In the Field

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# Advancing knowledge of gas migration and fugitive gas from energy wells in northeast British Columbia, Canada

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Abstract: Petroleum resource development is creating a global legacy of active and inactive onshore energy wells. Unfortunately, a portion of these wells will exhibit gas migration (GM), releasing fugitive gas (FG) into adjacent geologic formations and overlying soils. Once mobilized, FG may traverse the critical zone, impact groundwater, and emit to the atmosphere, contributing to greenhouse-gas emissions. Understanding of GM and FG has increased in recent years but significant gaps persist in knowledge of (1) the incidence and causes of GM, (2) subsurface baseline conditions in regions of development required to delineate GM and FG, and (3) the migration, impacts, and fate of FG. Here we provide an overview of these knowledge gaps as well as the occurrence of GM and FG as currently understood in British Columbia (BC), Canada, a petroleum-producing region hosting significant reserves. To address the identified knowledge gaps within BC, the Energy and Environment Research Initiative (EERI) at the University of British Columbia is implementing several field-focused research projects including: (1) statistical analyses of regulatory data to elucidate the incidence and causes of GM, (2) characterization of regional hydrogeology and shallow subsurface conditions in the Peace Region of the Montney resource play, and (3) investigation of the migration, impacts, and fate of FG in the shallow subsurface through controlled natural-gas release. Together, the EERI investigations will advance understanding of GM and FG, provide scientific data that can inform regulations, and aid

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development of effective monitoring and detection methodologies for BC and beyond. 

Keywords: fugitive gas; fugitive methane; gas migration; greenhouse gas emissions; groundwater; hydraulic fracturing; methane; natural gas

## Introduction

Over the last decade, a combination of well stimulation by hydraulic fracturing and horizontal drilling has led to rapid and unprecedented shale-derived natural-gas extraction across the USA and Canada.[1] Consequently, tens of thousands of energy wells have been drilled across regions underlain by gas-bearing shales. Following such intense 'unconventional' resource development, multiple cases of environmental impacts have been alleged and investigated,[2–5] resulting in controversy and various regional moratoria. One of the main issues of concern associated with shale gas development is accidental subsurface leakage of natural gas, termed gas migration (GM).[6–8] Gas migration describes unintentional, and uncontrolled subsurface release of a petroleum gas mixture, consisting primarily of methane ($CH_4$), outside of an energy well casing and into geologic material and overlying soils around the well.[9] Once outside the energy well bore, this gas becomes fugitive, and is often termed fugitive gas (FG). It should be noted that GM and FG are distinct from the migration of gas inside and along the surface casing annulus of an energy well where, depending on the region, it is either vented directly to the atmosphere (e.g. in Canada, through a surface casing vent) or is shut in and the pressure build up monitored (e.g. in the USA, termed Braiden head pressure).

Hydraulic fracturing has brought attention to them, but GM and FG are well documented and historic issues[10] associated with all petroleum-resource development and associated activities (e.g. underground gas storage).[11,12] GM and FG can be caused by energy wellbore integrity failure or mobilization of intermediate depth gas pockets along an energy wellbore during and / or after drilling.[9,13] Regardless of source or cause, GM results in the flow of both free-phase and dissolved natural gas in the subsurface,[14] resulting in various cases of groundwater contamination.[15–19] Once dissolved in groundwater, natural-gas constituents will migrate via advection and dispersion, where they may be attenuated by microbes (based on availability of electron acceptors), potentially generate undesirable byproducts (e.g. $H_2S$, $Fe^{2+}$, $Mn^{2+}$),[20–24] and / or potentially induce release of trace metals (e.g. As) by reductive dissolution of various minerals.[25] Due to buoyancy and density forces, some free-phase FG may also migrate through the whole geologic profile and efflux at the ground surface.[26,27] At this point FG is both a potential explosion risk[28,29] and a potent greenhouse gas, contributing to climate change.[30,31] Consequently, GM and FG involve the whole of the critical zone (the entire shallow subsurface including potable groundwater, the unsaturated / vadose zone and ground surface) and require a comprehensive understanding across the fields of petroleum engineering, geology, physical, and chemical hydrogeology, isotope geochemistry, microbiology, vadose zone processes, and atmospheric sciences to advance knowledge (Fig. 1).

Considering global energy demands and widespread abundance of natural gas resources, it is certain that development will continue, further creating a global legacy of aging energy wells. It is unfortunately likely that a number of these wells will ultimately exhibit GM and release FG into the subsurface, where it will impact groundwater and potentially emit to the atmosphere. Advanced understanding of GM and FG is therefore necessary to manage development effectively, and ultimately limit greenhouse gas emissions and protect groundwater resources; a concept previously stated.[32] Knowledge gaps regarding GM and FG can be categorized as a lack of understanding with respect to (1) the incidence and causes of GM, (2) the understanding of subsurface baseline conditions in regions of development required to delineate FG and GM, and (3) the migration, impacts and fate of FG. These knowledge gaps, including gaps in current understanding, are outlined in the following sections.

## Key knowledge gaps relating to gas migration and fugitive gas

### Incidence and causes

The true extent and occurrence of gas migration from energy wells is a point of significant controversy and contention in all regions where petroleum resource

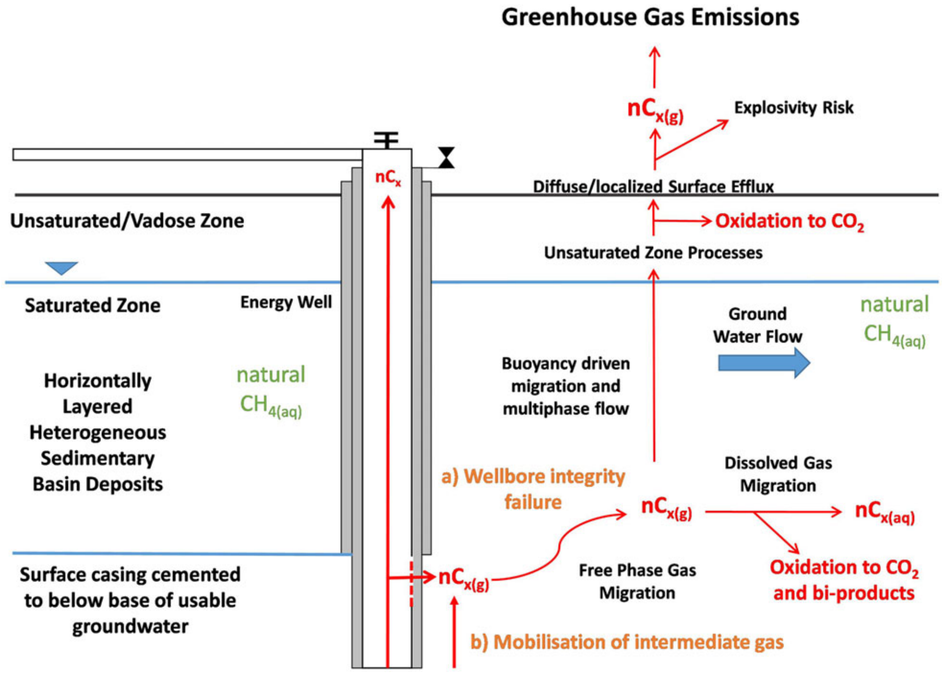


Figure 1. Conceptual model of gas migration and fugitive gas associated with energy wells, where nCx represents unintentionally released natural gas (a mixture of hydrocarbon gases, formed primarily of $CH_4$). Origins of subsurface fugitive gas include (a) wellbore integrity failure and (b) mobilization of intermediate-depth (i.e. between the reservoir and surface) gas pools along the energy wellbore. Following subsurface leakage, fugitive gas may traverse the whole of the critical zone, impact groundwater resources, and emit to the atmosphere. Currently there are many knowledge gaps concerning GM and FG including (1) how many wells leak and why, (2) subsurface baseline conditions with respect to methane in producing regions (a ubiquitous natural constituent of groundwater), and (3) how gas migrates, its impacts on groundwater resources, and ultimate fate in the environment.

development is taking place. Some studies claim that the issue is non-existent or rare (i.e. <5% incidence)[8,33] whereas others suggest that it is common (i.e. >50% incidence).[34,35] Nonetheless, it has been suggested that anything from 1.9–75% of wells exhibit integrity failure, which leads to gas migration and fugitive gas release.[13] Studies focusing on the causes of gas migration have shown that a combination of factors likely contributes to the development of fugitive gas release confirming the issue to be a complex, region-specific, and multifaceted problem.[36] For example, Bachu[37] investigated the occurrence up to 2013 of GM outside wellbore casings in Alberta by assessing records obtained from the Alberta Energy Regulator (AER). Factors potentially affecting well integrity and GM, such as completion type, cementation, well orientation, status, and production type, were individually evaluated and descriptive statistics were produced. Gas migration was found in 0.73% of oil and gas wells in Alberta (3276/~450 000) where insights gleaned included that well orientation was not a strong indicator for the development of GM and approximately 90% of wells with GM penetrate one or more intermediate-depth coal beds. Interestingly, these conclusions were at odds with earlier findings for the same region where, for example, well orientation was identified as a potentially important factor for the development of GM.[38] In another study, wellbore integrity failure was investigated through the analysis of compliance reports for 41 381 conventional and unconventional oil and gas wells drilled in Pennsylvania between 2000 and 2012.[39] These records were used to characterize statistics of casing and cement impairment, which can lead to GM or FG. Overall the study found that unconventional wells have a six times higher rate of integrity failure than conventional wells and wellbore age is a factor in development of integrity failure.

 

Most reported incidence rates are comparable and range from 1–10%. When considering that regional populations of energy wells are usually in the tens or hundreds of thousands, and that Alberta, Canada alone has >0.45 million energy wells, such poor estimates of GM and FG incidence are problematic from an environmental standpoint. Furthermore, GM and FG are likely underestimated by such studies because not all wells are tested, and GM wells are only identified by a verified observation. Similarly, while potential attributes and causes of GM are alluded to in various studies, significant regional variation is observed and no congruent causes of well integrity failure have been conclusively identified. Consequently, it is not currently possible to confidently bound general incidence rates in a given area or assign generalized attributes that may increase the risk for development of GM. A greater general understanding of incidence rates and causes of GM is therefore needed, as well as regionally specific understanding.

## Understanding of baseline groundwater conditions in regions of development

Methane is naturally ubiquitous in the subsurface, where it is almost always observed in groundwater at low (e.g. 1–3 mg/l) and in some cases higher (e.g. 5–20 mg/l) concentrations,[40,41] controlled primarily by groundwater redox state.[42] A poor understanding of the natural or baseline pre-development presence and origins of methane in groundwater in regions of resource development has made it difficult to identify GM and FG. Consequently, initial GM and FG research on potential impacts on groundwater has focused on regional-scale retrospective environmental forensic studies, which aim to identify presence and delineate sources of groundwater $CH_4$ in areas where impacts from oil and gas development are contested.[4,5] These studies continue to provide conflicting conclusions on the origins of dissolved gas. For example, some have identified a seemingly direct correlation between groundwater methane and distance to energy resource development[5] or occurrence of development and changes in proximal dissolved methane concentrations.[43] Meanwhile, others have shown that groundwater methane is for the most part naturally present and related to other factors such as topographic controls,[44] upwelling of deeper, older water,[45] the presence of fault systems,[46] and natural migration or accidental mobilization of intermediate depth non-economic gas pools.[47] More recent work continues to enhance our understanding on the natural presence, origins, and characteristics of dissolved methane in groundwater, where noble gas isotopes have proven a key tool in delineation and identification.[48] Clearly an advanced understanding of baseline groundwater conditions in all regions where development occurs or is planned / desired is needed and will be critical to delineate if and where GM and FG may have occurred. Similarly, continuous monitoring of groundwater should be employed as development progresses if changes with time are to be identified. Unfortunately, few mandatory predevelopment groundwater characterization programs are conducted in regions of intense energy resource development prior to drilling. A key exception to this is the work performed in Quebec, Canada where a moratorium on development is currently in place.[49–51] Nonetheless, natural subsurface and groundwater methane conditions in regions of historic, ongoing or planned development remain poorly understood.

## Migration, impacts, and fate of fugitive gas

Little research has investigated what happens during and after a specific leakage event at the individual energy-well scale. Exceptionally, several studies have reported on impacts to groundwater around historic well blowouts,[23,24,52] or at some distance from a suspected or confirmed leakage event.[16,53] However, while such studies indicate the potential longer term impacts of GM and FG on groundwater, measurements are typically taken many years after leakage may have begun, are spatio-temporally sparse and there is little or no information on the leakage rates, duration, or overall magnitude. It is consequently difficult to attribute cause and effect or comprehensively characterize migration, impacts, and fate of FG with time. To address these limitations it is necessary to obtain high-resolution spatio-temporal measurements around a real wellbore leakage event during and immediately after its development. However, no such data have been reported in the literature to date and to gain such would be extremely challenging due to logistical and legal issues.

To circumvent such research challenges, a multidisciplinary controlled natural-gas release investigation was recently completed, offering an opportunity to advance understanding of subsurface gas migration from a point source in a shallow groundwater system.[54] It was shown that, after entering the aquifer, free-phase methane preferentially migrated upward due to buoyancy while a significant portion migrated laterally five times faster than advective groundwater flow, due to subtle grain-scale bedding.[55] Results also showed that during the experimental leakage event, dewatered gas-migration channels formed and acted to facilitate emissions to the atmosphere[26] and limit retention in groundwater. After gas injection was stopped, these channels collapsed resulting in increased gas-water mixing, increased levels of dissolved hydrocarbon gases in groundwater,[56] and cessation of emissions to the atmosphere.

This study provided important insights to refine our conceptual understanding of a point source subsurface gas leak however forms only a single site-specific study and its overall applicability and relevance to regions of intense and extensive conventional and unconventional resource development (e.g. the Western Canadian Sedimentary Basin, WCSB) is limited. Many knowledge gaps consequently remain. For example, little research has addressed migration and fate of fugitive $CH_4$ at high spatiotemporal resolution at depths >10 m, in a highly heterogeneous geology, or in a confined groundwater system, where a significant and robust confining layer is in place (typical of the WCSB). Thus, in these circumstances, it is unknown if gas can reach the surface and emit (and be detected) or if it remains trapped in the subsurface. If the latter is the case, how far can it migrate? Does it readily degrade? If so, at what rates and what impacts does it have on groundwater quality?

To contribute to general understanding of gas migration and fugitive gas, here we outline the issue as it is currently understood in northeast British Columbia (BC), Canada, an area of significant historic and ongoing petroleum resource development. Subsequently, we describe research being conducted through the Energy and Environment Research Initiative (EERI), a multidisciplinary research program focused on investigating gas migration and fugitive gas in BC, based at the University of British Columbia (UBC).

## Petroleum resources of northeastern BC

### Regional overview

Northeastern BC forms the westernmost portion of the WCSB and hosts four main petroleum resource plays: the Montney, Liard and Horn River Basins and the Cordova Embayment. Between these plays, a total of 25 033 energy wells have been drilled since approximately 1950. The Montney, which is the largest and most productive, is a lower Triassic sedimentary deposit, which underlies approximately 130 000 $km^2$ of land straddling Alberta and British Columbia with a physiography of rolling glaciated plains between 600 and 800 m above sea level (ASL). The formation consists primarily of siltstone with thin interbedded sand and dolostone strata, increasing in depth from northeast (total vertical depth (TVD) to top of formation ~800 m) to southwest (TVD to top of formation ~4000 m) while reservoir pressure increases and liquid hydrocarbon content decreases. The formation, which is typically 100–300 m thick, has been subject to conventional oil and gas exploration and development since the 1950s, whereby sandstone and / or dolostone reservoirs of petroleum fluids bounded by siltstone have been identified and exploited, i.e. conventional development. The siltstone components of the formation have been long known to contain oil and / or gas but they remained undeveloped until 2005 when horizontal drilling and multistage hydraulic fracturing made extraction economically feasible. Current estimates suggest the Montney contains 12 719 billion $m^3$ (449 Tcf) of recoverable natural gas, 2308 million $m^3$ (14 521 million barrels) natural gas liquids and 179 million $m^3$ (1125 million barrels) of oil. Of these reserves, approximately 63% remain to be recovered in Alberta but >90% are in place in northeast BC. Consequently, development of the Montney and in particular natural-gas-based resource development in northeast BC is likely to continue at an increasing pace in the coming decades.

### Gas migration in northeast BC

The British Columbia Oil and Gas Commission (BC OGC) regulates all oil and gas activity in BC and during this process collects information on all energy wells drilled in the province where any identified incident of gas migration must be reported. Consequently, a current list of confirmed GM cases was obtained from the BC OGC as part of EERI's ongoing research. A total of 145 energy wells have been identified as exhibiting GM out of a total population of 25 033; an overall incidence rate of ~0.6%. A map of BC showing resource plays, energy well density, and

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locations of the 145 currently identified GM wells (indicated with red symbols) is shown in Fig. 2.

Gas migration occurrences appear geographically dispersed across northeast BC but the majority are located in the northernmost and least developed portion – i.e. in and amongst the northern resource plays of the Horn River basin and the area to the east, referred to as the Jean Marie. Here 118 GM wells are currently identified out of a total of 5541 energy wells, an incidence rate of 2.1% in this region. Significant clustering is also evident within this region with a total of 62 GM wells being located in a small area east of Fort Nelson (47.2% of all GM wells currently identified in the province). In contrast, the southern portion of BC's WCSB, which comprises the much more heavily developed Montney resource play (with a total of 19 337 equating to 77% of the total energy well population), has only 26 of the identified GM wells, for an incidence rate of 0.13%. Reasons for the geographic spread are currently poorly understood; however, some hypotheses are discussed below.

It should be noted that the overall incidence of 0.6% estimate of energy wells exhibiting GM in BC is likely to be conservative due to generally ineffective field-screening techniques (very limited spatio-temporal soil gas surveys around the well head) used to identify GM as stated by an internal BC OGC report.[57] Consequently, it is likely that more incidences of GM are yet to be identified. As regulations are developed, improved screening methods employed, and wells in the region age, more energy wells will likely be identified as releasing FG through GM. There is an urgent need to increase understanding on the causes and occurrence of GM as well as the implications of the resultant FG in terms of environmental impacts and fate, particularly in a BC context.

## Advancing knowledge in BC through field-focused multidisciplinary research

As described above, three generalized knowledge gaps persist with respect to FG and GM. To address these knowledge gaps in a BC context, a multifaceted and multidisciplinary research program, the Energy and Environment Research Initiative (EERI), has been founded within the Department of Earth, Ocean and Atmospheric Sciences, at the University of British Columbia, Vancouver, Canada. The EERI is a field-focused, multidisciplinary and highly collaborative research program involving leading earth science and environmental engineering researchers from across Canada and beyond. The EERI's core mission is to increase knowledge about GM and FG from energy resource development which is being achieved through (1) statistical analyses of regulatory data to shed light on incidence, occurrence and causes of GM; (2) characterization of regional hydrogeology and baseline subsurface conditions in the Peace Region of the Montney resource play, BC, and (3) investigation of migration, impacts, and fate of fugitive gas through controlled natural gas release. Each EERI research thrust is summarized in the following sections.

### Statistical analyses of incidence and causes of GM

In general, the causes and mechanisms of GM as well as the reasons for geographic clustering of occurrences are poorly understood in the BC context. However, the BC OGC maintains a database that contains extensive information and attributes for all wells that fall under the BC Oil and Gas Activities Act, including information on drilling and completions, subsurface fluids, geology, and spatial information. This data set may potentially offer some insight into those factors associated with GM by comparison of characteristics of GM wells with the general, non-GM well population. Overall there are >20 attributes, which may potentially be contributing to or be involved in the development of GM and FG. Nine key attributes identified as potentially playing a role are shown in Table 1.

A key research project underway through EERI involves developing a custom 'subset' database of selected relevant attributes for wells with GM and then conducting a comprehensive statistical analysis of the data in comparison to the general population of energy wells to develop (1) a science-based framework for assessing the likelihood for GM in Northeast BC, and (2) an enhanced understanding of potential causes of GM. Four key factors likely contributing to development and identification of GM initially being explored include: (1) geographic location and geology, (2) drilling and completion methods, (3) surface casing depth and vent flow, and (4) regulatory changes. Through this investigation these key factors will be interrogated to provide greater understanding of the occurrence and causes of GM and FG in BC with a



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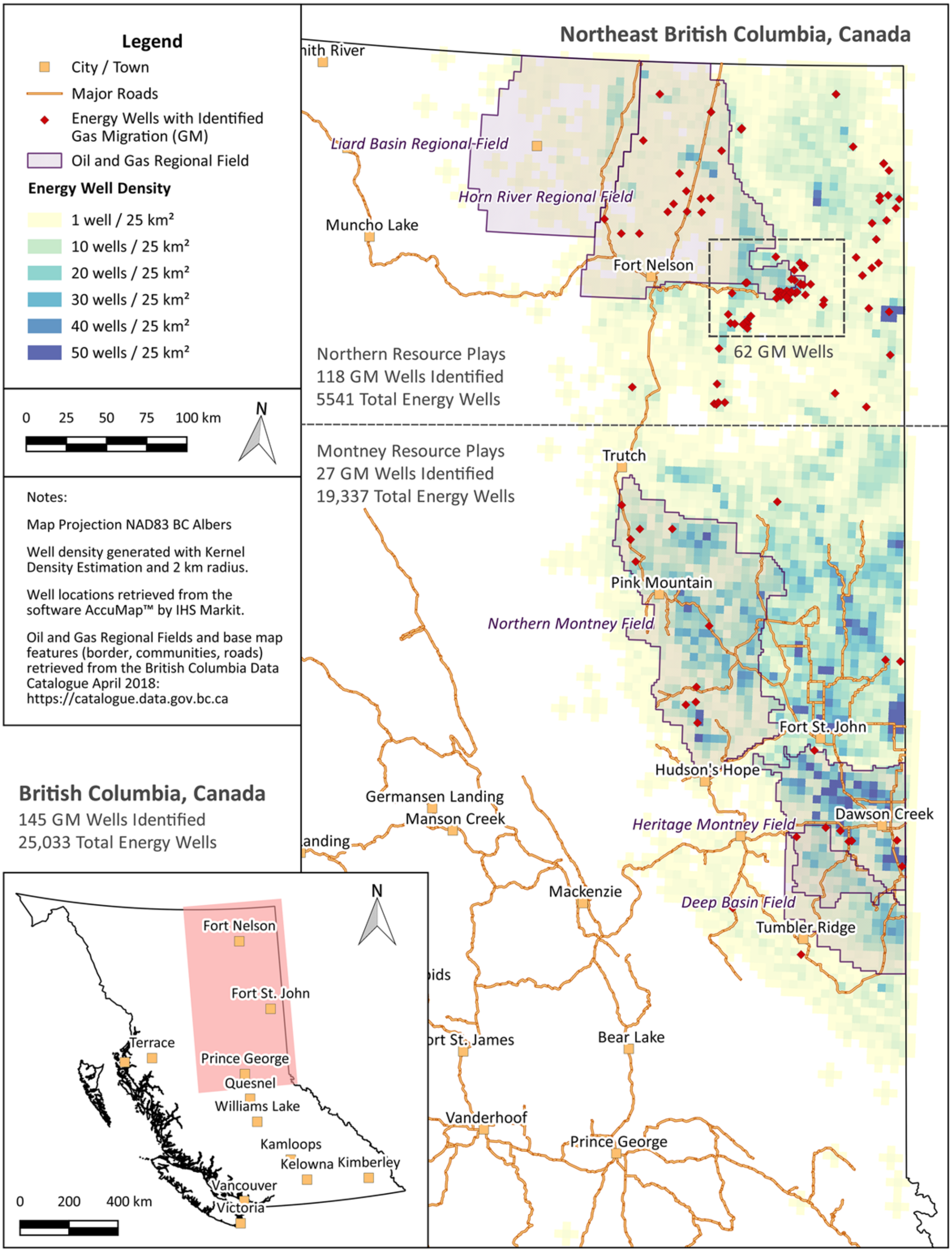


Figure 2. Map of BC showing energy wells currently identified with GM in relation to major resource plays and density of all other energy wells in BC per 25 km$^2$. The map shows that the majority of wells identified as exhibiting GM are in the northernmost portion of the province, east of Fort Nelson and associated with the Horn River Basin.

**Table 1. Description of energy well attributes that may contribute or be involved in the development of gas migration.**

| Well attribute name | Data example | Description |
|---|---|---|
| Well orientation | Horizontal | Direction of the wellbore in the subsurface. Generally characterized as vertical, deviated, or horizontal. |
| Well status | Producing | Life stage of the well, also known as the mode. |
| Fluid type | Gas | Type of fluid produced by the well. |
| Producing formation | Jean Marie | The geological formation producing the petroleum fluid. |
| Field | Sierra | A region representing the extent of an oil or gas deposit. |
| Surface casing depth | 276.0 m | The depth below ground that the outermost well casing extends. |
| Rig release date | 16 July 2007 | This indicates the well's age. |
| Treatment | Frac | The well was completed with hydraulic fracturing in the production zone. |
| Kicks and blowouts | Kick | High formation pressures cause formation fluids to enter the wellbore during drilling. If there is an uncontrolled release of fluids from the well it is referred to as a blowout. |

view to being able to predict if leakage may occur and prioritize individual wells or regions for monitoring as well as develop more effective monitoring and detection strategies.

## Characterization of regional hydrogeology and baseline conditions in the Peace Region, BC

The Peace Region lies within the Montney Resource play of northeast BC, hosting the main population centers as well as extensive historic and ongoing petroleum resource development. No assessments of baseline groundwater conditions were conducted in the region prior to energy resource development and only a few disparate efforts have been made more recently, so the hydrogeology and groundwater methane conditions in the region are generally poorly understood. There is also currently no dedicated scientifically designed groundwater monitoring network through which to monitor the evolution of groundwater conditions. Rather, assessments have been based upon samples collected from domestic wells for which reliability is a key concern.[58] An important EERI project, the Monitoring Well Installation Project (MWIP), aims to address this issue through the installation of 30 new purpose-built and scientifically designed groundwater monitoring wells across the region.

The project commenced in early 2018 with collection by sonic drilling of four continuous cores through the surficial quaternary sediments into the top of bedrock followed by installation of multilevel groundwater monitoring wells. These first monitoring wells were specifically set back at least 1.5 km away from existing oil and gas wells to characterize baseline conditions in the area. In subsequent drilling phases wells will be located nearer to oil and gas wells to assess subsurface conditions and groundwater quality. A map of the Peace region showing locations of the 2018 cores in the context of existing oil and gas development (including energy wells currently identified as exiting GM) and their geologic logs are shown in Figs 3 and 4 respectively.

Core logs from the initial drilling campaign (Fig. 4) are in line with several recent studies[59] and show the typical surficial geology of the region characterized by a veneer of glacial diamict, of varying thickness with interbedded layers of sand or even gravel, underlain by an interbedded sandstone-shale bedrock. The drilling campaign demonstrates the highly heterogeneous nature of groundwater resources in the region, which hosts two dominant aquifer types: (1) spatially discrete, laterally discontinuous quaternary aquifers, at times under artesian conditions (such as the 10 m thick seam of artesian gravel encountered at EERI 1) and (2) deeper more laterally extensive bedrock aquifers. However, depth to the bedrock in the Peace Region may be significant and low permeability of bedrock units may limit yields and form poor aquifer systems. Ongoing characterization of groundwater and hydrogeology at these newly established monitoring sites is under way. Subsequently drilling of monitoring wells is continuing into 2019 and 2020, and will

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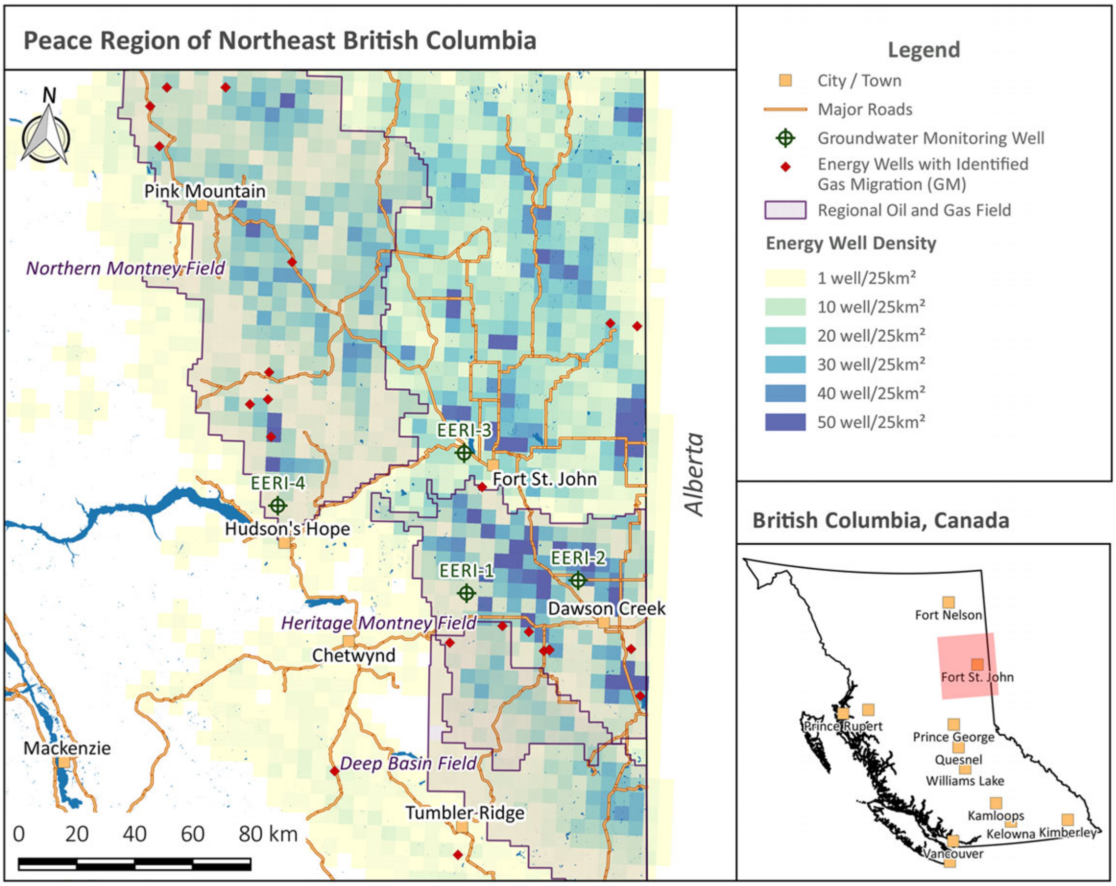


Figure 3. Map of Peace Region of northeast BC showing density of energy wells, wells identified as exhibiting GM and locations of four initial cores drilled as part of the MWIP in summer 2018.

establish a comprehensive portrait of geologic and hydrogeologic conditions in the Peace Region.

## Investigating migration, impacts, and the fate of fugitive gas through controlled release

The impacts and fate of fugitive natural gas from a point source during a single-well-scale leakage event are poorly understood. A previous controlled release experiment in a relatively simple and homogenous unconfined sandy aquifer demonstrated complex and extensive aquifer impacts,[54] but little is known about how a leak would evolve in a more complex surficial geology typical of the WCSB. To address this knowledge gap, the EERI have developed a controlled natural gas release field-research station within the Montney resource play of the Peace Region of northeast BC. The field station is located near the township of Hudson's Hope, located amongst historic and ongoing conventional and unconventional petroleum resource development (Fig. 5). The area's surficial geology is representative of the northeast BC portion of the WCSB with a reasonably continuous veneer of glacial diamictic clay (~10–12 m thick) overlying a complexly interbedded sequence with very fine to medium sands and silts, and pebbly silts, which show little lateral continuity.[60] Water in the confined aquifer is of Ca-Mg-$HCO_3$ type, with TDS of 600–700 mg/L, and low dissolved methane concentrations, ranging from undetectable to ~0.1 mg/l and, although likely to be biogenic exhibits a $\delta^{13}C_{CH4:}$ ~38 ‰ indicative of some *in situ* oxidation. Higher chain hydrocarbons (i.e. $C_2$+) are absent, suggesting no detectable impacts from nearby petroleum resource development.

The EERI have installed infrastructure at the Hudson's Hope Field Research Station (HH FRS) through which 100 $m^3$ of a synthetic Montney gas (Table 2) was injected at 26 m vertical depth into the aquifer at a rate of 1.5 $m^3$/day commencing on 12 June continuing for a total of 72 days. During and after injection the gas was and continues to be tracked through a comprehensive multidisciplinary monitoring

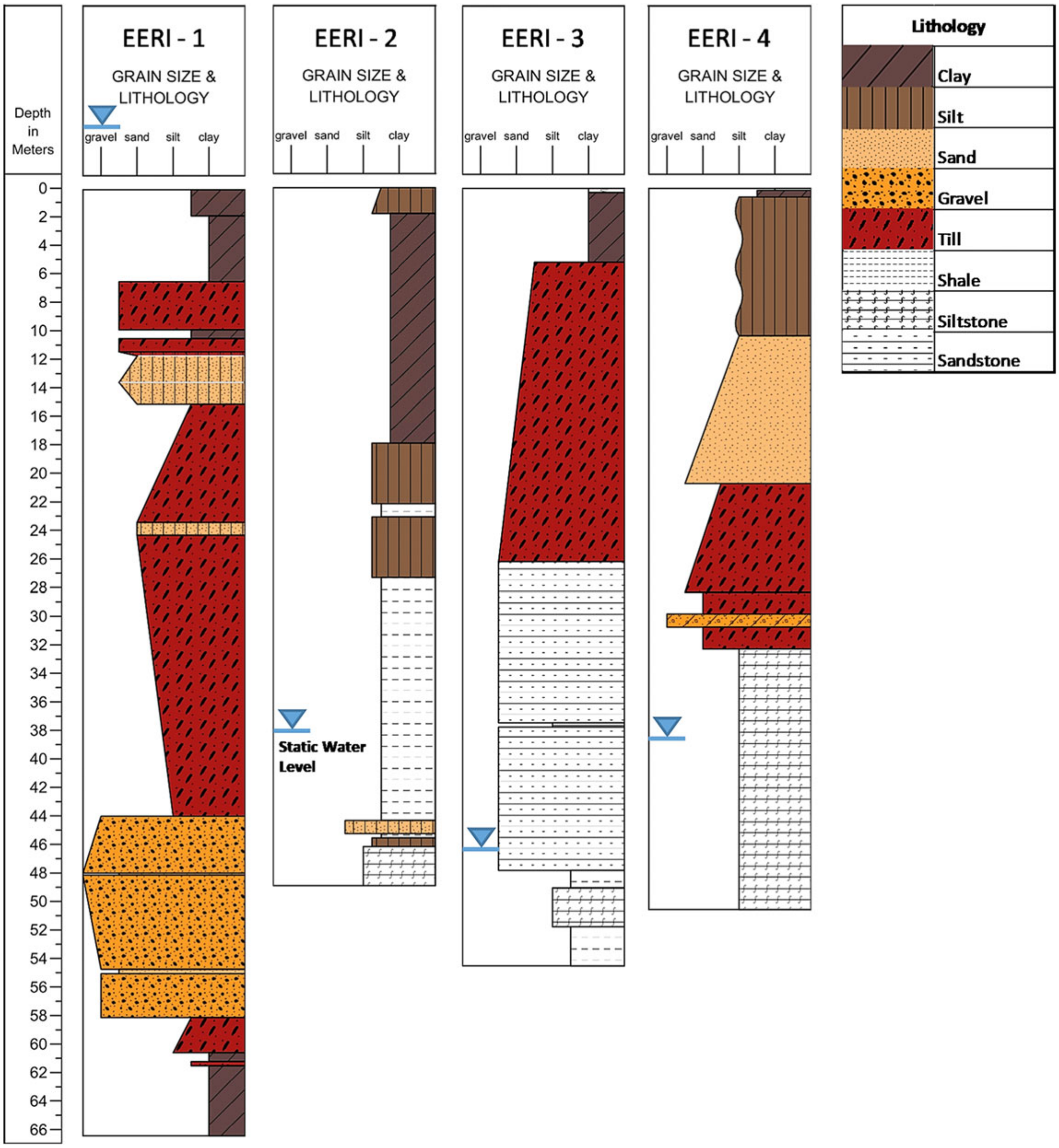


Figure 4. Core logs for Sonic boreholes EERI 1–4 showing static water levels. Note EERI 1 encountered an artesian gravel aquifer at 44–48 m depth with a static water level at approximately 1.5 m above ground level.

program spanning the whole of the critical zone characterizing geology, hydrogeology, hydro-geochemistry, geophysics, isotope geochemistry, vadose-zone processes, microbiology, and atmospheric sciences. Monitoring of the injected gas will continue throughout 2019. Table 3 summarizes the areas of the critical zone targeted for monitoring during the experiment, measurements taken, and their rationale.

The critical zone monitoring network tracks the injected gas and its reactive transport from release point through to atmosphere. A conceptual model of the site showing injection configuration and types of monitoring infrastructure being employed is shown in Figs 6 and 7. This unique and comprehensive multidisciplinary investigation will address key questions regarding FG and provide unprecedented insights that will advance understanding on the fundamental physical and chemical processes associated with point source subsurface leakage of natural gas.

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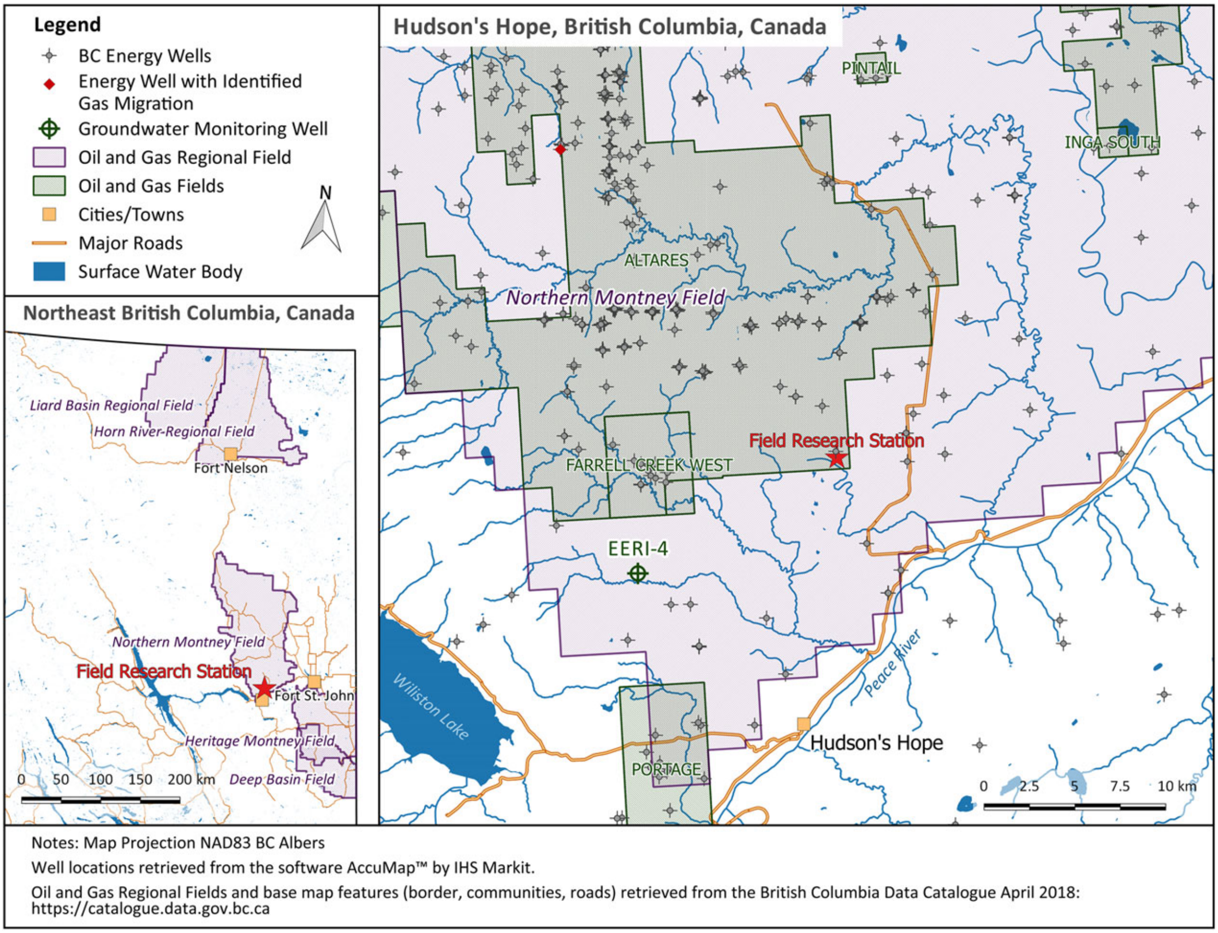


Figure 5. Map of Hudson's Hope area showing experimental field site location in relation to energy well density, location of identified well exhibiting gas migration and the core (EERI 4) drilled as part of the regional characterization project.

**Table 2. Composition (%) of typical Montney natural gas and synthetic gas formulated for injection experiment.**

| Gas | $C_1$ | $C_2$ | $C_3$ | $>C_4$ | $CO_2$ | $N_2$ | He |
|---|---|---|---|---|---|---|---|
| Typical Montney Gas | 0.85 | 0.08 | 0.03 | 0.02 | 0.001 | 0.002 | 0.0001 |
| EERI Synthetic Montney Gas | 0.85 | 0.08 | 0.05 | 0 | 0.01 | 0.005 | 0.005 |

## Summary and conclusions

Gas migration and fugitive gas resulting from energy wellbore integrity failure are issues that can be associated with all petroleum resource development and similar activities (e.g. underground gas storage). Leaky wells pose a risk to groundwater resources, form an explosion hazard, and may be a significant source of greenhouse gas emissions. Three knowledge gaps persist with respect to GM and FG: (1) the incidence and causes of GM, (2) the understanding of subsurface baseline conditions in regions of development required to delineate GM and FG, and (3) migration, impacts, and fate of FG. Meanwhile, the issues of GM and FG are set to increase in importance in a global context as natural gas resource development continues, oil and gas infrastructure ages, and integrity failures accumulate. Consequently, understanding the causes of GM and how FG migrates, its environmental impacts, and its ultimate fate will be critical in the coming decades.

Here we described GM as understood in northeast BC, an area at the forefront of the energy-environment nexus, underlain by significant natural-gas resources in a rural area rich in natural beauty and environmental value. To address the identified and persistent knowledge gaps regarding GM and FG, a

**Table 3. Summary of monitoring systems/networks by target monitoring zone including measurements taken and rationale.**

| Target monitoring zone | Analyses / measurement | Rationale |
|---|---|---|
| Boundary layer | $CH_4$, $CO_2$ and water vapor<br>3D Wind speed, direction and temperature<br>Precipitation, barometric pressure, relative humidity<br>Soil moisture, soil conductivity and soil temperature | To quantify flux of natural gas reaching the atmosphere, to assess methods for effectively and efficiently detecting and monitoring at surface, and to evaluate the role of climatic factors on emissions. |
| Ground surface and unsaturated zone | Soil gas composition and stable carbon isotopes<br>Surface efflux of $CH_4$ and $CO_2$<br>Microbial ecology | To assess migration and fate of natural gas in unsaturated soil, the extent of microbial oxidation, how much natural gas is attenuated versus transported to the ground surface and the atmosphere. |
| Saturated Zone | Groundwater chemistry (cations, anions and physical chemistry)<br>Dissolved gases<br>Stable carbon and noble gas isotopes<br>Microbial ecology<br>Surface-based electrical resistivity tomography<br>Refraction seismic surveys<br>Vertical seismic profiles<br>Fiber optic distributed temperature sensing | Track migration of free-phase natural gas from point of release through aquifer towards the capillary fringe. Assess extent of dissolution of hydrocarbon gas components and monitor the evolution of water chemistry and impacts to groundwater quality. Characterize microbial community response and evolution and extent and mechanism of attenuation of dissolved hydrocarbons. |

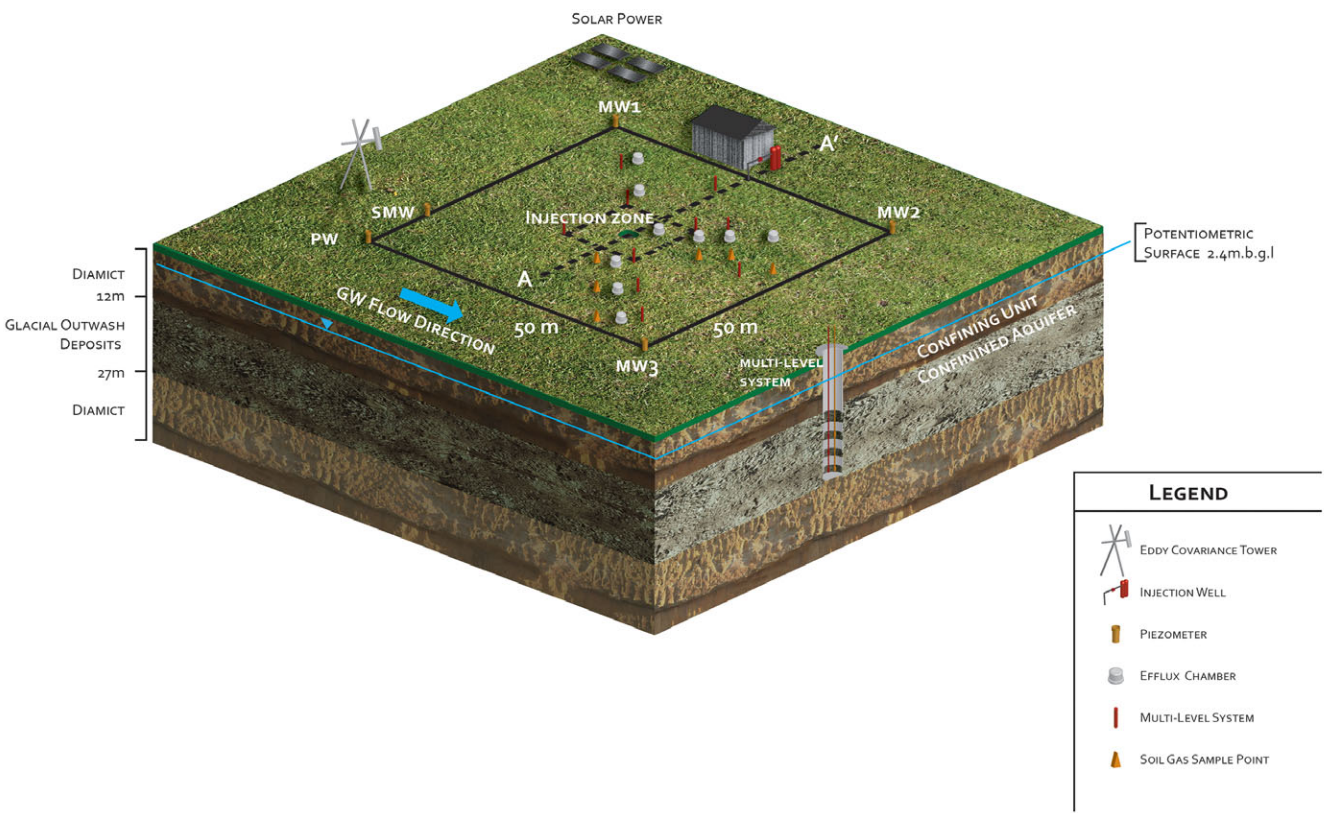


Figure 6. Conceptual model of HH FRS and the controlled synthetic natural gas release experiment infrastructure showing the confined glacial outwash aquifer confined by a 12 m thick layer of diamictic clay. Around the mass flow control valve operated inclined gas injection well a series of multidisciplinary monitoring systems are in place to track the migration impacts and fate of the synthetic Montney gas in high temporal-spatial resolution.

  | *Greenhouse Gas Sci Technol*. **00**:1–18 (2019); DOI: 10.1002/ghg

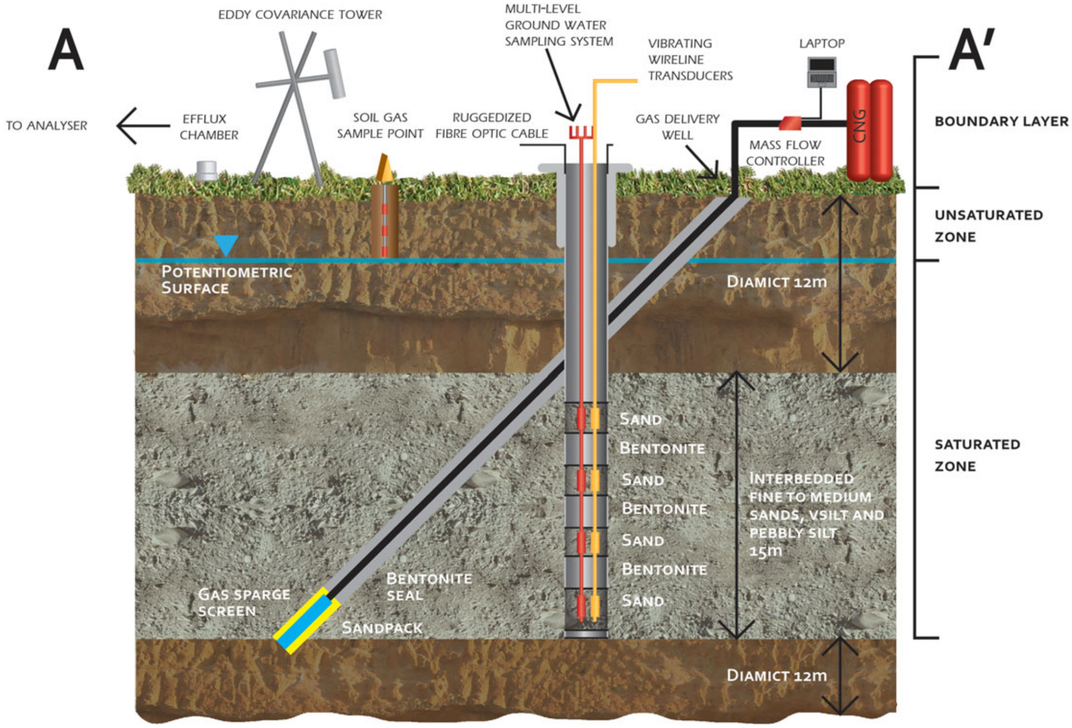


Figure 7. Transect through HH FRS showing the mass-flow valve controlled inclined gas delivery well and the critical-zone monitoring infrastructure in the saturated, unsaturated and boundary layers. The multidisciplinary monitoring networks will track migration and fate of the injected synthetic Montney gas as it moves in and through the subsurface, including emissions to the atmosphere.

multidisciplinary research program is being implemented through the EERI at the University of British Columbia, which focuses on the resource plays of northeast BC and particularly the Montney shale play. The EERI's multidisciplinary research program consists of (1) statistical analyses of regulatory data to elucidate incidence and causes of GM, (2) characterization of regional hydrogeology and baseline shallow subsurface conditions in the Peace Region of the Montney resource play, and (3) investigation of the migration, impacts, and fate of fugitive gas in the shallow subsurface through controlled natural gas release. The EERI project portfolio is combining the fields of petroleum engineering, geology, hydrogeology, hydro-geochemistry, geophysics, isotope geochemistry, vadose-zone processes, microbiology, and atmospheric sciences to provide scientific data to assess environmental risk, inform regulations, aid development of effective monitoring and detection methodologies and ultimately reduce the occurrence of GM and therefore greenhouse gas emissions.

## Acknowledgements

The EERI is a multidisciplinary team comprising research scientists and students from across Canada. Its directors and principal investigators are Aaron Cahill and Roger Beckie. Its co-principal investigators are Uli Mayer, Andy Black, Sean Crowe, Bernhard Mayer, Dirk Kirste, Rachel Lauer, and Laurie Welch. Its staff scientists are Bethany Ladd, Niko Finke, Cara Manning, and Iain Hawthorne. Graduate students are Jessie Chao, Elyse Sandl, Max Goetz, Julia Soares, Tim Cary, and Chitra Chopra. Funding for the EERI research is provided by Natural Resources Canada (award CEI-MET-196B), Geoscience BC (projects #2016-043 and 2017-002), and the British Columbia Oil and Gas Research Innovation Society (project HS-2018-02). We acknowledge that our research takes place on the treaty lands of the Treaty 8 First Nations. The authors thank the people of the Peace Region, and in particular Mr and Mrs Weder of Venator Ranch, for granting land access for the injection experiment and

 

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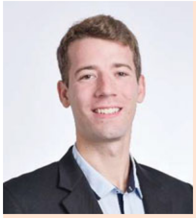

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Maximilian Goetz is a master's student in the hydrogeology group at University of British Columbia. Prior to beginning graduate school, he had four years of geoscience experience in the mining industry, primarily working as a site geologist / hydrogeologist at a copper porphyry-skarn mine in New Mexico. His favorite project at the mine was planning and managing an advanced pit dewatering program, where interceptor pumping wells were installed to lower the phreatic surface for future mining. He received his undergraduate degree in earth and planetary sciences from McGill University. He is currently working on the planning, implementation and data analysis of the Monitoring Well Installation Project (MWIP) in the Peace Region, BC.

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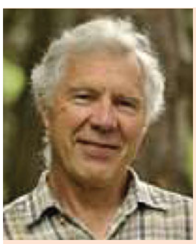

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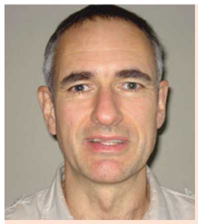
Dr Andrew Black is a professor in the Faculty of Land and Food Systems and leads the biometeorology and soil physics group at the University of British Columbia, Vancouver. He is actively involved in research in energy, water and carbon balances of temperate and boreal forests. For over 45 years, his research team has conducted research on the effects of weather on turbulent exchange in and above forest canopies. In the mid-1990s, he was a member of the science committee of the Boreal Ecosystem-Atmosphere Study and a member of a group that laid the foundation for the current international network of $CO_2$/$H_2O$ flux sites (Fluxnet).



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**Bernhard Mayer**

Professor Bernhard Mayer is an internationally known isotope tracer geochemist. He combines aqueous, gas and isotope geochemical approaches to determine the sources, transport and fate of methane, ethane and other redox-sensitive species in subsurface environments. His research applies innovative scientific approaches to improve the recovery of fossil fuels with the goal to reduce environmental impacts. He has (co-)authored more than 150 papers in international refereed journals and 15 book chapters on a wide variety of geochemical topics including shale gas development, geologic $CO_2$ sequestration, and the quality of groundwater and surface waters on several continents. His expertise has garnered him a member appointment on the national scientific review panel on Harnessing Science and Technology to Understand Environmental Impacts of Shale Gas Extraction, coordinated by the Council of Canadian Academies (CCA). The isotope-based tracer technologies employed by Dr Mayer can be used effectively for fingerprinting methane sources and for investigating the fate of fugitive methane in shallow subsurface environments in association with the development of unconventional energy resources, and are a critical tool for assessing the environmental impact of shale gas development in Canada and elsewhere.

**Andrew Allen**

Andrew is a recent Simon Fraser University graduate who completed his BSc (Honours) in earth sciences. His thesis topic was sources and distribution of arsenic in groundwater on the Gulf Islands of BC. He has a diverse background across geosciences and geology, with particular expertise in hydrogeology, hydrogeochemistry, and geographic information sciences, and is experienced with laboratory experiments and analytical equipment.

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Associate Professor Dirk Kirste is an aqueous geochemist at Simon Fraser University whose research is primarily directed towards understanding the processes controlling the composition of groundwater and surface water. His research involves both laboratory-based and field-based work, investigating the chemical and isotopic composition of water, minerals, and gases. By recognizing and using variations in the chemistry he is able to address problems in our environment, in characterizing and predicting the effects of climate change and in resource exploration and evaluation.

**Laurie Welch**

Dr Laurie Welch is a hydrogeologist with the British Columbia Oil and Gas Commission. Her work includes collaboration on research that has potential to inform the regulation of oil and gas activities, with a focus on groundwater protection aspects of oil and gas wells.