E. (1974), Development of Western Canadian Devonian reefs and comparison with Holocene analogues, *Am. Assoc. Petrol. Geol. Bull*., *58*(5), 787–799.

Machel, H. G. (2004), Concepts and models of dolomitization: A critical reappraisal, in *The Geometry and Petrogenesis of Dolomite Hydrocarbon Reservoirs*, *Geol. Soc. Lond., Spec. Publ*., vol. 235, edited by C. J. R. Braithwaite, G. Rizzi, and G. Darke, pp. 7–63, Geol. Soc., London, doi:10.1144/GSL.SP.2004.235.01.02.

Machel, H. G., P. A. Cavell, B. E. Buschkuehle, and K. Michael (2000), Tectonically induced fluid flow in Devonian carbonate aquifers of the Western Canada Sedimentary Basin, *J. Geochem. Explor*., *69*, 213–217, doi:10.1016/S0375-6742(00)00093-5.

Maxwell, S. C., and C. L. Cipolla (2011), What does microseismicity tell us about hydraulic fracturing?, in *SPE Annual Technical Conference and Exhibition*, 14 pp., Soc. of Petrol. Eng., Denver, Colo., doi:10.2118/146932-MS.

Maxwell, S. C., M. Jones, R. Parker, S. Leaney, M. Mack, D. Dorvall, D. D'Amico, J. Logel, E. Anderson, and K. Hammermaster (2010), Fault activation during hydraulic fracturing, in *72nd EAGE Conference & Exhibition*, 9 pp., Barcelona, Spain.

McGarr, A. (2014), Maximum magnitude earthquakes induced by fluid injection, *J. Geophys. Res. Solid Earth*, *119*, 1008–1019, doi:10.1002/2013JB010597.

Moore, P. F. (1989), Devonian reefs in Canada and some adjacent areas, in *Reefs—Canada and Adjacent Areas*, *Canadian Society of Petroleum Geologists Memoir*, vol. 13, edited by H. H. J. Geldsetzer, N. P. James, and G. E. Tebbutt, pp. 367–390, Can. Soc. of Petrol. Geol., Calgary, Alberta, Canada.

Mountjoy, E. W. (1980), Some questions about the development of Upper Devonian carbonate buildups (reefs), western Canada, *Bull. Can. Petrol. Geol.*, *28*, 315–344.

Mountjoy, E. W., H. G. Machel, D. Green, J. Duggan, and A. E. Williams-Jones (1999), Devonian matrix dolomites and deep burial carbonate cements: A comparison between the Rimbey-Meadowbrook reef trend and the deep basin of west-central Alberta, *Bull. Can. Petrol. Geol.*, *47*(4), 487–509.

Peterson, J., and K. E. MacCormack (2014), Paleotopography of the sub-Cretaceous unconformity surface, west central, Alberta (NTS 83°F, 83G, 83 J, and 83°K), Alberta Energy Regulator, AER/AGS Map 573, scale 1:500,000.

Purdy, E. G., and E. Gischler (2003), The Belize margin revisited: 1. Holocene marine facies, *Int. J. Earth Sci. (Geol. Rundsch.)*, *92*, 532–551, doi:10.1007/s00531-003-0324-0.

Purkis, S. J., P. M. M. Harris, and J. Ellis (2012), Patterns of sedimentation in the contemporary Red Sea as an analog for ancient carbonates in rift settings, *J. Sediment. Res.*, *82*(11), 859–870, doi:10.2110/jsr.2012.77.

Raleigh, C. B., J. H. Healy, and J. D. Bredehoeft (1976), An experiment in earthquake control at Rangley, Colorado, *Science*, *191*, 1230–1237, doi:10.1126/science.191.4233.1230.

Reiter, K., O. Heidbach, D. Schmitt, K. Haug, M. Ziegler, and I. Moeck (2014), A revised crustal stress orientation database for Canada, *Tectonophysics*, *636*, 111–124, doi:10.1016/j.tecto.2014.08.006.

Ross, G. M., and D. W. Eaton (1999), Basement reactivation in the Alberta Basin: Observational constraints and mechanical rationale, *Bull. Can. Petrol. Geol.*, *47*(4), 391–411.

Saller, A. H., K. Lounsbury, and M. Birchard (2001), Facies control on dolomitization and porosity in the Devonian Swan Hills Formation in the Rosevear area, west-central Alberta, *Bull. Can. Petrol. Geol.*, *49*, 458–471, doi:10.2113/49.4.458.

Schultz, R., V. Stern, and Y. J. Gu (2014), An investigation of seismicity clustered near the Cordel Field, west central Alberta, and its relation to a nearby disposal well, *J. Geophys. Res. Solid Earth*, *119*, 3410–3423, doi:10.1002/2013JB010836.

Schultz, R., V. Stern, M. Novakovic, G. Atkinson, and Y. J. Gu (2015a), Hydraulic fracturing and the Crooked Lake Sequences: Insights gleaned from regional seismic networks, *Geophys. Res. Lett.*, *42*, 2750–2758, doi:10.1002/2015GL063455.

Schultz, R., S. Mei, D. Pană, V. Stern, Y. J. Gu, A. Kim, and D. Eaton (2015b), The Cardston earthquake swarm and hydraulic fracturing of the Exshaw Formation (Alberta Bakken play), *Bull. Seismol. Soc. Am.*, *105*(6), doi:10.1785/0120150131.

Segall, P., and S. Lu (2015), Injection-induced seismicity: Poroelastic and earthquake nucleation effects, *J. Geophys. Res. Solid Earth*, *120*, 5082–5103, doi:10.1002/2015JB012060.

Skoumal, R. J., M. R. Brudzinski, and B. S. Currie (2015), Earthquakes induced by hydraulic fracturing in Poland Township, Ohio, *Bull. Seismol. Soc. Am.*, *105*, 189–197, doi:10.1785/0120140168.

Stern, V. H., R. J. Schultz, L. Shen, Y. J. Gu, and D. W. Eaton (2013), Alberta earthquake catalogue, version 1.0: September 2006 through December 2010, Alberta Geol. Surv. Open File Rep., 2013–15, 36 pp.

Sun, S. Q. (1995), Dolomite reservoirs: Porosity evolution and reservoir characteristics, *AAPG Bull.*, *79*, 186–204.

Waldhauser, F., and W. L. Ellsworth (2000), A double difference earthquakes location algorithm: Method and application to the northern Hayward fault, California, *Bull. Seismol. Soc. Am.*, *90*, 1353–1368, doi:10.1785/0120000006.

Walls, R. A., and O. G. Burrowes (1990), Diagenesis and reservoir development in Devonian limestone and dolostone reefs of Western Canada, in *The Development of Porosity in Carbonate Reservoirs*, *Canadian Society of Petroleum Geologists, Continuing Education Short Course Notes*, section 7, edited by G. R. Bloy and M. G. Hadley (comps.), pp. 1–13, Can. Soc. of Petrol. Geol., Calgary, Alberta, Canada.

Wang, B., R. M. Harrington, Y. Liu, H. Yu, A. Carey, and N. J. Elst (2015a), Isolated cases of remote dynamic triggering in Canada detected using cataloged earthquakes combined with a matched-filter approach, *Geophys. Res. Lett.*, *42*, 5187–5196, doi:10.1002/2015GL064377.

Wang, R., Y. J. Gu, R. Schultz, A. Kim, and G. Atkinson (2015b), Source analysis of a potential hydraulic fracturing induced earthquake near Fox Creek, Alberta, *Geophys. Res. Lett.*, *43*, 564–573, doi:10.1002/2015GL066917.

Weingarten, M., S. Ge, J. W. Godt, B. A. Bekins, and J. L. Rubinstein (2015), High-rate injection is associated with the increase in US mid-continent seismicity, *Science*, *348*(6241), 1336–1340, doi:10.1126/science.aab1345.

Wendte, J. C., and T. Uyeno (2005), Sequence stratigraphy and evolution of Middle to Upper Devonian Beaverhill Lake strata, south-central Alberta, *Bull. Can. Petrol. Geol.*, *53*, 250–354.

Wessels, S. A., A. De La Pena, M. Kratz, S. Williams-Stroud, and T. Jbeili (2011), Identifying faults and fractures in unconventional reservoirs through microseismic monitoring, *First Break*, *29*(7), 99–104.

Wetmiller, R. J. (1986), Earthquakes near Rocky Mountain House, Alberta, and their relationship to gas production facilities, *Can. J. Earth Sci.*, *23*, 172–181, doi:10.1139/e86-020.

Zhang, H., D. Eaton, R. Harrington, and Y. Liu (2016), Discriminating induced seismicity from natural earthquakes using moment tensors and source spectra, *J. Geophys. Res. Solid Earth*, *121*, doi:10.1002/2015JB012603.

Zhang, Y., et al. (2013), Hydrogeologic controls on induced seismicity in crystalline basement rocks due to fluid injection into basal reservoirs, *Groundwater*, *51*(4), 525–538, doi:10.1111/gwat.12071.