Faults and associated karst collapse suggest conduits for fluid flow that influence hydraulic fracturing-induced seismicity

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During December 2011, a swarm of moderate-magnitude earthquakes was induced by hydraulic fracturing (HF) near Cardston, Alberta. Despite seismological associations linking these two processes, the hydrological and tectonic mechanisms involved remain unclear. In this study, we interpret a 3D reflection-seismic survey to delve into the geological factors related to these earthquakes. First, we document a basement-rooted fault on which the earthquake rupture occurred that extends above the targeted reservoir. Second, at the reservoir’s stratigraphic level, anomalous subcircular features are recognized along the fault and are interpreted as resulting from fault-associated karst processes. These observations have implications for HF-induced seismicity, as they suggest hydraulic communication over a large (vertical) distance, reconciling the discrepancy between the culprit well trajectory and earthquake hypocenters. We speculate on how these newly identified geological factors could drive the sporadic appearance of induced seismicity and thus be utilized to avoid earthquake hazards.

| hydraulic fracturing | induced seismicity | hydraulically active faults | dissolution karst |

Induced seismicity is a phenomenon by which stress accumulating on a fault is suddenly released via anthropogenically triggered shear slip. This phenomenon is well documented, with numerous cases related to mining, waste-water disposal, reservoir impoundment, and geothermal development activities (1). More recently, induced earthquakes have also been recognized as the direct result of hydraulic fracturing (HF) stimulation of unconventional reservoirs (2–10). One such case occurred in southern Alberta, Canada, near the town of Cardston (Fig. 1) (11). Starting in December, 2011, anomalous earthquakes occurred contemporaneously with the completion of a multistage horizontal well in the uppermost Wabamun Group (also referred to as the “Exshaw play”). These induced events were of moderate magnitude (up to moment magnitude 3), with hypocenters located in the shallow crystalline basement (11).

Induced earthquakes are thought to require three geological conditions: (i) the presence of a fault, (ii) nearly critical slip-orientation of the fault, and (iii) a means to perturb stress on the fault past the critical condition (12). In general, the first two conditions are well-established requirements for fault rupture nucleation. However, the third point is contentious, since there are multiple anthropogenic means to communicate stress changes. For example, effective stress changes can be communicated to the fault either through pore-pressure perturbations transmitted along the damage zone of a mechanically active fault (13) or poroelastically through a (impermeable) rock matrix (14). For disposal cases, pore-pressure diffusion is often the favorite speculative explanation, since continued injection into permeable formations allows plausible communication over great distances until the interaction with a critically unstable fault (e.g., refs. 15 and 16). However, for HF, this reasoning is complicated by additional conceptual hurdles. For example, HF wells inject into impermeable formations to stimulate reservoir productivity (17); thus, reasonable pressure perturbations are restricted to the stimulated reservoir zone proximal to the well bore [up to hundreds of meters (18–21)]. Furthermore, geomechanical modeling reveals that poroelastic changes from HF are transmitted only locally (20). These results are in direct contradiction to HF-related earthquakes that are located kilometers away from the closest well bore (e.g., refs. 2, 6, 11, 22, and 23). Specific to the Cardston case, earthquakes (located on regional arrays) were observed within the uppermost crystalline basement, ~1.5 km deeper than the target upper Stettler–Big Valley Reservoir zone (SI Appendix, Fig. S1); this observation is further complicated by the fact that the fault slip response occurred immediately (i.e., ~1.5–3.0 h) after well stage stimulations (11). Due to geological complexities/unknowns in the subsurface, seismological and geomechanical approaches to explaining these discrepancies remain speculative.

Based on these complications, we instead look for geological indications of past fluid migration in a 3D reflection-seismic survey that surrounds the Cardston earthquakes (Fig. 1). In this paper, we describe the methods by which we analyzed this dataset and then bolster our interpretation with additional earthquake, drill core, and well log data. Together, the intersection of these independent datasets leads us to the conclusion that fault-associated fluid flow caused the dissolution of the Stettler Formation anhydrites (Wabamun Group) (SI Appendix, Fig. S1) and resulted in karst features that affected accommodation patterns in the overlying upper Stettler/Big Valley/Exshaw interval near the Cardston horizontal well (CHW) location. This interpretation has implications for understanding the induced seismicity caused by the CHW. The in-

Significance

Induced earthquakes can be caused by hydraulic fracturing (HF). However, the exact means by which stress changes are transferred to seismogenic faults are unknown. This paper provides evidence that a case of induced earthquakes in southern Alberta responded to increased pore pressure on a fault in hydraulic communication with the HF operation. Reflection-seismic and drill core data provide evidence that fluid flow along this fault caused strata underlying the target reservoir to dissolve, causing a karst collapse in the geological past. We suggest that seismogenic and hydraulically active faults are geologically rare and that the injection of fluid directly into them is even rarer, potentially explaining the small percentage of HF wells that cause induced earthquakes.

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A indication of fault-associated fluid flow is inferential evidence of a potential permeable pathway through which pore-pressure perturbations can be transmitted quickly and over great distance. We speculate on the potential implications of this interpretation for HF-related earthquakes, including the paucity of seismogenic wells at a basin scale (24, 25), and for fault-associated fluid-flow features as indicators of areas which may be prone to HF-induced seismicity.

**Tectonic Setting**

The area under investigation is in the southern Alberta Plains, ∼10 km east of the triangle zone of the foothills, which represents the approximate eastern limit of the Cordilleran deformation front. The sedimentary succession comprises Cambrian to Paleocene strata of the Western Canada Sedimentary Basin (WCSB), which overlie the Precambrian crystalline basement of the North American craton. The strata of the WCSB were deposited in three different general tectonic settings: a passive continental margin from the Neoproterozoic to Middle Devonian, a back-arc setting from the Late Devonian to Jurassic, and a foreland basin between the Jurassic and Eocene. Far-field stress related to the purported Late Devonian–Early Carboniferous Antler and the Jurassic-to-Early Eocene Cordilleran contraction to the west may be responsible for faulting in the investigated area. Postorogenic isostatic reequilibration of the Cordilleran foreland system was accompanied by the removal of two kilometers of strata in the Alberta Plains (26), which may have triggered minor Late Cenozoic faulting or fault reactivation. Quaternary deposits cover the bedrock.

First, we considered public 2D reflection-seismic transects from Canada’s LITHOPROBE study, thereby placing the study area into a regional context (Figs. 1 and 2). Specific to southern Alberta, the Southern Alberta Lithospheric Transect (SALT) includes 290 km of reflection-seismic lines acquired in 1995 between the Cordilleran deformation front and the western side of the Sweetgrass Arch in southern Alberta and northern Montana (27). This portion of the SALT consists of two east–west lines: line 30 (110 km) and line 31 (140 km), tied by the roughly north–south line 29 (40 km). The SALT data revealed a subhorizontal layer-cake structure of the WCSB stratigraphy affected by extensional faults dipping steeply dipping down to the west (Fig. 2). Subvertical faults spaced 11–15 km apart cut through a prominent near-basement reflector. These faults offset Cambrian, Devonian, Mississippian, Jurassic, and Cretaceous strata and appear to be sealed by undeformed Campanian Belly River Group strata (27). Lemieux et al. (28) inferred that the strike of these faults observable on the SALT data in the WCSB cover is similar to the basement magnetic trends, and therefore their positioning would be basement-controlled.
Evidence from a 3D Reflection-Seismic Survey

To begin examining the geological controls of the Cardston earthquakes, proprietary 3D reflection-seismic data were utilized to characterize the subsurface around the CHW (Fig. 1). The 3D reflection-seismic dataset, originally acquired in 1998, covers 60 km$^2$. This study used a version processed with surface-consistent deconvolution, finite difference migration, and noise removal by FXY deconvolution. The data were processed into 50 $\times$ 50 m bins. The bandwidth of the interpretation volume decreases with depth: the bandwidth at 750 ms is 10–70 Hz (with a dominant frequency of 55 Hz), while the bandwidth at 1,500 ms is 11–65 Hz (with a dominant frequency of 40 Hz). Comparisons with synthetic seismograms created from well logs suggest the phase of the reflection-seismic volume is reasonably stable and averages near 0°.

Synthetic seismograms were generated for 10 nearby wells with geophysical logs and were tied to the nearest observed reflection-seismic arrival. This process incorporated data throughout the sedimentary sequence and resulted in a velocity model of the sediment down to the Precambrian basement. Below this, the crystalline basement lacks continuous interfaces of contrasting acoustic impedance; thus, the basement interval is poorly suited for characterization by reflection-seismic data. Furthermore, the reflections that appear below the Precambrian horizon on the 2D and 3D data are interpreted as being seismic multiples and should be ignored. Based on horizon correlations, we examined stratigraphic surface attributes including coherence, curvature, and topography (see SI Appendix for details of analysis) (29, 30). Two significant structural features are detected by the 3D reflection-seismic data near the CHW: 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 (Figs. 3 and 4).

The appearance of a linear, approximately SSE-trending feature in the curvature attribute maps is persistent in numerous stratigraphic horizons from the top of the Belly River Group (the shallowest interpreted horizon) down to the Precambrian basement (Fig. 3). Due to its spatial overlap with the Cardston earthquakes and CHW (Fig. 3), we interpret the linear feature as the same West Stand-Off Fault (WSOF) that was previously conjectured to host the Cardston earthquakes (11). In the 3D reflection-seismic dataset, we observe that the WSOF strikes at $\sim 170^\circ$ across the entire 3D reflection-seismic survey ($\sim 4.8$ km) and dips at $\sim 80^\circ$ (to the west) through an interval of at least 2,300 m. The reflection-seismic data have limited vertical resolution, so this feature does not create a detectable offset of reflection-seismic horizons and therefore is not apparent in coherence attribute volumes. Given the dominant frequencies of the interpretation volume and interval velocities measured in well 14-21-4-25W4, the vertical resolution of the reflection seismic ranges from 15 m at 750 ms to 35 m at 1,500 ms, assuming the vertical resolution is approximately one-quarter of the dominant wavelength (31). 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 horizons. The anomalous trend of horizon flexure identified by the curvature attributes is interpreted as the manifestation of the WSOF in the reflection-seismic data.

The localized anomalous subcircular features visible on the lower Exshaw Formation curvature and depth structure maps as well as on the isopach maps for the Rundle-to-lower Exshaw Formation and lower Exshaw Formation-to-Precambrian intervals vary in diameter and morphology (Figs. 3 and 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4). The largest of these features is ellipsoid with major and minor axes of $\sim 1,600$ m and $\sim 600$ m, respectively; the depression appears to be up to 40 m deeper than the adjacent area. We note that the lateral positioning of these anomalies is spatially coincident with an overall thinning of the interval between the lower Exshaw Formation and Precambrian (Fig. 4).

Fig. 4. Processed seismic-reflection horizons. Maps of the topography of three reflection-seismic horizons (Left) are shown alongside the thickness between these intervals (Right). The locations of nearby wells (black circles/lines) and earthquake epicenters (red crosses) are displayed for geographic context.
Exshaw Formation (coincident with the WSOF) is suggestive of some localized process being the causal mechanism.

**Evidence from Well Logs and Drill Cores**

The stratigraphic interval of interest for this part of the study includes the Devonian Wabamun Group and the Exshaw and Banff Formations (SI Appendix, Fig. S1). The Wabamun Group is divided into the Stettler and Big Valley Formations, which comprise predominantly evaporites with lesser carbonates and carbonates, respectively (SI Appendix, Fig. S1). The Stettler Formation can be further subdivided into a lower Stettler anhydrite and a relatively thin upper Stettler carbonate. The latter is overlain by limestone of the Big Valley Formation, which may be erosional in the study area. The Wabamun Group strata are unconformably overlain by the black shales of the Exshaw Formation, which can be subdivided into an informal lower Exshaw Formation (black shales), and an upper Exshaw Formation comprising a silty carbonate (SI Appendix, Fig. S1). This is in turn overlain by shale assigned to the Banff Formation (Banff A in SI Appendix, Fig. S1).

The 3D reflection-seismic dataset revealed the presence of a series of subcircular anomalies at the Exshaw Formation/Wabamun Group interval (Fig. 3). Because the anomalies are spatially limited in extent (Fig. 4), it was conjectured that they may be features associated with karst-related dissolution of the underlying Stettler Formation anhydrite (herein we refer to karst as being a process operating only in the anhydrite of the Stettler Formation). We inferred concomitant subsidence within the overlying carbonates of the upper Stettler and Big Valley formations through collapse of the karst-related dissolution features in the Stettler anhydrite, resulting in increased accommodation and overthickening of the overlying Exshaw Formation, which is 22.4 m thick in well 14-24-4-25W4. To substantiate this, we have considered geological drill core and well log data. Unfortunately, no drill cores from this interval exist from the CHW area; in their absence, nearby analogs have been investigated instead. To find these analogs, we have considered geological drill core and well log data. Unfortunately, no drill cores from this interval exist from the CHW area; in their absence, nearby analogs have been included. The log section from A–A’ (blue line) is discussed further in Fig. 6.

Fig. 5. Map of drill core and well log data. Locations of wells with logs reaching as deep as the Wabamun Group are plotted as gray squares; wells which have an Exshaw Formation logged thicker than 10 m are highlighted in red around a gray square. Reviewed cores are labeled with their unique well identifier (e.g., 6-16-6-22W4), except for well 14-21-4-25W4, which had no core but exhibits Exshaw Formation overthickening nearby the CHW. The CHW that caused the HF-induced earthquakes (star) is displayed alongside the extent of the Lower Banff-Exshaw-Big Valley administrative pool boundaries (green area) and all other HF wells completed in this play (black dots). For geographic context, the 3D reflection-seismic area (hatched area), SALT lines (black lines), and previously identified faults (F1–F5, red stars; and WSOF, dashed red line) have been included. The log section from A–A’ (blue line) is discussed further in Fig. 6.

18 analog wells where the Exshaw Formation is thicker than 10 m were identified in the study area (Fig. 5) (a thickness of >10 m was used as a metric to identify potential wells with analogous core) (Fig. 6). From these analog wells, four drill cores were available within the study area (Fig. 5). In these overthickened Exshaw Formation wells, there is commonly an associated decrease in the thickness of the underlying Stettler Formation anhydrite, although the lack of deeper well control prohibits the thorough quantification of the thickness of these evaporites within the study area (only 91 of the 187 total wells fully penetrate the Stettler Formation (SI Appendix)). First, to observe examples of an intact succession, areas outside (well 13-5-4-25W4) and on the edge (well 4-24-7-22W4) of Exshaw Formation overthickening were reviewed within two drill cores. The lower Stettler Formation in these areas comprises sabkha- and/or salina-type anhydrite with interbedded dololaminites. The upper Stettler, typically 5–8 m thick, comprises dololaminites and microbial laminites, with common organic-rich laminations and peloid grainstones. The Stettler Formation is overlain by the mid- to distal-ramp deposits of the Big Valley Formation, typically less than 2 m thick or absent beneath the lower Exshaw Formation and comprising dark-colored shales with bioclastic nodular lime mudstone-wackestone and common cnidoid columnals. The Big Valley Formation is abruptly overlain by the laminated organic-rich black shales of the lower Exshaw Formation, which in turn are overlain by the silty dolostones of the upper Exshaw Formation. In areas outside the overthickened Exshaw Formation, the thickness of the combined lower and upper members ranges from 3.2 to 6.7 m, although this is also variable due to absence of the upper Exshaw Formation member in parts of the study area (32). The interpretations in this study of the sedimentology and stratigraphy from these drill cores are consistent with prior studies (32, 33).

Four drill cores were examined in areas where the Exshaw Formation thickness is greater than 10 m (e.g., well 6-16-6-22W4) (Fig. 6). In three of the drill cores, the upper Stettler and Big Valley Formations are dominated by intervals of intraclast breccia (Fig. 6 B and C) or dipping and offset laminations where unbrecciated. Many of the unbrecciated intervals are highly
Reflection-Seismic Modeling of the Exshaw Formation/Wabamun Group Anomalies

To further explore our conjecture regarding the Exshaw Formation/Wabamun Group anomalies, we employed forward modeling to compare (or reject) depositional case scenarios against the observed reflection-seismic waveform amplitudes. Using wireline logs for interval transit time (sonic logs) and bulk density, an acoustic impedance log is calculated for a well and convolved with a zero-phase wavelet to produce synthetic seismograms (see SI Appendix for details). The acoustic impedance log of well 14-21-4-25W4 was used as the basis for describing geological scenarios in the forward modeling because of the proximity of the well to the Exshaw Formation/Wabamun Group anomalies and the CHW. Well log interpretation indicates considerable thickening (22.4 m) of the Exshaw Formation at 14-21-4-25W4, which is supported by sonic and density logs of 14-21-4-25W4. (Lower) Core photographs of 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.

Three scenarios and their seismic responses were considered (Fig. 7). In each scenario, 35 m of extra accommodation is created by removing the uppermost portion of the Wabamun Group. The aspect that distinguishes the three scenarios is the interval which is thickened to fill the extra accommodation created by the dissolution of underlying anhydrite: (i) syndepositional thickening of only the upper Exshaw Formation member, (ii) syndepositional thickening of both the lower and upper Exshaw Formation, and (iii) syndepositional thickening of only the lower Exshaw Formation member. The cases are differentiated by the forward seismic models. Although the Exshaw Formation/Wabamun Group transition is marked by a strong amplitude peak in all cases, a significant amplitude increase is only associated with the Exshaw Formation/Wabamun Group anomaly in cases two and three. In addition, only...
the forward reflectivity models for cases two and three exhibit a continuity of the amplitude trough immediately above the Exshaw Formation/Wabamun Group peak. Last, cases one and two exhibit an extra peak–trough of moderate amplitude above the Exshaw Formation/Wabamun Group interface within the area of anomalously thick Exshaw Formation.

An equivalent portion of real reflection-seismic data exhibits some of the characteristics identified in the forward seismic models (Fig. 7): The amplitude of the reflection from the Exshaw Formation/Wabamun Group interface is consistent across the section; the amplitude trough immediately above the Exshaw Formation/Wabamun Group peak is continuous; and an extra peak–trough of moderate amplitude above the Exshaw Formation/Wabamun Group interface within the area of anomalously thick Exshaw Formation is evident. From these qualitative observations, case three can be dismissed as a viable model for the Exshaw Formation/Wabamun Group anomalies. Although cases one and two both resemble the real reflectivity, they each demonstrate some aspect that differentiates it from the actual response. Case one lacks continuity of the amplitude trough above the Exshaw Formation/Wabamun Group peak. The amplitude increase along the Exshaw Formation/Wabamun Group horizon in the anomaly in case two is not evident in the real reflection-seismic field data. Qualitatively, cases one and two both show reasonable similarity to the reflection-seismic field data. The forward modeling of the reflection-seismic data demonstrates that dissolution of Stettler Formation anhydrite and continuous infill of sediments during Exshaw Formation time can produce anomalies similar to those seen in the field data. Although the modeling does not discern the details of the timing, it suggests that overthickening occurs throughout Exshaw Formation time. These results are consistent with the dissolution timing suggested by the brecciation of uppermost Wabamun Group carbonates in the overthickened Exshaw Formation drill cores.

However, we recognize that this simplistic approach to forward seismic modeling has ignored any seismic acquisition illumination effects. Contrary to the zero-offset simplification used for this modeling, reflection-seismic data are acquired with some offset between source and receiver. This can become an issue when the geometry of the source–receiver anomaly precludes source energy from reaching or reflected energy from returning from the anomalous structural feature. Should the reflection-seismic data be affected by these illumination complications, the magnitude of the reflections in the structural lows of the Exshaw Formation/Wabamun Group anomalies would appear smaller than expected. Therefore, caution should be taken when comparing horizon amplitudes in the anomalies with those outside the anomalies.

**Discussion**

**Evidence for Faulting in Southwestern Alberta and the WSOF.** Previous studies in the southern Alberta Plains have identified (or inferred) extensional faults, which suggest subsequent accommodation of Late Cretaceous compression. For example, clear evidence of extensional faulting in southern Alberta in general. Specific to the study area, inferred evidence points to the possibility of local extensional faulting, interpreted as the WSOF, in the study area (Fig. 1): (i) basement lineaments derived from magnetic and Bouguer gravity maps which may represent Precambrian basement discontinuities prone to reactivation (34–36), (ii) gradients in maps of formation tops (11), and (iii) evidence of earthquake hypocenters induced by the CHW (11).

Specific to the 3D reflection-seismic data analyzed here, our confidence that the identified linear feature represents a genuine geological structure is bolstered by several factors. First, the orientation of the anomaly is not aligned to the acquisition geometry or to any geographical factors. Second, the plane of flexure dips to the west, translating the curvature anomalies westward for deeper horizons, suggesting that the anomaly has geological causes and is not a processing error. Finally, the lineament stretches across the entire 3D survey, indicating that this feature is significant in at least the investigated region. Considering these supporting pieces, the interpretation of the newly imaged ~SSE lineament (Figs. 3 and 4) as a basement-rooted extensional fault is likely.

**Evidence for the commonly invoked Late Devonian–Early Carboniferous Antler orogeny (e.g., ref. 37) is limited and controversial at this latitude in the Cordillera (38, 39). However, Paleozoic tectonism at the western margin of ancient North America is recorded by multiple Famennian and Tournaisian unconformities (40). Therefore, the possibility that far-field
stresses associated with the Antler tectonism triggered faulting of the Paleozoic stratigraphy in southern Alberta is not precluded. On the other hand, the west-dipping normal faults depicted by SALT that extend at least into the Upper Cretaceous strata constitute undisputed evidence for downflexing of the North American craton during the well-documented Cordilleran tectonic loading (41). The trend of the WSOF identified here is similar to that of the extensional faults in the Cordilleran foreland. Furthermore, the WSOF is subparallel to and just west of a basement magnetic lineament (11), a spatial relationship that may indicate a genetic relationship. We speculate that the WSOF may be the shallow expression of a Precambrian basement discontinuity, most likely reactivated during the foreland stage of the basin’s evolution. We infer this relationship because the fault can be traced upwards through the Campanian-aged Belly River Group.

Given the presence of a fault, its orientation with respect to in situ stress conditions dictates its degree of mechanical activity. The stress regime in the WCSB (42) likely supports a reactivable stress state on the −SSE-orientated WSOF (Fig. 3), as evidenced by the induced earthquakes (11). Often, mechanically active faults are also hydraulically active (43–45), since fluid flow is established along the damage zone of the shear slip (13, 46, 47). For example, fault-associated fluid flow has significantly influenced the spatial distribution of localized “pockmark” features in strata overlying faults in paleo-basins (48).

**Interpretation of the Exshaw Formation/Wabamun Group Anomalies.** Localized overthickening of the Exshaw Formation suggests syndepositional accommodation (49–51). The creation of this accommodation space is associated with brecciation of the Big Valley and upper Stettler Formations in the examined analog drill cores. There is no evidence of subaerial karst within the Big Valley and upper Stettler Formations in the cores examined. Rather, the brecciation is associated with collocated overthickening of the Exshaw Formation and decreased thicknesses in the underlying anhydrite of the lower Stettler Formation. This suggests that dissolution of anhydrite by fault-associated fluids within this interval led to the collapse or subsidence of the overlying carbonates of the Big Valley and upper Stettler Formations, resulting in the brecciated textures observed. This interpretation is consistent with the subcircular sinkhole-type morphology of Exshaw Formation/Wabamun Group anomalies in the 3D reflection-seismic dataset (Fig. 3).

![Fig. 8. Proposed depositional and dissolution sequence.](image)

The interpretation of a solution–evaporite collapse origin for the breccias of the Big Valley and upper Stettler Formations is supported by (i) the wide ranges in clast sizes, (ii) poor sorting, (iii) large rotated clasts, (iv) thickness of brecciated intervals, (v) high frequency of microfracturing and offset sedimentary structures, and (vi) proximity to evaporite strata interpreted as being partially removed (Fig. 6) (52, 53). Although previous interpretations of some of these breccias include vertical faults (54, 55). Intervals of secondary dolomitization in the Big Valley Formation carbonates indicate that, in at least one analog thickness of brecciated intervals, (v) proximity to evaporite strata interpreted as being partially removed (Fig. 6) (52, 53). Although previous interpretations of some of these breccias include vertical faults (54, 55). 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contrast to the localized karst-related subcircular anomalies near the CHW, dissolution features related to basin-scale fluid flow are often associated with more regionally pervasive karsting, for example, as recognized in the Prairie Evaporite Formation in northern Alberta (58). Finally, the best supporting evidence for the potential hydraulic conductivity of a deep-seated fault in the study area comes from induced earthquakes linked to HF of the overthickened Exshaw Formation (11).

**Implications for HF-Induced Earthquakes.** Together, our findings suggest the presence of fault-associated fluid flow in the geological past. However, remineralization and cementation of fault-damage zones can eventually seal faults, drastically reducing their permeability (46). The stress regime in southern Alberta (42) has likely kept the WSOF mechanically/hydraulically active since the Laramide orogeny, as evidenced by natural earthquakes presently occurring in southern Alberta (59). Additionally, repeated overpressurization from HF stimulations has the potential to propagate shear/tensile failures along the fault pathway, reopening any (semi)sealed segments encountered (23, 60–62). In fact, shallow in situ measurements of fault hydraulic diffusivities computed during reactivation experiments estimate values of 3,500 m²/s (63). Because of these considerations, it is possible that the WSOF is permeable enough to support the large hydraulic diffusivity estimated seismologically (4.5–64 m²/s) (11). We note, however, that denser arrays would have defined the seismologically estimated hydraulic diffusivity more faithfully. Based on these findings, future geomechanical studies wishing to understand HF-induced earthquakes should seriously consider the influence of fluid flow along faults and fractures on modeled outputs.

Given these prior arguments, it is natural to presume that these indicators of fault-associated fluid flow have had a causal influence on the expression of induced earthquakes at the CHW (Fig. 8) and possibly for all HF wells in the upper Stettler–Big Valley Reservoir play. By this reasoning, the relative paucity of geological conditions conducive to induced seismicity could reflect the small fraction of seismogenic petroleum operations (24, 25). To test this conjecture with available data for the Exshaw Formation, we consider Fig. 5. In this plot, wells with a relatively thickened Exshaw Formation (>10 m) are potentially diagnostic of the conditions required for induced seismicity. On the other hand, we note that very few regions indicating thick Exshaw Formation overlap with HF development of the play; the CHW is one of the few nearby cases (Fig. 5). While we recognize this assertion is hardly definitive for this case, it supports an established idea that geological factors influence the likelihood of encountering induced earthquakes (62, 64–70). For example, HF operations susceptible to induced seismicity in the Duvernay play display a statistically significant spatial correspondence to the margins of a fossil reef (65). Some of these carbonate margins have undergone hydrothermal dolomitization, a process related to structurally controlled fluid flow (68, 71, 72). These considerations are anecdotally supported by north-south strike-slip earthquakes (8, 9) and evidence of a transcontinental flower structure (68, 73), a structure known to be conducive to vertical fluid flow (72). In this light, considering any features recognized during the reflection-seismic survey, wire-line log mapping, and drill core analysis that are indicative of these processes could provide cost-effective insight to the geological susceptibility for these types of earthquakes (69).

We note that documenting these geological factors helps develop a conceptual understanding of induced seismicity, with ramifications for location models in forecasting induced seismic hazard (65) and for identifying future sites (during exploration) that may be prone to these events. For example, pre-HF reflection-seismic site assessments may be unable to resolve the offsets/geometry of deep-seated faults to confidently establish their propensity for reactivation. The results of this paper suggest, instead, that geological indicators of hydraulic connectivity may be utilized during site assessment to characterize fault influences and that proxies for fault-associated fluid flow may bolster confidence during pre-HF assessment or provide some level of input when reflection-seismic is either unresolvable or unfeasible. Scaled up to the basin level, the acquisition of 3D reflection-seismic survey data may help us understand induced seismicity potential in a given area.

**Data Availability**

Additional earthquake-related data are available online through the Alberta Geological Survey Earthquake Catalogue at the Incorporated Research Institutions for Seismology (https://www.iris.edu/hq/) and in prior published material (11, 59). All well log and drill core data used in this study are publicly available through the Alberta Energy Regulator (www1.aer.ca/ProductCatalogue/230.html; https://aer.ca/providing-information/about-the-aer/contact-us/information-services-and-facilities/core-research-centre). Input 3D reflection-seismic survey data from which our results were derived are proprietary. All data needed to evaluate the conclusions of the paper are present in the paper.

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