

**ENVIRONMENT IMPACT ASSESSMENT OF HYDRAULIC FRACTURING IN NORTH
EASTERN BRITISH COLUMBIA**

BY

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DEDICATION

Firstly, I dedicate this project report to the ALL SUFFICIENT AND MAGNIFICENT GOD for HIS mercy and grace through the hurdles of this program. I also the dedicate this report to my late father- Pastor J.I. Makinde, who trained me both morally, academically and spiritually but never waited to reap the fruit of his labour. Dad, continue to rest in the bosom of the Almighty God!

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EXECUTIVE SUMMARY

For over six decades that hydraulic fracturing (also known as fracking) has run in North America, people have benefitted from the increase in production of natural gas and oil through this unconventional method of oil and gas production. Some of the benefits include creation of more jobs, cheaper cost of fossil fuel and a boost in the nation's economy. However, there have been recent concerns of the potential impacts of fracking on the environment. The public has raised concerns of fracking, causing water quality impairment, air pollution and increase in the occurrence and magnitude of induced earthquakes. Based on this, several researchers have reported on the impacts of fracking but with divergent results and views. While, some scientists oppose fracking vehemently, others opined that fracking has little or no effects on the environment. In addition, there has been limited scientific knowledge of fracking due to limited availability of data which has led to inconclusiveness of researchers on the impacts of fracking.

This project was targeted to address the public and the provincial government of British Columbia on the issue of fracking. Thus, the specific objectives of this project work were: (i) to assess impacts of fracking on water resources; and (ii) to conduct meta-analysis of impacts of fracking on induced seismicity in North Eastern British Columbia.

Based on personal communication with researchers currently working on fracking and preliminary studies from literatures, it can be concluded that (i) if boreholes are done properly with due to diligence and mechanical integrity, there will be no or very limited groundwater contamination; (ii) if the sites are properly managed, there is little or no chance of environmental pollution (including air and water resources) by shale gas; (iii) fracking induces seismicity and if fracking continues, the magnitude and effects of earthquake will increase; and (iv) lastly, ongoing research in Northeastern British Columbia shows the concern of well leakage due to gas migration, which may lead to air pollution and groundwater contamination by methane gas.

1.0 Introduction

The term hydraulic fracturing or ‘fracking’ is known to have several benefits that include financial profits, job creation, lower price of natural gas and the ‘halo effect’ from chemical companies profits to other industries, such as manufacturing and energy, and increase foreign investment opportunities (Conserve Energy Future, 2019). Figure 1 depicts the rapid growth of oil and gas in Canada over past ten years (Rivard et al., 2013); British Columbia Oil and Gas Commission (BCOGC), personal communication, 2018). However, beyond these benefits, there are risks that are posed to the environment by hydraulic fracturing (Conserve Energy Future, 2019).

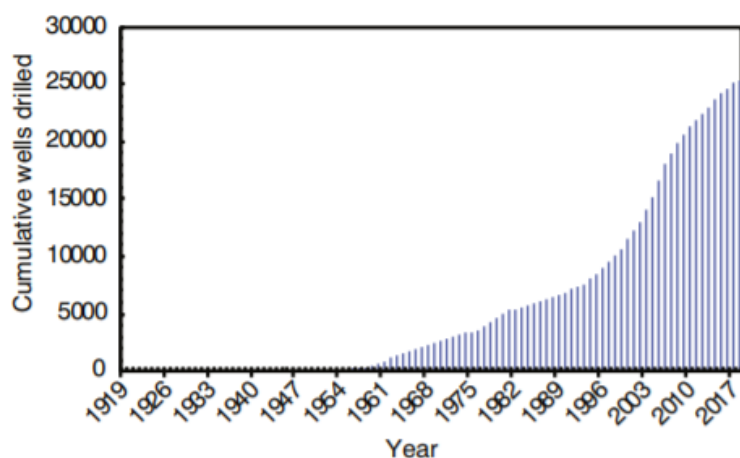


Figure 1. Cumulative wells drilled in British Columbia from 1919 to 2018 reaching a total of 25,309 wells (BCOGC, personal communication, 2018)

Hydraulic fracturing is defined as a well stimulation method in which rock is cracked by a pressurized liquid. The process involves the high-pressure injection of 'fracking fluid' into a wellbore to create cracks in the deep-rock formations through which natural gas, petroleum, and brine will flow more freely (Gandossi and Von Estorff, 2015). A report by Kargbo *et al.* (2010) categorizes fracking fluids as: carrier/base fluid, biocides, scale inhibitors, solvents, friction reducers, additives, corrosion inhibitors, and non-ionic surfactants (which include a catch-all category for dozens of fluids like naphthenic acid, ethoxylate or Poly (Oxy-1,2-Ethanediy1), Alpha-(4-Nonylphenyl)- Omega-Hydroxy-, branched). The

exact proportions of additives used in the fracturing mixture depends on the specific depth of the site, thickness and characteristics of the target formation. These additives used as fracturing fluids are believed to pose serious health risks and environmental pollution (Kargbo *et al.*, 2010).

There have been concerns raised against hydraulic fracturing in recent years. Some scientists believe that hydraulic fracturing has potential hazards to the environment, such as air pollution, groundwater contamination, water quantity deficit, waste disposal and induced seismicity (Hoffman, 2015). Bao and Eaton (2016) demonstrated how fracking triggers seismicity by increasing the pressure in tectonic faults in Western Canada. While, Rubinstein and Mahani (2015) reported that hydraulic fracturing does not induce felt earthquakes. However, the public have been protesting this method of shale gas and oil extraction, saying that it induced earthquakes. Quoting the Op-Ed in Vancouver Sun Newspaper written by Palmer in 2019, "...the public reports of felt events consistently mention a loud bang period by jarring motion or short period of rumbling, rattling or shaking..."

Thus, the overall goal of this project is to evaluate the impact of fracking on the environment and public concerns.

2.0 Concerns about Fracking – Co-analysis

2.1 Fracking and Shale Gas

Hydraulic fracturing involves methods of producing unconventional gas. Sovacool (2014) and Rogner (1997) referred unconventional gas as majorly six types of gas field or ‘play’ with low permeability, which includes: coal bed methane(present in coal seams); tight gas (present in low permeable formations); geo-pressured gas(gas trapped in high pressure deep reservoir); gas hydrate (methane in crystalline form found in marine sediments); shale gas (gas trapped in shale gas formation of sedimentary rock) and ultra deep gas (offshore reservoir locked in high depth).

Shale gas refers to natural gas mined from the gas shale deposits, porous rock that contains the gas. Zou (2013) summarizes the major characteristics of shale gas in Table 1.

Table 4. Major characteristics of shale gas (Zou, 2013)

Geological characteristics	<p>Integrated source rock and reservoir, early reservoir formation, continuous accumulation, no obvious trap boundary, sealing or caprock is necessary.</p> <p>Tight reservoirs with natural gas stored in an absorbed gas and free gas pattern.</p> <p>Not controlled by structure, continuous and large areas of distribution, same area as effective gas-generation source rock.</p>
Mineral characteristics	<p>Large resource potential with 'local sweet spot' core areas.</p> <p>Amount of non-residual organic carbon is greater than 2%.</p> <p>It contains over 40% of Brittle mineral (e.g. quartz) content and less than 30% clay mineral content.</p> <p>Maturity of dark organic-rich shale is greater than 1.1%.</p> <p>Air porosity is greater than 2%, permeability is more than $0.1\mu\text{m}^3$.</p> <p>Effective thickness of organic-rich shale is over 30-50 m.</p>
Development characteristics	<p>Low individual well production cycle and long field production cycle.</p> <p>Lower recovery ratio of non-Darcy flows of production.</p> <p>Requires horizontal wells, multistage fracturing, micro-seismic and other advanced technologies to implement reservoir stimulation treatment.</p>

Fracking is one of the seven fundamental phases of shale gas production. Ridley (2011) outlined the steps of shale gas production, which include:

- Seismic exploration: involves the mapping of underground rock formation with sound waves and three-dimensional reconstruction to identify the depth and thickness of the shale gas formation;
- Pad construction: it is a levelled platform for drilling rig positioned over a discovered play, usually about 5 acres (2 ha);
- Vertical drilling: it refers to creating dozens of small holes down to the shale rock through a borehole with small derrick drills;
- Horizontal drilling: refers to creating horizontal wells into shale formation of thousands of feet by slant drilling each well in different directions with a large drilling derrick (of about 46m high) assembled on site;
- Fracking: involves the perforation of horizontal pipe with small explosives charges and proppants (such as mixture of sand and water) and other fracking fluids to stimulate well to produce the gas; The proppants are pumped through the holes at a very high pressure of about 5000 psi (35,000KPa) to fracture the rock hairline up to 305m from the pipe;
- Sustained production: refers to when a 'branch-like' valve assembly and a set of small tanks is installed on the site to collect the gas, which then flows to the compressor station through the underground pipes to serve the well heads and to truck pipelines; and
- Waste disposal: this is when tanks collect the waste water that flows back out of the well. Usually, the water is treated and re-use for future fracking.

However, it is important to note the differences between conventional and unconventional gas production. Sovacool (2014) reported, that horizontal drilling and fracking are the two steps that are absent in conventional gas production. Also, unlike conventional gas (shale gas), conventional gas does

not flow naturally into the well but can be made to flow by hydraulic fracturing (or fracking) (Boyer *et al.*, 2011); (International Energy Agency, 2012).

2.2 Hydraulic Fracturing Processes

As outlined by (Kargbo *et al.*, 2010), before the actual hydraulic fracturing processes occur, there are vertical drilling of wells and casings on the site for active extraction. Several (approximately 15) holes to a depth of 980m (3000ft) are made in each wellbore through the casing and cemented at predetermined locations with the use of a perforated gun. It was reported in Fracfocus (2010) that the process is repeated with smaller steel casing until the oil and gas formation is reached (which is usually about 6000ft - 10,000ft or 1,000m – 3,000m). To produce a fracture, pressure greater than the rock tensile strength and the tectonic forces present must be applied to the shale gas rock. This is accomplished by the injection of high-pressure fracking fluid inserted through the holes to increase the porosity of the shale gas bed and decrease the viscosity of the gas. This is necessary as shale gas does not flow naturally, and the gas shale deposit is found in a very tight and a low permeable formation (siltstone or limestone), which can not be extracted by conventional extraction process. Thus, large amount of shale gas can be produced via multi-stage hydraulic fracturing. In this process, drillers use both vertical and horizontal wells and fracking process is repeated in each well as many as 20 times (House, 2013). Therefore, during the fracking process, there is huge amount (litres of gallons) of water combined with thousands of litres of proppants injected into the well as fracking fluids (Sovacool, 2014).

Figure 2a illustrates an on-site fracking site in British Columbia. The major stages involved in fracking is summarized in Figure 2b.

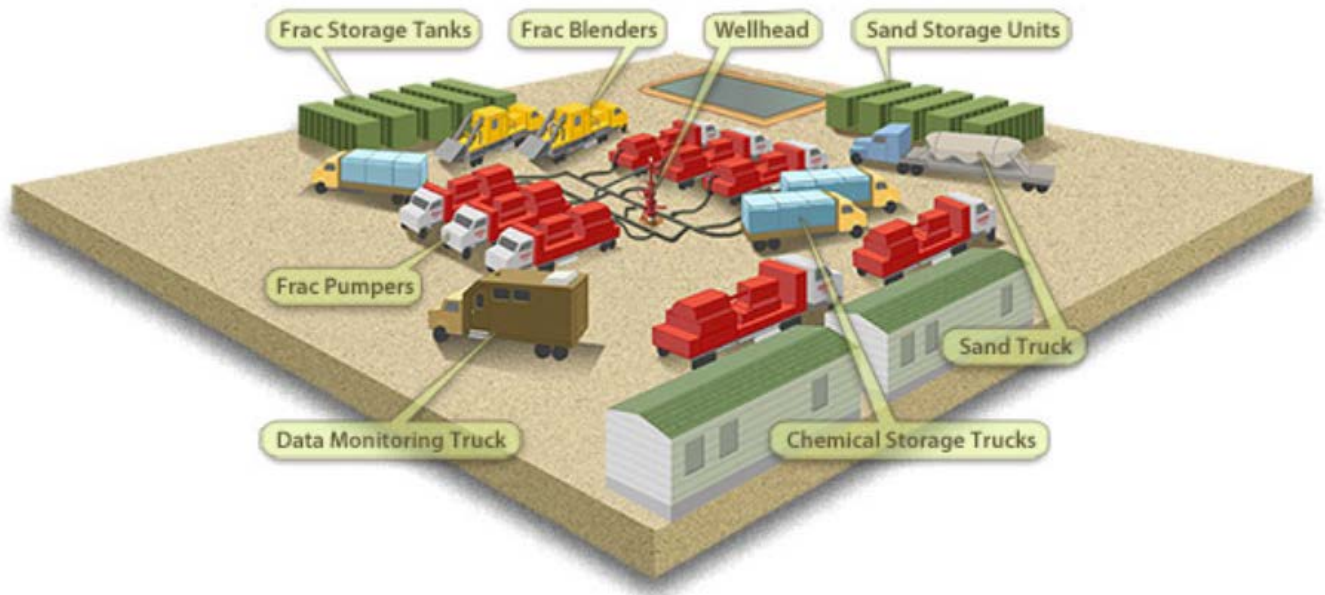


Figure 2a: In-situ Hydraulic fracturing Processes in North Eastern BC (fracfocus, 2018)

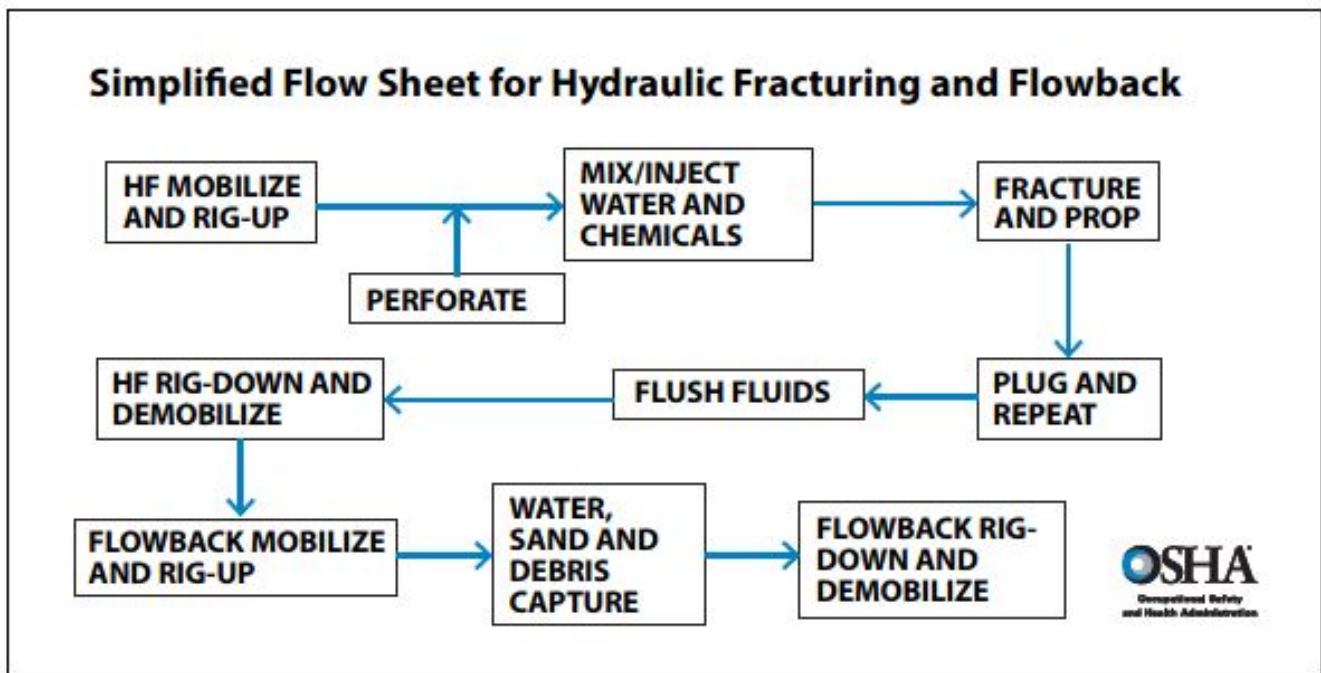


Figure 2b. Flowsheet of Hydraulic Fracturing (<https://www.environmentalsafetyupdate.com/alternative-energy/safety-bulletin-for-hydraulic-fracturing/>)

Fracfocus (2010) summarized the stages as:

- Spearhead stage: Also known as an acid stage, where a mixture of water with diluted acid (hydrochloric acid) is injected to clear debris that may be present in the wellbore, thus, creating a clear pathway for fracture fluids to access the formation;
- Pad stage: A batch of carrying fluid, without proppant (sand and water mixture), is used to break the formation and initiate the fracking of the target formation;
- Proppant stage: During this stage a mixture of water and sand (i.e. proppant) is fed into the wellbore. The proppant is composed of non-compressible material, such as sand, that is carried by the fracture fluid into the formation and deposited. The proppant remains in the formation once the pressure is reduced and ‘prop’ opens the fracture network. Thus, maintaining the enhanced permeability created by the hydraulic fracture program; and
- Flush stage: A volume of fresh water is pumped down the wellbore to flush out any excess proppant that may be present in the wellbore.

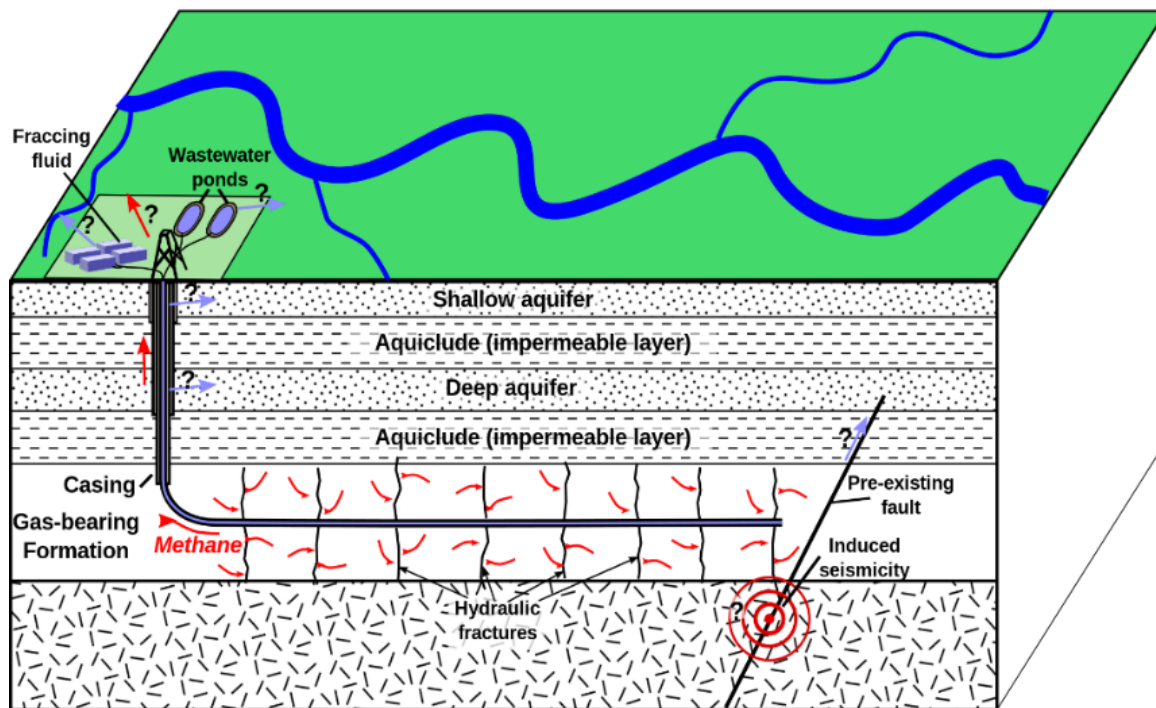


Figure 3. Induced hydraulic fracturing showing the hydrogeology of the formation (source: en.wikipedia.org, 2019).

2.3 Fracking fluids and Produced Water

Fracking fluids, also known as hydraulic fracturing fluids, are mixtures which consists majorly of 98 to 99.5% proppants (sand and water) and chemical additives of differing formulations, depending on the site (Fracfocus, 2018). The constituents and a volumetric composition of hydraulic fracturing fluids given in Table 2 (Gregory et al., 2011).

The produced water (or flowback water) refers to waste water produced after there is active gas production and usually 10- 40 percent of fracking fluid flows back into the surface during the first few weeks of fracking (Sovacool, 2014). This period is known as the ‘flowback period.’ Produced water consists of chemicals with different concentration levels of the fracking chemicals. Gregory et al. (2011) reported that the properties of the constituents of the flowback water depends on the length of the operation and vary with the number of wells (that is, if there are multiple wells or a single well) as shown in Table 3.

Table 5. Volumetric composition and purposes of the typical constituents of fracking fluids (Gregory et al., 2011)

Constituent	Composition by volume (%)	Example	Purpose
Water and sand	99.50	Sand suspension	Proppants- sand grains open microfractures
Acid	0.123	Hydrochloric acid or muriatic acid	Dissolves minerals to clear the wellbore and initiates cracks in the rock
Friction reducer	0.088	Polyacrylamide or mineral oil	Reduces the friction between the fluid and the pipe
Surfactant	0.085	Isopropanol	Increases the viscosity of the fracking fluid
Salt	0.06	Potassium chloride	Creates a brine carrier fluid
Scale inhibitor	0.043	Ethylene glycol	Prevents scale deposits in pipes
pH- adjusting agent	0.011	Sodium or Potassium carbonate	Maintain effectiveness of chemical additives
Iron control	0.004	Citric acid	Prevents precipitation of metal oxides
Corrosion inhibitor	0.002	n,n-Dimethyl formamide	Prevent pipe corrosion
Biocide	0.001	Glutaraldehyde	Minimizes the growth of corrosive and toxic bacteria

Table 6. Typical range of concentrations for common constituents for produced water from natural gas development in the Marcellus Shale Formation (Gregory et al., 2011)

Constituent	Single well (early) (mg/L)	Single well (Late) (mg/L)	Multiple well (Late) (mg/L)
Total dissolved solids	66,000	150,000	261,000
Total suspended solids	27	380	3,200
Hardness (as CaCO₃)	9100	29,000	55,000
Alkalinity (as CaCO₃)	200	200	1,100
Chloride	32,000	76,000	148,000
Sulfate	5	7	500
Sodium	18,000	33,000	44,000
Calcium, total	3,000	9,800	31,000
Strontium, total	1,400	2,100	6,800
Barium, total	2,300	3,300	4,700
Bromide	720	1,200	1,600
Iron, total	25	48	55
Manganese, total	3	7	7
Oil and grease	10	18	280

2.4 Concerns: Global, North America and Canada Scope

Because of several environmental implications associated with unconventional gas development, the invention of hydraulic fracturing has led to several public concerns, both globally and in North America. Bacora (2012) reported that since unconventional gas (or shale gas) are in tight or low permeability formations, they are difficult to extract. Therefore, it poses serious environmental risks as it requires considerable amount of drilling, larger oil rig installation and usage of fracking fluids, which are hazardous to the environment and human health (Rowe and Fortunato, 2010). Another global concern is that fracking uses extensive amount of water. IEA (2012) estimates about 20,000 cubic meter of water may be used in a single well. Therefore, arid or semi-arid regions like South Africa, Australia or China could be faced with serious challenges of low water quantity (Bacora, 2012). Increase in the concentration of green house gases (e.g. methane) released into the atmosphere is also an environmental concern of fracking because about 40-60% of methane concentration higher than that of conventional gas is released into the atmosphere and water bodies, which causes air pollution, contribution to global warming and water pollution (Bacora, 2012). Howarth *et al.* (2012) predicted from their studies that in two decades time, due to methane concentration level released in fracking process, shale gas will have a larger carbon footprint than coal. Hence, Sovacool (2013) summarised the negative effects of fracking as pollution and public health, climate change, displacement and social opposition, induced earthquake and unclear profitability. However, the IEA (2012) argues, in its Golden Rules for a Golden Age of Gas report, that most of the negative impacts can be eliminated by applying simple but strict rules and regulations which will add to the financial cost of a well development by a 7% premium. Thus, stricter regulations for all stakeholders (mostly, oil and gas companies) to abide with and good policy making towards fracking would reduce the impact of fracking on the environment.

In the Canadian context, a report by the BC Women Institute (2019) reveals that British Columbia is said to have the largest development of shale gas extraction both in Canada and North America.



Figure 4. Map of areas in North America containing shale gas deposit. Areas shown as red are contain shale gas that are extracted by the fracking process (B.C. Women Institute).

Therefore, in a bid to review the studies conducted in British Columbia due to increasing public concerns, the British Columbia provincial government appointed three panelists to research the impacts of hydraulic fracturing on the natural environment and human health in North Eastern British Columbia. In 2019, this team of panelists presented a progress report entitled ‘Scientific Review of Hydraulic Fracturing in British Columbia.’ This report was based on the review of the impacts of hydraulic fracturing on water quantity, water quality, human health and occurrence of induced seismicity. The report acknowledged that there were limitations encountered during their findings in British Columbia. The limiting factors include: (1) limited available data in British Columbia to assess and quantify the potential risks associated with fracking; and (2) complexity related to fracking activities in the natural

environment such as variability in landscape, hydrogeology and climate. Also, the impact of other anthropogenic activities (such as agriculture and resource development) on the environment makes it difficult to study the impact of fracking on the environment in isolation. The report pointed out clearly that BC's regulatory framework did not adequately address the potential impacts of hydraulic fracturing. This conclusion was based on the current regulations for hydraulic fracturing processes which are embedded in other regulations (such as Water Protection Act, Mining Act, etc.). This appears to the public to be problematic in practice, unlike a single and clear window of oil and gas regulations which includes how fracking activities can be effectively managed. However, the panelists suggested that BC's regulatory framework on fracking activities can be improved for effective safety risk management to water and induced seismicity, if the knowledge gaps can be bridged by conducting further scientific research and peer review aimed at hydraulic fracturing activities and potential impacts to the environment. On the positive side, due to high use of limited fresh water resources in the fracking processes, a scientific breakthrough has been achieved in fracking by addressing the major concern of reduced water quantity by recycling the water disposed as waste water during hydraulic fracturing. This has reduced the fresh water needs (Scientific Review of Hydraulic Fracturing in British Columbia, 2019).

2.5 Impacts of Hydraulic Fracturing on Groundwater Quality

Studies have shown that there is potential hazard of methane contamination in shallow groundwater system in hydraulic fractured areas (Osborn et al., 2011). Figure 5 presents data on the concentration level of methane in drinking wells close to gas wells in active extraction areas of shallow groundwater systems and indicates methane is higher than the drinking water wells in non-active extraction areas with the same geological and hydrogeological formations.

- Water withdrawals for fracking during period of low water availability, or in areas with limited or declining groundwater resources;
- Spills during the handling of fracking mixtures and produced water that result in high concentrations of chemicals reaching groundwater resources;
- Careless injection of fracking fluids into wells due to inadequate mechanical integrity, allowing gases or liquids to move to groundwater resources;
- Direct injection of fracking fluids into groundwater resources;
- Improper discharge of wastewater or discharge of inadequately treated fracking wastewater to surface water; and
- Disposal or storage of hydraulic fracturing wastewater in unlined pits resulting in contamination of groundwater resources.

Table 2 and Table 3 provide the volumetric composition and concentration of constituents in fracking fluid and produced water which are hazardous to the environment, if they are not properly treated or handled and therefore, a source of surface and groundwater pollution.

Recently, there has been increase in production of natural gas, which has drawn more concerns to potential risks associated with groundwater contamination (Jackson et al., 2013) and green house gases (GHG) emissions (Alvarez et al., 2018). Also, it has been estimated that 8% of 10,256 wells in British Columbia, 6.56% of 446,289 in Alberta and 6.26% of 8030 in Pennsylvania were reported by Forde et al., (2019) to have well integrity issues, which includes gas migration (GM) and surface casing vent flows (SCVFs) (Forde et al., 2019). Eventually, these issues might lead to emission of fugitive methane and CO₂ to the atmosphere and the pollution of groundwater resources. BCOGC (2013) reported that out of 308 wells inspected based on visual, olfactory and auditory evidence for GM, commonly associated to bubbling in standing water at the well head and vegetation stress, or elevated CH₄ in air, it was shown that 11 of them has direct evidence of GM.

Thus, from the weight of evidence provided by different reports, it may be inferred that hydraulic fracturing processes could pose potential hazard to both surface water, groundwater and most notably, the production of greenhouse gases.

2.6 Impacts of Hydraulic Fracturing on Induced Earthquake Occurrence

Davies et al. (2013) reported 198 possible examples of induced earthquakes that have occurred since 1929 with observed magnitude from 1.0 to 7.9. In the report, it was stated that hydraulic fracturing was not the only cause of induced earthquakes. The potential causes and magnitudes of earthquakes (M) caused by anthropogenic activities were recorded as:

- Mining (M 1.6 - 5.6);
- Reservoir impoundment (M 2.0 – 7.9);
- Water injection for secondary oil recovery (M 1.9–5.1);
- Oil and gas field depletion (M 1.0–7.3);
- Solution mining (M 1.0–5.2);
- Geothermal operations (M 1.0–4.6);
- Waste disposal (M 2.0–5.3);
- Academic research boreholes investigating induced seismicity and stress (M 2.8–3.1) and
- Fracking for recovery of gas and oil from low-permeability sedimentary rocks (M 1.0–3.8).

However, Davies et al. (2013) reported that some scientists argue that hydraulic fracturing does not cause “felt” induced earthquakes. Figure 6 illustrates fracking causing the smallest number and magnitude of induced earthquakes from the 198 possible examples of earthquakes. Although, due to limited published data available, there are many examples of induced seismicity that are not included on the graph. While, Figure 7a and 7b show the causes and the maximum magnitude of the causes.

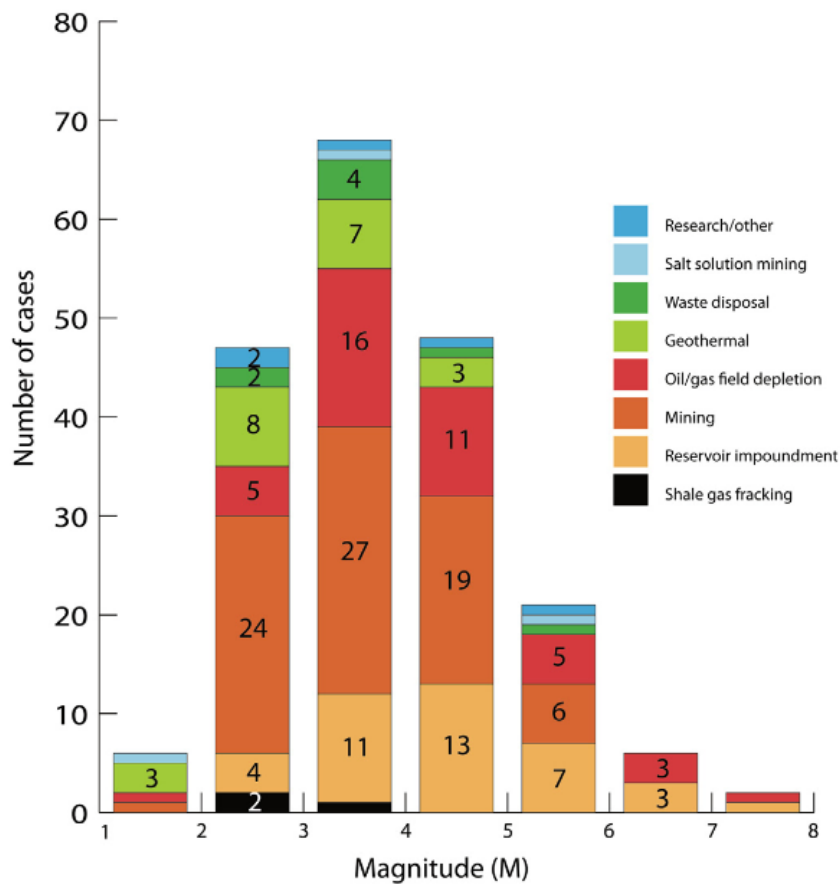


Figure 6. Frequency vs. magnitude for 198 published examples of induced seismicity (Davies et al. (2013))

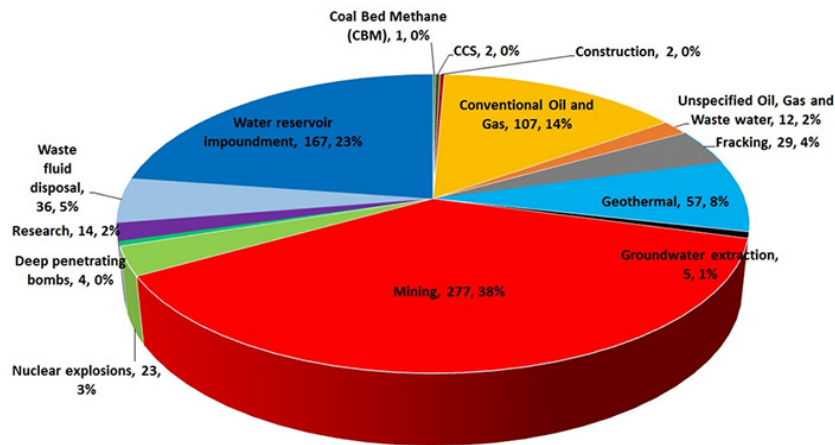


Figure 7a. Causes of Human Induced Earthquakes (The Human-Induced Earthquake Database / inducedearthquakes.org)

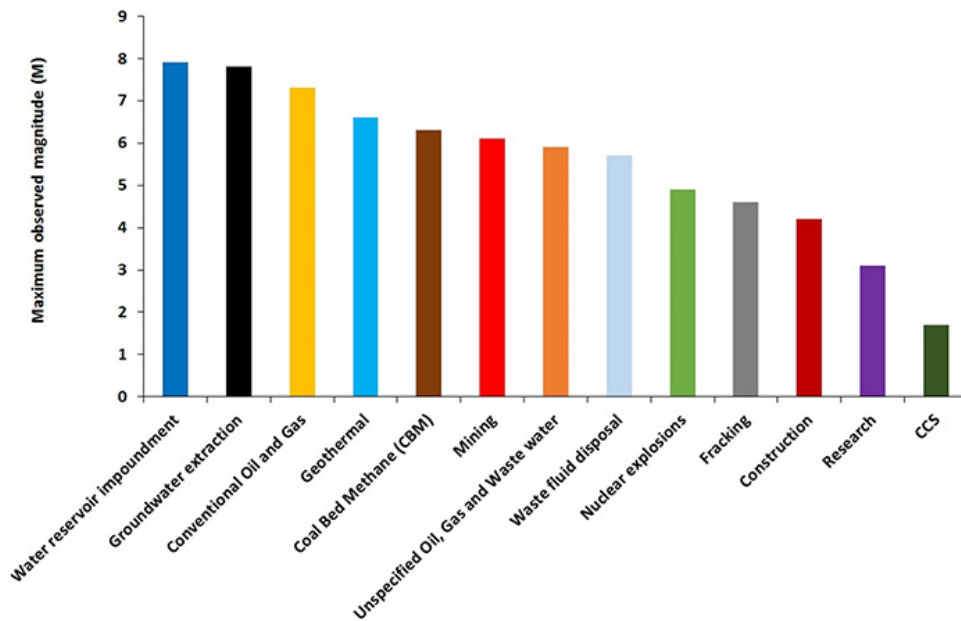


Figure 7b. The maximum magnitude of the causes ([The Human-Induced Earthquake Database / inducedearthquakes.org](http://inducedearthquakes.org))

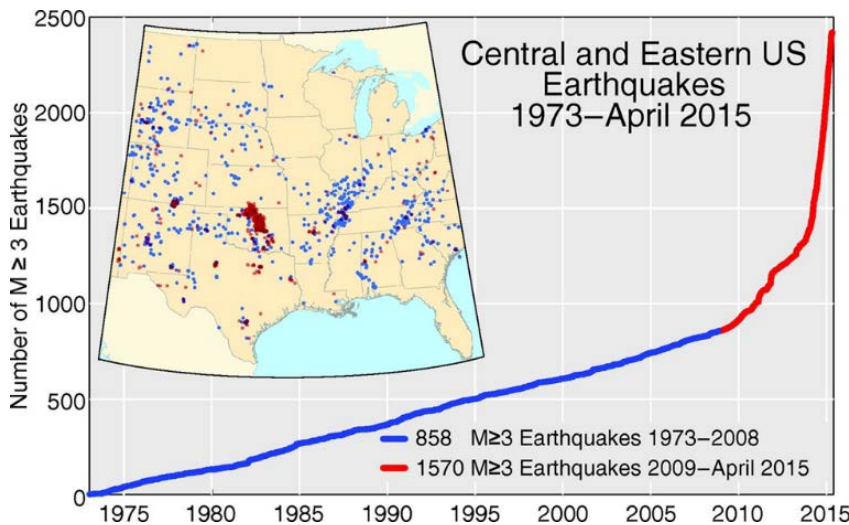


Figure 8. Count of $M \geq 3$ earthquakes in the central and eastern United States from 1973 to April 2015. (Rubinstein and Mahani, 2015)

Figure 8 illustrates that the two abrupt increases in the earthquake rate that occurred in parts of the United States in 2009 and 2013 by the red dots, that represent earthquakes that occurred between 2009 and April 2015, and blue dots represent earthquakes that occurred between 1973 and 2008. The earthquake rate and distribution of earthquakes changed in 2009. From the inset map in the graph, it can be seen that

prior to 2009, earthquakes were spread across the United States. From 2009 the earthquakes are tightly clustered in a few areas (central Oklahoma, southern Kansas, central Arkansas, southeastern Colorado and northeastern New Mexico, and multiple parts of Texas) which are rich in oil and gas.

However, it is important to note that artificial injection of fluid into the earth crust does induce seismicity (Green, et al., 2012). Fluid injection not only increases stress (Fig. 9) (Scholz, 1990) and creates new fissures, but also causes slip along the fault to occur earlier than it would otherwise have done naturally, because of the pressurised fluids are potentially introduced into pre-existing crack (or fault) zones (Davies *et al.*, 2013). The mechanism of induced earthquake is illustrated in the Mohr circle diagram in Figure 8 reported by Rubinstein and Mahani (2015).

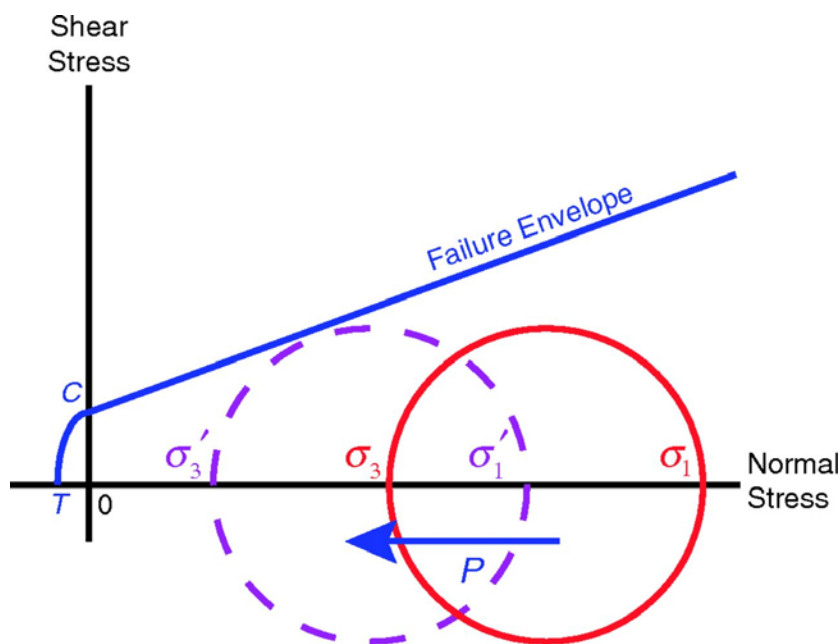


Figure 9. Mohr circle diagram showing the effect of increased fluid pressure on a fault (Rubinstein and Mahani, 2015).

Rubinstein and Mahani (2015) explain how fluid injection induce earthquake occur by:

- Raising pore-pressure within cracks or faults,
- Causing poro-elastic deformation due to fluid expansion and compression within pores,

- Causing thermoelastic deformation due to colder fluid than the rock injected to the rock pore space and
- Mass addition to the injection formation due to fluid injected.

Raleigh et al. (1976) and Mc Clure and Horne (2011) reported increased fluid pressure within rock pore spaces cause induced earthquakes. In a bid to explain this claim further, Maxwell (2013) illustrated a mechanism of fracture formation using the Mohr Circle (Figure 8). The Figure shows the maximum and minimum normal stresses acting in any given location and are plotted as σ_1 and σ_3 . The Mohr circle (shown in red) is drawn to represent the range of stresses acting on a plane at one location, showing both the shear and normal stress at a given location. Normal stresses are reduced by P, when fluid pressure (P) is increased resulting in new normal stresses. The Mohr circle diagram shows the effect of increased fluid pressure on a fault. The purple coloured dotted circle indicates that Mohr circle is closer to the failure envelope (blue line) and makes shear or tensile failure to occur more likely. The failure envelope with the slope is equal to the frictional resistance at that point on the plane. When the minimum principal normal stress σ_3 is less than T, the tensile strength of the rock, the rock will fail in tension, that is, fractures will open. Thus, continuous injection of high-pressured fracking fluid causes continuous fracturing of the rocks and increases fluid pressure in the fault zone, which triggers earthquakes (Davies *et al.*, 2013).

Moreover, a report published by Greebe (2019) in NRCan explains that induced earthquake occurs when there is forceful injection of fracking fluid into the plate boundary zones beneath the earth surface which causes disturbance and imbalance between the stresses that hold the intraplate faults, thereby, releasing accumulated tectonic energy. This report also affirms that most of this induced seismicity occur frequently where the tectonic strain rate is wide—usually 150 km wide band immediately to the east of the Rocky Mountains (that is in Western Canada—the boundary between British Columbia and Alberta).

Elsworth *et al.* (2016) pointed out several examples of locations where fracking causes induced earthquakes and reported that fluid injection- induced earthquakes have been occurring frequently in most oil and gas producing areas in the United States and Western Canada. It has been occurring at alarming rates and with acute effects in Oklahoma. This was reported as the injection of highly pressure fluid weakens the strength of the fault intersecting the disposal aquifers which result in tectonic reactivation (Elsworth et al., 2016).

Nikiforuk (2015), published in The Tyee Newspaper, states that about 400 small earthquakes (mostly of magnitude less than 3.5) has been experienced between 1985 to 2010 in the Northeastern part of British Columbia. It is suggested that it is the result of increase fracking activities in 2014, Fox Creek—an oil and gas producing city in Alberta experienced their highest earthquake ever with a magnitude of 4.4 in 2014. This earthquake caused buildings, walls to bend and beds to move.

Hence, the weight of evidences provided by these reviewed literatures is an indication that fracking could be a potential risk causing induced earthquake.

3.0 Case Study

In this project, a case study in North Eastern British Columbia was selected as an example. The specific objectives of this case study were:

- To assess impacts of fracking on water quality and quantity, and;
- To conduct meta-analysis of the impacts of fracking on induced earthquakes in North Eastern British Columbia.

4.0 Study Area and Method of Assessment

The areas selected for the case studies are in Northeastern British Columbia. Figure 10 shows the locations of six major gas fields in Northeastern British Columbia are; Deep Basin Cadomin, Montney, Jean Marie, Cordova Embayment, Liard Basin and Horn River Basin.

Twelve of these well pads were located above the Late Devonian Jean Marie Formation, a productive carbonate platform hosting several gas pools (Gunnel Creek, Helmet, Sierra, Elleh, Ekwan). The remaining five well pads were located above Mid Devonian shales (Muskwa, Otter Park and Evie Formations) in the Horn River Basin (Forde et al., 2019). Previous researches have suggested that Jean Marie Formation and the Horn River Basin are known for having several shallow gas bearing regions which, are susceptible to gas migration (Bachu, 2017; BCOGC, 2013; Hickin et al., 2008; Dusseault and Jackson, 2014; Jackson, 2014).

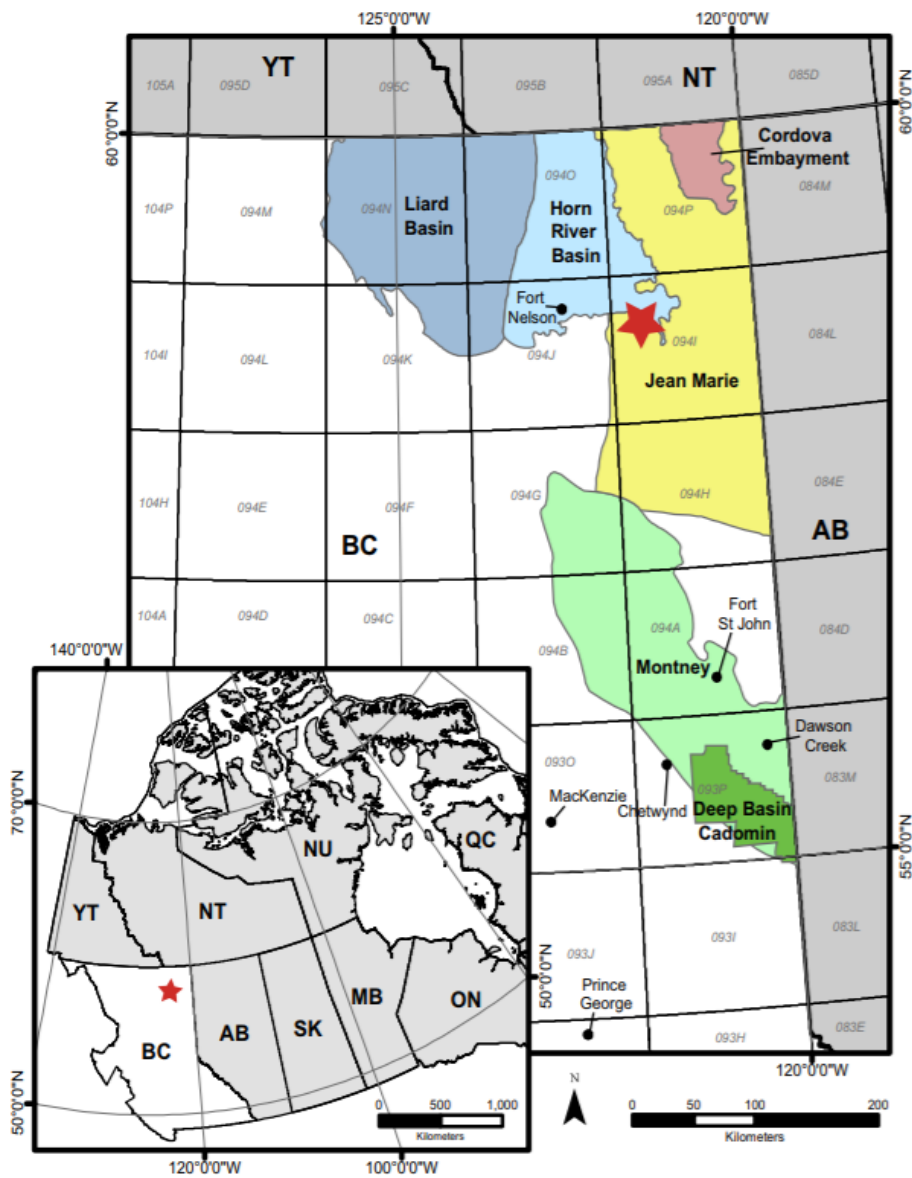


Figure 10. Gas plays in Northeastern British Columbia, Canada (modified from BCOGC, 2012) with region of study marked by a red star (Source: Forde et al., 2019).

The British Columbia provincial government claimed that there have been recent concerns in Northeastern British Columbia about oil and gas leakages in gas well pads. This is due to the low permeability of the region in Northeastern British Columbia, which may lead to lateral gas transport and the potential of a breakthrough via preferential pathways to the ground surface (Forde et al., 2019). However, the report concluded that the field screening method used to detect gas migration in the oil and

gas wells were ineffective (BCOGC, 2013). Further research by Forde et al. (2019) attempted to identify the spatial extent and distribution of fugitive gas migration on the well pad scale by studying and demonstrating the effluxes of methane gas released to the atmosphere in the field, supported with carbon isotope data (Fig.11). Therefore, there is recent concern that leaking oil and gas wells can lead to subsurface CH_4 gas migration (GM), which may cause both aquifer contamination and atmospheric emissions of GHG in the system (Forde et al., 2019).

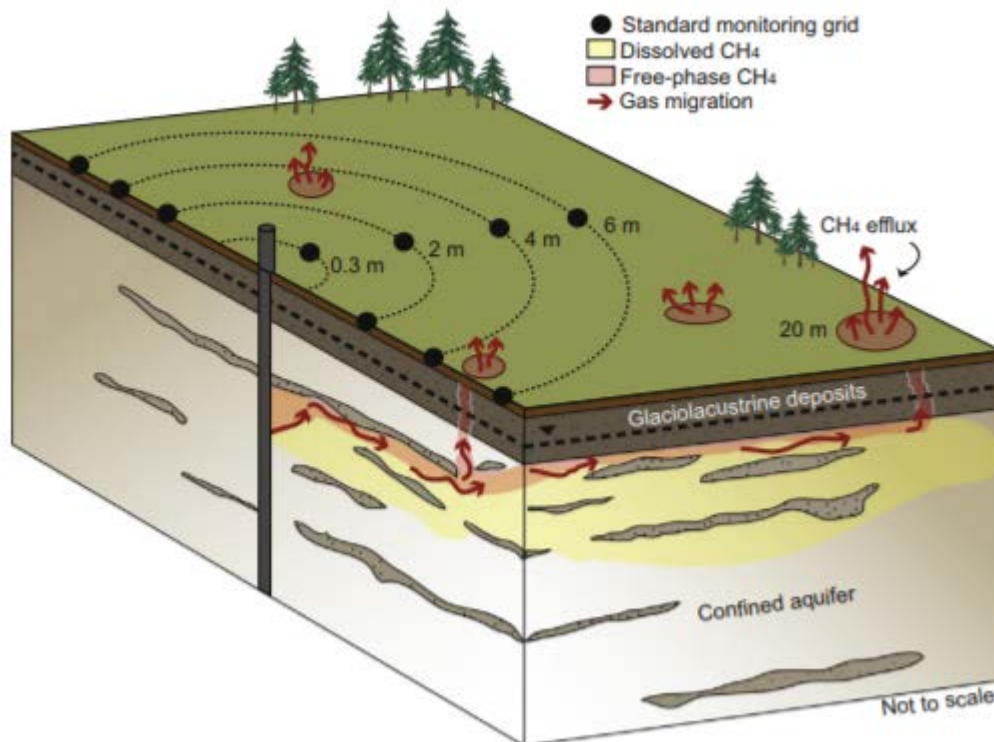


Figure 11. Cross section of a conceptual diagram depicting a well with fugitive GM in a confined aquifer.

It is important to note that methane effluxes can occur in unpredictable locations, potentially far from the well head. Black dots marked with distance from the well head indicate standard industry practice in Western Canada for selecting soil gas measurement locations to check for GM surrounding an oil and gas well (Source: Forde et al., 2019).

During the compilation of this report, I contacted Dr Roger Beckie, Dr Ulrich Mayer and a graduate student from the Department of Earth Ocean and Atmospheric Sciences at the University of British Columbia, Vancouver, Canada for their understanding of fracking in Northeastern British Columbia. Then, preliminary studies and ongoing studies raise the following;

- If boreholes are done properly with due to diligence and mechanical integrity, there will be no groundwater contamination;
- If the sites are properly managed, there is little or no chance of environmental pollution (including air and water resources) by shale gas;
- There are ample evidences that fracking induces seismicity. Thus, if fracking continues, it implies the magnitude and effects of earthquake increases (Beckie, 2019). A typical example is one that occurred recently in Red Deer, Alberta province, Canada with magnitude of 4.6 (Global News, 2019);
- Beckie (2019) reported that from greater than 2500 wells observed in Northeastern British Columbia, less than 150 are known to be leaking; and lastly, this data shows the concern of well leakage in Northeastern British Columbia due to gas migration, which may lead to air pollution and groundwater contamination.

5.0 Conclusion

In conclusion, there is uncertainty about the impacts of hydraulic fracturing to water resources and its effects on the occurrence on induced seismicity as researchers and scientists are inconclusive on the subjects matter due to lack of assess to data. Although, there are a lot of research ongoing on the effects of fracking on the environment. The major recent concern in the Northeastern British Columbia is gas leakage which may be potential water contaminant in the subsurface aquifer and air pollution due to release of methane (Green House Gas) to the atmosphere.

6.0 Recommendation

Based on the literatures reviewed and personal interviews done with researchers, it is recommended that:

1. There is a need to do more site-specific monitoring for:
 - Induced seismicity
 - Gas migration
 - Water contamination / use
2. There needs to be transparency among industry, government, researchers (academics) and public concerning the issues and the environmental impacts of fracking.

7.0 Limitations / Challenges Faced

During the project, the challenges I faced were:

- Limited access to primary data as there is no availability of data to study the impacts of fracking in Northeastern British Columbia
- Most of the literature reviewed provided diverse perspectives of the impacts of fracking on the environment. Many of them were inconclusive of the potential hazard associated with the process. Even, the scientific review of hydraulic fracturing in British Columbia, released in 2018 did not take a firm stand on the impacts of fracking in British Columbia due to lack of data to assess its potential risks on the environment and human health.

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