geoconvention
Calgary • Canada • May 13-17 2019

Connecting fluid-flow along faults to hydraulic fracturing induced seismicity: an integrated geoscience study

Elwyn Galloway[1], Tyler Hauck[1], Hilary Corlett[2], Dinu Pana[1], Ryan Schultz[1]
[1]Alberta Geological Survey, Alberta Energy Regulator; and [2]Department of Physical Sciences, MacEwan University

Summary

A swarm of moderate-magnitude earthquakes was induced by hydraulic fracturing (HF) in 2011, near Cardston, Alberta. Though the cause of the earthquakes was not in question, the mechanism(s) linking the HF to the earthquakes was not clear. This geoscience study combines insights from earthquake seismology, seismic geophysics, and geology to identify the factors that contributed to the seismicity observed in this case. We demonstrate that conduits of paleo-fluid-flow communicated HF pressure a great distance, triggering movement along a basement-rooted fault ~1.5 km below the Stettler—Big Valley Reservoir zone. The revelation that paleo-hydrology can influence present-day susceptibility to HF-induced seismicity suggests another geological factor that should be utilized to avoid earthquake hazards.

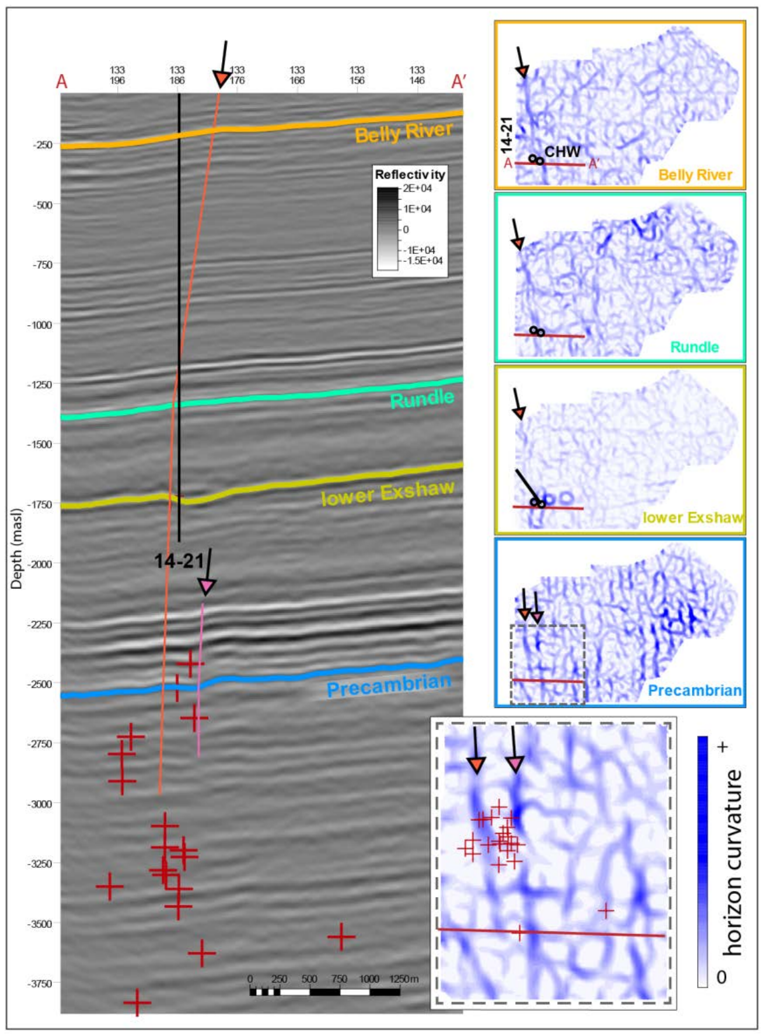

Figure 1. Interpreted 3D reflection-seismic cross-line (Left). Locations of earthquakes (red crosses), the 100/14-21-004-25W4 vertical well (black line), stratigraphic markers (subhorizontal colored lines), and lineament interpretations (red/pink lines/arrows) are shown. (Right) Corresponding maximum positive curvature attributes (blue area) for each horizon with callouts to locations of the cross-line data (red line), the lineament interpretations (orange/pink arrows), and the vertical (black circles) and lateral extent (black line) of drilled wells. Subcircular Exshaw Formation/ Wabamun Group anomalies can be seen east of the CHW in the lower Exshaw Formation curvature map. An enlarged view of the Precambrian curvature horizon (dashed box) more closely shows the lineament interpretations with respect to the earthquake epicenters.

Workflow

We consider this study from three perspectives: seismology, seismic geophysics, and geology:

- The separation between earthquake hypocenters and fluid injection at the Cardston Horizontal Well (CHW) requires some mechanism for stress change communication (e.g., hydraulic communication).
- 3D reflection-seismic data over the CHW reveals indications of the seismogenic fault. In addition, the shape of local structural anomalies on the 3D seismic suggests karsting may have influenced the area targeted by the CHW.
- Well logs are used to map pertinent strata in the region around the CHW. Regional mapping indicates sporadic thickness variations in formations directly above and below the CHW. Secondary structures in drill core reveal that thickness variations are coincident with evidence of karst collapse.

Though none of these perspectives is conclusive on their own, together they point to a single interpretation. This agreement is confirmed by forward seismic modelling, which demonstrates that anomalous thickness variations can generate structural anomalies like those seen on the 3D seismic.

Our understanding is summarised in a model that demonstrates some of the depositional and karst history of the area. The model illustrates the connection between the seismogenic fault, the hydrology of the past, and the fluid injection that triggered the Cardston earthquakes.

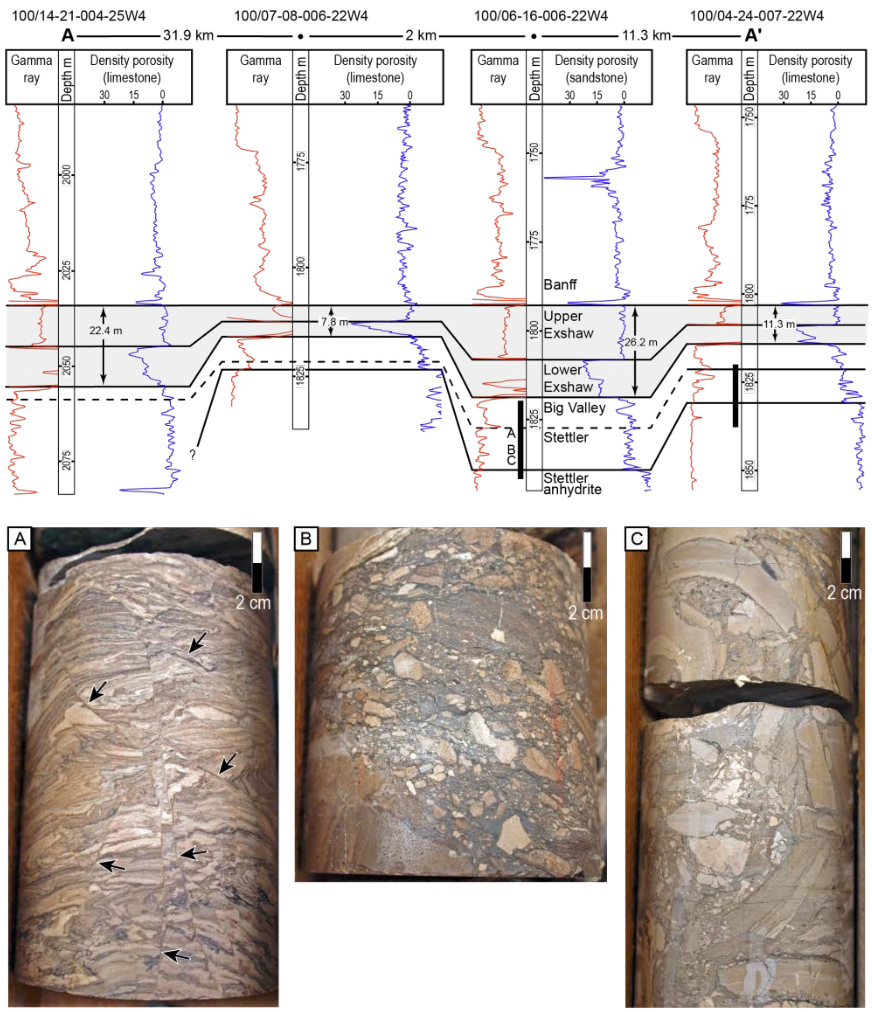

Figure 2. Cross-section A–A′ and images of drill cores. (Upper) A cross-section showing the nature of sporadic isopach anomalies is displayed on the upper half of this figure, datumned on the upper Exshaw Formation. Well log 100/06-16-006- 22W4 is labeled with the stratigraphic nomenclature used in this study and displays overthickened Exshaw Formation (>10 m) relative to nearby well 100/07-08- 006-22W4. (Lower) Core photos show microfaulted brecciation (arrows, A) with possible flow banding recognized by faint matrix laminations and subtle alignment of clasts (B) and vertical brecciated clasts (C) from the upper Stettler and Big Valley formations in well 100/06-16-006-22W4, which are interpreted as resulting from dissolution-related karst in the underlying Stettler Formation anhydrite.

Observations

Schultz et al., (2015) demonstrate the causal relationship between the HF and the swarm of earthquakes with very high confidence. The vertical separation between the Devonian–Mississippian-age reservoir and the hypocenters in the Archean basement is ~1.5 km, necessitating an extensive conduit for hydraulic communication. They propose that the nearby regional-scale fault system provides a reasonable means of hydraulic communication. In particular, they attribute the seismicity to movement along the West Stand Off Fault (WSOF) – a Late Cretaceous fault identified by offset mapping of formation tops.

Proprietary 3D reflection-seismic data are used to characterize the subsurface structure around the CHW (Figure 1). Two significant structural features are evident: a linear feature trending approximately south-southeast (SSE) and a small number of anomalous subcircular depressions of the lower Exshaw Formation reflector localized on the linear feature.

The linear, approximately SSE-trending feature appears in curvature attribute maps and persists through numerous stratigraphic horizons from the top of the Belly River Group (the shallowest interpreted horizon) down to the Precambrian basement (Figure 1). Although distinct faults are not imaged, a zone of strain manifested as flexure of strata along a linear trend is captured by the reflection-seismic. The anomalous trend of horizon flexure identified by the curvature attributes is interpreted as the manifestation of the WSOF in the reflection-seismic data because of its location and orientation.

The 3D reflection-seismic also shows a cluster of localized subcircular anomalies on the lower Exshaw Formation curvature and depth structure maps, as well as isopach maps for intervals above and below the lower Exshaw horizon. The anomalous depressions are generally circular to ellipsoid in shape, with diameters on the order of hundreds of meters, and appear to be up to 40 m deep. The anomalous structures affect a narrow interval, perhaps limited to the Wabamun Group and the Exshaw and Banff formations. Based on the character of the structural anomalies, attributing them to karst processes is reasonable. The co-location of the linear feature observed on seismic and the karst collapse features suggests that they may be related to a localised causal mechanism. We propose this to be the case.

Well 100/14-21-004-25W4 is in the immediate vicinity of the CHW, and penetrates one of the structural anomalies identified on the 3D reflection-seismic. The stratigraphic picks for 14-21 are considered in context with regional mapping of the Stettler and Big Valley formations of the Wabamun Group as well as the Exshaw and Banff formations (Figure 2). The structural maps reveal that 14-21 encountered anomalously thin Stetter anhydrite and anomalously thick Exshaw sediments. Similar thickness anomalies are present sporadically throughout the region. Though not available for 14-21, core through the Stettler and Big Valley formations is available for several other wells exhibiting anomalous thicknesses of Stettler and Exshaw formations. The drill cores from wells with anomalous thicknesses show deformation or brecciation of the carbonate strata between the Stettler anhydrites and the Exshaw sediments. We expect that a vertical succession of thinned Stettler anhydrite, overlain by deformed/brecciated carbonates, which are in turn overlain by over-thickened Exshaw Formation, will be encountered in other areas of anomalous thickness, including those near the CHW. Together, regional elevation mapping and core observations provide further evidence to support the interpretation that karst processes are responsible for the anomalous thicknesses of Exshaw and Stettler formations seen near the CHW.

Forward seismic modelling strengthens our karst interpretation. The synthetic models approximate the reflection-seismic response of over-thickened Exshaw sediments, and demonstrate a strong similarity to the subcircular anomalies observed in the 3D seismic survey (Figure 3).

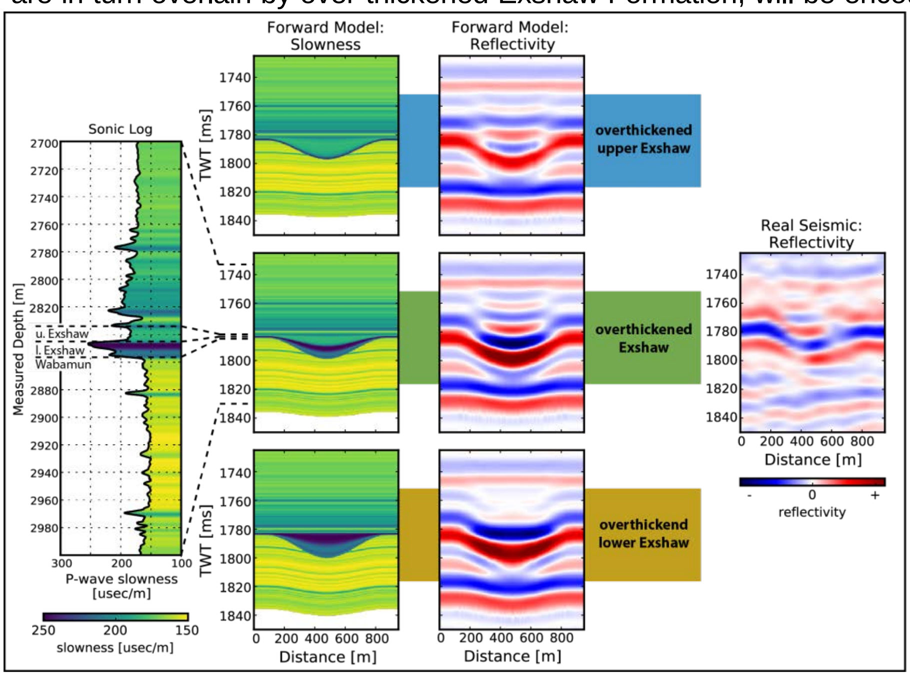

Figure 3 Forward modeling of the Exshaw Formation/Wabamun Group anomalies. Modeling results are shown for three scenarios proposed for infill of the subcircular Exshaw Formation/Wabamun Group anomalies. (Left) The sonic log from well 100/14-21-004-25W4 has been modified to approximate regional Exshaw Formation thickness and is shown with elevations of the Wabamun Group and the upper and lower units of the Exshaw Formation. (Center Left) Three geological models for depositional infill of the anomalies are shown in time. (Center Right) Respective zero-offset seismic reflectivity sections. (Right) An actual reflectivity section is shown for comparison.

Conclusions

Examining this instance of induced seismicity from multiple perspectives provides several lines of evidence. No single perspective is definitive on its own, but together the evidence points to a consistent interpretation.

We do not believe the appearance of karst features along the WSOF fault is a coincidence. Rather, we suspect that undersaturated fluids may have been migrating along the WSOF dissolving the Stettler Formation anhydrites local to the CHW, creating subcircular anomalies in the the Exshaw Formation /Wabamun Group. Given that fluid injection at the CHW triggered movement of a deep-seated fault, we suggest that the same fluid conduit remains to this day. Our interpretation is summarized as a conceptual model that explains how HF of the CHW induced seismicity in the crystalline basement (Figure 4).

The insights of this study should be considered for other plays where HF is used. The recognition of geological indicators of fault-associated fluid flow may help to understand induced seismicity in a given area.

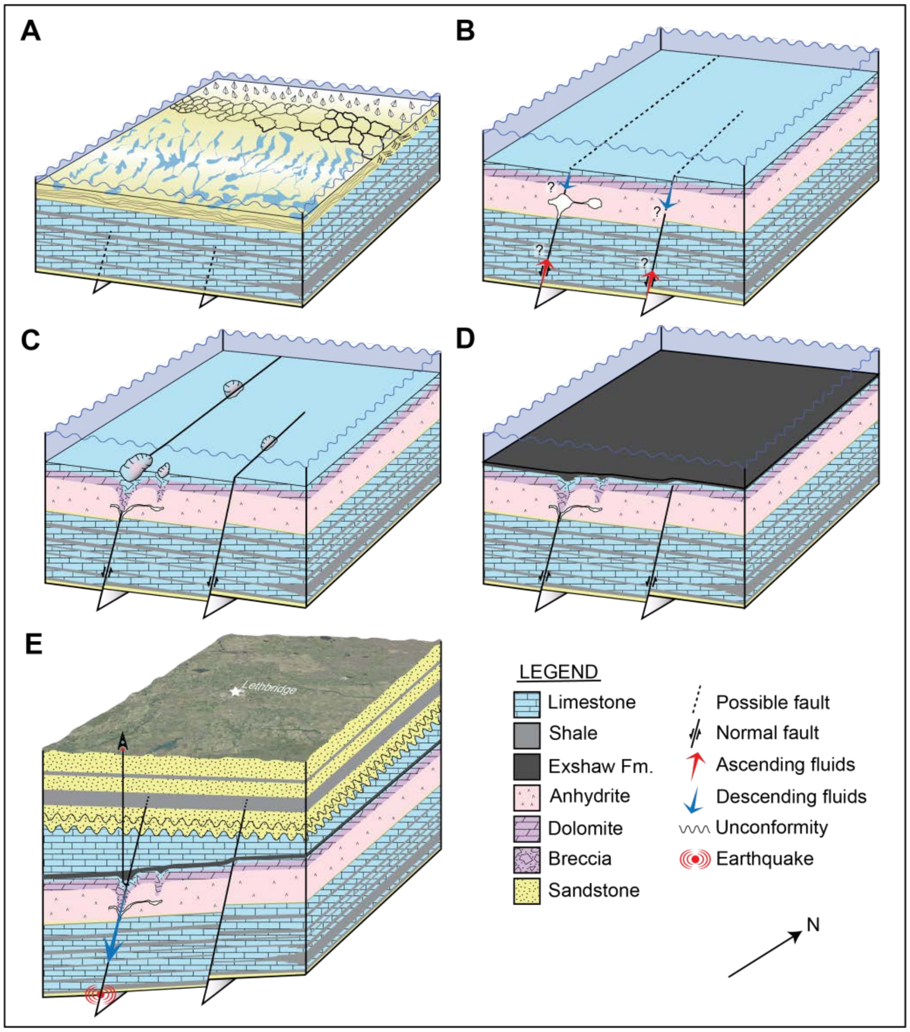

Figure 4. Proposed depositional and dissolution sequence. (A) Salina/sabkha depositional setting of the Stettler Formation overlying Paleozoic carbonates (blue bricks) and Cambrian sandstones (deepest yellow layer). (B) Following deposition of the Big Valley Formation limestones, late Devonian extensional faulting provide a conduit for (possibly) ascending hydrothermal fluid (red arrows along faults) and fault-associated dissolution of the lower Stettler Formation anhydrite (cavity in pink layer). (C) Collapse of karst cavity in the Stettler Formation anhydrites affecting the upper Stettler and Big Valley Formations (purple and blue bricks, respectively) and causing brecciation and accommodation. (D) Syndepositional overthickening of the Exshaw Formation (black layer). (E) Present-day horizontal HF well (drill rig and black line) drilled in the Big Valley Formation and causing an earthquake (red circle).

Additional detail and further discussion of this study is available in Galloway et al., (2018).

Acknowledgements

We thank ExxonMobil for the donation of the 3D reflection-seismic dataset license that this study describes and Matt Grobe for critiques that improved this study.

References

Galloway, E. J., Hauck, T. E., Corlett, H., Pana, D., Schultz, R. (2018). Faults and associated karst collapse suggest conduits for fluid-flow that influence hydraulic fracturing induced seismicity. Proceedings of the National Academy of Sciences, doi: 10.1073/pnas.1807549115.

Schultz R, et al. (2015) The Cardston earthquake swarm and hydraulic fracturing of the Exshaw Formation (Alberta Bakken play). Bulletin of the Seismological Society of America 105: 2871–2884, doi: 10.1785/0120150131.