Assessment of Fugitive Natural Gas on Near-Surface Groundwater Quality

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Geoscience BC Project 2016-043 Final Report

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Executive Summary

Subsurface fugitive gas associated with oil and gas activity raises environmental concern because, due to its composition of primarily methane, it can contribute to greenhouse gas emissions if it reaches the atmosphere, and potentially affect shallow groundwater quality. While the issue of fugitive gas is not confined to unconventional resource development, the rapid growth of unconventional gas extraction and exploration of the late 2000s led to increased attention and concern about potential environmental impacts of fugitive gas, in large part because it was not well understood. In British Columbia (BC), where large unconventional resource reserves have enabled accelerated growth in development in the past two decades, there was particular need for the science to catch up with resource development.

This project, conducted through the Energy and Environment Research Initiative (EERI) at the University of British Columbia and performed in complement to two other projects (see http://www.geosciencebc.com/projects/2017-002/ and http://www.bcogris.ca/sites/default/files/hs-2018-02-gas-migration-final-report-march20.pdf), addresses the knowledge gaps regarding subsurface fugitive gas migration, environmental impacts, and environmental fate in geology typical of northeastern BC. The project centered around a controlled natural gas release experiment conducted in the shallow subsurface of an area of active oil and gas activity, in order to trace, monitor, and quantify gas migration from a 'leakage' point analogous to that of a leaking oil and gas well. Given the multidisciplinary nature of the project, a project team was compiled such that there was a team lead for the following disciplines and/or monitoring techniques: saturated zone and groundwater sampling, unsaturated zone and surface efflux, micrometeorology/atmospheric zone, microbiology, geophysics, and portable mass spectrometer monitoring. Beginning on June 12, 2018, the active injection occurred at 26 m depth over 67 days, releasing a total of 97.5 cubic meters of a gas mixture mimicking that of Montney natural gas. All teams monitored and collected data throughout the active injection and continued for over a year after the injection stopped.

In this report, we provide the motivation, background, and experimental set up of the project, before presenting our findings through summaries of our published knowledge products. These include:

- An overview of the potential fate and impact of fugitive gas in northeastern BC, and preliminary results from this project in the context of the wider EERI program.
- A description of and insights into the geological and hydrogeological controls on gas migration through a full characterization of the injection site subsurface.
- A paper showing how barometric-pumping influences fugitive gas emissions from a vadose zone natural gas release.
- A study focusing on monitoring of gas migration in the unsaturated zone and the quantification of surface effluxes.
- An assessment of using eddy covariance to quantify and map methane emissions to the atmosphere from the natural gas release experiment.
- A manuscript describing how geophysical techniques were used to image and track the free-phase gas plume of injected gas, with insights to use time-lapse electrical resistivity imaging as a monitoring tool for fugitive gas.

Among the many insights gained through this project, major conclusions include: 1) the confining surface diamict layer present throughout the study site proved to be a barrier to vertical free phase gas flow, but preferential pathways (both natural and introduced) allowed some gas to reach the surface; 2) a majority of the injected gas (~75%) remained in the subsurface after about two years of monitoring, and individual site characteristics play a large role in how much gas may be released to the surface; 3) data collected thus far show limited groundwater impacts beyond elevated hydrocarbon concentrations; 4) continuation of monitoring may be useful to study any potential longer-term effects on groundwater; and 5) given the nature of gas migration in saturated, unsaturated, and atmospheric zones, a variety of monitoring techniques are useful to track and quantify the movement, impact, and fate of fugitive gas.

Introduction

The oil and gas sector are a key industry in the Canadian economy and will continue to be as Canada transitions to a low-carbon future. A critical aspect of this transition is to identify, quantify, and mitigate environmental impacts from the oil and gas industry. This project focused on subsurface fugitive natural gas, which is gas (primarily methane) associated with oil and gas activities that is unintentionally released into the subsurface. Fugitive gas (FG), which originates as free phase gas but may perpetuate in both free phase and dissolved gas forms, released in the subsurface that travels outside the well casing is called gas migration (GM), and presents environmental concerns because it may 1) cause the degradation of groundwater quality if natural gas dissolves into potable groundwater under certain conditions (e.g., microbial communities, redox conditions), 2) present risk of explosion due to the combustibility of natural gas, which may reach surface infrastructure such as houses and water wells, and/or 3) be a potential source of greenhouse gas emissions, if released to the atmosphere (Kelly et al., 1985; Van Stempvoort et al., 2005; Cahill et al., 2017; Forde et al., 2018; Van De Ven and Mumford, 2020a).

Although both FG and GM have been identified long ago (Chafin, 1994; Dusseault et al., 2000), significant knowledge gaps regarding GM, environmental impacts and environmental fate still exist, largely because of the complexity of the physical and biogeochemical processes involved, but also due to the distinct geological environments of the various resource plays. In BC, most oil and gas activity is located in the northeastern region of the province, which is characterized by highly complex and variable geology. Consequently, there is a pressing need to address knowledge gaps related to FG and GM in northeastern BC, particularly in light of the technological improvements in unconventional completion methods in the last decade and the accompanying increase in exploration and development of petroleum resources (Jackson et al., 2013; Council of Canadian Academies, 2014). A principal objective of this research program, and the Energy and Environment Research Initiative (EERI) at The University of British Columbia (UBC), is to provide the science knowledge base that can be used to inform the management of oil and gas development in BC.

To advance understanding of FG and GM in the context of oil and gas activity in northeastern BC, a controlled natural gas release experiment was performed, in which a measured volume of natural gas was purposefully released into the subsurface while various monitoring methods were put in place to track its movement and measure its environmental effects. Questions that guided this study include:

- How does natural gas move in the subsurface of northeastern BC?
- How much gas stays in the ground and how much is released to the atmosphere (measured over a two-year study), contributing to greenhouse gas emissions?
- What are the impacts to groundwater resources?
- What are the best ways to monitor fugitive gas migration?

To answer these questions, the experimental site was actively monitored before, during, and after a controlled release of natural gas in the subsurface. Baseline groundwater conditions were monitored during the year leading up to the natural gas release, while vadose zone, atmospheric, and geophysical measurements were conducted during the month prior. The active injection occurred over 67 days at a depth of 26 m below ground surface and at a rate of approximately 1.5 m^3/day, and post-injection monitoring continued for approximately two years after injection ceased. The data collected, using a wide variety of monitoring methods, provides a comprehensive dataset from which to evaluate the behavior and impacts of fugitive gas in a northeastern BC setting.

Background

For a detailed description of the mechanisms for gas flow, mass transfer and fate of methane in groundwater systems, refer to Cahill et al. (2019a, b, 2020). Generally, when GM occurs in a shallow groundwater system, the free phase gas movement is governed by the rate at which the gas enters the system (leak rate), buoyancy of the gas, permeability and the variation in capillary forces associated with the porous media through which it flows (Ji et al., 1993; Brooks et al., 1999; Geistlinger et al., 2006; Selker et al., 2007; Van De Ven and Mumford, 2019). This results in an upward movement of free phase gas through complex interconnected channels. Flow may also be directed laterally and form pools due to both subtle (e.g., bedding structure) and stark (e.g., clay or silt lenses) contrasts in the permeability of the geological strata through which it flows (Kueper et al., 1993; Glass et al., 2000; Steelman et al., 2017; Cahill et al., 2018). This free phase gas can either 1) span the subsurface system, enter the vadose zone, and be released at the surface (surface expression) causing potential safety concerns or be released as greenhouse gases to the atmosphere, and/or 2) dissolve into groundwater (aqueous expression) potentially causing water quality concerns (Cahill et al., 2017; Forde et al., 2019c; Van De Ven and Mumford, 2020a, b).

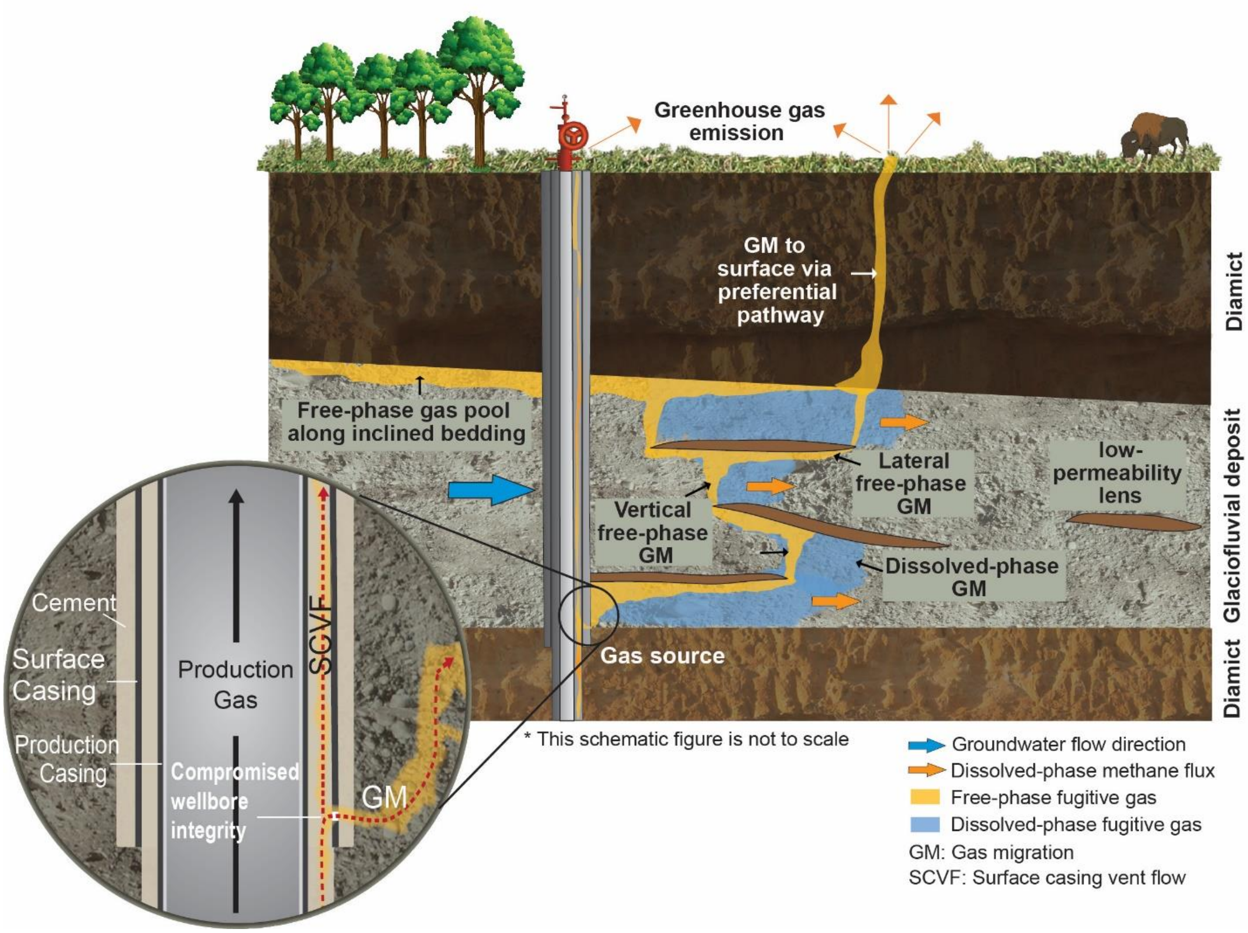


Figure 1. Conceptual model of gas migration (GM) and surface casing vent flow (SCFV) associated with energy wells in glaciofluvial deposits. The potential GM pathways are illustrated, including vertical and lateral migration of free-phase gas, free-phase gas pooling underneath the low permeability lenses and along inclined strata, and GM

to surface via preferential pathways, leading to greenhouse gas emission to the atmosphere. Dissolved-phase gas moves with groundwater flow direction. Note that this diagram is a generic representation of an energy well showing key features relevant to the current study. It is not to scale nor does it include all features or detail.

The extent to which leaked free-phase gas is dissolved and transported in groundwater depends on several variables including the rate of groundwater flow, surface area of gas exposed to water, the water pressure, the groundwater temperature and salinity, the presence of other dissolved gas species, the heterogeneity of the system and chemical characteristics of the native groundwater and leaked gas (Powers et al., 1998; Cirpka and Kitanidis, 2001; Sale and McWhorter, 2001; Parker and Park, 2004; Koch and Nowak, 2015). Once dissolved, methane is relatively benign to human health if consumed (McIntosh et al., 2014; Hamilton et al., 2015). However, as a result of secondary effects associated with microbial oxidation (i.e., the consumption of methane as a source of energy for microbes), which converts methane (CH_4) to carbon dioxide (CO_2), changes in water quality can occur, such as changes in alkalinity and pH, that can drive other geochemical processes (Kelly et al., 1985; Van Stempvoort et al., 2005; Roy et al., 2016; Forde et al., 2019b). These other processes can lead to further decline in water quality through the liberation of metals as a result of mineral dissolution.

If the leaked free-phase gas does not completely dissolve into groundwater, or if it dissolves and exsolves at a later time due to geochemical changes, it may pass through the saturated groundwater zone and enter into the unsaturated zone above the water table (Bachu, 2017; Forde et al., 2018). This unsaturated zone is connected to the atmosphere and therefore presents a potential pathway for surface expression. Methane can also be oxidized to CO_2 in this zone, therefore changing the form of greenhouse gas emitted. The mechanisms for free-phase gas entering the unsaturated zone then moving to the atmosphere are not well known. Previous work as part of this project has shown that free-phase gas reaching the unsaturated zone can migrate both by advection and diffusion and then be released to the atmosphere (Forde et al., 2019a). The flux of CH_4 and CO_2 was found to be dependent on atmospheric conditions (i.e., barometric pressure), which causes fluctuations in the amount of emitted greenhouse gas over time.

During and after a gas leak, the amount of GM that will be present in the environment in the groundwater zone, the unsaturated zone (or the residence time in those environments), or released into the atmosphere, is currently not well understood. Developing this knowledge is however a pressing need because the proportionality will determine, for example, how severe water quality impacts will be, the longevity of the impacts to groundwater systems, the potential contribution to greenhouse gas emissions and therefore global climate change, and what safety risks can be expected in proximity to sites impacted by GM. This project addresses these questions, such that GM can be quantified and constrained.

Study site location

The project took place in northeastern British Columbia, a region of intensive oil and gas activity (Figure 2). With an abundance of unconventional gas resources, the area has experienced a major increase in development over the past two decades as technology has become available to extract these resources profitably. There are some 25,000 gas wells in the region, of which 0.6% have reported gas migration (Sandl et al., 2021). The region is within the Western Canada Sedimentary Basin (WCSB), with a highly heterogeneous surficial geology composed of complex sequences of till, glaciolacustrine, glaciofluvial, fluvial and lacustrine deposits overlying bedrock (Mathews, 1978; Mathews, 1980; Shaw, 1982; Hickin and Fournier, 2011; Shaw, 1982; Cahill et al., 2019a; Chao et al., 2020). Therefore, the region is complex in terms of understanding the impacts of GM on groundwater resources and the emissions of GM to the atmosphere because previous field-based GM research has mainly focused on relatively homogeneous, sand and gravel aquifer systems (e.g. Cahill et al., 2017). To address the knowledge gaps associated with GM in complex geological settings, the Hudson's Hope Field Research Station (HHFRS) was established within the Northern Montney oil and gas field in order to perform a controlled, synthetic natural gas injection in the shallow subsurface (Cahill et al., 2019a, b, 2020).

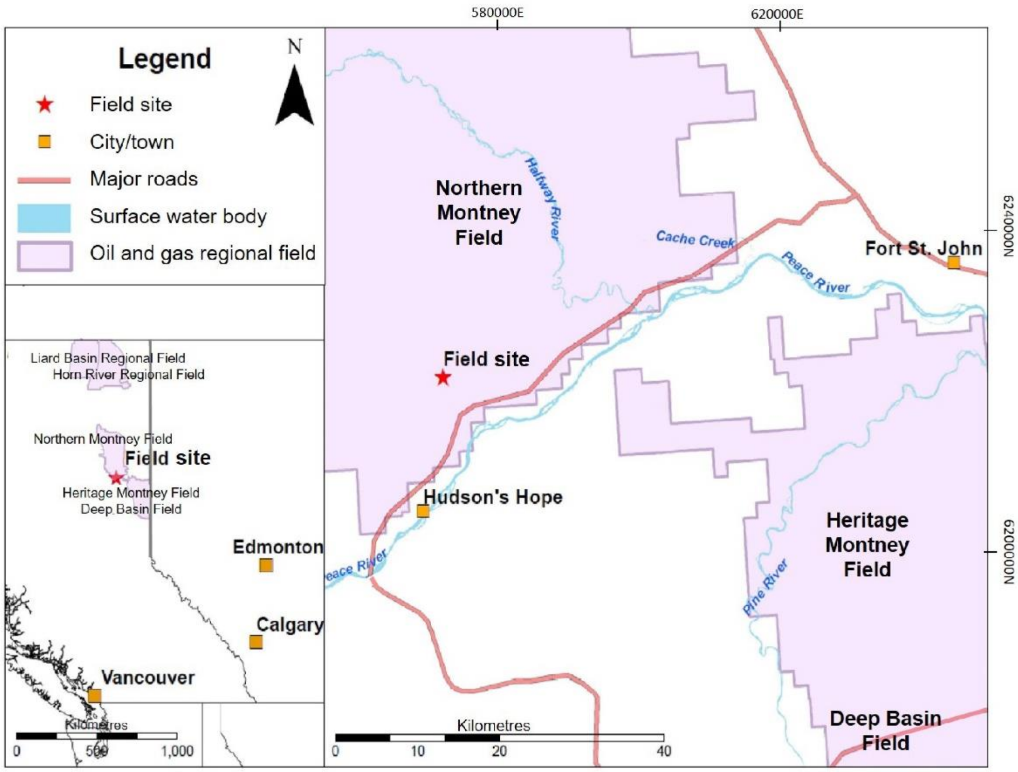


Figure 2. Location of the Hudson's Hope Field Research Station (HHFRS) in northeastern British Columbia with BC-based oil and gas fields (DataBC, 2018). UTM Zone 10N, NAD 83.

The exact location of HHFRS, about 20 km from Hudson's Hope, was chosen because the site has a 12 m thick low-permeability layer at the surface (typical of much, but not all, of NEBC), was far from communities and local users, and was undisturbed by past or present oil and gas activities. Before the experiment started, we characterized the shallow stratigraphy using a number of techniques, including data from installation of monitoring wells, collecting drill core and sediment samples, imaging with geophysics, and analyzing sediment geochemistry.

Experimental Setup

We designed a controlled natural gas release field experiment in an area of active unconventional gas development with characteristic complex geology in the Peace Region of northeastern British Columbia. This involved establishing HHFRS, which included drilling and installation of groundwater monitoring wells, installation of an off-grid remote solar power station, setup of a gas delivery and injection system, construction of an eddy covariance tower, hand-augering soil gas wells, and installation of various other infrastructure both scientific and operational (Figures 3 and 4). The field experiment centered around a natural gas release point 26 meters below ground level, from which approximately 97.5 cubic meters of natural gas was released into the subsurface at a rate of about 1.5 m^3/day for 67 days. Nowamooz et al. (2015) consider leakage rates of less than 300 m^3/day to be minor (Abboud et al., 2020). Monitoring infrastructure and equipment was installed around the release point to track the gas and observe responses in the groundwater zone, the unsaturated zone, and the atmosphere. Team leads were designated in the following areas:

- Groundwater geochemistry: sampling groundwater from a network of multilevel monitoring wells (total of 55 ports in 19 wells) for major ion composition, isotopes, and dissolved gas.

- The unsaturated zone between the water table and ground surface: measuring soil flux using dynamic long-term soil flux chambers, survey chambers, and soil gas samples from soil gas wells for major gas species composition and isotope analysis.

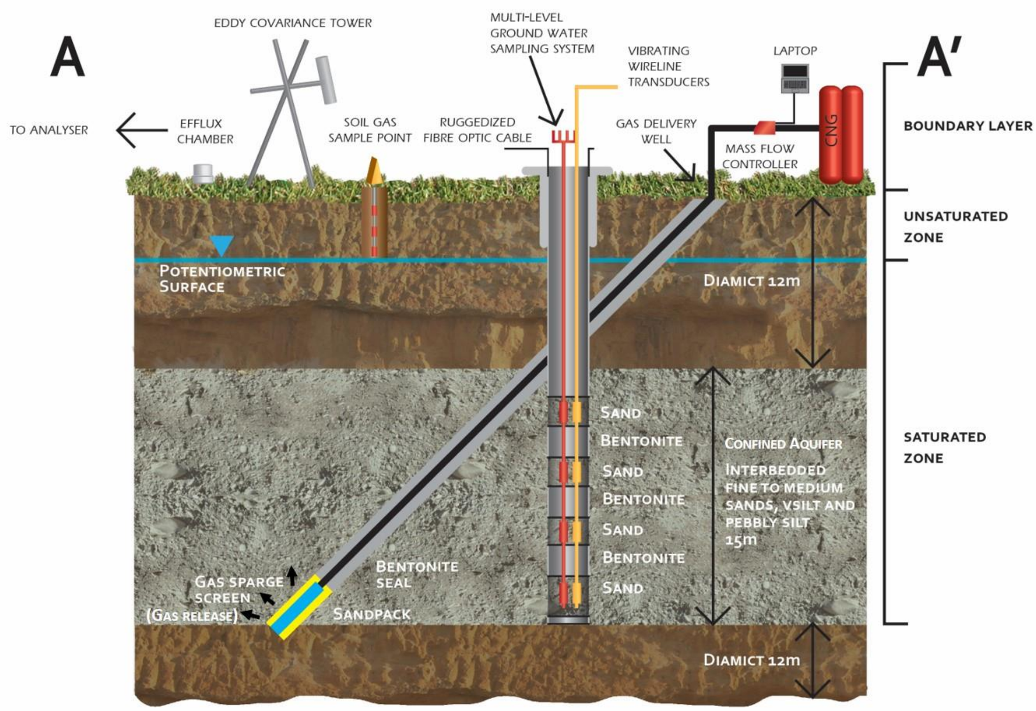
- Free phase gas emissions to the atmospheric zone within the experimental area: measuring injection gas emissions to the atmosphere using a technique called eddy covariance.

- Subsurface geophysics: Using time-lapse electrical resistivity imaging to measure and track the subsurface gas plume as it evolved throughout and after the active injection.

- Soil and groundwater microbiology: Soil and groundwater sampling to measure microbiological indicators of fugitive gas impacts.

- Portable mass spectrometry: a novel method for fugitive gas and gas migration studies, used to measure real-time concentration of free phase and dissolved gas samples, which allowed for the informed adjustment of other monitoring techniques during the experiment.

Figure 3. Conceptual plan view model of HHFRS, including the controlled natural gas release experiment infrastructure and the subsurface geology of the site (Cahill et al., 2019).



Items from diagram	Purpose/explanation
Efflux chamber	Measurement of free phase gas emissions directly from soil
Eddy covariance tower	Combination of weather system and gas analyzers to measure atmospheric gas
Soil gas sample point	Shallow well that allows sampling for gas concentration analysis
Multilevel GW sampling system	A groundwater well that provides multiple, discrete sampling points
Sand and bentonite	Sand is permeable (allows groundwater to enter) and bentonite is impermeable (prevents groundwater flow), creating connections and barriers between the well's sampling points and aquifer
Mass flow controller	A unit that continuously controls the rate of gas injection into the aquifer
Diamict	Low permeability (10^{-8} m/s) glacial deposit
Saturated zone	Subsurface below the groundwater table
Unsaturated zone	Subsurface above the groundwater table
Potentiometric surface	The level to which groundwater in a confined aquifer rises under hydrostatic pressure in wells
Gas sparge screen	Subsurface gas release location; the sparge screen consists of fine pores, such that gas enters the subsurface as small bubbles

Figure 4. Cross-section A-A' from Figure 3, showing the natural gas release system and the monitoring infrastructure in the saturated, unsaturated, and atmospheric layers and Definition Chart (modified from Cahill et al., 2019).

Findings

Here we compile and present our findings by providing summaries of, and links to, our published knowledge products.

1. Cahill et al 2019. Advancing knowledge of gas migration and fugitive gas from energy wells in northeast British Columbia, Canada. https://doi.org/10.1002/ghg.1856.

   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 subsurface, affect 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, 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 development of effective monitoring and detection methodologies for BC and beyond.

2. Chao et al., 2020. Propensity for fugitive gas migration in glaciofluvial deposits: An assessment of near-surface hydrofacies in the Peace Region, Northeastern British Columbia. Science of the Total Environment. 10.1016/j.scitotenv.2020.141459.

   The fate of fugitive gas in the shallow subsurface is controlled by sediment heterogeneity, hydrostratigraphy and hydraulic connectivity. We characterized the shallow subsurface at Hudson's Hope Field Research Station in northeastern British Columbia, Canada. The study site was approximately the size of a well pad, designed at a scale consistent with a fugitive-gas event. We collected 13 core profiles, 9 cone-penetrometer profiles, 58 sediment samples and 4 electrical resistivity profiles. At the site, a ~12 m thick layer of low-permeability diamict (10^{-8} m/s) overlays a more permeable (10^{-6} - 10^{-4} m/s) but highly heterogeneous sequence of glaciogenic sand, clay, and silt. We develop a conceptual hydrostratigraphic model for fluid flow in this system in the context of fugitive-gas migration. Driven by buoyancy forces, free-phase gas will move upward through discontinuous permeable zones within the Quaternary sediments, until it encounters lower permeability interbeds where it will pool, flow laterally or become trapped and dissolve into flowing groundwater. The vertical extent of gas migration will be significantly limited by the relatively continuous overlying diamict, a feature common across the Western Canadian Sedimentary Basin. However, intra-till lenses observed embedded within the diamict may provide pathways for gas to move vertically towards ground surface and into atmosphere. This study provides one of the few investigations examining geological and hydrogeological heterogeneity in the shallow subsurface at scales relevant to gas migration. For glaciated regions with similar surficial geology, such as Western Canada Sedimentary Basin, gas that is released into the subsurface from an energy wellbore, below a surface diamict, will likely migrate laterally away from the wellbore, and be inhibited from reaching ground surface and emitting to atmosphere.

3. Chao, 2021. In-progress thesis work to be published on dissolved phase gas monitoring and groundwater quality impacts.

   Groundwater samples were collected from the 55 monitoring points distributed across the field site at HHFRS and analyzed for dissolved gas concentrations (hydrocarbons and trace gases), stable hydrocarbon and hydrogen isotopes, major ions, and other water quality parameters. The distribution of dissolved injected gas was found to be spatially (only 10 of 19 wells saw elevated hydrocarbon concentrations) and temporally sporadic in the heterogeneous glaciofluvial sediments throughout the monitoring period (760 days), with CH_4 concentrations ranging from 0.1 to 27 mg/L, well below the theoretical equilibrium solubility (average of 69 mg/L). CH_4 dissolution was also found to be limited in this setting, as significant increases in dissolved CH_4 were mostly observed ~70 days after injection. Due to the slow CH_4 dissolution, dissolved gas impacts on groundwater quality will likely be less evident in heterogeneous sediments at the early time (i.e., 2 – 3 years) of a gas leakage event. The time-series geochemical and microbial data, as well as isotopic signatures of dissolved gas samples indicated limited changes during the entire monitoring period, suggesting the absence of anaerobic methane oxidation. Sampling and analysis will continue after project completion to determine long-term groundwater impacts.

4. Forde et al., 2019. Barometric-pumping controls fugitive gas emissions from a vadose zone natural gas release. Scientific Reports, 9, 14080. https://doi.org/10.1038/s41598-019-50426-3.

   Gas migration is controlled by complex interacting processes, thus, constraining the distribution and magnitude of "fugitive gas" emissions remains a challenge, especially in the unsaturated (vadose) groundwater zone. In order to investigate the vadose zone specifically, a second controlled release experiment was conducted at a site adjacent to HHFRS (~5km west) where the water table was deeper (~60 m below ground surface). We simulated wellbore leakage in the vadose zone through injection of natural gas at 12 m depth over 24 days and demonstrate that fugitive gas emissions can be directly influenced by barometric pressure changes. Decreases in barometric-pressure led to surface gas breakthroughs (>20-fold increase in <24 hours), even in the presence of low-permeability surficial soils. Current monitoring strategies do not consider the effect of barometric pressure changes on gas migration and may not provide adequate estimates of fugitive gas emissions. Frequent or continuous monitoring is needed to accurately detect and quantify fugitive gas emissions at oil and gas sites with a deep water table.

5. Soares, 2019. Characterization of gas migration and surface emissions through a controlled release experiment at the Hudson's Hope Field Research Station, BC, Canada. (https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0389535)

   This work focused on monitoring gas migration in the shallow unsaturated zone at HHFRS and the quantification of surface effluxes associated with the controlled natural gas release experiment. To do so, twelve long-term soil flux chambers were installed across the surface of the site to measure both methane and carbon dioxide effluxes. This provided a high-resolution time-series dataset to understand dynamic variation in effluxes over the duration of the experiment. Additionally, survey chambers were employed at 105 locations to measure the spatial distribution of effluxes at discrete time intervals. Also, soil gas samples were collected from 22 depth-discrete soil gas wells across the site, enabling isotopic analysis to quantify biodegradation of hydrocarbons within the unsaturated zone. The results showed that the injected gas migrated upgradient of the injection point and broke through at the surface six weeks after the injection started. Elevated CH_4 effluxes were continuously detected at the surface in a constrained geographical region and decreased one week after the cessation of gas injection. Soil gas composition and isotopic data showed evidence confirming that gas migrated from the saturated zone, through the soil towards the ground surface and that biodegradation of hydrocarbons to carbon dioxide occurred. It is likely that injected gas was able to reach the surface due to the presence of a preferential pathway in the confining diamict layer leading to greenhouse gas emissions. The results of this study allow us to better understand the expected amount of stray gas which may become a greenhouse gas emission because of transport through the unsaturated groundwater zone and provide insight how to better detect and monitor impacted sites.

6. Chopra, 2020. Quantification and mapping of methane emissions using eddy covariance in a controlled subsurface synthetic natural gas release experiment. (https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0395399)

   The eddy covariance (EC) technique was used to monitor emissions into the atmosphere resulting from a controlled natural gas release at a depth of 26 m below ground surface, with the aim to quantify and potentially locate the emissions using flux footprint analysis. The EC tower was set up 26.4 m northeast (prevailing wind direction) of the injection point. Site-wide methane fluxes as high as 0.22 µmol m^2 s^{-1} were observed during the injection period when wind was from the injection area. Additionally, continuous CO_2 and H_2O fluxes were measured using an enclosed-path infrared gas analyzer, LI7200 (LI-COR Inc.). A set of climate instruments including soil and radiation sensors were also installed to monitor weather conditions and energy balance closure.

   Downscaling the EC fluxes to quantify emissions indicated that the volume of methane released into the atmosphere ranged from 21.9 m^3 to 24.6 m^3 (out of the total 83 m^3 of methane injected; methane made up 85% of the 97.5 m^3 of synthetic gas injected). After further investigation it was found that injected gas was escaping the subsurface through a groundwater monitoring well which had been installed at the site. This provided evidence that preferential pathways for gas flow from the subsurface to the atmosphere can occur due to infrastructure used for water supply and monitoring and detection of GM impacts. Because methane was being emitted from an installed monitoring well (~1 m above surface) it was conjectured that the total emissions could be underestimated because flux footprint models are applied to releases occurring at the ground and not at a height above the surface. The results suggest the need for an alternate flux footprint model, which considers the height of the source. Furthermore, an inversion approach was tested in an attempt to locate the leak and the results were compared with the original information about the location of the leak, as observed using chamber measurements and a groundwater sampling well. A point source controlled-release experiment was also conducted by releasing 93% v/v methane into the atmosphere to evaluate the flux footprint models being used in this study.

7. Cary, 2019. Time-lapse Electrical Resistivity Imaging of Methane Gas Migration in a Shallow Confined Aquifer. (https://prism.ucalgary.ca/handle/1880/110240)

   Temperature-corrected time-lapse electrical resistivity tomography (ERT) was utilized to monitor the migration and fate of a subsurface gas plume generated during a 67-day natural gas injection period at a depth of 26 m in a control well, into a near-surface confined aquifer. The relatively thick surface diamict, and relatively high conductivity subsurface precluded application of other geophysical techniques such as ground-penetrating radar. Three permanently installed ERT lines were deployed, centred on or close to the injection location. Surveys were repeated several times during and after the injection. The data were inverted using SimPEG producing time-lapse difference images. This research demonstrated the utility of ERT methods to characterize gas-affected zones over large spatial areas and established an inversion workflow to interpret time-lapse resistivity data. Resistivity was observed to increased up to 15% near the injection zone, consistent with a poorly conductive gas displacing a relatively conductive water phase. ERT indicated that injected gas migrated upwards and spread laterally beneath the surface diamict. ERT allowed the gas distribution to be characterized beyond the monitoring well network.

Conclusions

Although some of the studies referenced above have been completed, analysis of the collected data is ongoing, and additional peer-review publications are being formulated presenting the cumulative results of this project. General insights gained from the project have allowed for our guiding research questions to begin to be answered and understood. Current conclusions include:

- *How does natural gas move in the subsurface of northeastern BC?*
  The subsurface environment for gas migration studied at the field site was highly heterogeneous and complex. Representative of much of northeastern BC, this study provided evidence that understanding and quantifying gas migration in this region will be challenging and vary from site to site. However, it was generally found that some proportion of leaked free phase gas will migrate upward toward the surface through sand and silt interbedded layers. Hydrostratigraphic analysis and geophysical results showed that vertical migration will be hindered by low permeability layers (specifically the confining diamict layer) typical of northeastern BC. Our data shows that fugitive gas can travel laterally below these layers, increasing the spatial footprint of leaked gas. Below low permeability layers, some free-phase gas will become trapped and then begin to dissolve into flowing groundwater, which was found to be relatively slow in the hydrogeologic environment at the site. Although strong evidence suggests that the confining diamict layer entrapped gas in the subsurface, surface detection indicates that injected gas reached the surface becoming a greenhouse gas emission through both natural and anthropogenic preferential pathways.

- *How much gas stays in the ground and how much is released to the atmosphere, contributing to greenhouse gas emissions?*
  Based on the combined results of this project, a majority (~75%) of injected gas remained in the subsurface after approximately two years of monitoring. As mentioned above, the surface diamict layer provides a barrier to vertical gas flow, but preferential pathways allowed some gas to travel through the subsurface to the atmosphere and through and around installed monitoring wells. Based on the findings, the amount of leaked gas that stays in the subsurface versus that released to the atmosphere may vary significantly, depending on site characteristics. This project demonstrates the importance of site characterization in these quaternary environments with emphasis on understanding natural preferential pathways (e.g., interbedded coarse sediments, root networks, fractures) through the confining diamict layer. Additionally, the research shows the importance of location and completion methods (confinement efficacy) of water supply and monitoring wells in the vicinity of suspected gas migration which can form preferential pathways leading to enhanced greenhouse gas emissions. Oxidation of hydrocarbons in the unsaturated zone also occurred, converting these gases to CO_2, which can be emitted at surface, however this association was not studied in this work.

- *What are the impacts to groundwater resources and quality?*
  The data collected thus far show limited groundwater impacts beyond elevated hydrocarbon concentrations. At the time of writing, we have not observed significant changes in major or trace elements in the groundwater geochemistry at the site. Research on the overall impacts to

groundwater in the longer-term is recommended. The current findings at the research site suggest that GM in the early time after release of natural gas did not lead to degradation of groundwater quality. Surface emissions (and therefore their effects in the atmosphere or upon surface infrastructure), depend critically on both the volume of the leak and the existence of the surface diamict and preferential flow paths through it.

- *What are the best ways to monitor fugitive gas migration?*
  The project utilized and tested a variety of techniques to monitor and detect GM. These techniques included geophysical, hydrogeological, and surface-based approaches. Geophysical testing enabled subsurface observation of the vertical and lateral migration of free-phase gas and can provide evidence of the suspected area of the impacted subsurface. Groundwater monitoring was able to capture the spatial and temporal distribution of dissolved phase gas, helping to delineate the gas migration area and also to understand the longevity of potential impacts. Migration of gas through the unsaturated zone was performed using flux chambers and soil gas wells. Each provided valuable data independent of the other and together provided increased understanding of effluxes and biodegradation. These techniques coupled with the EC system allowed for the cumulative emissions associated with the gas release to be quantified and compared. Finally, we gained understanding of factors which might impact our interpretation of surface detection, especially the influence of barometric pressure on emissions. Each technique on its own provided valuable data to better understand GM, and the combination of multiple techniques enabled enhanced understanding of GM at the HHFRS site as a whole.

Future work

Our work suggests future research directed at addressing these questions:

- What is the longer-term fate (years to decades) of the injected methane at the research injection site: will its fate be dominated by dissolution of free-phase gas from pools and zones of residual saturation followed by conservative transport by groundwater flow as a dissolved phase, or are anaerobic oxidation kinetics and the potential alteration of groundwater geochemistry significant on longer timescales?
- What is the spatial distribution of preferential pathways, natural or anthropogenic, through the surface diamict? Our work shows that the surface diamict is an effective capillary barrier and where present, surface efflux is only possible through preferential pathways.
- What is the contribution of CO_2 to the overall greenhouse gas emissions associated with gas migration, resulting from methane oxidation which was observed in the unsaturated zone? Is the total mass generated of significant concern in these subsurface environments?
- Can geophysical methods, particularly ERT, effectively characterize gas-affected regions in the subsurface without a survey before gas affects a region of the subsurface? Our results showed that time-lapse ERT was an effective tool to characterize gas-affected areas. The method uses the difference between the resistivity image before gas entered a region of the subsurface and the image after gas entered the region. It is likely that at many sites, baseline, pre-gas images will not be collected. Can these gas-affected zones also be detected in the northeastern BC geological context when baseline resistivity images are not available before gas enters region of the subsurface?

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