Controlled Natural Gas Release Experiment in a Confined Aquifer, Northeastern British Columbia (NTS 094A/04): Activity Report 2019–2020

C.J.C. Van De Ven, The University of British Columbia, Vancouver, British Columbia, colevandeven@eoas.ubc.ca

A.G. Cahill, The Lyell Centre, Heriot-Watt University, Edinburgh, Scotland

B. Ladd, The University of British Columbia, Vancouver, British Columbia

J. Chao, The University of British Columbia, Vancouver, British Columbia

J. Soares, The University of British Columbia, Vancouver, British Columbia

T. Cary, University of Calgary, Calgary, Alberta

N. Finke, The University of British Columbia, Vancouver, British Columbia

C. Manning, The University of British Columbia, Vancouver, British Columbia

A.L. Popp, University of Oslo, Oslo, Norway

C. Chopra, The University of British Columbia, Vancouver, British Columbia

K.U. Mayer, The University of British Columbia, Vancouver, British Columbia

A. Black, The University of British Columbia, Vancouver, British Columbia

R. Lauer, University of Calgary, Calgary, Alberta

C. van Geloven, British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development, Prince George, British Columbia

L. Welch, British Columbia Oil and Gas Commission, Kelowna, British Columbia

S. Crowe, The University of British Columbia, Vancouver, British Columbia

B. Mayer, University of Calgary, Calgary, Alberta

R.D. Beckie, The University of British Columbia, Vancouver, British Columbia

Van De Ven, C.J.C., Cahill, A.G., Ladd, B., Chao, J., Soares, J., Cary, T., Finke, N., Manning, C., Popp, A.L., Chopra, C., Mayer, K.U., Black, A., Lauer, R., van Geloven, C., Welch, L., Crowe, S., Mayer, B. and Beckie, R.D. (2021): Controlled natural gas release experiment in a confined aquifer, northeastern British Columbia (NTS 094A/04): activity report 2019–2020; *in* Geoscience BC Summary of Activities 2020: Energy and Water, Geoscience BC, Report 2021-02, p. 135–144.

Introduction

As a result of petroleum resource development, a potential environmental concern exists in the form of fugitive gas (FG; Jackson et al., 2011; Vidic et al., 2013; Vengosh et al., 2014). Fugitive gas is natural gas that is able to escape from both production formations and intermediate gas-bearing formations in the subsurface (Council of Canadian Academies, 2014; Dusseault and Jackson, 2014). This gas can migrate vertically, as a result of density contrasts between the light natural gas (mainly methane) and heavier formation fluids, along two potential preferential pathways: 1) inside a surface well casing that contains compromised cement (termed surface casing vent flow, SCVF) or 2) outside of a wellbore, along the adjacent formation (termed gas migration, GM). Gas migration 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). The risks associated with these environmental expressions of GM require focused attention on the investigation of 1) mechanisms governing the migration of

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free-phase and dissolved-phase gas, 2) biogeochemical processes affecting the fate of natural gas in both the saturated and unsaturated zones of the subsurface, and 3) the release of gas to the atmosphere.

Petroleum resource development is active in northeastern British Columbia (BC), where economic gas-bearing formations exist. There are some 25 000 gas wells in the region, of which 0.6% have exhibited visible signs of gas migration (Cahill et al., 2019a). 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 (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 GM research has mainly focused on relatively homogeneous, sand and gravel aquifer systems (e.g., Roy et al., 2016; Cahill et al., 2017; Schout et al., 2019; Van De Ven and Mumford, 2020c). To address the knowledge gaps associated with GM in complex geological settings, the Hudson's Hope Field Research Station (HHFRS) was established in order to perform a controlled, synthetic natural gas injection in the shallow subsurface (Cahill et al., 2019a, b, 2020).

This paper presents a summary of the progress made with respect to the fieldwork undertaken at the HHFRS, which looks to advance the scientific understanding of GM in groundwater systems, the unsaturated zone and the atmosphere to reduce future risk. The principal objective of this research project is to provide scientific knowledge and understanding to inform the practice and management of resource development in BC. Ultimately, the aim of the project is to 1) characterize the physical and biogeochemical processes that control subsurface gas migration and impact, and quantify the amount of natural gas that remains, degrades or leaves the subsurface, 2) test a variety of FG monitoring and detection methodologies, and 3) inform regulations to facilitate safe and sustainable development of petroleum resources.

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 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 gas through complex interconnected channels. However, the flow can also be lateral if the gas is entering the system at a high leak rate, causing the gas to spread in all directions due to the high driving force. Flow is also directed laterally and forms 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 gas can either 1) span the subsurface system 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).

The ability for leaked gas to dissolve and be transported in groundwater depends on a variety of variables including the rate of groundwater flow, surface area of gas exposed to water, 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, the components of natural gas (mainly methane and other hydrocarbons such as ethane and propane) are 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 gas does not completely dissolve into groundwater, 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. The natural gas can also be oxidized to CO_2 in this zone, therefore changing the form of greenhouse gas emitted. The mechanisms for gas (natural gas or CO_2) entering the unsaturated zone then moving to the atmosphere are not well known. Previous work as part of this project has shown that 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.

Understanding the amount of GM that will be present in the environment either in the groundwater zone, the unsaturated zone or released into the atmosphere is currently not well understood. Developing this knowledge is, however, pressing 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 is actively addressing these questions, such that GM can be quantified and constrained.

Description of the Study Site and the Injection Experiment

The HHFRS is situated in the Peace Region just northeast of the town of Hudson's Hope, BC (Figure 1). The HHFRS is approximately 10 000 m^2, situated in a typical landscape of the WCSB. The site has a shallow piezometric surface, fluctuating between 1–1.5 m below ground surface (bgs). Near to the centre of the site, the screen of a gas injection well was placed 26 m bgs, and a comprehensive monitoring network was constructed around this injection point. The monitoring system (Figure 2) was designed to look specifically at

- near-surface geology—achieved by well core analysis and geophysical surveys;
- groundwater conditions—achieved by installing 24 monitoring wells, including 17 multilevel wells, allowing for groundwater samples to be collected for dissolved gas concentrations, geochemical parameters and stable isotopes analyses;
- vadose zone processes—achieved by placing 12 dynamic flux chambers at 100 locations for time-discrete flux survey measurements and 22 soil-gas wells for soil-gas collection for composition and stable isotopes analyses;
- atmospheric boundary layer—achieved by installing an eddy covariance station for sitewide gas emission measurements.

The injection of natural gas commenced on June 12, 2018 and continued for 66 days. Synthetic natural gas, designed to emulate the gas composition within the Montney Formation, was injected at a rate of 1.5 m^3/day, for a total injection volume of approximately 97 m^3 (standard temperature and pressure) of gas. Groundwater and surface zones were monitored prior to, during and following the completion of gas injection. Sampling has continued each year since the commencement of the experiment, allowing the long-term impact of the injection to be assessed. The most recent sampling event occurred on July 17, 2020. An in-depth description of the site, instrumentation and injection experiment can be found in Cahill et al. (2019a, b, 2020).

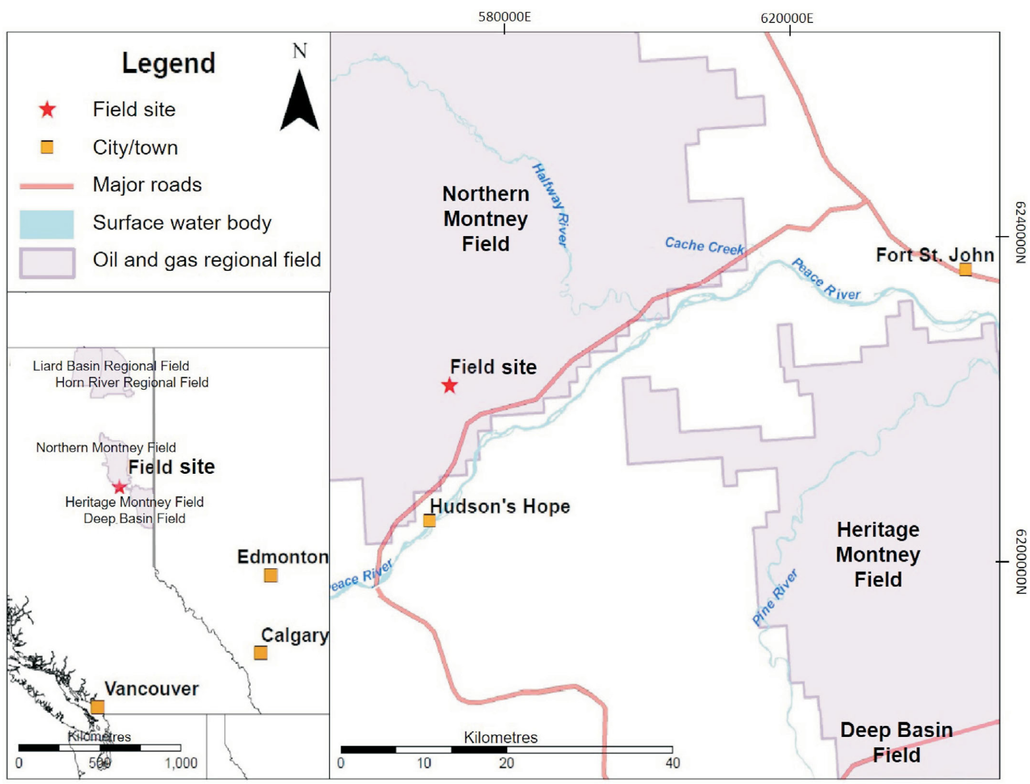


Figure 1. Location of the Hudson's Hope Field Research Station in northeastern British Columbia with regional oil and gas fields (DataBC, 2018). UTM Zone 10N, NAD 83.

Figure 2. The Hudson's Hope Field Research Station groundwater monitoring, surface flux monitoring and injection systems (photo taken September 28, 2018).

Summary of Activities and Progress

A variety of research objectives have been achieved over the last 12 months. These achievements include

1) characterization of the near-surface (above 30 m bgs) geology at the HHFRS, including publication of a journal article in *Science of The Total Environment* (Chao et al., 2020);
2) data analysis and interpretation of groundwater monitoring and geochemical data during and following the injection of synthetic natural gas;
3) data analysis and interpretation of surface flux data during and following the injection of synthetic natural gas; and
4) data analysis and interpretation of emissions data using eddy covariance during and following the injection of synthetic natural gas.

A summary of the progress and highlights of the findings for each of these activities is provided below.

Near-Surface Geology and Hydrostratigraphy

A key objective of this project was to characterize the near-surface geology at a scale relevant to understand gas flow, mass transfer and fate of GM in complex systems (centimetre to metre scale). This work has been completed and a peer-reviewed article has been published in *Science of The Total Environment* (Chao et al., 2020).

The near-surface geology at the HHFRS was characterized using a variety of tools including core profiles, cone-penetrometer testing (CPT), sediment samples and electrical resistivity surveys. Specific emphasis was placed on understanding the movement and resulting distribution of free-phase natural gas in the complex, interbedded systems expected in the WCSB. A conceptual hydrostratigraphic model of the site with respect to gas flow was developed, showing that the pattern of buoyancy-driven gas in glaciofluvial deposits can be complex and spatially heterogeneous (Figure 3). This layered system can cause both the vertical migration of gas (through the more permeable units 1 and 3; Figure 3) and lateral migration of gas due to capillary barriers (layers which impede gas flow due to high

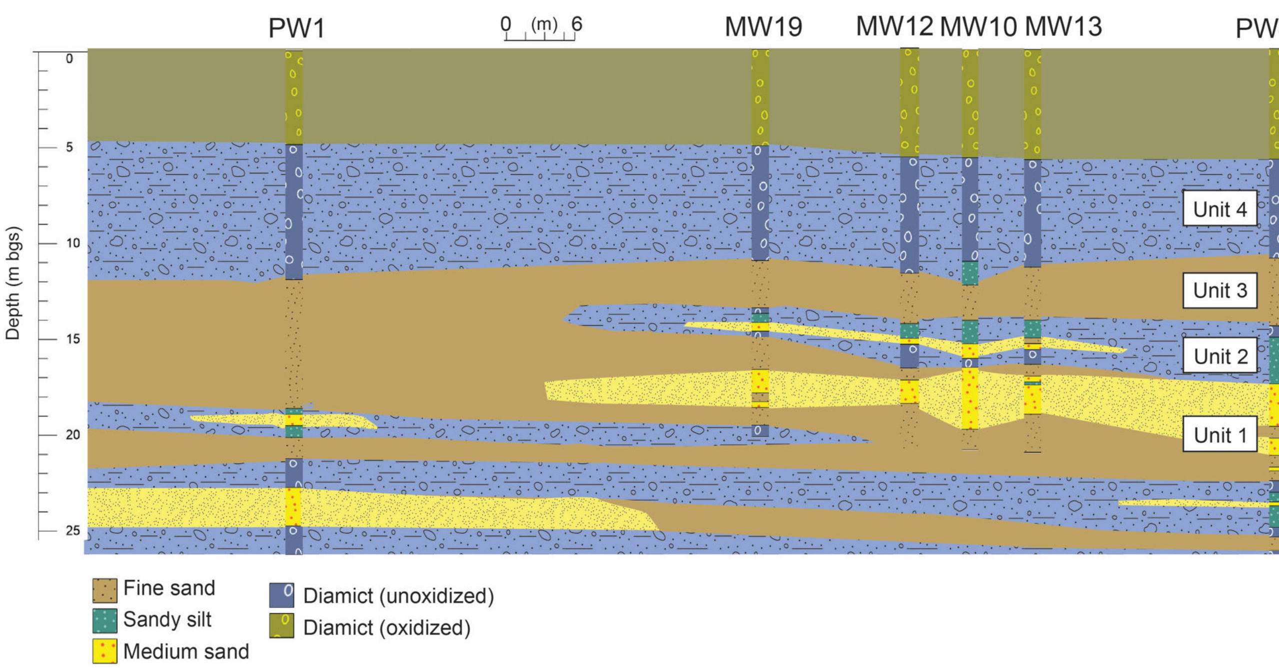


Figure 3. Hydrostratigraphic conceptual model developed for the near-surface geology at the Hudson's Hope Field Research Station (Chao et al., 2020). Abbreviations: bgs, below ground surface; MW, monitoring well; PW, pumping well.

pressure requirements to move gas through the tightly distributed pore space; units 2 and 4 in Figure 3). The local capillary barrier in the permeable zone (e.g., unit 2 in Figure 3) controls the lateral extent of gas migration, fostering significant gas pooling below the barrier. The surficial diamict (till; unit 4 in Figure 3; Figure 4), a feature common across the WCSB, can limit a significant portion of vertical gas migration from reaching the ground surface. In this system, the majority of natural gas is expected to be confined to aqueous expression because of high pressure requirements to pass through the upper diamict. The diamict was found to be oxidized between the surface and a depth of 3.5 to 5.7 m bgs then transitioned to unoxidized material (Figure 3). There was some evidence of till lenses observed embedded within the oxidized diamict. Both natural pathways and anthropogenically induced pathways (e.g., installed wells), which may have lower pressure requirements for gas to enter and flow through, could provide conduits for gas to move vertically toward the ground surface and into the atmosphere. If gas was able to enter the diamict unit, the oxidized portion might have greater capacity to degrade methane and convert it to CO_2 before reaching the surface.

One tool used to assess the near-surface geology and hydrostratigraphy was CPT. Traditionally, this approach is used in geotechnical applications, however, the properties of soil that allow differentiation between soil behaviour types (SBT) can be used to infer the hydrostratigraphic layers. That is, when coupled with soil samples collected from core, the CPT results can be used to understand the distribution of hydrofacies along a vertical profile (e.g., see Figure 5). This technique allowed for nine profiles over the extent of the HHFRS study area to be measured at the centimetre scale. This provides a very high-resolution means of constructing a conceptual site model where GM may occur.

Hydrogeology and Groundwater Monitoring

Understanding the dissolution of natural gas in the complex subsurface environment at the HHFRS is a key objective of the project. By measuring the evolution of dissolved gas using the groundwater monitoring network at the site (see Cahill et al., 2020), information on the magnitude, duration and extent of groundwater impacts can be assessed. Additionally, estimates of the amount of gas trapped in the subsurface can be assessed.

During the injection period, four sampling ports (out of 49 sampling ports in 19 wells) showed increases in concentrations of dissolved injected gas (mainly methane, ethane and propane). Approximately 40 days after the injection ceased, groundwater obtained from two more sampling ports across the site showed increases in dissolved methane (0.1–14 mg/L). The most recent measurements (490 days after the start of the injection) showed that elevated dis-

Figure 4. The upper diamict layer at the Hudson's Hope Field Research Station (unit 4) is a plasticine-like material that will limit gas flow through the layer.

solved methane appeared in 17 sampling ports in 10 wells (Figure 6). The most significant increase in dissolved methane (~1 to 27.1 mg/L) appeared at a depth of 18 m in monitoring well 9, representing a highly heterogeneous distribution of the gas. This depth corresponds to unit 1, as expected because this is a permeable unit that would allow for gas to migrate and accumulate. Moderate increases (~0.1–8.0 mg/L) in dissolved methane occurred at monitoring depths of 12 and 16 m (unit 3). No significant increases in dissolved gas concentrations were observed at the deepest monitoring depth of 20 m. Note that the measured concentrations are lower than the expected solubility of methane that varies with depth, ranging from 42 to 68 mg/L from 12 to 26 m bgs.

Sample collection (most recent field event was July 17, 2020) and analysis of groundwater for dissolved gas and isotope compositions of methane are ongoing. Currently, the focus is on understanding the rate of dissolution of free-phase gas trapped within the system. Using upscaled mass transfer approaches (Christ et al., 2006, 2010) and sitewide dissolved methane concentrations, the aim is to estimate the longevity of the free-phase gas within the system. Based on preliminary analysis, the time for complete dissolution of all injected gas will be on the order of tens of years. In addition to mass transfer considerations, the fate of natural gas is being assessed by analyzing degradation products associated with microbial oxidation (CO_2) coupled with isotopic analysis. The potential degradation of the injected gas can reduce the timescale of its presence in groundwater systems.

Soil Gas and Surface Efflux

To quantify the surface expression of GM at the HHFRS, the release of CH_4 and CO_2 to the surface was measured using a variety of soil flux techniques including dynamic long-term soil flux chambers, survey chamber measure-

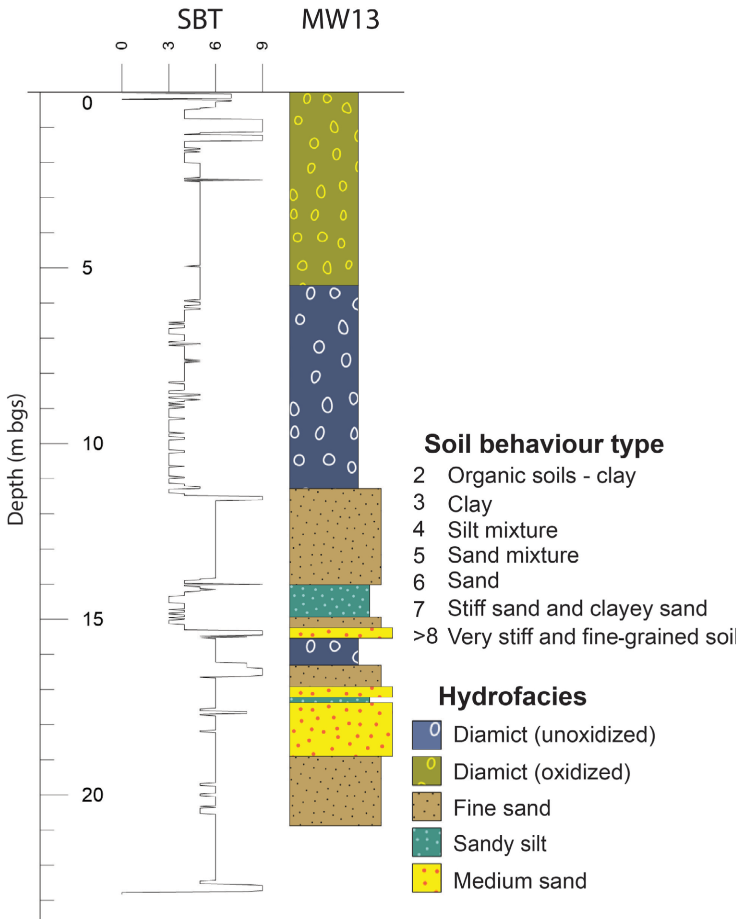
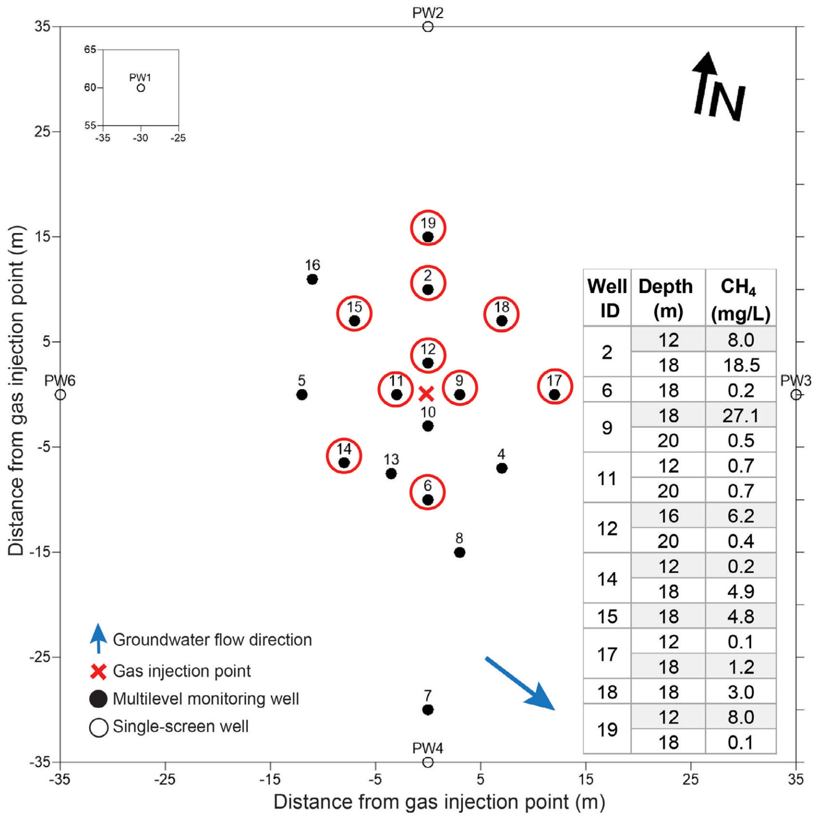


Figure 5. Vertical profile of soil behaviour types (SBT) for monitoring well (MW) 13 compared to the hydrofacies observed from the core log. Abbreviation: bgs, below ground surface.

ments and soil-gas wells distributed over the surface of the HHFRS (Figure 7a). The combination of these three monitoring approaches allowed for temporally and spatially expansive monitoring and for isotopic data to be collected to assess methane and ethane degradation in the subsurface. With these multiple lines of data, a better understanding of the surface expression of GM associated with a leaking energy well could be developed.

Methane fluxes above background levels were measured to the northwest of the injection point (approximately 16 m; Figure 7b). This location is upgradient of groundwater flow, suggesting that free-phase gas movement in the heterogeneous subsurface was governed by contrasts in entry pressure and permeability as opposed to groundwater flow. The CH_4 fluxes in the area of the release fluctuated between 0.1 and 8 μmol/m^2/s, suggesting that a preferential flow pathway developed between the saturated zone and the surface. The CO_2 fluxes were more challenging to interpret because natural increases of CO_2 fluxes from the subsurface due to increased root respiration associated with warmer summer months occurred concurrently with the release of the natural gas. Although an increase from background CO_2 levels was observed, it is difficult to determine if this was the result of injected CH_4 being oxidized. Measurements using the survey chambers at 12 different time points (every 2–4 weeks following the initiation of gas injection) allowed for a larger area to be monitored to determine fluxes across the HHFRS. These measurements, however, confirmed that elevated CH_4 fluxes were localized to the area northwest of the injection point near to monitoring well (MW) 2 (Figure 7b). The flux data suggest that gas migration from the unsaturated zone to the surface is likely attributed to preferential flow paths through the upper diamict layer, described by Chao et al. (2020). This confirmatory evidence of the localized fluxes reiterates the findings of Chao et al. (2020), and suggests that gas will reach the surface only through naturally formed pathways in the diamict (e.g., fractures in the material, seams of coarse-grained sediments) or as a result of anthropogenic-formed pathways (e.g., along installed wells).

In addition to the flux data, soil-gas compositions (CH_4, CO_2, N_2, Ar) and isotope ratios provide further insights on the mechanisms of surface expression at the HHFRS. The carbon isotopic composition ($\delta^{13}C$) of CH_4 present in the



Well ID	Depth (m)	CH_4 (mg/L)
2	12	8.0
	18	18.5
6	18	0.2
9	18	27.1
	20	0.5
11	12	0.7
	20	0.7
12	16	6.2
	20	0.4
14	12	0.2
	18	4.9
15	18	4.8
17	12	0.1
	18	1.2
18	18	3.0
19	12	8.0
	18	0.1

Figure 6. Groundwater monitoring well locations, including sampling locations that showed elevated dissolved methane (CH_4) concentrations (red circles) 490 days after the injection began at Hudson's Hope Field Research Station. Abbreviation: PW, pumping well.

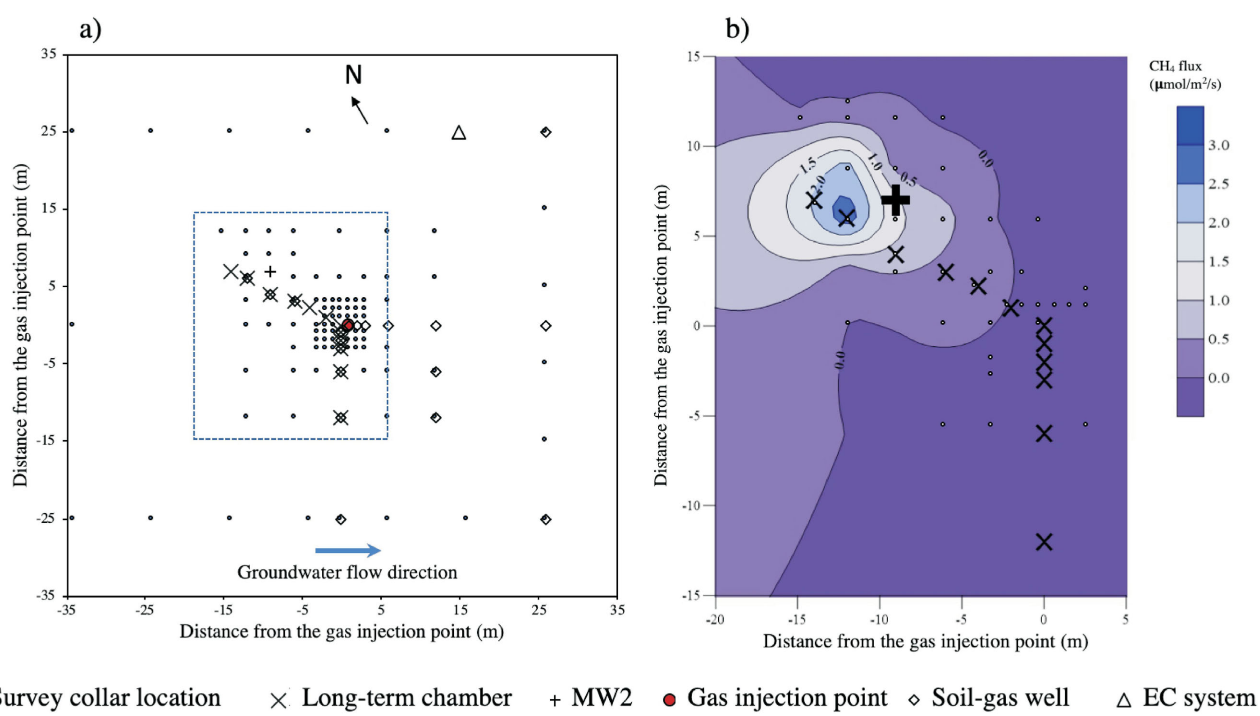


Figure 7. a) Location of surface flux monitoring equipment at the Hudson's Hope Field Research Station and **b)** methane (CH_4) flux using an integrated interpolation of long-term soil flux chambers and survey chamber measurements, 45 days after the beginning of injection. Dashed box in a) represents the area presented in b). Abbreviations: EC, eddy covariance; MW, monitoring well.

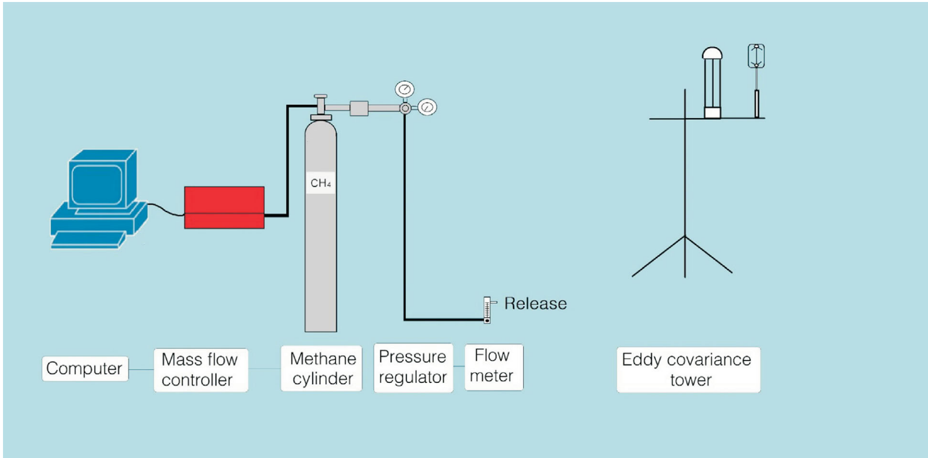


Figure 8. Schematic diagram showing the experimental setup of the controlled gas release experiments at Hudson's Hope Field Research Station.

unsaturated zone is less negative than that of the injected CH_4 and $\delta^{13}C$ of CO_2 is more negative than is typical for background conditions. This suggests that oxidation of the injected CH_4 is occurring facilitated by microbes. With further investigation, the rate of oxidation of the injected CH_4 can be determined when coupled with investigation of the microbial community structure and activity at the site.

Eddy Covariance and Micrometeorology

The eddy covariance (EC) tower was deployed prior to and during the natural gas release in the subsurface at the site in 2018 (see Cahill et al., 2020 for a detailed description). The EC system was redeployed to the site in the summer of 2019. During this time a controlled release at the surface was conducted to better constrain the results from the subsurface release (described below), after which the EC system was decommissioned. A comprehensive analysis of the dataset collected over the injection experiment enabled the gathering of knowledge about gas leakage to the atmosphere (location and volume).

The controlled surface release experiments were of paramount importance, and helped confirm and validate: 1) the flux footprint model to be used for data analysis, and 2) the methodology of data analysis to be followed, that is, converting the EC measurements to values that are more representative of gas leakage to the atmosphere. During the surface release experiments, CH_4 was released using a mass flow controller under varying conditions and was measured using the EC system (Figure 8). Various factors associated with the gas source, such as along-wind distance from the tower, the height of the source from the surface and release rates, were tested to understand the dependence of the flux footprint model on these factors. All the controlled releases indicated that the flux footprint model of Kljun et al. (2015) performed the best under the conditions of this project.

The approaches for flux footprint analysis included 1) down-scaling the EC measurements to the surface measurements by knowing the location and nature of the leak as informed by the chambers, and 2) demonstrating an inversion approach (based on Lewicki et al., 2009) to independently use EC measurements to obtain a surface flux distribution over the domain of the field site, and identify the location of the leak. The data analysis is complete and the results will be described in detail in a peer-reviewed publication.

Conclusions and Ongoing Work

Field activities at the Hudson's Hope Field Research Station have been completed with the exception of annual groundwater sampling events to monitor continued dissolution and degradation of the injected natural gas. Long-term groundwater monitoring infrastructure will remain for this purpose, whereas other systems such as the eddy covariance and solar power stations have been decommissioned. In addition to the publication of the near-surface geology and hydrostratigraphy investigation results in *Science of The Total Environment*, several other manuscripts are in preparation detailing 1) the surface flux monitoring and the key findings of these efforts, 2) the evolution of dissolved gas at the site, and 3) the geochemical processes occurring at the site as a result of the controlled gas release. Further dissemination of this research has occurred through conferences including GeoConvention, the American Geophysical Union Fall Meeting and The Geological Society of America Annual Meeting.

Acknowledgments

This manuscript was peer reviewed by L. Smith. The authors gratefully acknowledge C. and E. Weder for allowing this work to take place on their grazing lease. This work was funded by Geoscience BC, Natural Resources Canada

Clean Energy Innovation Program, the BC Oil and Gas Commission, and the BC Oil and Gas Research and Innovation Society.

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