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Alberta Energy Regulator

A Review of the Potential Correlation between Low-Magnitude Earthquakes and Oil and Gas Industry Activity in Alberta

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A Review of the Potential Correlation between Low-Magnitude Earthquakes and Oil and Gas Industry Activity in Alberta

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Abstract

This study examined the potential spatial and temporal correlations between low-magnitude earthquakes recorded as having occurred between 2006 and 2010 in the AGS earthquake catalogue and oil and gas industry activity in Alberta. This study is the first of its kind to review earthquake and oil and gas activity and begin to evaluate the spatial and temporal relationships at a provincial scale. Wells that were subjected to hydraulic fracturing, water disposal, water injection, and acid-gas injection were used in the correlation study. Based on the data available, no correlation between earthquakes and hydraulic fracturing performed from 2006 to 2010 was found. For water disposal wells, the temporal correlation is more complex to constrain since pore pressures increase over time and could cause sufficient stress change along a fault. Therefore, a correlation between earthquakes from 2006 through 2010 and water disposal wells in Alberta may be possible. In particular, two water disposal wells (00/06-33-037-09W5 and 00/10-25-043-16W5) were located within 10 km of significant seismic event clusters. A more detailed analysis of injection rates and pressures of these wells may help further establish a correlation. There were only two acid-gas injection wells that were within a 20 km radius of a seismic event and it is unlikely that the acid-gas storage sites have been adversely affected by seismicity.

Using currently available data, a definitive causal correlation is not possible. In areas of concern, more work is needed to expand the array of seismic stations to precisely determine an earthquakes' epicentre and hypocenter. Detailed geological mapping and geophysical surveys are also needed to identify fault locations. This information could be used in conjunction with well-specific injection, disposal, or production data to provide the fluid pressure, as well as absolute state of stress.

1 Introduction

Alberta is enriched with hydrocarbon resources and has an extensive history of oil and gas development. Recent seismic events triggered by oil and gas activity (specifically, hydraulic fracturing) in the United Kingdom and British Columbia have drawn increased public attention to the potential link between these events. This attention has prompted many regions to take a closer look at the relationship between oil and gas activities and earthquakes. This is especially relevant as energy development grows and potentially overlaps with other infrastructure. This study is the first of its kind to review, at a provincial scale, earthquake and oil and gas activity and begin to evaluate the spatial and temporal relationships between oil and gas activity and seismic events.

In 2009, the Alberta Geological Survey (AGS), part of the Alberta Energy Regulator (AER), began the Alberta Microseismicity Project in collaboration with researchers from the University of Alberta and the University of Calgary. The purpose of this project was to support the expansion of the seismic station network in Alberta and compile a digital dataset of the Alberta earthquake catalogue identifying the location and magnitude of earthquakes that occurred between 2006 and 2010 (Stern et al., 2013a). A companion report to the dataset was published to provide information on where all historical and current seismic stations are in Alberta and discuss the acquisition and processing of the seismic data (Stern et al., 2013b). For this study, the data from the earthquake catalogue was used in conjunction with oil and gas data from the AER.

2 Background

Earthquakes are a natural, world-wide phenomenon that can range in intensity from undetectable to devastating. In 2011, the damaging Tohoku earthquake in Japan measured a magnitude of 9.0. The largest earthquake ever recorded was a magnitude of 9.5 in Chile in 1960 (USGS, 2013). In Alberta, the largest earthquake recorded was a magnitude 5.4 event near the Alberta–British Columbia border in 2001. Hundreds of low-magnitude earthquakes have occurred in Alberta since seismic monitoring began (Figure 1). However, there is no record of a major destructive seismic event (Lamontagne et al., 2007).

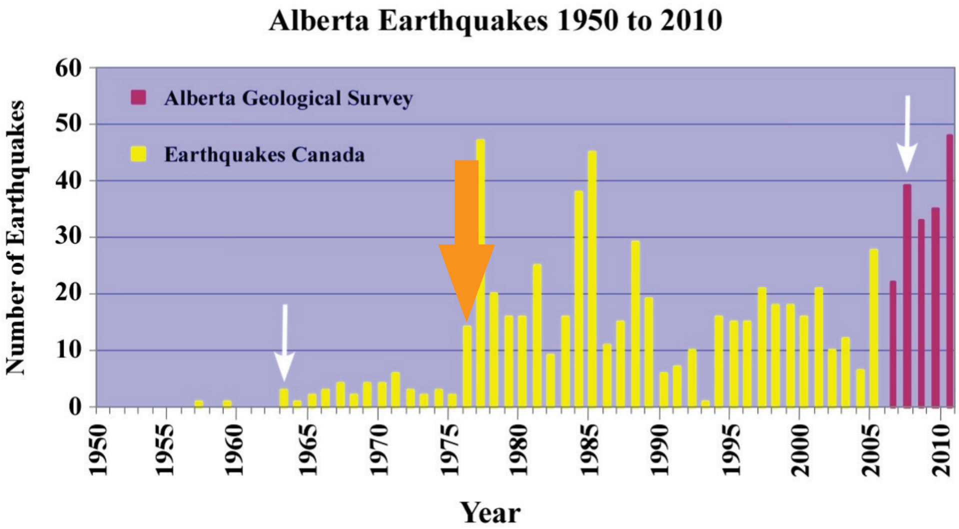

Figure 1. Earthquakes in Alberta from 1950 to 2010 (Stern et al., 2013b). The first and last white arrow indicate when improvements in the seismic station coverage were made. The orange arrow indicates an increase in earthquakes that do not correspond with new stations (Baranova et al., 1999).

Earthquakes are caused by the energy released when slip occurs along a fault plane, creating seismic waves that create ground motion. The amount of energy released depends on the amount of slip along the fault and the attenuation of seismic energy. The Richter magnitude scale (Richter scale) was developed to assign a number to quantify the amount of energy released during an earthquake. The Modified Mercalli Intensity (MMI) scale is used to describe the effects caused by the intensity of an earthquake. The magnitudes of all earthquakes noted in this report are measured on the Richter scale in local magnitude (M_L or M). According to the MMI scale, earthquakes with a magnitude of 5 are felt and may cause slight damage. Table 1 shows the relationship between the Richter scale and the MMI scale with corresponding descriptions of what would be felt or experienced at those scales.

Table 1. Earthquake intensity ranges typically observed near the epicentre of earthquakes at different magnitudes (USGS, 2013).

Richter scale magnitude	MMI	Description[1]
1.0–3.0	I	Detected only by sensitive instruments.
3.0–3.9	II	Only felt by a few people at rest (especially on the upper floors of buildings). Many people do not recognize it as an earthquake.
	III	Felt quite noticeably by people indoors (especially on the upper floors of buildings). Many people do not recognize it as an earthquake. Standing motor cars may rock slightly, with the vibrations similar to that of a passing truck.
4.0–4.9	IV	Felt indoors by many, outdoors by a few during the day. At night, some may awaken. Dishes, windows, and doors may be disturbed and walls may make cracking sounds. Sensations that feel like a heavy truck striking a building may be felt. Standing motor cars can rock noticeably.
	V	Felt by nearly everyone. Many may be awakened. Some dishes and windows may break. Unstable objects may overturn.
5.0–5.9	VI	Felt by all. Many may be frightened. Some heavy furniture may move and, in a few instances, plaster may fall. Damage is slight.
	VII	Damage negligible in buildings designed and constructed well, but slight to moderate in well-built ordinary structures. Damage may be considerable in poorly built or badly designed structures.

[1] Descriptions here have been abbreviated from their actual descriptions in the MMI.

3 Previous Work

Most earthquakes occur naturally. However, it became recognized that human activity can trigger a seismic event by altering the stress regime and causing slip on a pre-existing fault—petroleum extraction (early 1920s), reservoir impoundment (1930s), high-pressure injection (mid-1960s), and gas extraction (late 1960s) (McGarr et al., 2002). Figure 2 illustrates the following documented anthropogenic triggers for earthquakes: reservoir impoundment (Gough and Gough, 1970; Bell and Nur, 1978; Gupta and Rastogi, 1976; Gupta, 1985), mining (Pomeroy et al., 1976; Gendzwill et al., 1982), oil and gas extraction (Milne, 1970; Rebollar et al., 1982; Wetmiller, 1986; Segall, 1989; Grasso and Wittlinger, 1990; Doser et al., 1991, 1992; Grasso, 1992; Segall et al., 1994; Horner et al., 1994; Baranova et al., 1999; Van Eijs et al., 2006), hydraulic fracturing (Holland, 2011; de Pater and Baisch, 2011; BCOGC, 2012) fluid or gas disposal (Healy et al., 1968; Hsieh and Bredehoeft, 1981; Zoback, 2012, Keranen et al., 2013) or injection for enhanced oil recovery (Gibbs et al., 1972; Raleigh et al., 1972; Nicholson and Wesson, 1990, 1992; Davis and Frohlich, 1993, Horner et al., 1994; Davies et al., 1995).

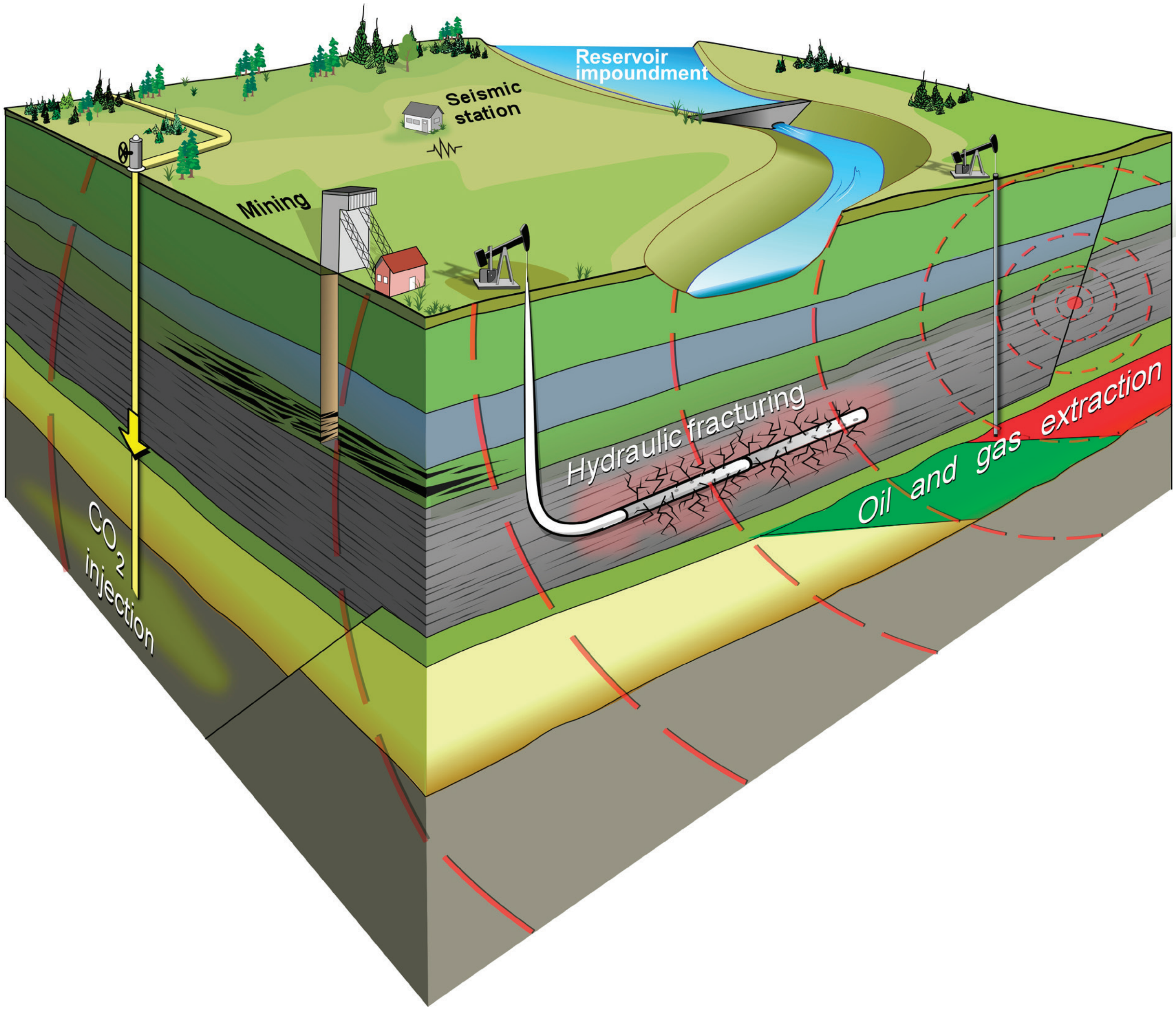

Figure 2. Potential sources of induced seismicity (reservoir impoundment, mining, oil and gas extraction, hydraulic fracturing, fluid or gas disposal or injection for enhanced oil recovery).

The prevailing theory is that under certain conditions, low-magnitude earthquakes (less than 4.5) can be triggered by hydrocarbon extraction, fluid injection, and hydraulic fracturing. However, such earthquakes are very rare and their magnitudes are generally low (Suckale, 2009; NRC, 2012).

3.1 Fluid Extraction

Oil and gas production have long been known to have the potential to trigger earthquakes (Segall, 1989; Grasso and Wittlinger, 1990; Doser et al., 1991; Grasso, 1992; Nicholson and Wesson, 1992; Segall et al., 1994; Baranova et al., 1999). According to Segall (1989), if a producing unit is compacting from the fluid being extracted and the subsequent decrease in pore pressure, the resulting stress changes could trigger a seismic event. The most important factors in triggering an earthquake are the pumping-induced pore pressure drop, presence of existing faults, and the contrast in Young's modulus (stiffness) between the reservoir and adjacent formations (Van Eijs et al., 2006).

An example of a well-documented case of induced seismicity from fluid extraction was in the Lacq gas field in France (Grasso and Wittlinger, 1990; Segall et al., 1994). Gas production began in 1957 and between 1974 and 1983 there had been 800 seismic events ranging in magnitude from 1.0 to 4.2. In Alberta, Milne (1970) speculated that the 5.1 magnitude earthquake at Snipe Lake in 1970 had been caused by hydrocarbon production. He based this on the anomalous nature of the location and the magnitude of the event but due to the lack of on-site monitoring, his claim is unverified (Horner et al., 1994). The connection between gas production in the Strachan pool near Rocky Mountain House, Alberta, and a cluster of earthquakes was investigated by Rebollar et al. (1982, 1984) and Wetmiller (1986) and revisited by Baranova et al. (1999). The timing of the Strachan events suggest that seismic activity began approximately five years after the onset of gas extraction.

Suckale (2009) reviewed numerous case studies and compiled a list of common observations on induced seismicity from hydrocarbon extraction, which are summarised in Table 2.

Table 2. Common observations on induced seismicity from hydrocarbon extraction (Suckale, 2009).

Earthquake characteristic	Observation
Magnitudes range	Typically lower than 4.5.
Correlation with production	An obvious correlation is rarely observed.
Location	Occurred directly above or below the reservoir.
Spatial clustering	Typically observed.
Temporal patterns	Characteristic time lapse of several years between beginning of production and changes in seismicity.
Faulting	Dominated by the pre-existing stress field.

3.2 Injection and Disposal

Earthquakes triggered by fluid injection occur if pore pressure at the fault increases beyond the critical threshold—lowering the effective normal stress on a fault and leading to failure (Figure 3) (Hubbert and Rubey, 1959; Healy et al., 1968; Raleigh et al., 1976; Suckale, 2009; Zoback and Gorelick, 2012). Earthquakes associated with fluid injection occur along pre-existing faults and if close to injection, tend to stop soon after injection stops, with a delay in when seismicity stops the further you get from the injection site (McGarr et al., 2002).

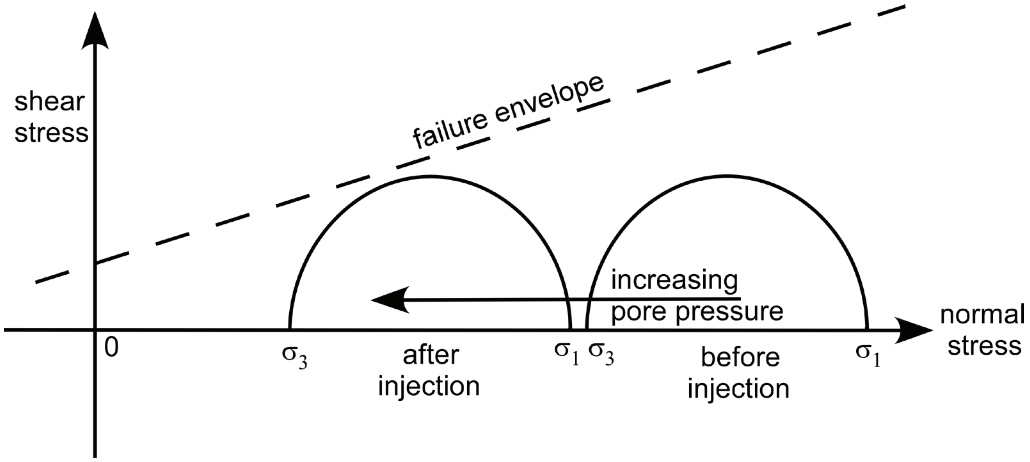

Figure 3. Mohr-Coulomb diagram illustrating how fluid injection lowers the normal stress.

The first example of water disposal inducing earthquakes occurred at the Rocky Mountain Arsenal near Denver, Colorado (Healy et al., 1968; Hsieh and Bredehoeft, 1981; Nicholson and Wesson, 1990). The disposal well was 3.7 km deep and had been injected into a relatively impermeable crystalline basement (Nicholson and Wesson, 1990). The three largest earthquakes, ranging in magnitudes from 5 to 5.5, occurred long after injection stopped.

From 1969 to 1973, USGS researchers conducted controlled induced seismicity experiments in the Rangely oil fields (Gibbs et al., 1972; Raleigh et al., 1976). In 1957, waterflooding of these fields began in response to declining production and decreased reservoir pressures. In 1962, pore pressures had increased to a level that was exceeding the preproduction pressures. In that same year, a series of seismic events small in magnitude were detected in the region. The largest earthquake measured was in 1970 at a magnitude of 3.1 (Raleigh et al., 1976). These experiments showed that in a seismically active zone, controlled variations in fluid pressure could trigger seismic events.

In November 2011, magnitude 5.0, 5.7, and 5.0 earthquakes occurred in Prague, Oklahoma. Keranen et al. (2013) suggested that the cause of the earthquakes was linked to waste-water injection that had been happening over the last 18 years, which had lowered the effective stress on the reservoir-bounding faults. However, the Oklahoma Geological Survey also conducted a review of the Prague earthquakes and concluded that they were the result of natural conditions and were not induced.

3.3 Hydraulic Fracturing

Hydraulic fracturing is being increasingly used to produce oil and gas from low-permeability reservoirs. This process involves injecting fluids and proppant to create permeable fractures in tight formations. The National Research Council's report on induced seismicity (2012) stated that the current process for the hydraulic fracturing of a well for shale gas recovery does not pose a high risk for inducing felt seismic activity. However, due to the potential risks (however small) and public concern, some governments are developing risk management plans to prevent seismic events triggered by hydraulic fracturing.

In Lancashire County, near Blackpool in the United Kingdom, two events of magnitude 2.3 and 1.5 were detected near the Preese Hall well site in April and May of 2011, respectively (de Pater and Baisch, 2011). These events led the British government to place a moratorium on hydraulic fracturing while it investigated the events. The well was 2477 m deep (vertical) and had five hydraulic fracturing stages completed on it. The first earthquake occurred during the second stage and the second one had occurred during the fourth stage. There had also been an additional 50 smaller seismic events. The investigation indicated that seismicity was most likely due to direct injection into a fault zone (de Pater and Baisch, 2011). However, in December 2012, the British government lifted the ban and announced that the hydraulic fracturing of shale gas wells could resume once new measures were in place to prevent seismic risks.

Also in 2011, forty-three earthquakes (magnitudes 1.0 to 2.8) occurred near the Eola Field of Garvin County, Oklahoma (Holland, 2011). All the earthquakes were within 3.5 km of a well and occurred within 24 hours of a vertical gas well stimulation completion. The researchers were unable to confirm a causal link due to uncertainty of the event's location.

In 2012, the BC Oil and Gas Commission (BCOGC) released a report showing the results from a study investigating the potential connection between seismic events and hydraulic fracturing in the Horn River Basin between 2009 and late 2011. The report concluded that the seismic events detected were caused by fluid injection during hydraulic fracturing near pre-existing faults. They also concluded that the nearby disposal wells were not the source of the seismicity. Figure 4 shows the 27 seismic events that occurred in the Etsho area within a 10 km radius of the five horizontal-multistage hydraulically fractured wells. The seismic events ranged in magnitude from 1.9 to 3.0 and occurred during or between the stages.

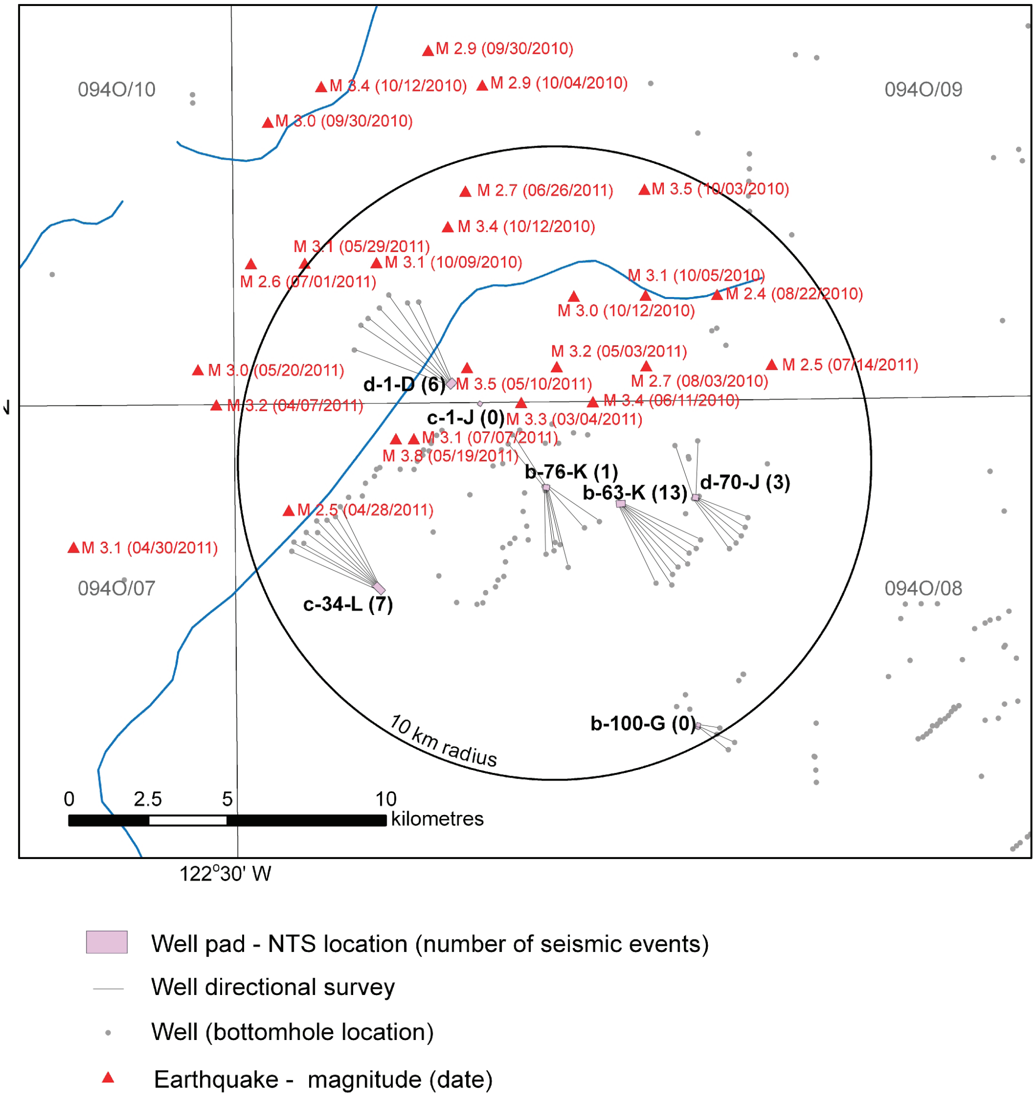

Figure 4. BCOGC's (2012) report on seismicity in the Horn River Basin reported 27 seismic events that occurred within a 10 km radius of 5 hydraulically fractured horizontal wells (modified from BCOGC, 2012).

4 Methodology

A simple methodology was used to determine if there is a spatial and temporal correlation between oil and gas activity and the seismic events. The review included the seismic events from the AGS earthquake catalogue (Stern et al., 2013a). Due to the distribution of seismographs and relatively low-magnitude events, the location of epicentres is considered accurate to within 10 km. It was also not possible to determine accurate focal depth (Stern et al., 2013b). The data for the oil and gas wells in Alberta are from the AER.

4.1 Hydraulic Fracturing

To find a spatial correlation between earthquakes and hydraulic fracturing, the methodology involved searching for all hydraulic fracturing activity within a 5 and 10 km radius around a seismic event. A conservative 10 km buffer was used to account for the uncertainty in the location of seismic epicenters (Stern et al., 2013b). A 5 km buffer was established by Davis and Frohlich (1993) as part of their induced seismicity criteria. These criteria were also used as part of the BCOGC Horn River Basin study and were found to be sufficient to connect their induced seismic events with hydraulic fracturing (BCOGC, 2012).

Once a spatial correlation was found, the correlation was further refined to include a temporal link. For the hydraulic fracturing cases, instances of hydraulic fracturing occurring within a week or a day before a seismic event occurred were gathered. From previous studies, the temporal correlation is within hours and days—not weeks (BCOGC, 2012). Previous research indicates that triggered earthquakes can occur either during or hours after hydraulic fracturing begins (Holland, 2011; BCOGC, 2012). The weekly correlations were included in this study for completeness and not as an indication of the correlatable relationship.

4.2 Injection and Disposal

The spatial correlation criterion for disposal wells was extended to a 10 km and a conservative 20 km radius around the seismic events. Again, the uncertainty in knowing the location of the epicenters, and previous studies that linked seismic events to disposal or injection up to 15 km away (Zhang et al., 2013), were taken into account.

Compared with the spatial correlation, a temporal correlation with disposal operations is more difficult to constrain. Previous studies have suggested a link between seismicity with disposal, but the disposal wells in those cases had been operating for as little as months (Horner et al., 1994) or as much as years—18 years in the case of the Oklahoma study (Keranen et al., 2013). Over time, injection or disposal into a formation can increase the pore pressure, which can reactivate faults by decreasing the normal stresses towards the Mohr-Coulomb failure envelope (Figure 3). Therefore, the criterion used for the temporal correlation was that the injection had to have begun before the event occurred. To further refine the temporal correlation, wells were excluded if the injection or disposal had stopped before 1996. It was decided that 10 years without injection was enough time for pressures to dissipate within the formation.

The uncertainty is greater when correlating injection and disposal wells with seismic activity because of the wide temporal boundaries. More work is required to determine a more meaningful temporal correlation between the events and injection.

5 Results

5.1 Seismic Events

In the AGS earthquake catalogue a total of 171 seismic events were recorded from September 2006 to 2010, ranging in magnitude from 0.4 to 4.1 (Table 3; Figure 1). Most earthquakes occur in western Alberta with isolated events scattered throughout the province (Figure 5). The largest event, magnitude 4.1, occurred in Township 2, Range 21, West of the 5th Meridian, approximately 60 km south of Lethbridge. This event was the only earthquake greater than magnitude 4 in the catalogue. The smallest detected earthquake was in the Brazeau River area in Township 43, Range 15, West of the 5th Meridian.

Table 3. Number and magnitude range of seismic events in Alberta, from September 2006 to December 2010.

	2006	2007	2008	2009	2010	Total
Number of events	16*	39	33	35	48	171
Magnitude	0.4–4.1	0.6–3.8	0.5–3.8	0.7–3.7	1.4–3.5	0.4–4.1

* Only measured for four months.

The low-magnitude earthquakes in Alberta occurred both in clusters and as isolated events (Figure 5). A number of spatially-clustered earthquakes have been identified in previous studies (Rebollar et al., 1982; Rebollar et al., 1984; Wetmiller, 1986; Baranova et al., 1999; Stern et al., 2013b). The first identified cluster was located in the Rocky Mountain House area (Rebollar et al., 1982). Baranova et al. (1999) identified the Brazeau River and Turner Valley clusters and Stern et al. (2013b) identified the Del Bonita cluster at the border between Canada and the US. Although an analysis of specific spatial clusters was not within the scope of this project, further study is needed to evaluate their relationship to oil and gas activity since induced events are characterized by such clusters.

Provincial seismic events were divided into three regions to highlight the spatial trends in earthquakes that occurred between 2006 and 2010 (Table 4). The regions identified are the western provincial and national parks, deformed belt (not included the area in the parks), and interior craton separated based on geological setting and activity.

Table 4. Number and magnitude range of seismic events in Alberta by region, from September 2006 to December 2010.

Region		2006	2007	2008	2009	2010	Total
Western Parks (including BC)	Number of events	4	8	14	11	11	48
	Magnitude	2.2–3.7	1.8–2.8	1.3–3.6	0.7–3.3	1.5–3.1	0.7–3.7
Deformation Belt (outside of park)	Number of events	9	22	10	10	20	71
	Magnitude	0.4–2.9	0.6–3.3	0.5–3.6	1.2–3.7	1.4–2.9	0.4–3.7
Interior Craton	Number of events	3	9	9	14	17	52
	Magnitude	2.0–4.1	2.1–3.8	1.9–3.8	1.3–3.6	1.7–3.5	1.3–4.1

Under the *Federal Canada National Parks Act*, all national parks are protected from all forms of industrial development, including mining, oil and natural gas development, and any hydro-electric development. From 2006 to 2010, a total of 48 earthquakes occurred within parks along the western border between Alberta and British Columbia (Table 4; Figure 5). Due to the restriction on development in the national parks, it can be assumed that these events are part of the normal background seismic activity in the Rocky Mountains. The magnitudes of the events ranged from 0.7 in 2009 to 3.7 in 2006.

As expected, most seismic events occur in the highly faulted, deformed belt region. Figure 6 shows the earthquakes in relation to some major faults in the deformed belt region (Hamilton et al., 1999). Faults exist to a lesser degree in the rest of the province but little data is available in the public domain. Seventy percent of the seismic events occur in the western parks and deformed belt regions. The deformed belt region had the highest number of earthquakes, with a total of 71 events from 2006 to 2010 (Table 4).

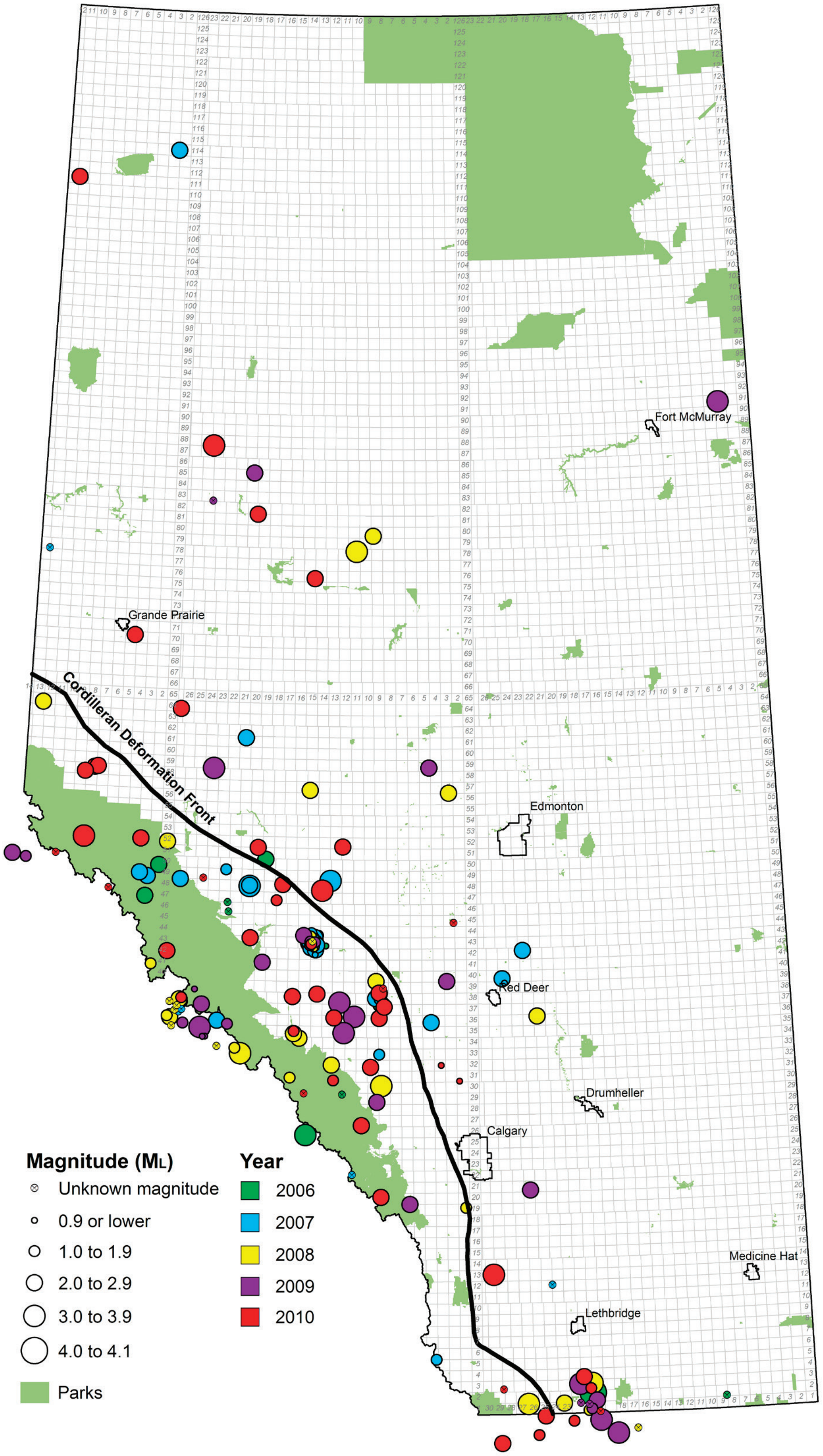

Figure 5. The locations of earthquakes that occurred in Alberta between 2006 and 2010 (Stern et al., 2013a).

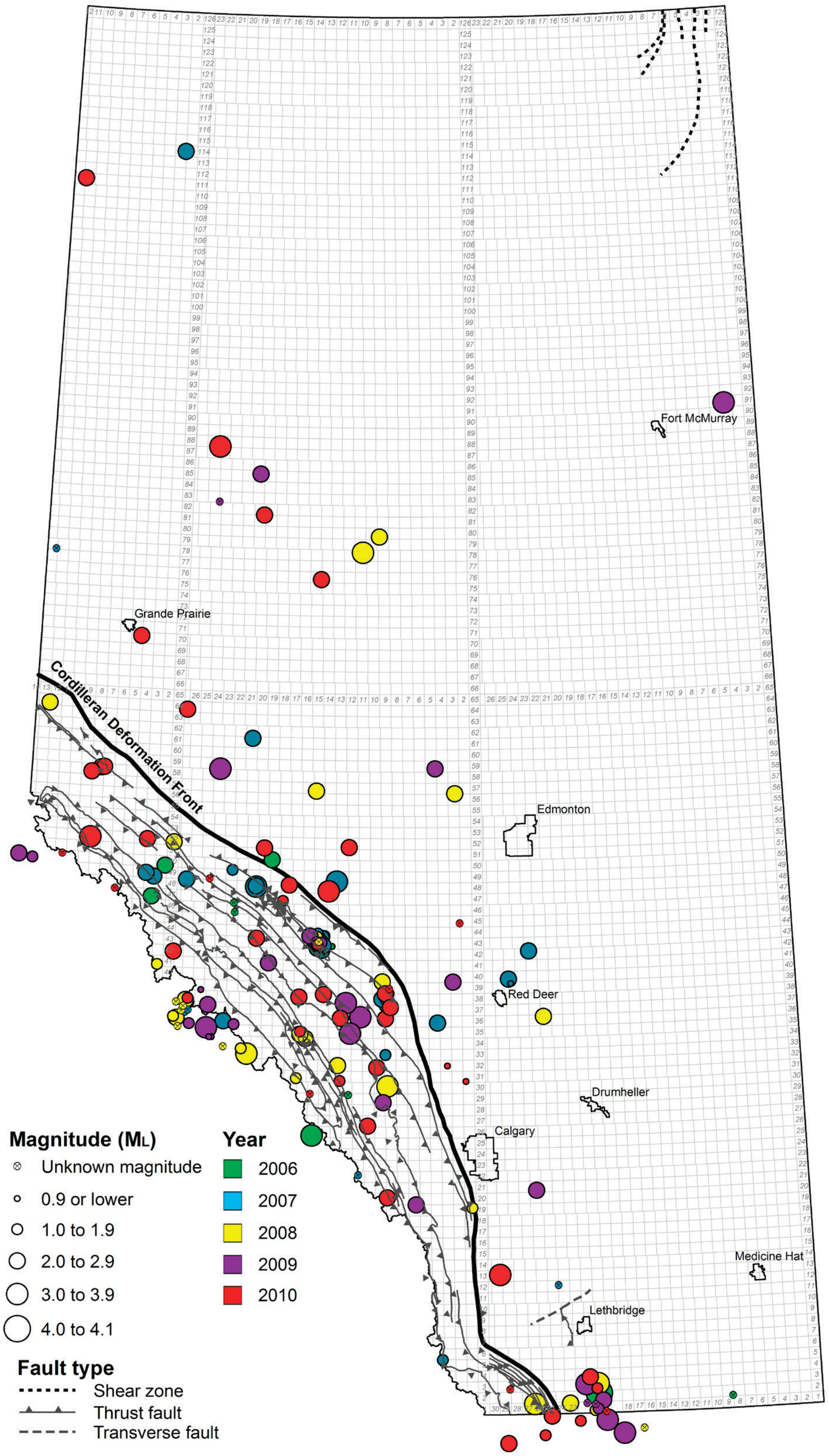

Figure 6. The locations of earthquakes that occurred between 2006 and 2010 (Stern et al., 2013a) and major faults in Alberta (Hamilton et al., 1999).

Overall, the lowest magnitude event was in the deformed belt region (0.4 in 2006). The highest magnitude event in this same region was recorded as 3.7 in 2009 near Strachan.

The lowest rates of seismic activity at any part of the earth's crust are in the interior cratons at the core of the continents (Fenton et al., 2006). The region of the province to the east of the Cordilleran deformation front is an interior craton. The craton has the largest areal extent of the three regions but had only 30% of the total 171 seismic events. In this study, the largest event occurred in the interior craton region in 2006 near the US border within the Del Bonita cluster (magnitude 4.1).

Since the first gas well was drilled in 1883, over 550 000 oil and gas wells have been drilled in Alberta. Figure 7 shows where oil and gas wells are in relation to the epicentres of earthquakes that occurred between 2006 and 2010. Due to the high well density, the correlation of oil and gas production wells and the seismic events was outside the scope of this project.

5.2 Hydraulic Fracturing

Alberta has a long history of enhanced oil and gas recovery, using both injection-based enhanced oil recovery (EOR) and hydraulic fracturing techniques. The first recorded hydraulic fracturing event occurred in 1929. Figure 8 shows the location of all hydraulically fractured wells in Alberta—over 169 000 conventional hydraulically fractured wells and over 6000 horizontal-multistage hydraulically fractured (HMHF) wells. With the development of tight hydrocarbon plays in Alberta, the number of HMHF events has been increasing steadily over the last 10 years. In comparison, the number of vertical wells drilled and hydraulically fractured has been decreasing. Figure 9 shows the locations of 14 000 HMHF events from 2006 to 2010 in relation to seismic events during the same time period.

Table 5 lists the number of seismic events and corresponding hydraulic fracturing events that occurred within a 0 to 10 km radius of the seismic event, either within one week before or within one day before the seismic event. A similar search for hydraulic fracturing activity done within a 0 to 5 km radius only one seismic event occurred within the one week limit of the methodology. All hydraulic fracturing events that were found using the methodology for this study lack the typical characteristics seen in confirmed cases of induced seismicity, such as those in BC (Figure 2) where multiple earthquakes were detected during the hydraulic fracturing of wells.

Table 5. Number of hydraulic fracturing events occurring within a 10 km radius and within one week before or one day before a recorded seismic event.

	1 week		1 day	
Year	**Number of seismic events**	**Number of hydraulic fracturing events**	**Number of seismic events**	**Number of hydraulic fracturing events**
2010	1	3	0	0
2009	0	0	0	0
2008	2	3	1	1
2007	4	9	1	2
2006	1	1	0	0
Total	**8**	**16**	**2**	**3**

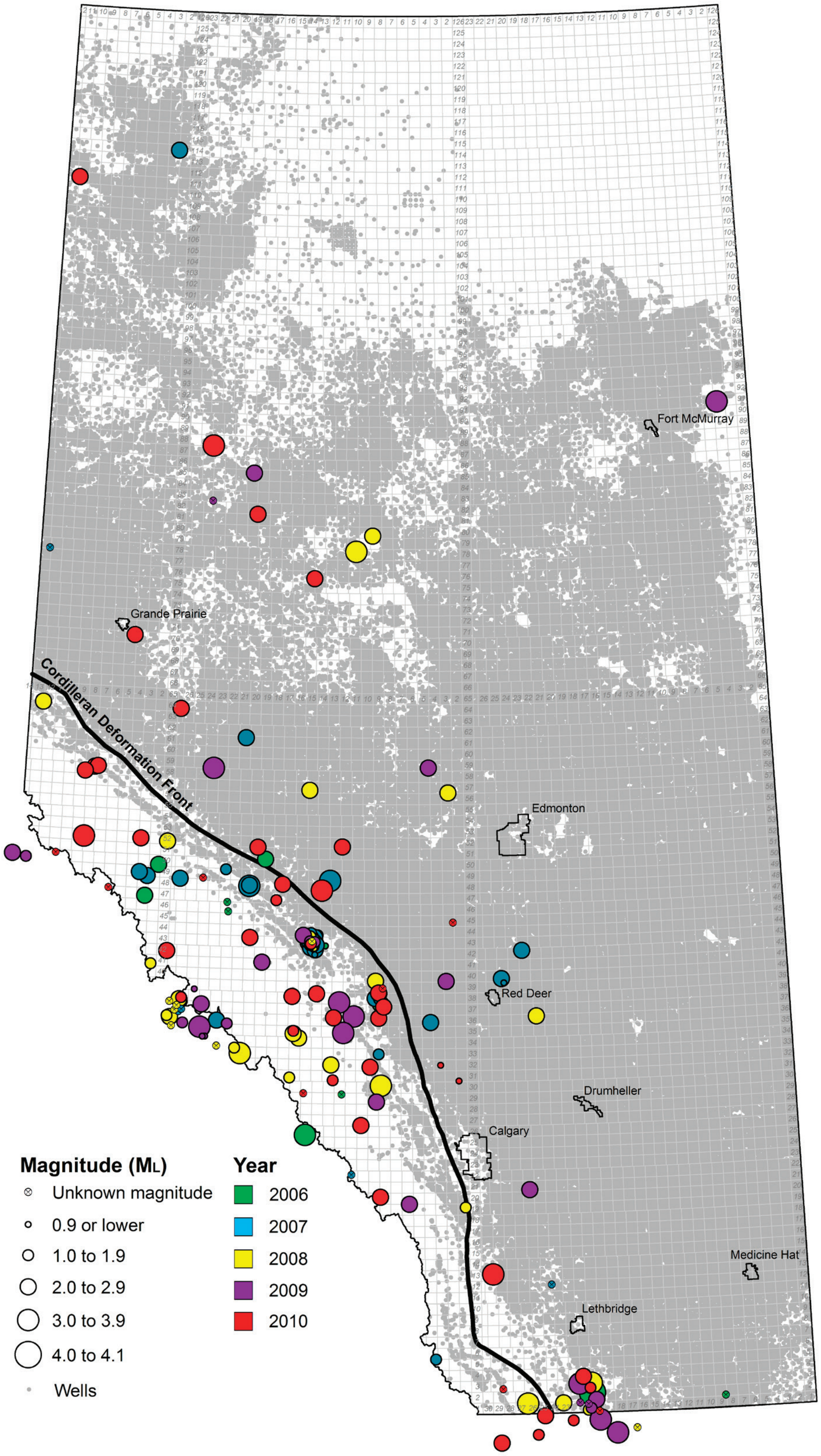

Figure 7. The locations of earthquakes that occurred between 2006 and 2010 (Stern et al., 2013a) and all oil and gas wells in Alberta.

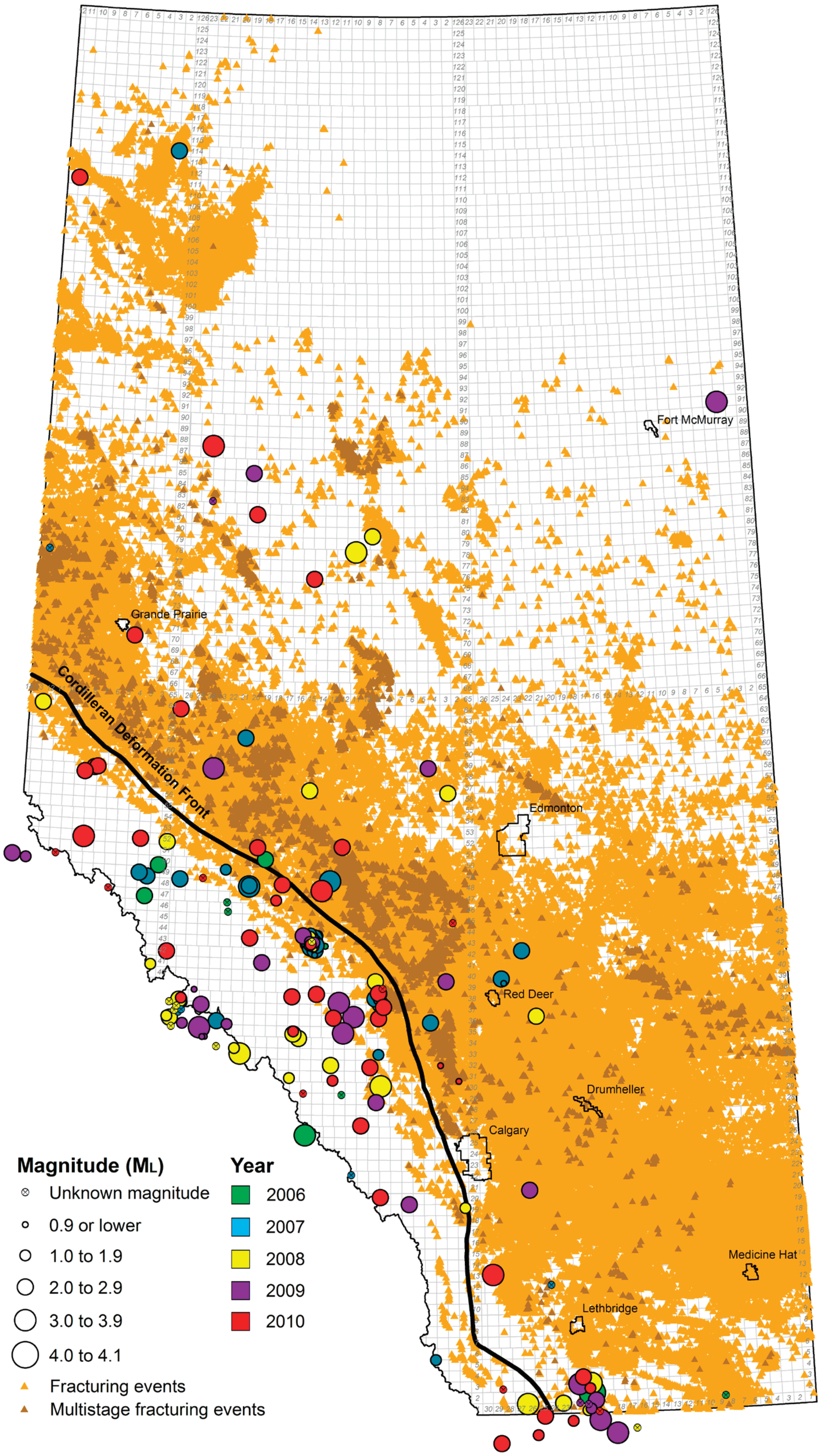

Figure 8. The locations of earthquakes that occurred between 2006 and 2010 (Stern et al., 2013a) and all hydraulically fractured wells in Alberta.

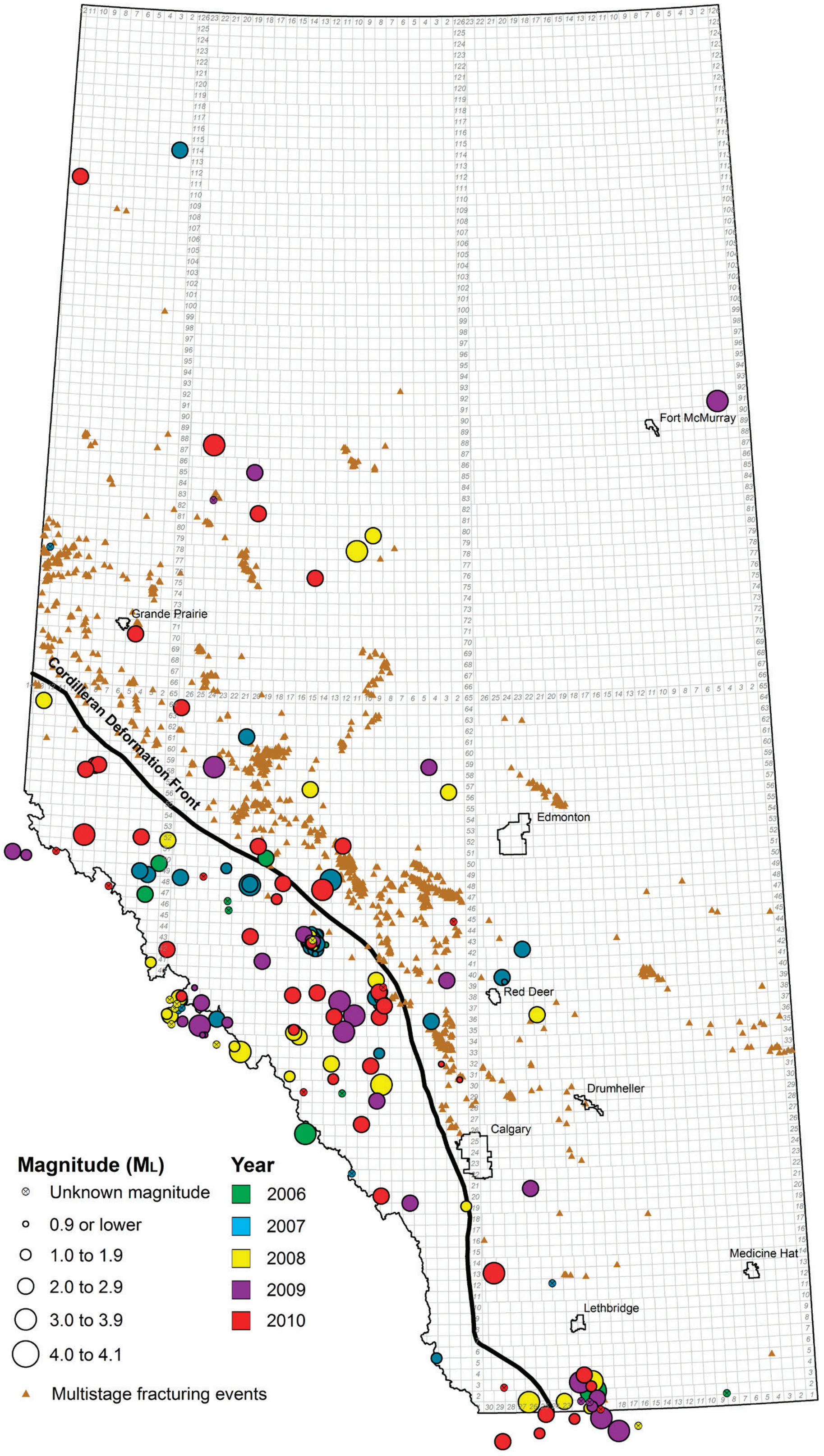

Figure 9. The locations of earthquakes (Stern et al., 2013a) and horizontal multistage hydraulically fractured wells in Alberta between 2006 and 2010.

Figure 10 shows the locations of over 45 000 hydraulic fracturing and HMHF events in 2006 in relation to the locations of 16 earthquakes in the same year ranging in magnitude from 0.4 to 4.1. When the correlation methodology is applied to this data only one earthquake is located (Figure 11). Figure 12 shows the location of the magnitude 2.4 earthquake with respect to the location of a deviated well (00/11-16-044-14W5), which was hydraulically fractured four days before the seismic event.

In 2007, over 40 000 hydraulic fracturing and HMHF events and 39 earthquakes (magnitude 0.6 to 3.8) occurred (Figure 13). When the correlation methodology is applied to the data, three earthquakes are located (Figure 14). Figure 15 shows the location of the magnitude 2.1 earthquake, which occurred seven days after a vertical well (00/11-09-36-04W5) was hydraulically fractured. Figure 16 shows the location of an earthquake of unknown magnitude and four vertical hydraulically fractured wells within a 10 km radius. Two of these wells were fractured six days before the earthquake and two wells were fractured a day before the earthquake.

Figure 17 shows the location of the magnitude 2.7 earthquake with respect to the location of four vertical wells that were hydraulically fractured. Two of these wells were fractured five days before the seismic event and two wells were fractured two days before. Three of these wells were within 5 km of the seismic event and are the only examples of hydraulic fracturing occurring within the temporal and 5 km spatial limits of the methodology.

In 2008, over 35 000 hydraulic fracturing and HMHF events and 33 earthquakes, ranging in magnitude from 0.5 to 3.8, occurred (Figure 18). When the correlation methodology is applied to the data, two earthquakes are located (Figure 19). Figure 20 shows the location of the magnitude 2.9 earthquake found with the methodology, which occurred one day after hydraulically fracturing a horizontal well (00/04-32-064-12W6). Figure 21 shows the location of the magnitude 2.8 earthquake with respect to the location of a hydraulically fractured vertical well (00/05-05-037-22W4) that was fractured six days before the earthquake.

In 2009, over 20 000 hydraulic fracturing and HMHF events and 35 earthquakes, ranging in magnitude from 0.7 to 3.7, occurred (Figure 22). There was no spatial and temporal correlation between these events based on our methodology.

In 2010, over 20 000 hydraulic fracturing and HMHF events and 48 earthquakes, ranging in magnitude from 1.4 to 3.5, occurred (Figure 23). When the correlation methodology is applied to the data, only one earthquake is located (Figure 24). Figure 25 shows the location of an earthquake with unknown magnitude, which occurred five days after a horizontal well was hydraulically fractured (00/18-16-031-03W5).

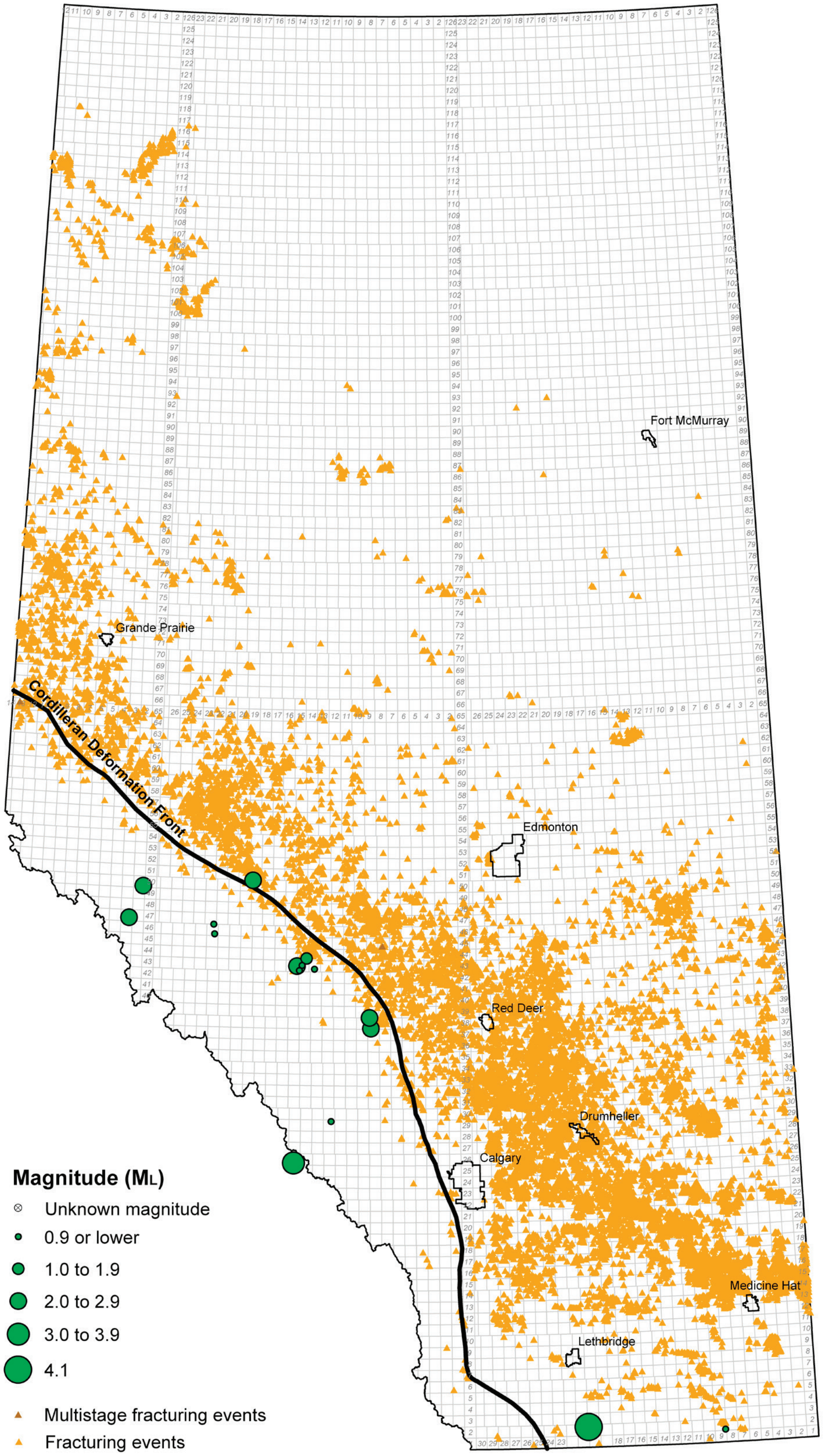

Figure 10. The locations of wells with hydraulic fracturing events in 2006 and earthquakes in Alberta in the same year (Stern et al., 2013a).

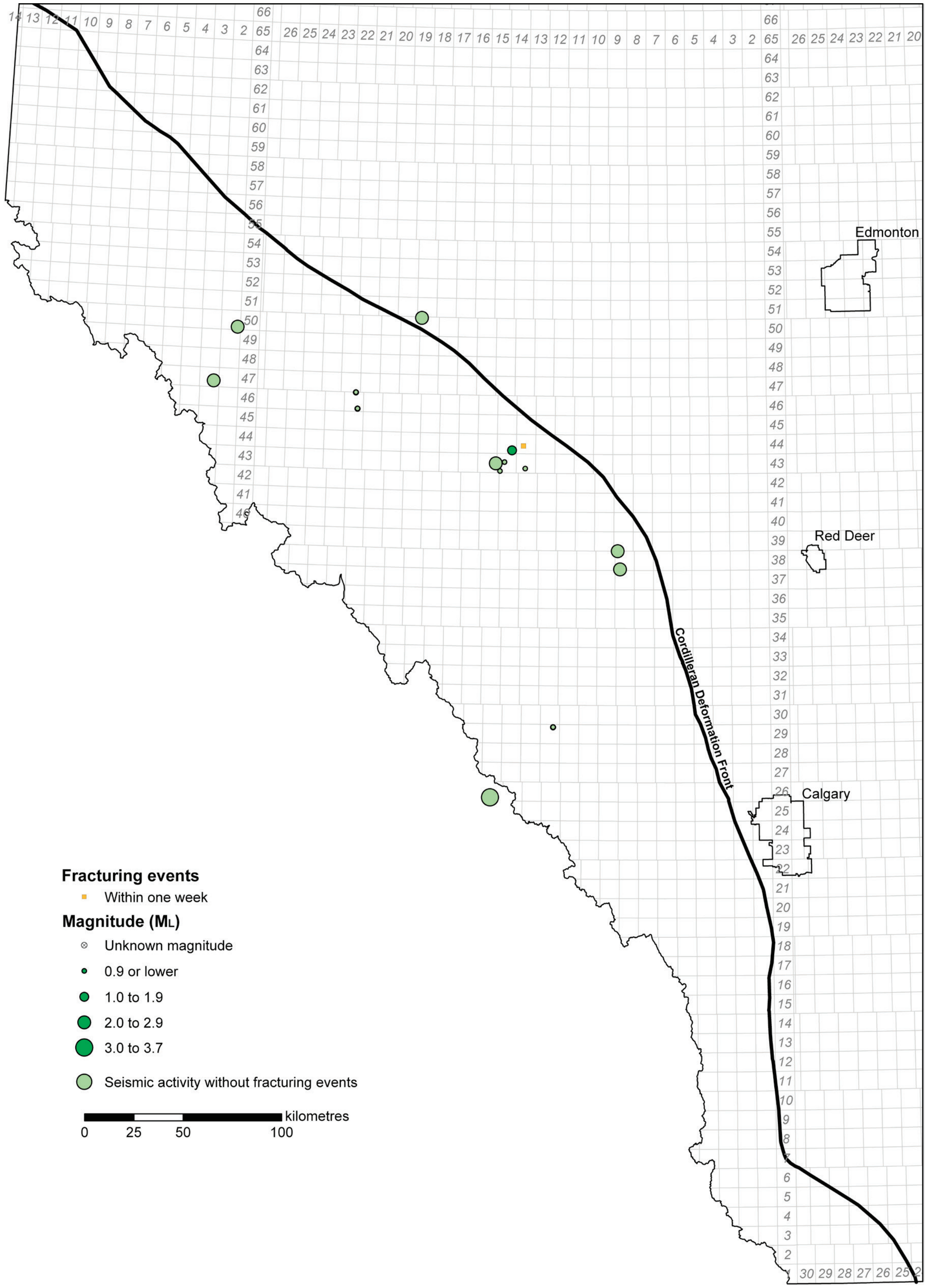

Figure 11. The bottomhole locations of wells with hydraulic fracturing events that fit the spatial and temporal correlation with an earthquake in 2006 (Stern et al., 2013a).

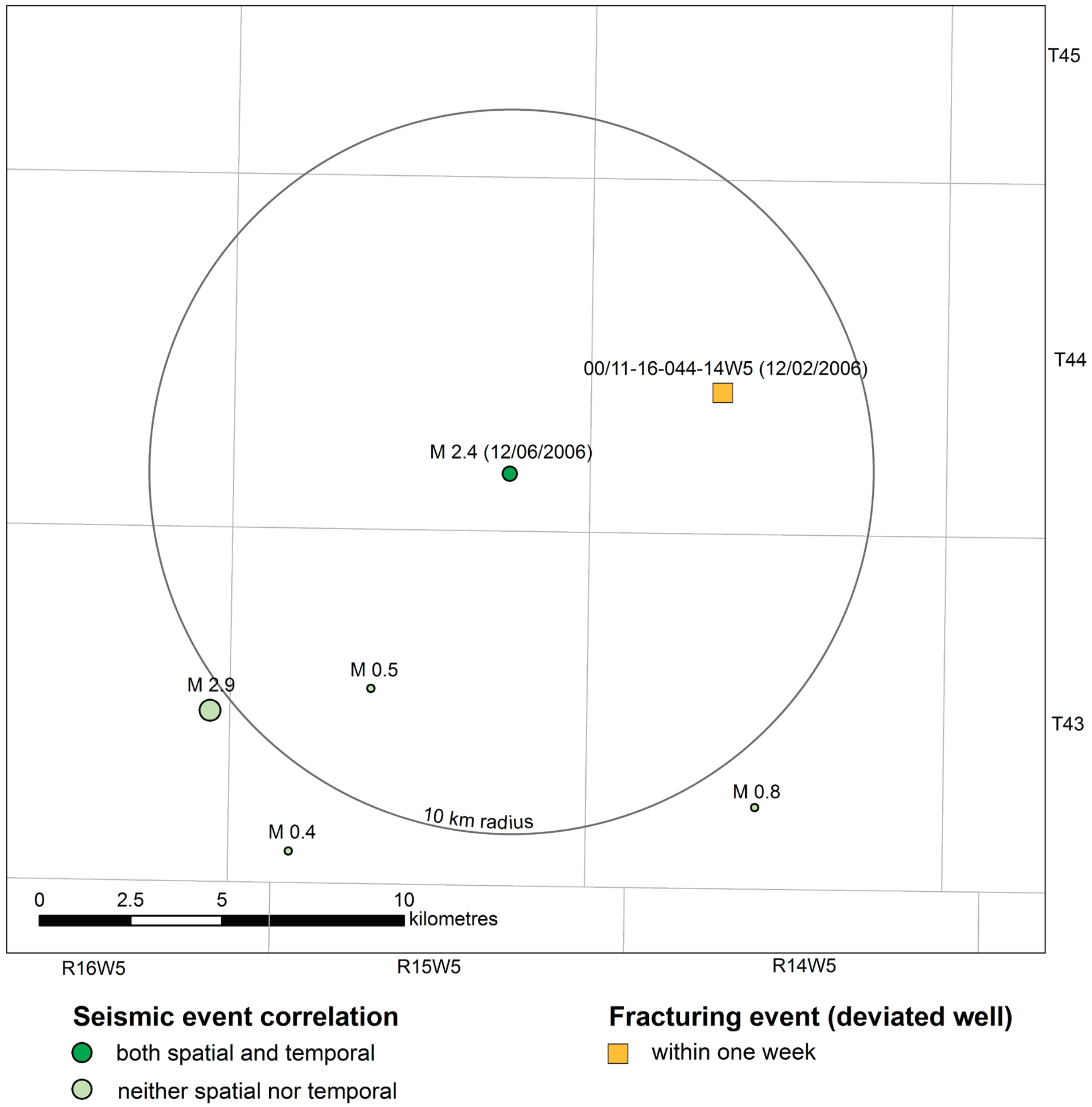

Figure 12. The bottomhole location of a well with a hydraulic fracturing event that fits the spatial and temporal correlation with a 2.4 magnitude earthquake in 2006 (Stern et al., 2013a).

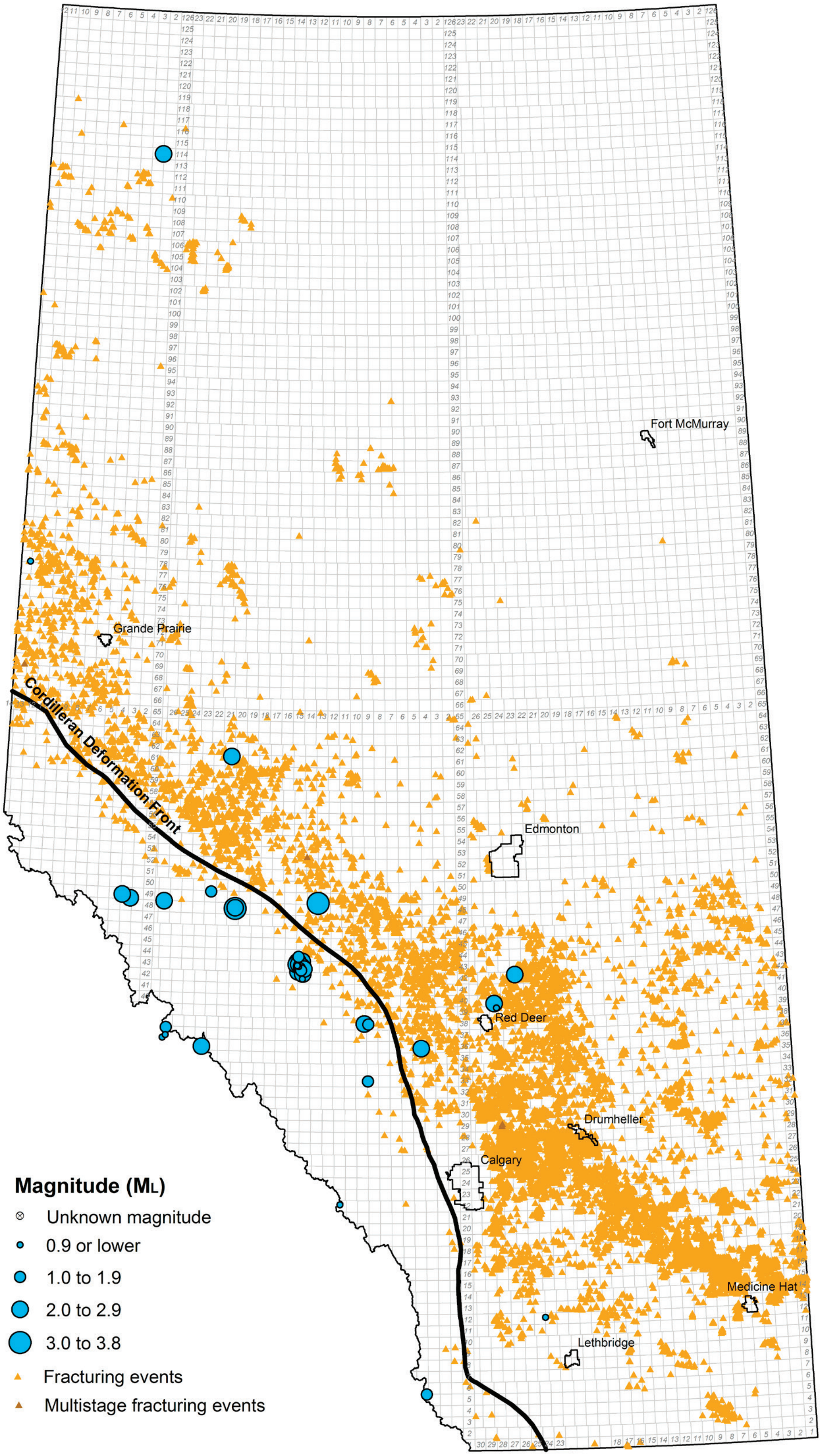

Figure 13. The locations of wells with hydraulic fracturing events in 2007 and the locations of earthquakes in Alberta in the same year (Stern et al., 2013a).

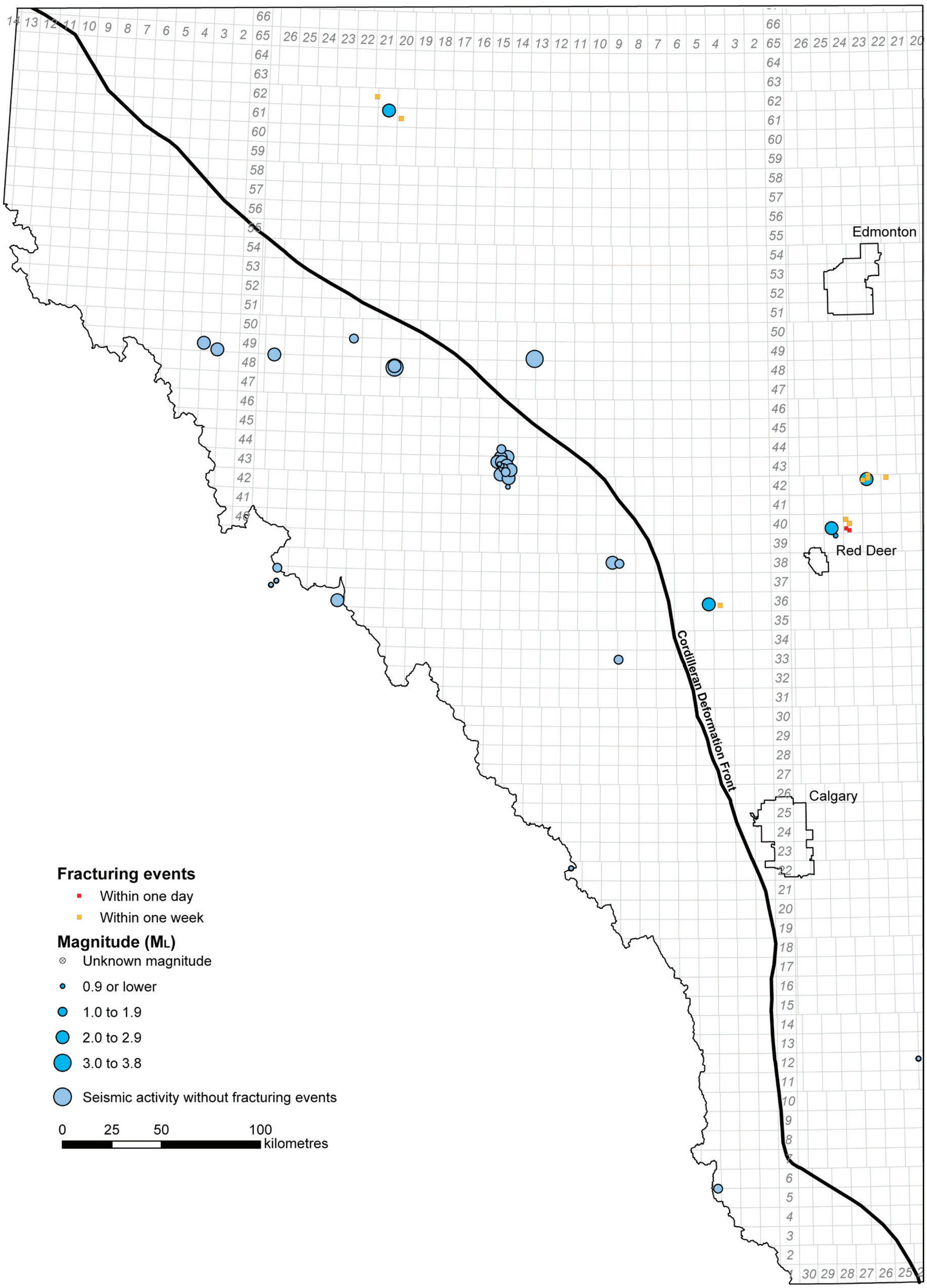

Figure 14. Bottomhole locations of wells with hydraulic fracturing events that fit the spatial and temporal correlation with earthquakes in 2007 (Stern et al., 2013a).

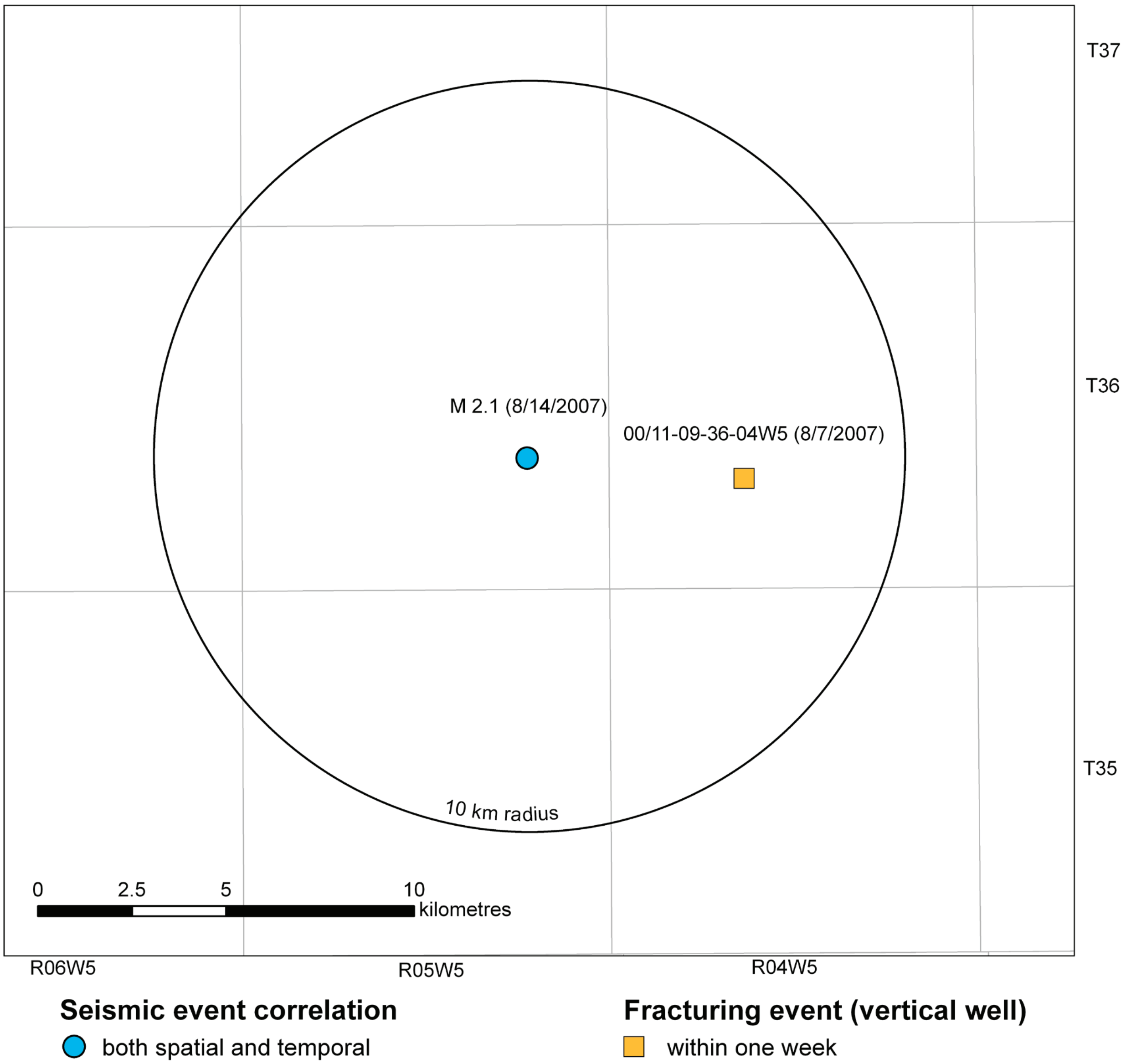

Figure 15. The location of a single vertical well with a hydraulic fracturing event that fits the spatial and temporal correlation with a 2.1 magnitude earthquake in 2007 (Stern et al., 2013a).

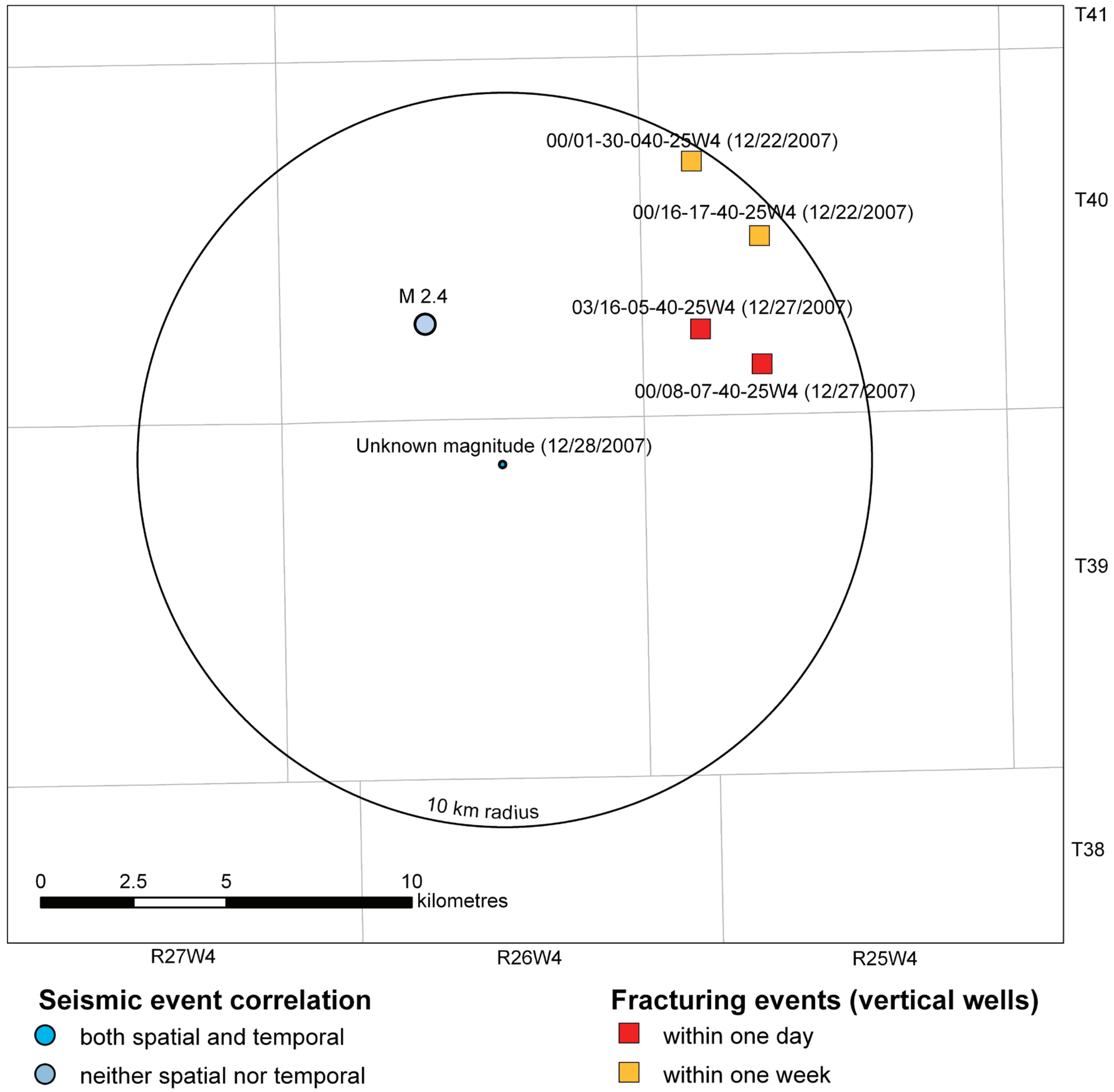

Figure 16. The locations of four vertical wells with hydraulic fracturing events that fit the spatial and temporal correlation with an earthquake of unknown magnitude in 2007 (Stern et al., 2013a).

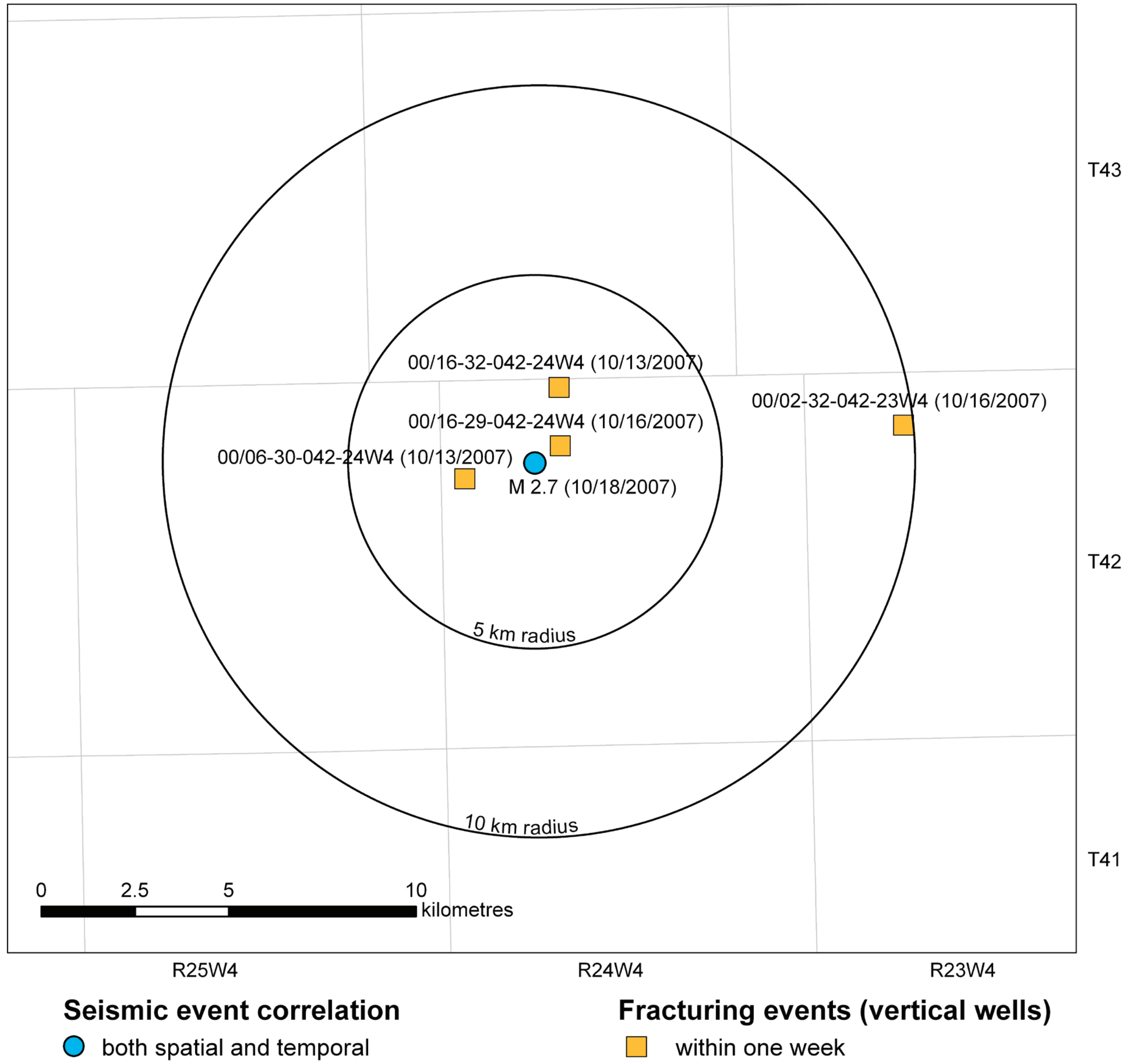

Figure 17. The locations of four vertical wells with hydraulic fracturing events that fit the spatial and temporal correlation with a 2.7 magnitude earthquake in 2007 (Stern et al., 2013a).

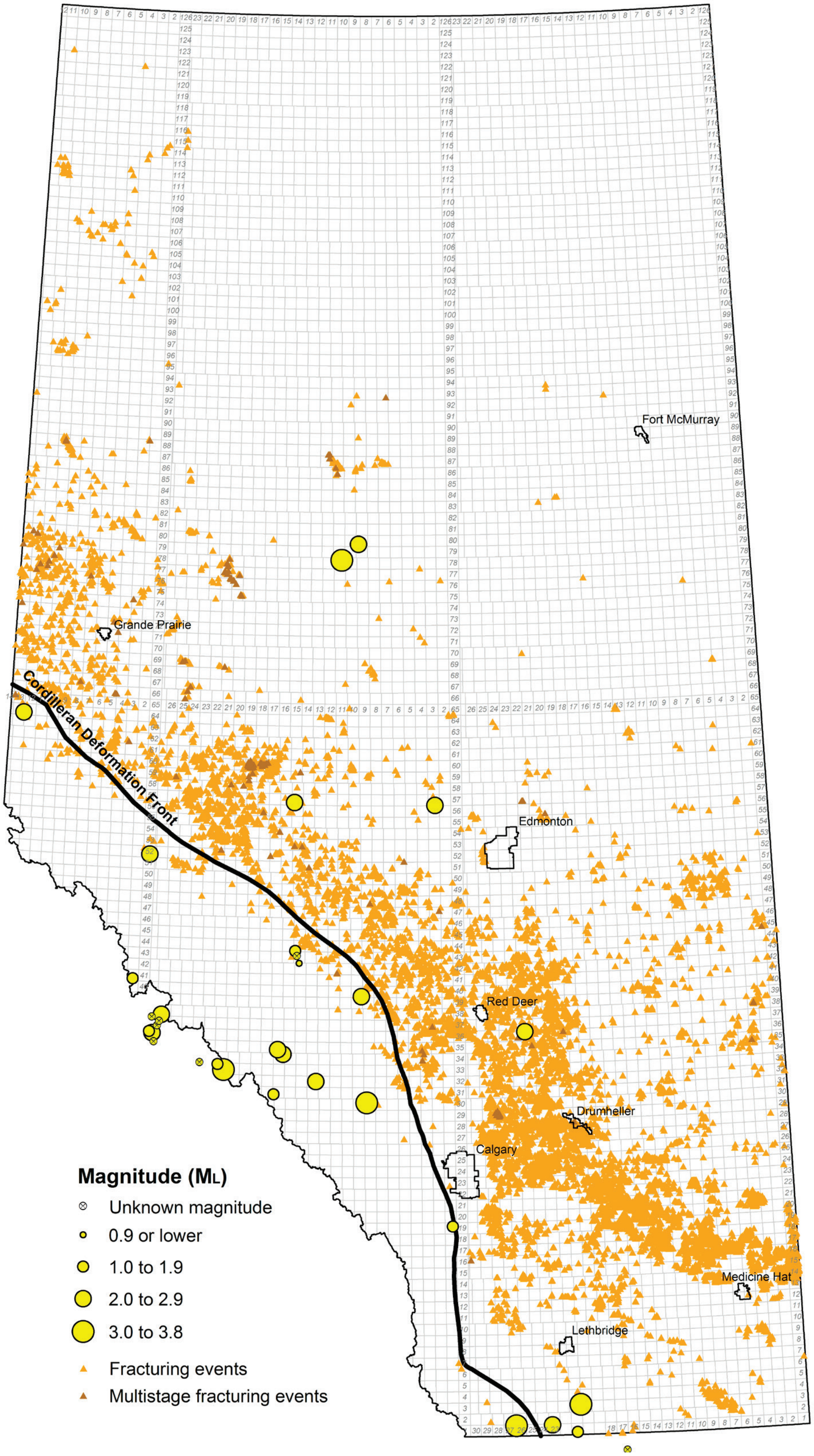

Figure 18. The locations of wells with hydraulic fracturing events and the locations of earthquakes in Alberta in 2008 (Stern et al., 2013a).

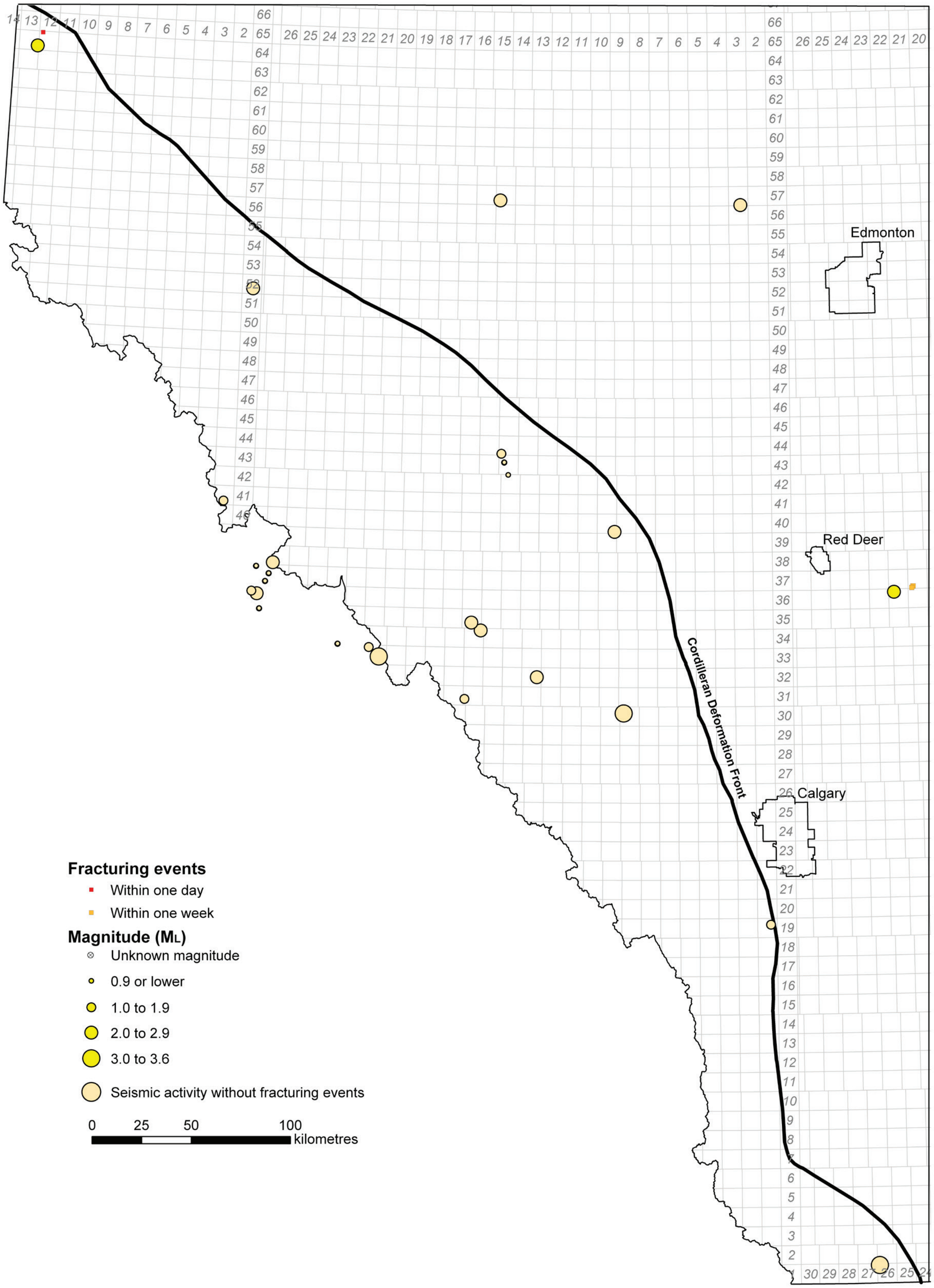

Figure 19. The bottomhole locations of wells with hydraulic fracturing events that fit the spatial and temporal correlation with an earthquake in 2008 (Stern et al., 2013a).

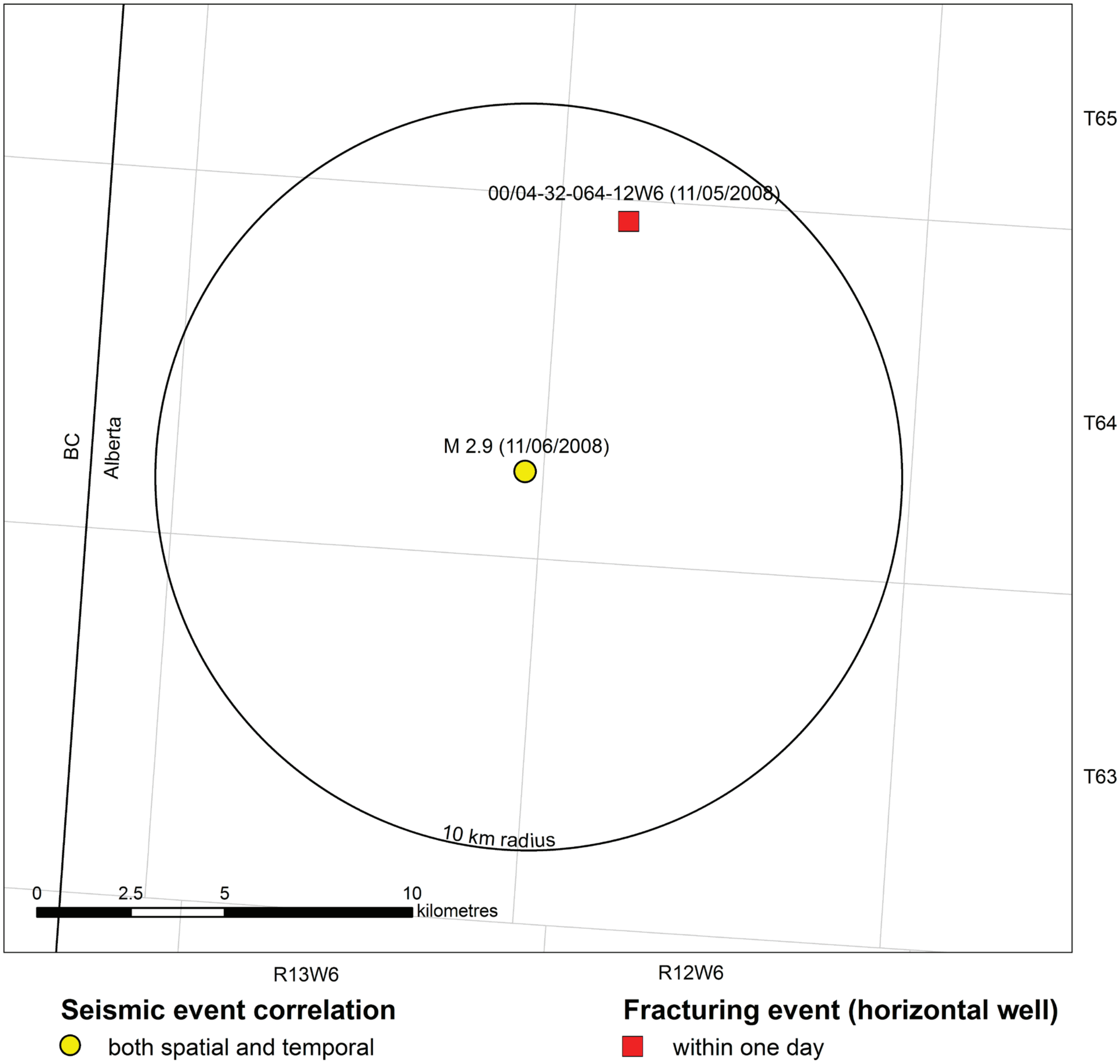

Figure 20. The bottomhole location of a single horizontal well with a hydraulic fracturing event that fit the spatial and temporal correlation with a 2.9 magnitude earthquake in 2008 (Stern et al., 2013a).

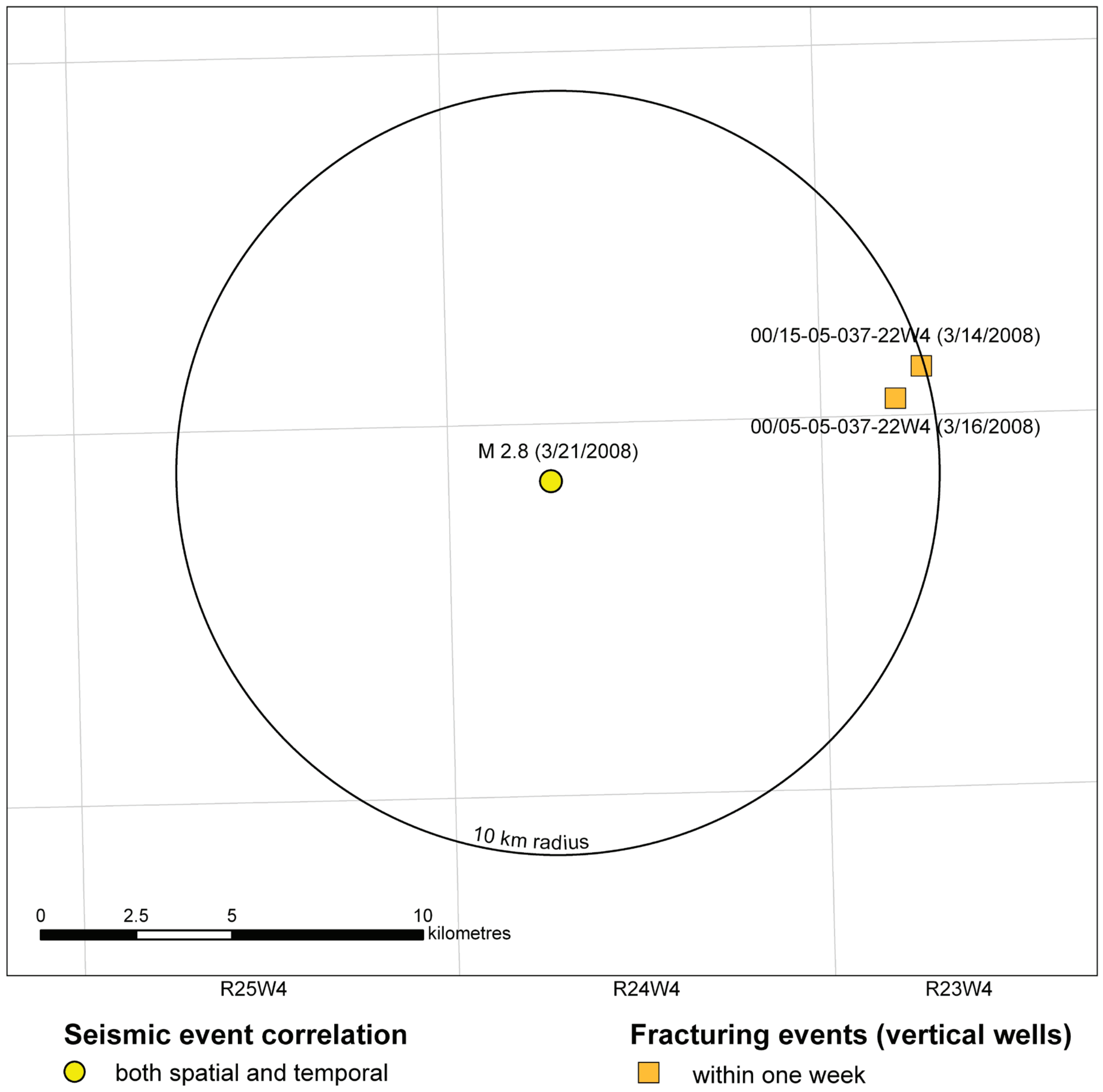

Figure 21. The locations of two vertical wells with hydraulic fracturing events that fit the spatial and temporal correlation with a 2.8 magnitude earthquake in 2008 (Stern et al., 2013a).

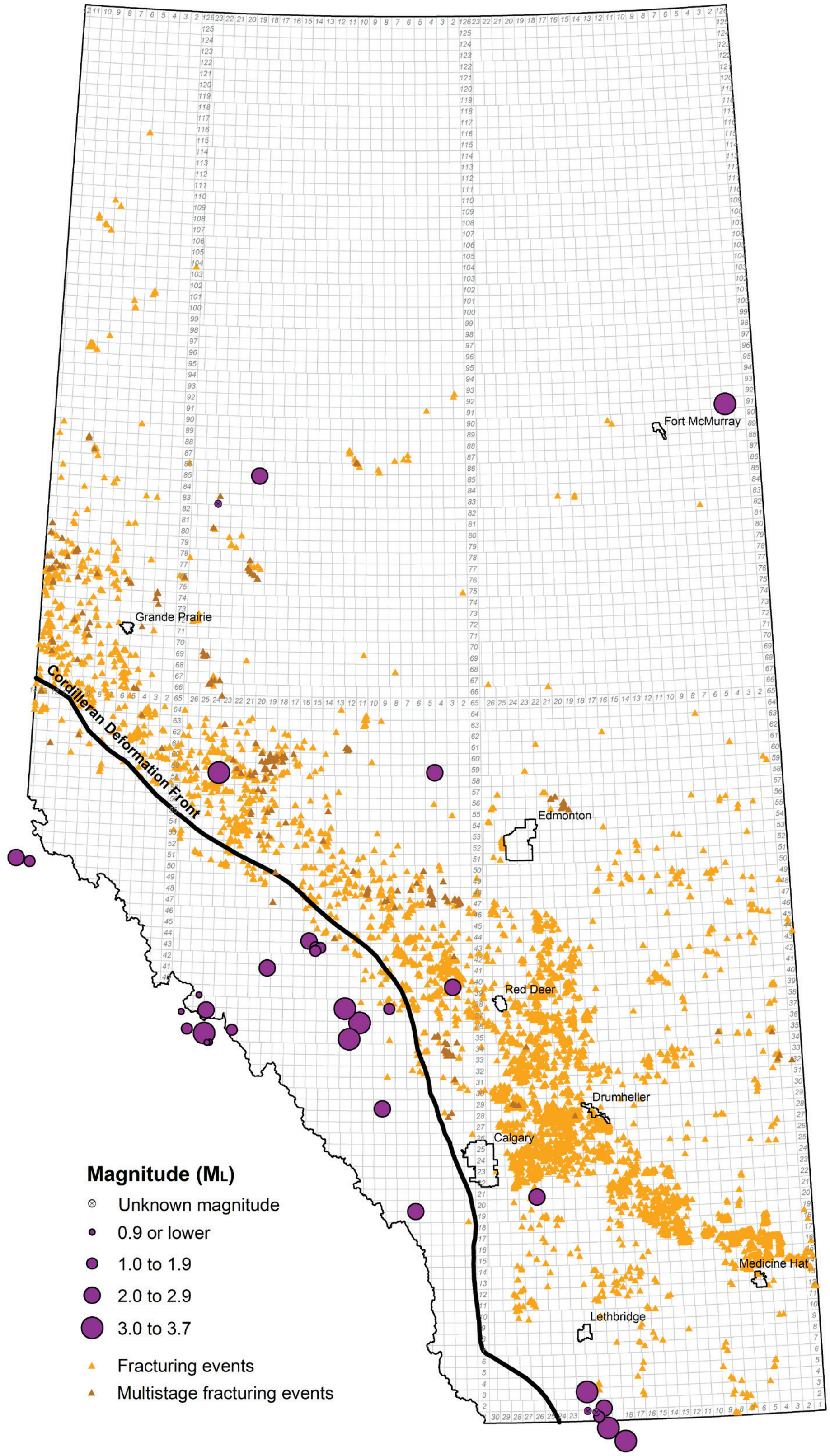

Figure 22. The locations of wells with hydraulic fracturing events and earthquakes in Alberta in 2009 (Stern et al., 2013a).

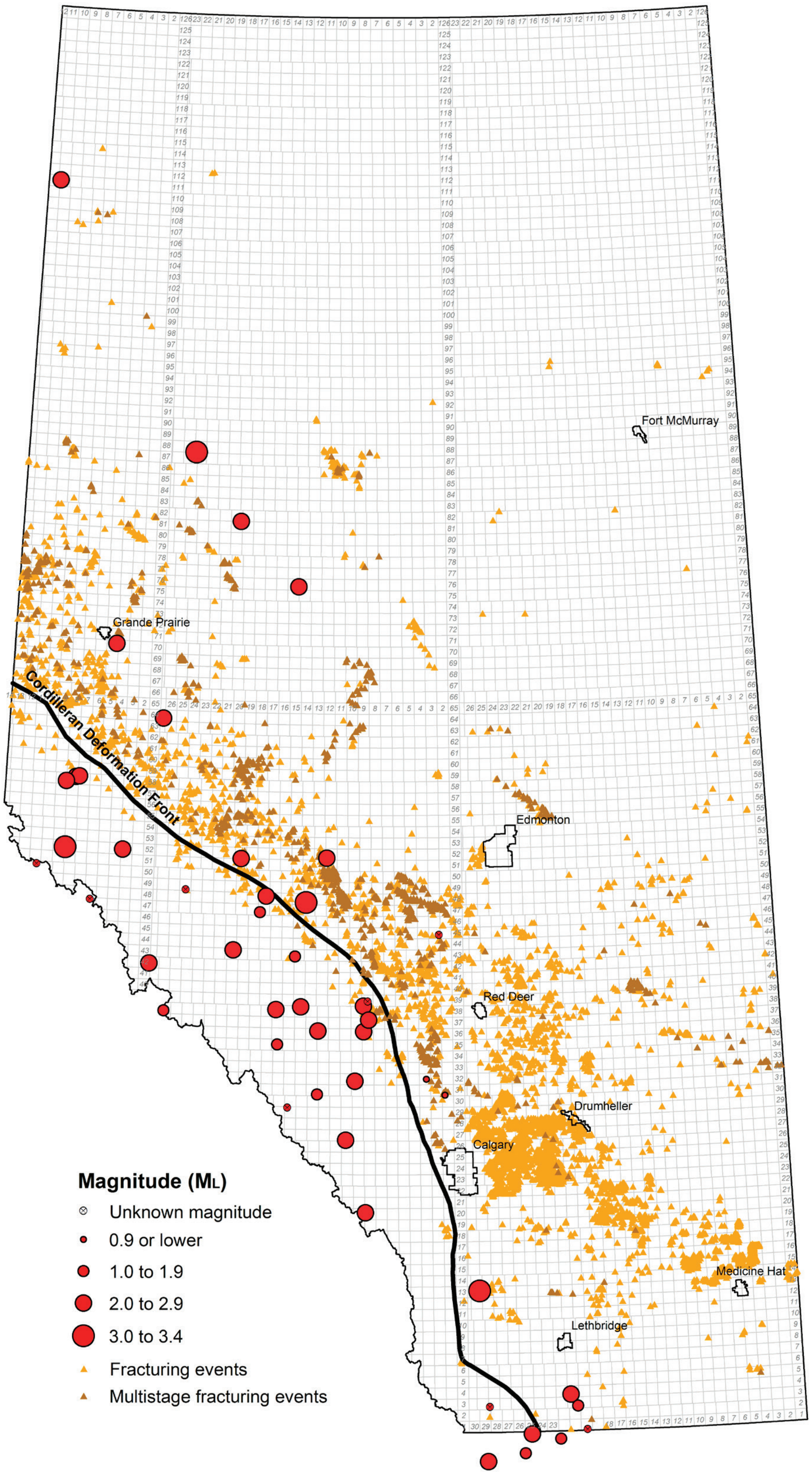

Figure 23. The locations of wells with hydraulic fracturing events and earthquakes in Alberta in 2010 (Stern et al., 2013a).

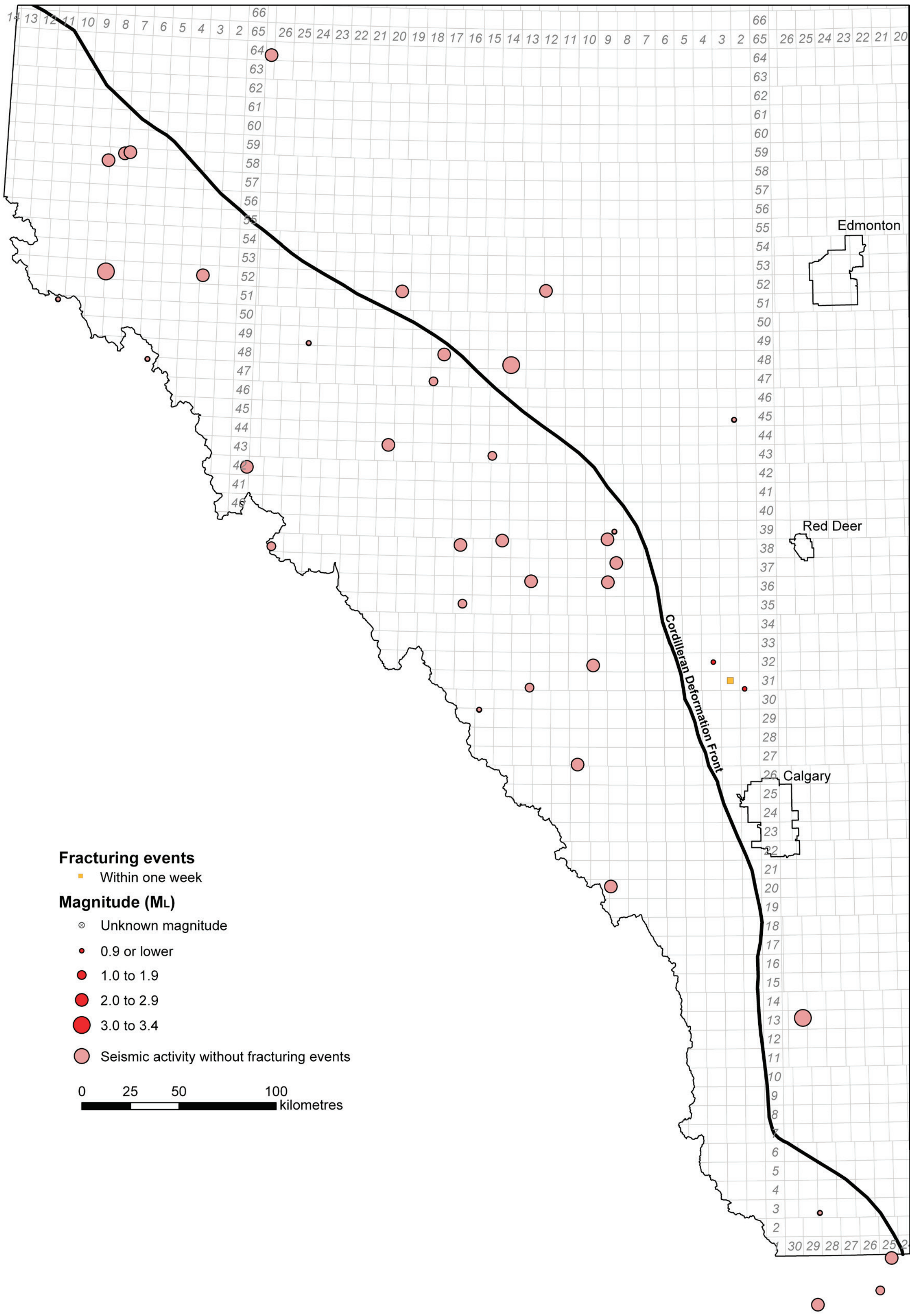

Figure 24. The bottomhole locations of wells with hydraulic fracturing events that fit the spatial and temporal correlation with an earthquake in 2010 (Stern et al., 2013a).

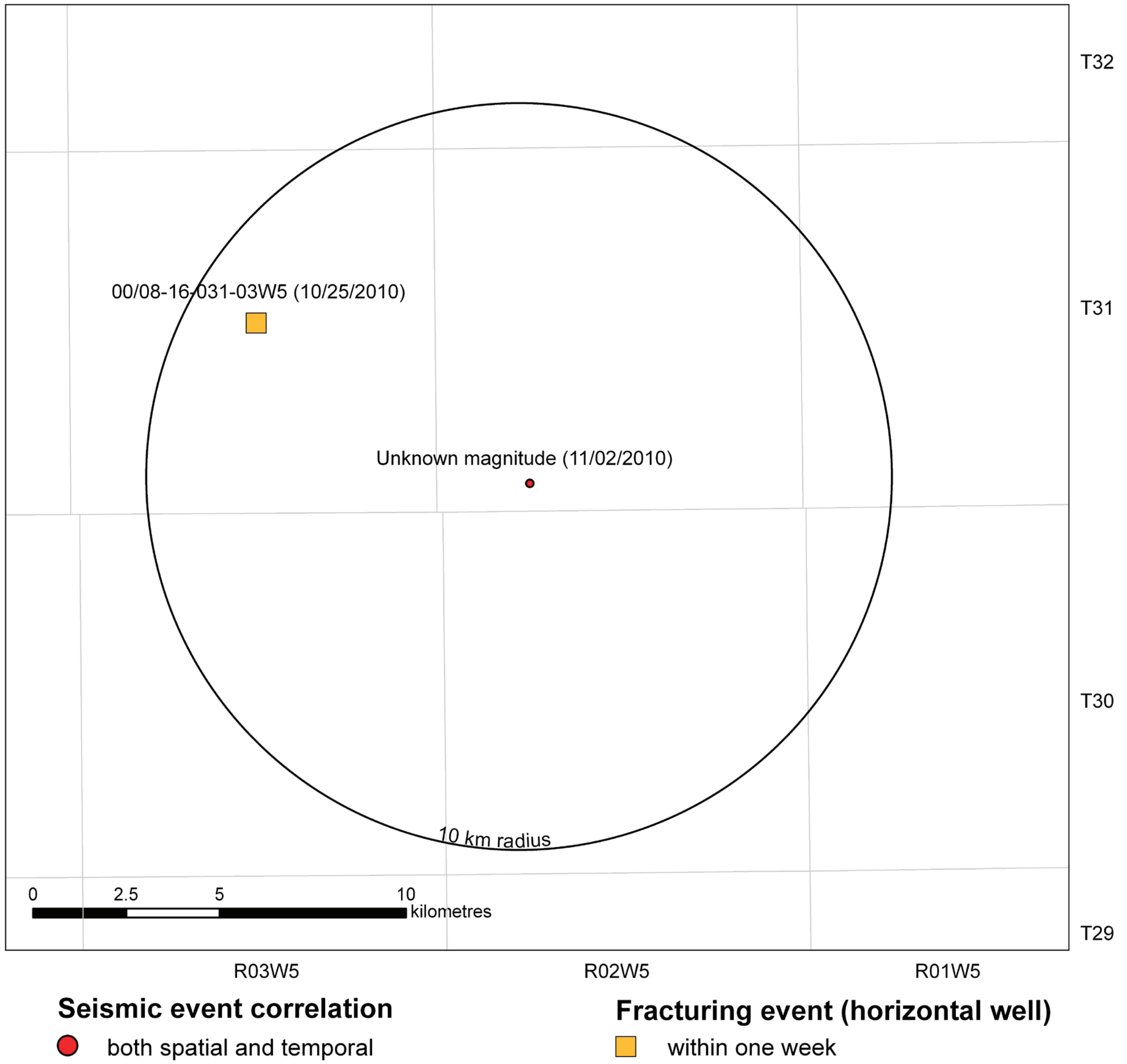

Figure 25. The bottomhole location of a single horizontal well with a hydraulic fracturing event that fit the spatial and temporal correlation with an earthquake of unknown magnitude in 2010 (Stern et al., 2013a).

5.3 Water Disposal

Water disposal has been occurring for over 60 years, with over 3000 water disposal wells licensed in Alberta (Figure 26). One active water disposal well in the Redwater oil field in particular has been operating since 1952. The largest volume that has been injected into a water disposal well is approximately 1.2 x 10^6 m^3 of water. As of 2013, there are over 1800 active disposal wells in Alberta.

Figure 27 shows the location of disposal wells that are within a 0 to 10 km or 0 to 20 km radius of the epicentre of a seismic event. A total of 28 disposal wells correlated within a 10 km radius of 47 seismic events and 123 disposal wells within a 0 to 20 km radius of 67 events (Table 6). Based on the methodology described previously, events were excluded if water disposal had stopped before 1996 or if disposal began after the seismic event occurred. The fewest correlations occur in 2006: six seismic events occurred within a 0 to 10 km radius of three disposal wells and 9 seismic events occurred within a 0 to 20 km radius of five disposal wells. The highest level of correlation is in 2007, with 19 seismic events occurring within 10 km of six disposal wells and 25 seismic events occurring within a 0 to 20 km radius of 30 disposal wells.

Table 6. Number of water disposal wells within a 0 to 10 km or 0 to 20 km radius of a seismic event.

	0 to 10 km radius		0 to 20 km radius	
Year	Number of seismic events	Number of disposal wells	Number of seismic events	Number of disposal wells
2006	6	3	9	5
2007	19	6	25	30
2008	6	7	9	44
2009	8	7	11	26
2010	8	12	13	27
Total	**47**	**28***	**67**	**123***

* Duplicates were not counted when multiple disposal wells correlated to multiple seismic events.

Of the over 3000 disposal wells analyzed, only 2 wells were correlated with seismic event clusters. One disposal well in particular (06-33-037-09W5) was within a 10 km radius of 25 seismic events that had occurred between 2006 and 2010 in the Brazeau River cluster (magnitudes 0.4 to 2.7). Another disposal well (10-25-043-16W5) was within a 10 km radius of the Rocky Mountain House cluster. This particular cluster had about one event every year between 2006 and 1010 (magnitudes 1.8 to 2.5). Baranova et al. (1999) concluded that the seismicity in the Rocky Mountain House cluster had no relationship with water injection but was likely due to gas extraction. Further work is needed to determine if there is a connection between the disposal wells and the earthquake clusters. The remaining 26 disposal wells within the 10 km radius only correlated to one seismic event each and not to any recognized cluster. Due to insufficient data, primarily on earthquake depth, any further correlation between the 26 wells and seismic events would be inconclusive. This is also true with respect to the 123 wells within a 0 to 20 km radius of a seismic event.

5.4 Water Injection

Water injection is the most prevalent EOR technique used in Alberta. Over 10 000 wells have been classified as water injection wells in Alberta since 1945 (Figure 26). These wells typically cluster in large, heavily depleted oil fields, such as the Pembina Field southwest of Edmonton. Currently, there are over 7000 active water injection wells. One of the longest running EOR schemes injected more than

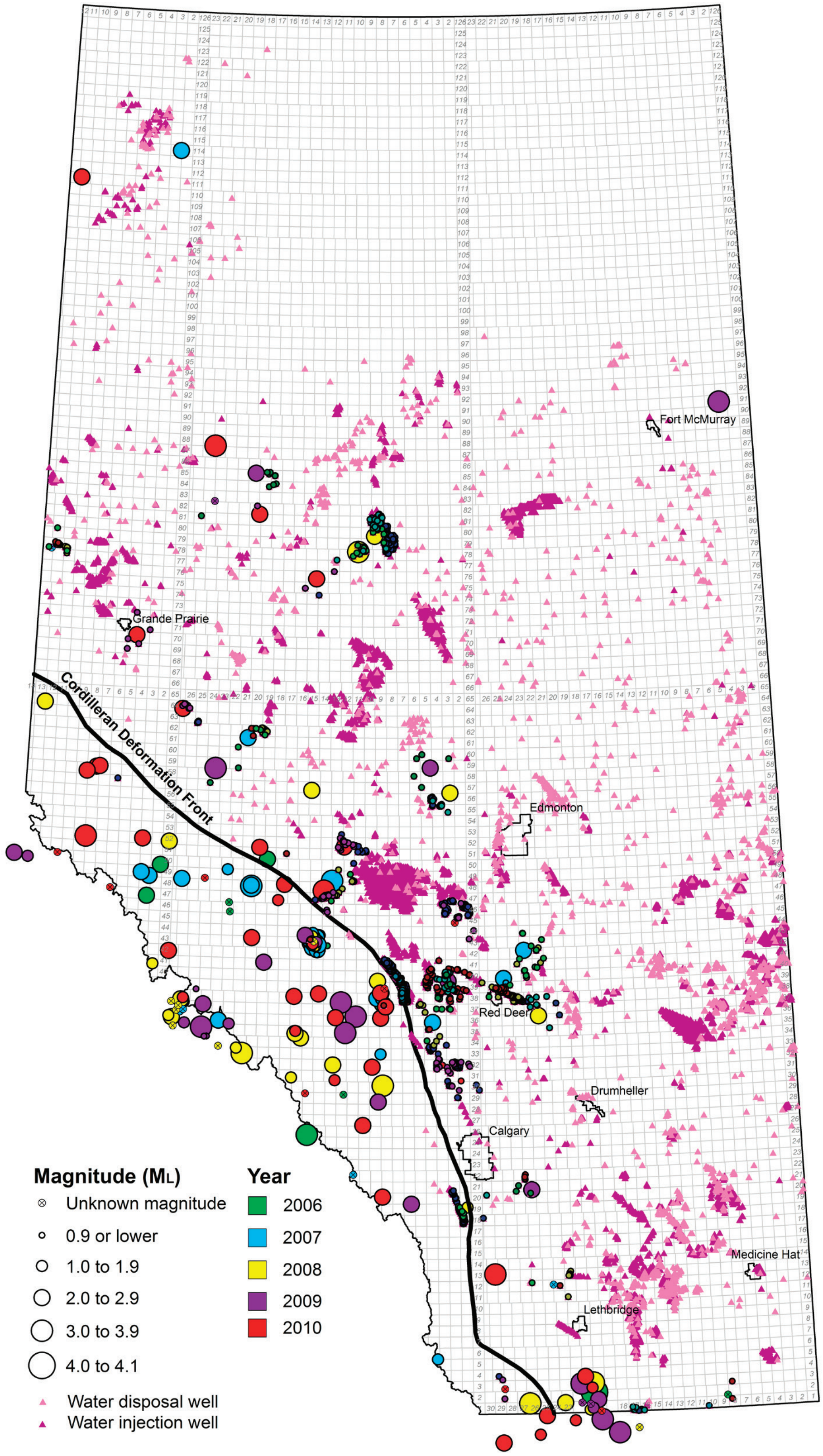

Figure 26. The locations of earthquakes (Stern et al., 2013) that occurred and all water injection and water disposal wells in Alberta.

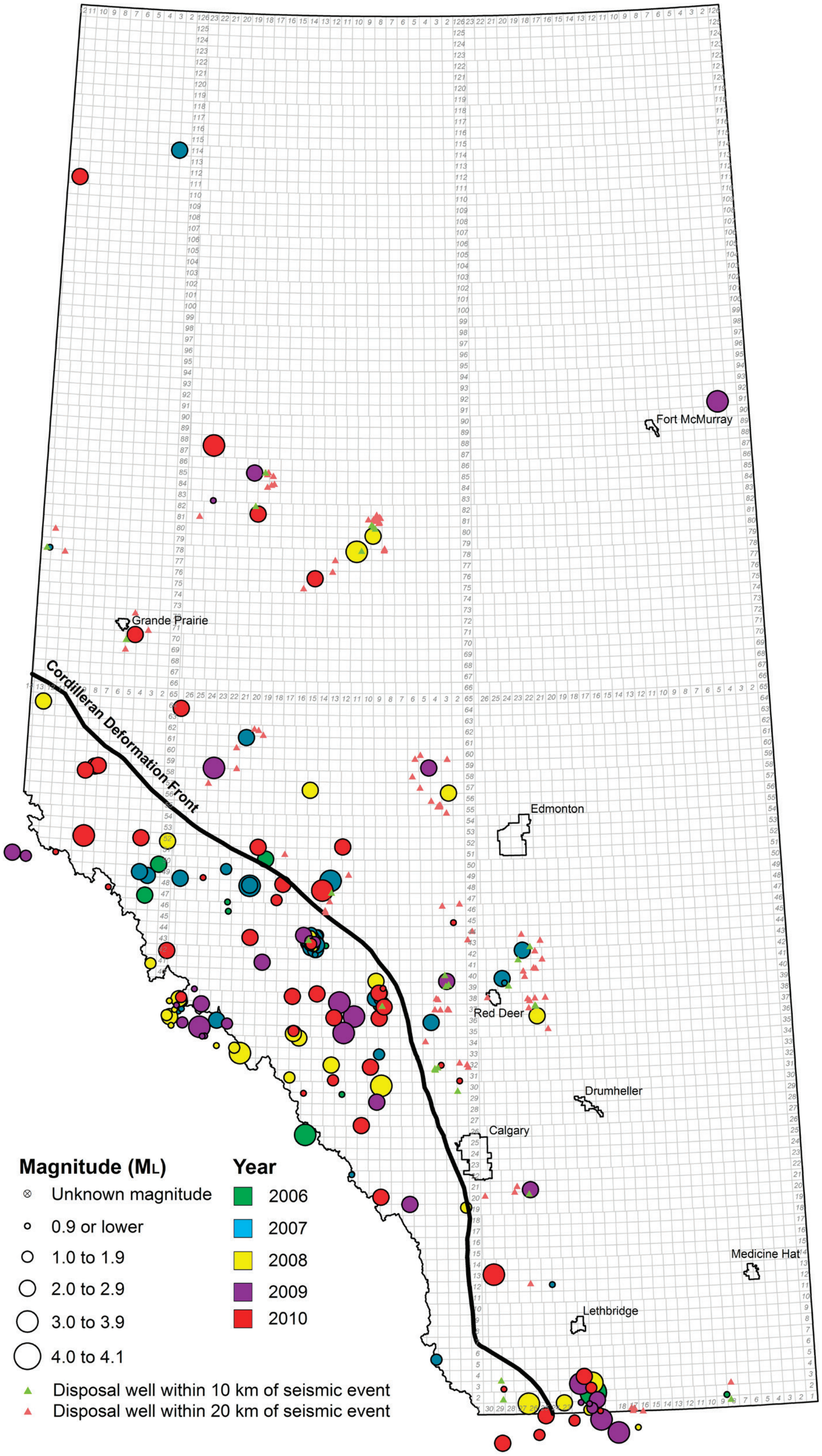

Figure 27. The locations of all water disposal wells in Alberta within 10 or 20 km of an earthquake between 2006 and 2010 (Stern et al., 2013a).

2 MMbbl (million barrels) of water over a period of 58 years. Water injection is thought to be less likely to trigger an earthquake since water is injected into a depleted reservoir and oil extracted from the same pool limits an increase in pore pressure.

Table 7 list the number of injection wells that are within a 0 to 10 and 0 to 20 km radius of a seismic event (Figure 28). Like the disposal wells, injection wells that were abandoned before 1996 were excluded from the correlation. In addition, wells on which injection began after a seismic event occurred were also excluded. In total, 216 injection wells were within a 0 to 10 km radius of 17 seismic events and 715 wells were within a 0 to 20 km radius of 36 events. In 2006, no seismic events within a 10 km radius of an injection well occurred. Significantly more injection wells correlate with seismic events than with disposal wells—likely due to the high density of injection wells. A more detailed assessment could further exclude wells from this list of injection wells by evaluating the virgin and current reservoir pressures. However, further refinement would not lead to a definitive correlation without the earthquake depth.

Table 7. Number of water injection wells within a 0 to 10 km or 0 to 20 km radius of a seismic event.

	10 km radius		**20 km radius**	
Year	**Number of seismic events**	**Number of injection wells**	**Number of seismic events**	**Number of injection wells**
2006	0	0	3	32
2007	6	37	9	159
2008	3	73	7	250
2009	1	52	4	150
2010	7	54	13	256
Total	**17**	**216***	**36**	**715***

* Duplicates were not counted when multiple disposal wells correlated to multiple seismic events.

5.5 Acid Gas Injection

In Alberta, the injection of acid gas into deep formations has been in practice since 1989. Acid gas is a by-product of “sweetening” sour hydrocarbons during processing and is a mixture of hydrogen sulphide (H_2S) and carbon dioxide (CO_2) with minor traces of hydrocarbons. Acid-gas injection sites have been characterized by AGS in a series of publications using acid-gas injection as an analogue for CO_2 sequestration (Bachu et al., 2008a, b). A total of 52 operations to date have been approved by the AER with a total of 61 acid-gas injection wells.

Figure 29 shows where acid-gas injection wells in Alberta are in relation to the location of seismic events that occurred between 2006 and 2010. Two acid gas disposal sites—Pembina Wabamun I (Pembina I) and Brazeau River Nisku Q pool (Brazeau)—were within a 20 km radius of a seismic event. Injection operations at Pembina I have been ongoing since 1994 and those at Brazeau have been ongoing since 2002.

At Brazeau (10-29-47-13W5) acid gas is injected into a depleted gas pool in the Upper Devonian Nisku Formation of the Winterburn Group. Two seismic events within the 20 km radius were the 3.8 magnitude event in 2007 (about 11.5 km away) and the 3.2 magnitude event in 2010 (about 13 km away) (Figure 30). At Pembina I (14-22-049-12W4) acid gas is injected into the Wabamun Group limestone aquifer.

The seismic event within the same radius was the 3.2 magnitude event in 2010 about 17 km away (Figure 30). Bachu et al. (2008a, b) stated that there were no known faults in these areas.

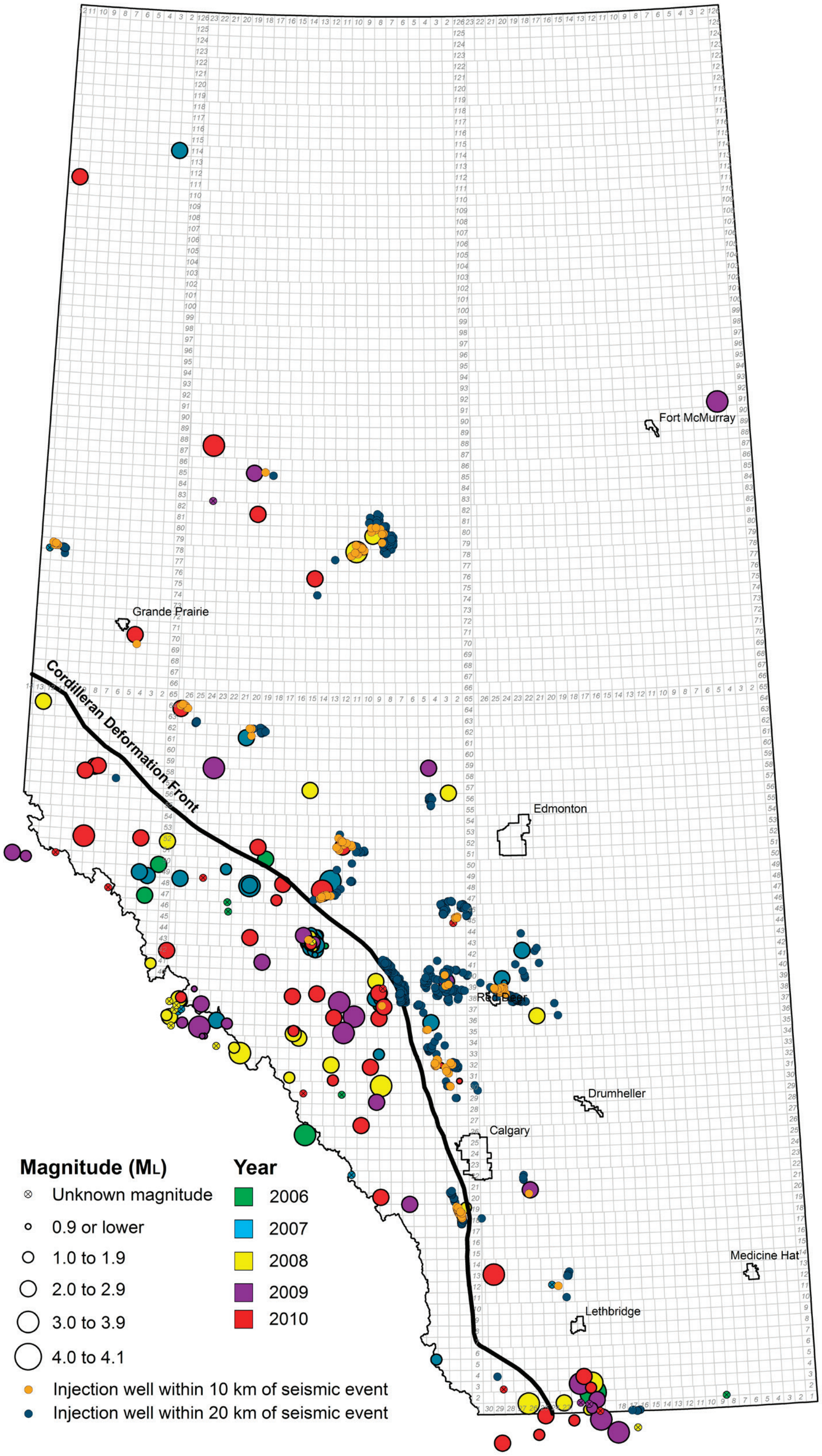

Figure 28. The locations of all water injection wells in Alberta within 10 or 20 km of an earthquake between 2006 and 2010 (Stern et al., 2013a).

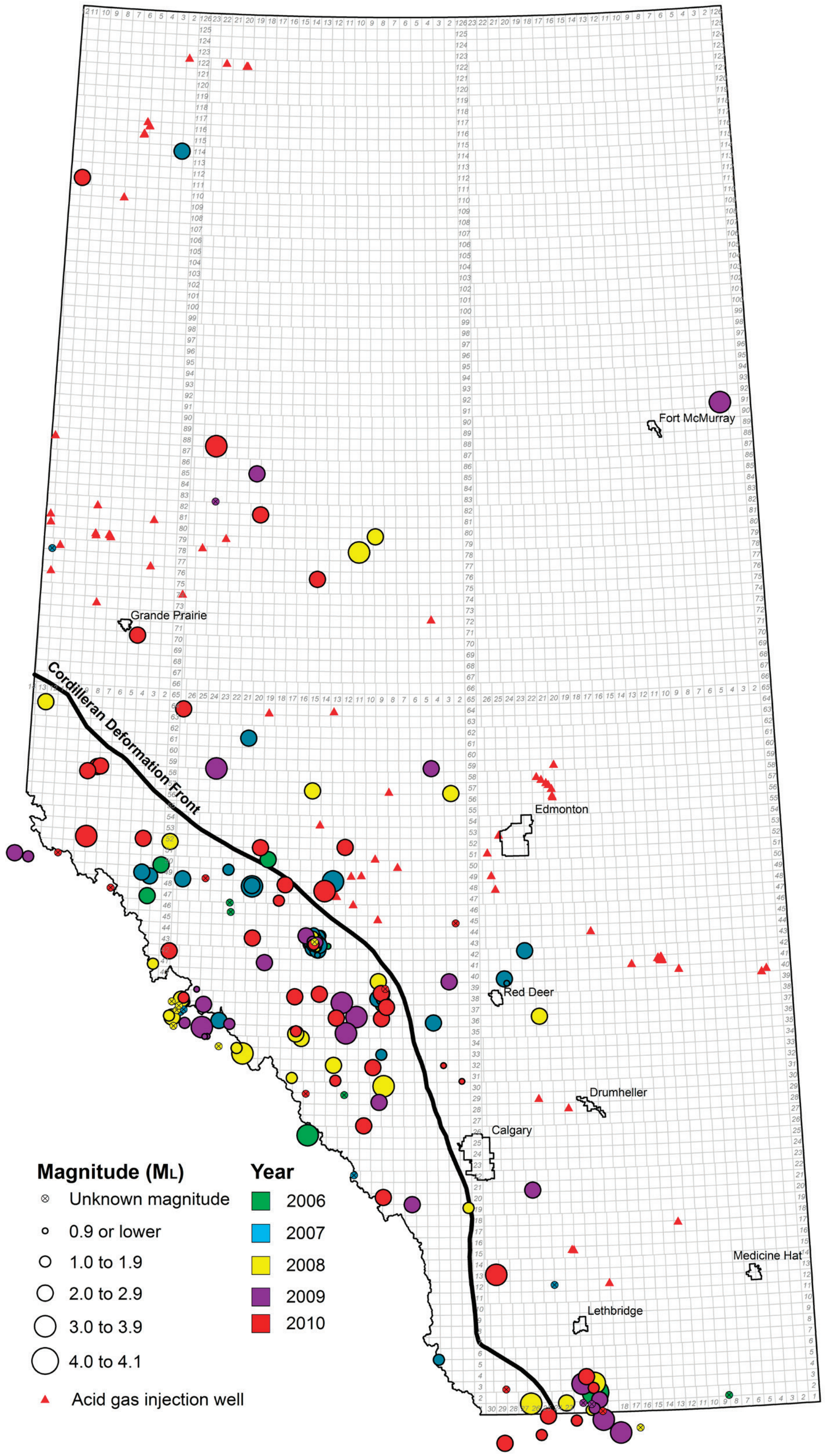

Figure 29. The locations of earthquakes that occurred between 2006 and 2010 (Stern et al., 2013a) and all acid gas injection wells in Alberta.

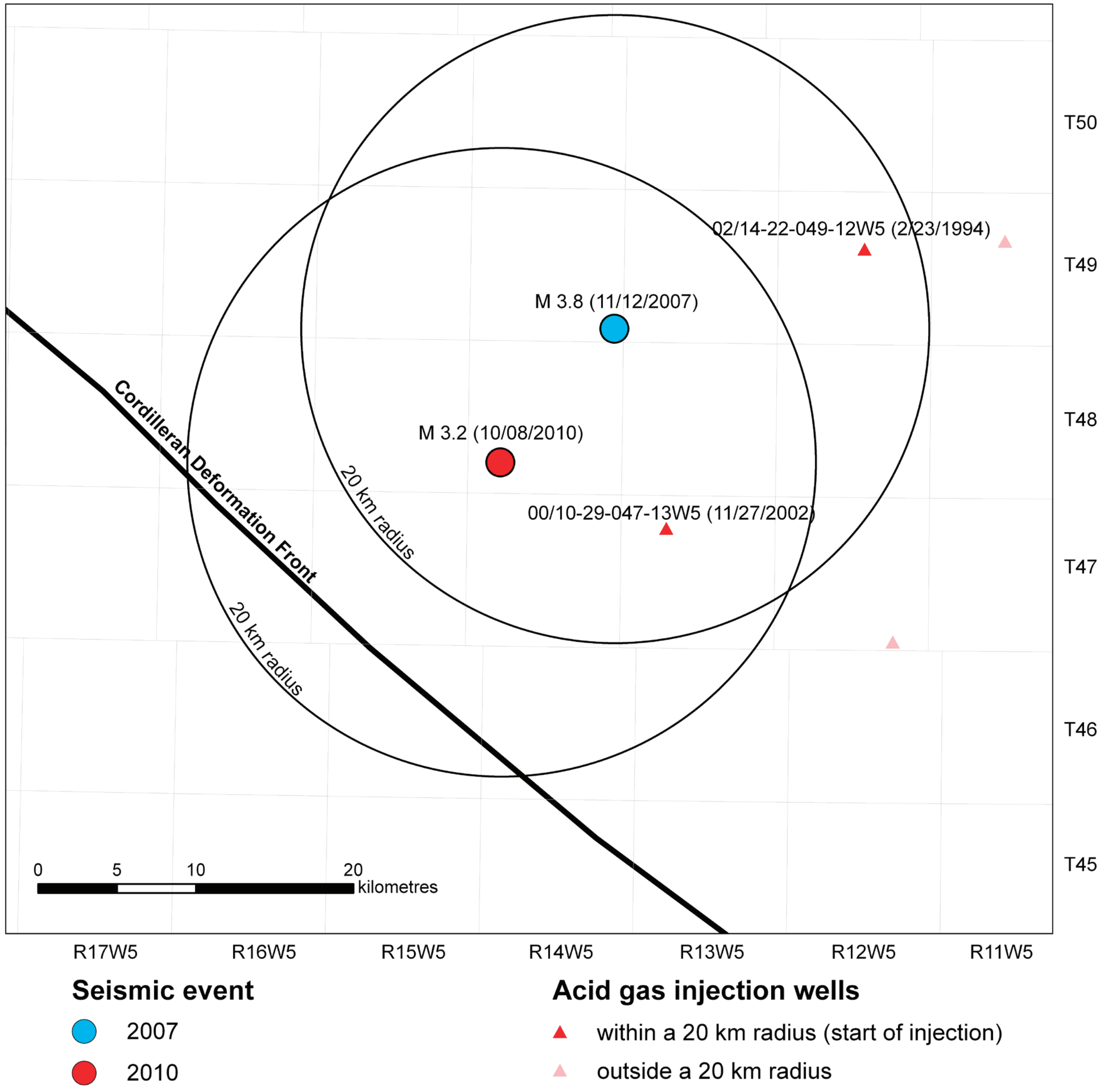

Figure 30. The bottomhole locations of two acid gas injection sites that fit the spatial correlation of two earthquakes with magnitudes of 3.8 and 3.2 (Stern et al., 2013a).

6 Discussion

Davis and Frohlich (1993) established a set of criteria that has been generally accepted for establishing the link between fluid injection (either for disposal or hydraulic fracturing) and seismicity (Table 8). Table 8 lists the results of these criteria being applied to the three wells that were hydraulically fractured a day before a seismic event and the two disposal wells correlated to seismic clusters. In both cases, insufficient information on spatial correlation and injection practices preclude the use all of the criteria to determine if the events were induced or not. This study found that these criteria would be more applicable for a more detailed study of individual cases of suspected causal correlation between fluid injection and seismicity.

Table 8. Davis and Frohlich (1993) fluid injection and hydraulic fracturing criteria as applied to the three hydraulically fractured wells within a 0 to 10 km radius and fractured one day before a seismic event.

Category	Criterion	Hydraulically fractured wells	Disposal wells
Background seismicity	1) Are these events the first known earthquakes of this character in the region?	no	no
Temporal correlation	2) Is there a clear correlation between injection and seismicity?	no	no
Spatial correlation	3a) Are epicenters near wells (within 5 km)?	no	no
	3b) Do some earthquakes occur at or near injection depths?	unknown	unknown
	3c) If not, are there known geologic structures that may channel flow to sites of earthquakes?	unknown	unknown
Injection practices	4a) Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?	unknown	unknown
	4b) Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?	unknown	unknown

7 Conclusion

This study examined the potential spatial and temporal correlation between low-magnitude earthquakes recorded as having occurred between 2006 and 2010 in the AGS earthquake catalogue and oil and gas industry activity in Alberta. The study focused on wells that had been used for water disposal, water injection, acid-gas injection and wells that had been hydraulically fractured. The results show that while a significant amount of oil and gas activity occurred, only a very small percentage of that activity shows any correlation with seismic activity given the spatial and temporal constraints of this study.

Based on the data available in the catalogue for 2006 through to 2010, no correlation was found between earthquakes and hydraulic fracturing. Out of the 175 000 hydraulically fractured wells, only three were hydraulically fractured a day before and within a 10 km radius of an earthquake's epicentre. The hydraulic fracturing done on the three wells was all single-stage. The two vertical wells targeted coal-bed methane reservoirs and the horizontal well fractured into the Nikasassin Formation. The three events do not demonstrate the typical characteristics found in previously published studies on events triggered by hydraulic fracturing where the horizontal-multistage hydraulic fracturing simultaneously creates a cluster of seismic events within 5 km of the hydraulic fracturing.

The temporal correlation is more complex to constrain for disposal wells since pore pressures increase over time and may lead to a stress change. Therefore, there is a possible correlation between seismic events and disposal wells in Alberta. Two disposal wells (00/06-33-037-09W5 and 00/10-25-043-16W5) were located within 10 km of significant seismic event clusters. A more detailed analysis of injection rates and pressures may help further establish a correlation.

The correlation between the remaining 216 injection and 28 disposal wells within a 10 km radius of isolated seismic events is possible but unlikely. There is greater uncertainty with injection wells because their purpose is to maintain pressure in the reservoir and extend the production life of the well. Rarely is preproduction pore pressure exceeded, which would be necessary to cause any significant change in stress. Reservoir pressure data could further refine the correlating well list to exclude wells where pressures have not exceeded the virgin reservoir pressure. These injection and disposal wells are also not located near seismic clusters, which would be more typical of a triggered event.

Out of the 61 acid gas wells, only two were within a 20 km radius of a seismic event. The closest events were a 3.8 magnitude event 11.5 km away and a magnitude 3.2 event 13 km away from the nearest acid-gas injection site. There is no evidence that any of the acid-gas storage sites had been adversely affected by seismicity.

Based on the available data, the risk of induced seismic activity due to oil and gas activity causing damage in Alberta is low. However, if it becomes necessary to verify or refute a definitive causal correlation, it would be hard to do so with the currently available data. In the areas of concern, more work is needed to expand the array of seismic stations to precisely detect the epicentre and hypocenters of an earthquake. In addition, detailed geological mapping and geophysical surveys are needed to identify fault locations. This information could be used in conjunction with well-specific injection, disposal, or production data to provide the fluid pressure, as well as the absolute state of stress.

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