# Establishment of Field Stations for the Multidisciplinary Study of Fugitive Gas, Northeastern British Columbia

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## Introduction

Fugitive gas, comprising primarily methane, can be unintentionally released from upstream oil and gas development either at surface from leaky infrastructure or in the subsurface through failure of well bore integrity. For the latter, compromised cement seals around well casings can permit flow of natural gas into the subsurface, tending toward ground surface and potentially into the atmosphere. Concerns associated with fugitive gas release at surface and in the subsurface include contributions to greenhouse gas emissions, subsurface migration of gas leading to accumulation in nearby infrastructure and impacts to groundwater quality. Current knowledge of fugitive gas is incomplete, including how to best detect and monitor it over time and, particularly, its migration and fate in the subsurface at the individual event scale. Consequently, an experimental field observatory has been established to evaluate surface and subsurface fugitive gas leakage in an area that hosts historic and ongoing hydrocarbon resource development—the Montney play of the Western Canada Sedimentary Basin, northeastern British Columbia (BC). At the field laboratory, natural gas has and will be intentionally released at various low rates (<10 $m^3$/day [d]), durations and configurations. Resulting migration patterns and impacts will be evaluated through examination of the geology, hydrogeology, hydrogeochemistry, isotope geochemistry, hydrogeophysics, vadose zone and soil gas processes, microbiology and atmospheric conditions. The use of unmanned aerial vehicles and remote sensors for monitoring and detecting methane will also be assessed as environmental monitoring tools. Herein the progress to date is outlined, including significant successful efforts undertaken to leverage the base funding provided by Geoscience BC to enhance the multidisciplinary nature of the research program. Activities undertaken in order to select and secure suitable locations for the field observatory and then develop detailed site conceptual models are also described. Ongoing research, which will take place at the newly established field observatory, will a) create rigorous, evidence-based

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knowledge to inform surface gas flux and groundwater monitoring approaches with respect to fugitive gas, b) aid in quantifying and reducing greenhouse gas emissions, and c) help to guide changes to associated regulatory and technical guidance policies.

## Background

Over the last decade the combination of well stimulation by hydraulic fracturing and horizontal drilling has led to rapid and unprecedented tight-rock–derived natural gas extraction across the United States and Canada (Kerr, 2010). Consequently, tens of thousands of energy wells have been drilled across regions underlain by gas-bearing shales (e.g., 7226 wells were drilled in Pennsylvania between 2005 and 2013; Brantley et al., 2014). Following such intense unconventional resource development, cases of environmental impacts were alleged and investigated (Osborn et al., 2011; Fontenot et al., 2013; Jackson et al., 2013; Hammond, 2015) resulting in significant controversy and various regional bans and moratoria. One of the main issues of concern is accidental leakage of natural gas, often termed fugitive methane ($CH_4$; Vengosh et al., 2013, 2014; Vidic et al., 2013). Although hydraulic fracturing brought attention to the issue, fugitive $CH_4$ is a historic engineering challenge associated with all petroleum resource development and associated activities (e.g., underground gas storage; Dusseault et al., 2000; Robertson et al., 2012). In general, two key configurations of fugitive $CH_4$ leakage can occur in the context of upstream petroleum development: 1) surface or 2) subsurface leakage, for which there are multiple conduits (Figure 1). Surface fugitive $CH_4$ can originate at the well head either by leakage from associated distribution infrastructure or from within or along the well casing (e.g., surface casing vent flow) leading to direct emission to atmosphere (Kang et al., 2014). Subsurface fugitive $CH_4$ has several potential origins, including subsurface well casing failure or mobilization of intermediate in situ gas pockets during or after drilling. Regardless of source, subsurface leakage results in entry of gas into the adjacent geological media, which is followed by three generalized outcomes: 1) subsurface migration through the geological profile and efflux to atmosphere; 2) free-phase gas migration and entrapment in the subsurface; and 3) dissolution into groundwater, aqueous-phase migration and attenuation. Likely, a

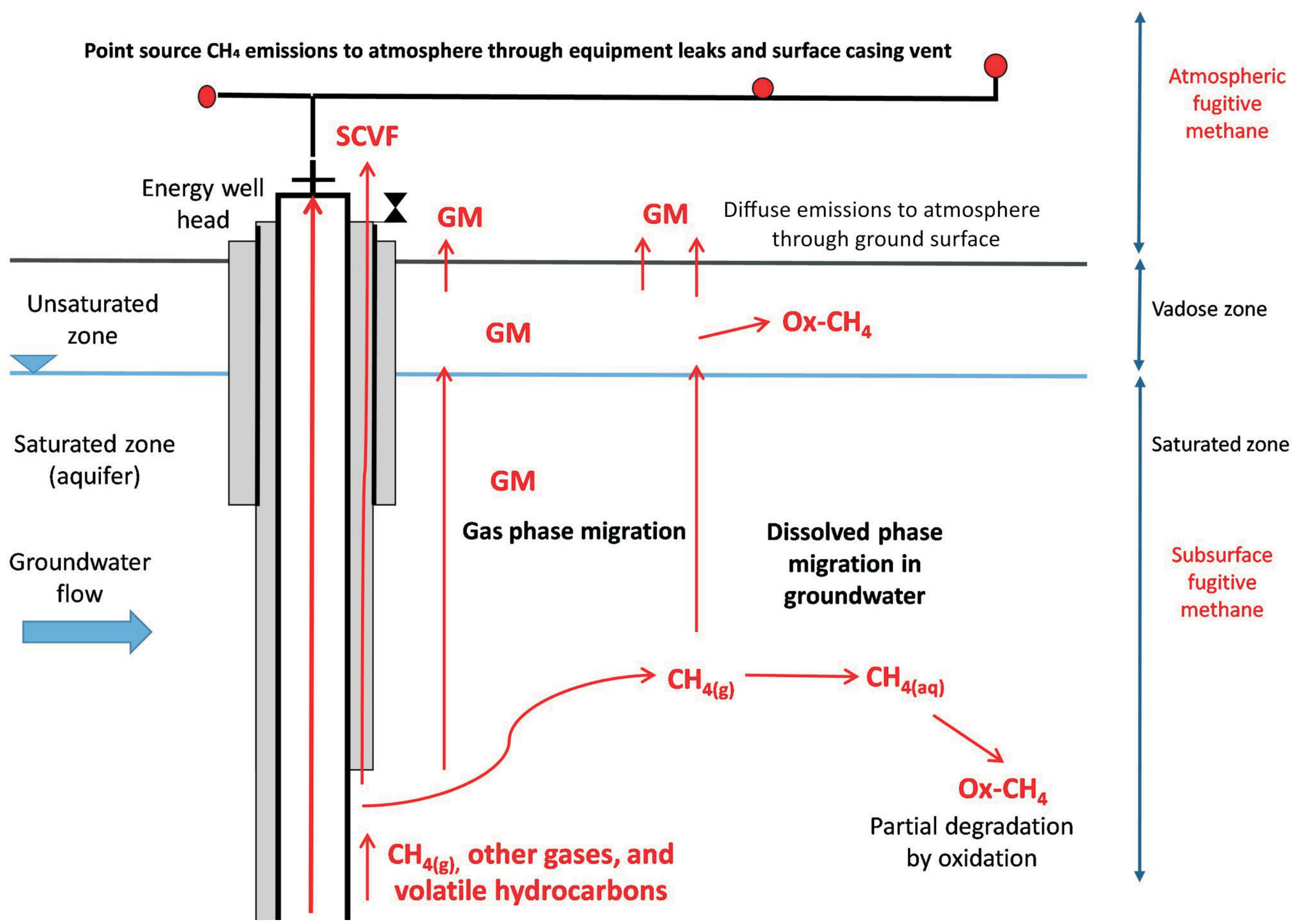


**Figure 1.** Conceptual model (not to scale) showing fugitive gas release from a gas well. Abbreviations: $CH_{4(aq)}$, dissolved/aqueous methane; $CH_{4(g)}$, gas phase methane; GM, gas migration; Ox-$CH_4$, oxidation of methane; SCVF, surface casing vent flow. Modified from Cahill et al. (2017).

combination of these processes occur dependent on site-specific conditions, however, detailed knowledge on how to predict or estimate this is lacking.

Fugitive $CH_4$ causes concern as it poses three potential risks to human health and/or the environment. Firstly, fugitive $CH_4$ poses an explosion hazard (lower explosive limit of 5% in air; LeBreton, 2009) if released into a confined space. Secondly, $CH_4$ is a potent greenhouse gas (a factor of 25 times greater in a 100-year period than $CO_2$; United States Environmental Protection Agency, 2010). Considering emissions of $CH_4$ from energy resource development (particularly shale gas operations) have been identified as potentially significant to overall greenhouse gas emissions (Caulton et al., 2014), fugitive $CH_4$ therefore has potential to contribute significantly to climate change (Shindell et al., 2009; Stocker et al., 2013). Thirdly, fugitive $CH_4$ can impact groundwater resources by migrating in the aqueous phase and forming an explosion risk following extraction, and also following microbial attenuation (based on availability of electron acceptors, according to the redox sequence; Christensen et al., 2000; Le Mer and Roger, 2001) where it may generate undesirable byproducts (e.g., $H_2S$, $Fe^{2+}$, $Mn^{2+}$) or potentially induce the release of trace metals (Bennet and Dudas, 2003; Van Stempvoort et al., 2005, 2007; Amos et al., 2012; Ng et al., 2015). Although much research has recently been undertaken with respect to fugitive $CH_4$, it has for the most part taken the form of retrospective environmental forensic studies to assess if detectable impacts to groundwater have occurred. Unfortunately, little research has comprehensively assessed migration, impacts and fate of fugitive $CH_4$ in a holistic manner or at the single event scale. Exceptionally, a recent multidisciplinary study, upon which the current study builds, monitored groundwater, soil gas and surface efflux at high spatiotemporal resolution during release of a small volume of natural gas into a shallow (i.e., ~9 m depth) unconfined aquifer system. Results from this study showed that although a significant proportion of injected gas reached the surface and emitted to atmosphere with some oxidation observed in the unsaturated zone, a large portion remained in the saturated zone where it created a dispersed and laterally extensive volume of impacted groundwater (Cahill et al., 2017). Although this study provided important and detailed insights regarding fugitive $CH_4$, it forms only a single site specific study and its overall applicability and relevance to regions of resource development (e.g., the Western Canada Sedimentary Basin) is limited. Consequently, many knowledge gaps remain and more studies such as this are needed in a range of geological settings where petroleum resource development takes place in order to improve an understanding of the fugitive $CH_4$.

In March 2017, Geoscience BC entered into a contribution agreement with The University of British Columbia's Energy and Environment Research Initiative (UBC EERI; directed by R. Beckie and A. Cahill), located at the Department of Earth, Ocean and Atmospheric Sciences, in order to address the paucity of field data concerning fugitive gas. Based on a proposal submitted in 2016, Geoscience BC agreed to provide \$0.5 million funding in order for UBC EERI to undertake a groundwater-focused, controlled natural gas release investigation at a field station to be located in the Peace region of northeastern BC. This paper has a description of the progress on this project beginning with the significant successful efforts enacted by UBC EERI to leverage the base funding provided by Geoscience BC in order to increase the multidisciplinary nature of the research program (i.e., above and beyond groundwater alone). Progress on site selection and field station characterization and setup undertaken during 2017 is also presented.

## Summary of Activities and Progress

### Leveraging and Increase of Project Scope

Although UBC EERI recognized that the \$0.5 million awarded by Geoscience BC to conduct a groundwater-focused study (hereafter referred to as 'the base funding') was a significant award, it was quickly identified that this would be insufficient for a fully comprehensive multidisciplinary investigation, which has been seen to be required to truly advance knowledge on fugitive gas (Cahill et al., 2017). Consequently, UBC EERI rapidly formulated and enacted a successful strategic plan in order to enhance the multidisciplinary aspects of the research program through leveraging the base funding wherever possible. Two leveraging opportunities were identified and successfully advanced after significant development and efforts. The major leveraging opportunity took the form of the Clean Energy Innovation component of the Energy Innovation Program administered by Natural Resources Canada (NRCan). A proposal was formulated and submitted seeking to leverage the base funding by approximately 3:1 and attain an additional \$1.617 million to include enhanced geological investigations, soil gas and surface efflux, eddy covariance, microbial and geophysical components to the study program. This proposal was ultimately successful and a full contributions agreement signed between UBC EERI and NRCan on August 24, 2017. Additionally, a proposal and work plan to include drone measurements and remote sensors during the project was formulated and submitted to the BC Oil and Gas Research and Innovation Society (BC OGRIS) with an additional value to project of \$93 000 in April 2017. This proposal was subsequently confirmed as successful May 12, 2017. These leveraging opportunities led by UBC EERI and its collaborators have brought the overall project cash value to >\$2.2 million; meaning the base funding has been leveraged by 3.4 to 1 (Table 1).

## Identification and Characterization of Field Sites

As part of a Geoscience BC groundwater mapping project (which took place in the primary area of interest for the current study), a series of aerial geophysical surveys were conducted in 2015 (i.e., airborne transient electromagnetic measurements by SkyTEM; Brown et al., 2016). These surveys were used to aid in the identification of two areas close to Hudson's Hope as potentially suitable to host the fugitive gas investigations. At first it was envisioned that one site could be representative of the Peace region and would include both a saturated aquifer and a significant unsaturated zone. However, this was ultimately not possible and instead two separate sites were identified near Hudson's Hope: one a saturated aquifer or the saturated zone (SZ; with no unsaturated zone) and the other a dry soil site or the unsaturated zone (USZ) field research sites (FRS; Figure 2a, b).

Having both dry and saturated soil systems into which natural gas could be released was deemed a critical design requirement of the research program. The USZ FRS is located on the west side of Lynx Creek (a tributary of the Peace River), which has incised approximately 50 m into the local relief at an elevation of ~800 m asl. The airborne survey identified the USZ area as having a low resistance surface layer (inferred to be glacial till) underlain by a highly resistive material (inferred to be unsaturated glacial outwash sand, silt and gravel; Figure 2b). Sonic core drilling confirmed this to be the case with ~10 m of glacial diamict (gravel suspended in a matrix of clay and/or silt) overlying a fine to very fine dry sand. Based on the airborne SkyTEM data, the SZ FRS appeared to be located in a buried paleovalley with a layer of low resistance overlying a channel of moderate resistance suggesting a confined aquifer, typical in the area. This hypothesis was confirmed by drillcores, which showed glacial diamictic clay overlying a saturated glacial outwash deposit; albeit this time the glacial deposits appeared more heterogeneous being composed of interbedded layers of sand, silt and gravel. The two sites are typical of the Quaternary geology found within the Peace region's Montney play and ideal for simulating how fugitive gas may manifest.

## Initial Results

### Unsaturated Zone Field Research Site

Following identification of the USZ FRS as potentially suitable for controlled release investigations, a drilling campaign was undertaken in order to better characterize site geology (e.g., assess heterogeneity) and to install multilevel soil gas monitoring wells and a gas injection well. An auger capable geoprobe rig was used to drill nine boreholes to 12 m depth (Figure 3a) with full geological logging and a range of depth discrete sampling undertaken for a variety of parameters (e.g., grain size distribution; Figure 3b). Boreholes were subsequently installed with depth discrete soil gas sampling systems made 'in house' using polyethylene tubing with geotextile screens, backfilled with sand pack and hydrated bentonite chips. A short duration gas release experiment was then planned to be rapidly implemented in September 2017 in order to precede the onset of winter, during which a slowdown in field activities is inevitable. Consequently, many activities were rapidly initiated including setting up a full surface efflux monitoring system, including seven continuous measuring chambers and ~100 additional spatially discrete survey collars (Figure 3a), installation of a $20 000 solar power system to provide continuous power to the site, and collection of several background soil gas samples (Figure 4). Subsequently 29 $m^3$ of compressed natural gas was injected at a constant rate at the site at 12 m depth over five days with monitoring of gas migration and fate (i.e., where it ultimately goes: being either released to atmosphere; oxidized by bacteria; or remaining trapped in the subsurface) ongoing. Results from this experiment are still being collected and are yet to be processed thus are not reported here. They will, however, be reported in next year's reporting phase.

**Table 1.** Funding structure for project including increased multidisciplinary components achieved through leveraging of Geoscience BC funding.

| Project funding component | Value | Project component |
|---|---|---|
| Geoscience BC (i.e., base funding) | $0.5 million | Identify field site, obtain release, setup infrastructure<br>Groundwater |
| Natural Resources Canada | $1.617 million | Enhanced geological data<br>Soil gas and surface efflux<br>Microbiology<br>Surface geophysics<br>Enhanced isotope geochemistry<br>Eddy covariance |
| BC Oil and Gas Research and Innovation Society | $93 000 | Drone (aerial) measurements |

### Saturated Zone Field Research Site

Following identification of the SZ FRS as potentially suitable for controlled release investigations, a further drilling campaign was undertaken in order to better characterize site geology (e.g., assess heterogeneity) and to install groundwater monitoring wells and a gas injection well. These initial monitoring wells would allow the UBC EERI team to collect initial water samples for assessing baseline conditions, including groundwater quality, flow direction and magnitude, and to advance the design of the

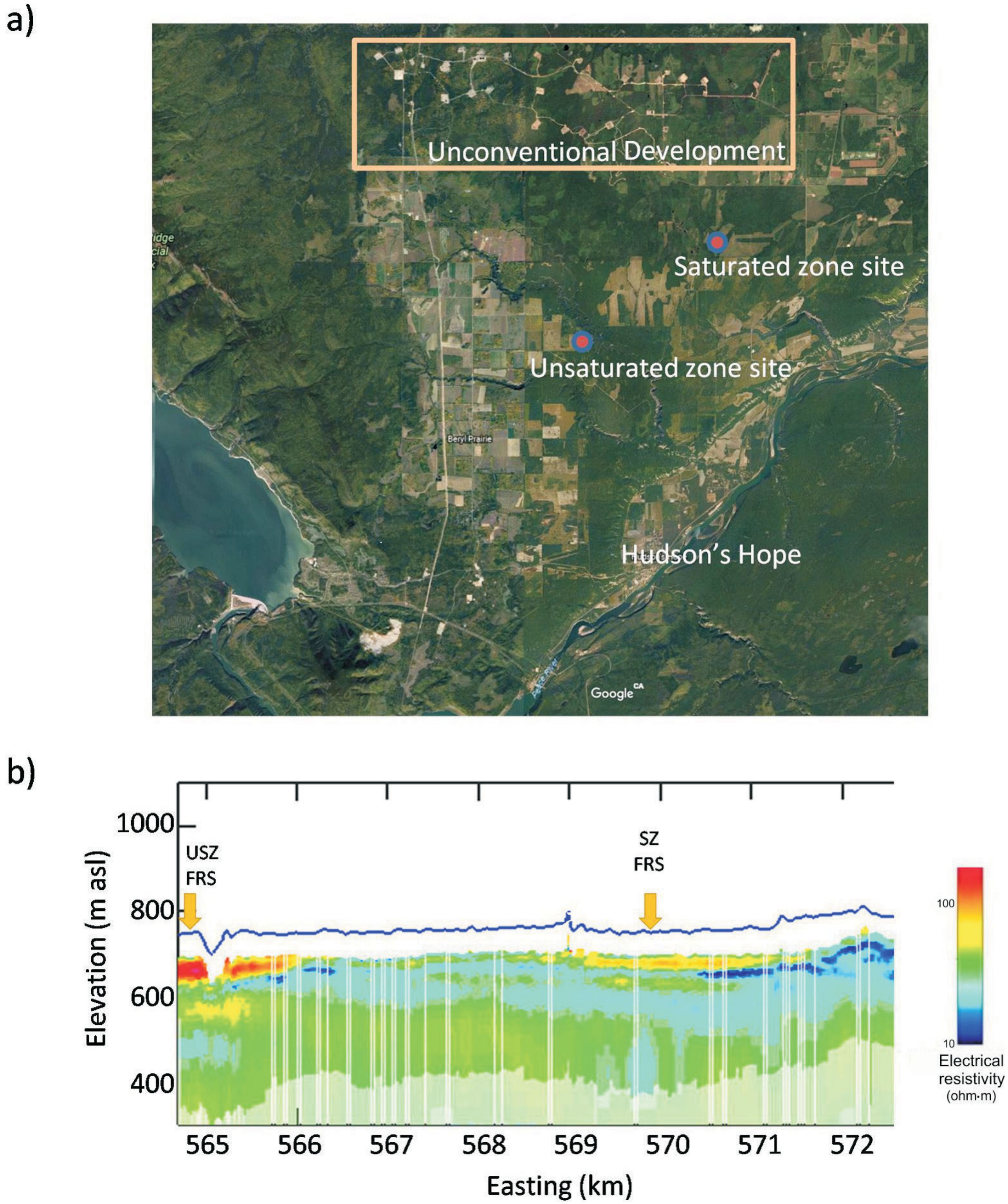


**Figure 2. a)** Image of study area showing location of unsaturated and saturated zone field research sites. Significant unconventional resource development is underway approximately 2 km north of the study area demonstrating relevance of site setting. Red dashed line between sites indicates approximate location of the aerial geophysics SkyTEM survey line, initially used to identify the sites as potentially suitable for investigation. Imagery ©2017 Landsat/Copernicus, map data ©2017 Google, Canada. **b)** Airborne geophysics (electromagnetic) survey line, flown as part of a separate Geoscience BC Peace project (Aarhus Geophysics ApS, 2016), showing inferred resistivity of the subsurface geology, with warm colours indicating higher resistivity and cool colours lower resistivity. Blue line indicates flight line of sensor. Abbreviations: FRS, field research site; SZ, saturated zone; USZ, unsaturated zone.

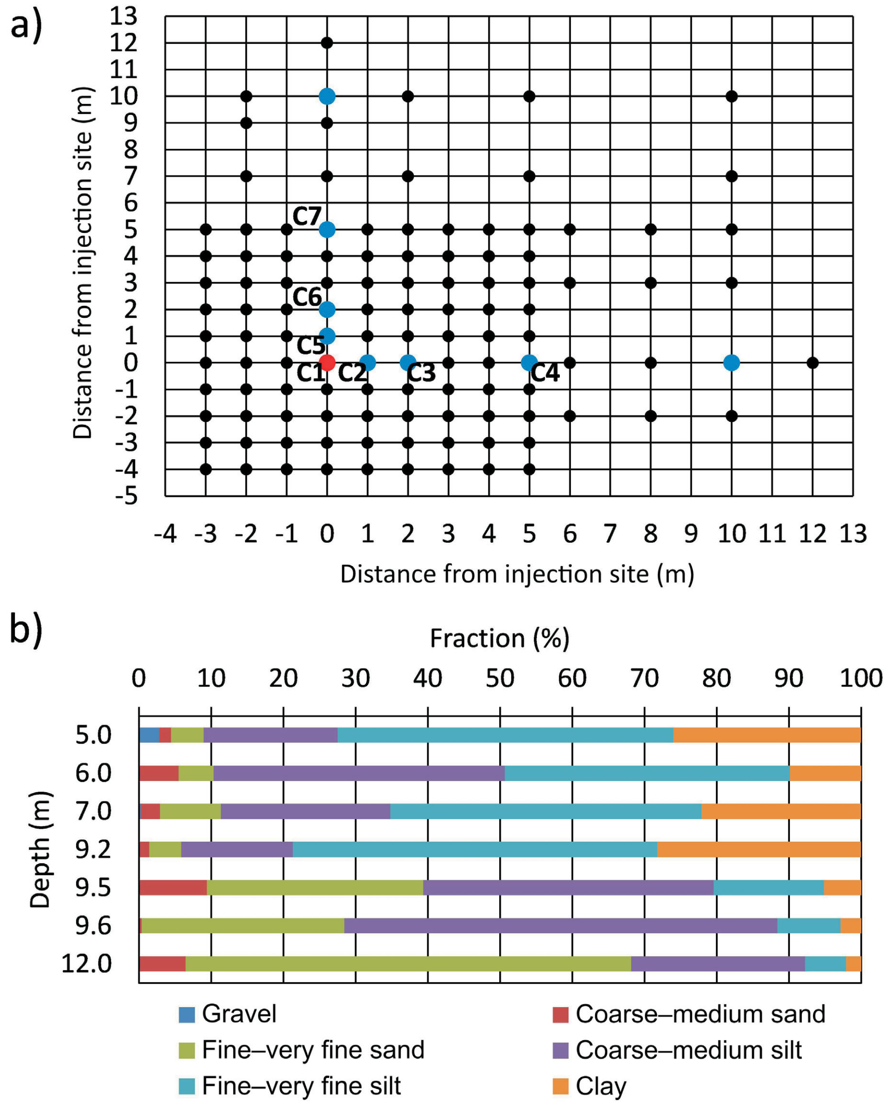


**Figure 3. a)** Monitoring network installed at the unsaturated zone field research site. The red circle indicates the injection location and the blue circles indicate the locations of the multilevel soil gas monitoring wells. Continuous flux chambers, indicated by C1 through C7, are co-located with selected multilevel wells. Spatial flux measurements were collected at locations indicated by the black circles. **b)** Grain size distribution with depth for sediments in the multilevel well next to C6, 2 m from the injection location.

experiment. Drilling of five monitoring wells and an inclined gas injection well to approximately 25 m depth (Figure 5a, b) was conducted using a Sonic coring rig. These investigations confirmed the hypothesis that the site consisted of a confined aquifer formed by ~12 m of diamict (confining layer) overlying a complex interbedded sequence of water-bearing very fine to fine sand, silt and pebbly silt. Moreover, this increasing understanding of the site begins to show a highly heterogeneous environment that exhibits little lateral continuity. Once monitoring wells were installed, initial water samples were taken and analyzed for physical chemistry, major and minor cations, as well as dissolved gases. Results from these initial groundwater sample tests are provided in Tables 2 and 3. Water levels were also measured and pressure transducers installed to track changes in water levels and calculate flow direction and magnitudes (Figure 5b, c). Additionally, extensive surface-based electrical resistivity surveys were also conducted through the project's key collaborator at the University of Calgary, R. Lauer, results from which are currently being interpreted and will increase understanding on heterogeneity (results not shown here but available on request). During this period other site infrastructure, such as an experimental control building and electric fencing system to keep animals out of the primary investigation area, were installed. An aerial drone photograph of the SZ FRS is

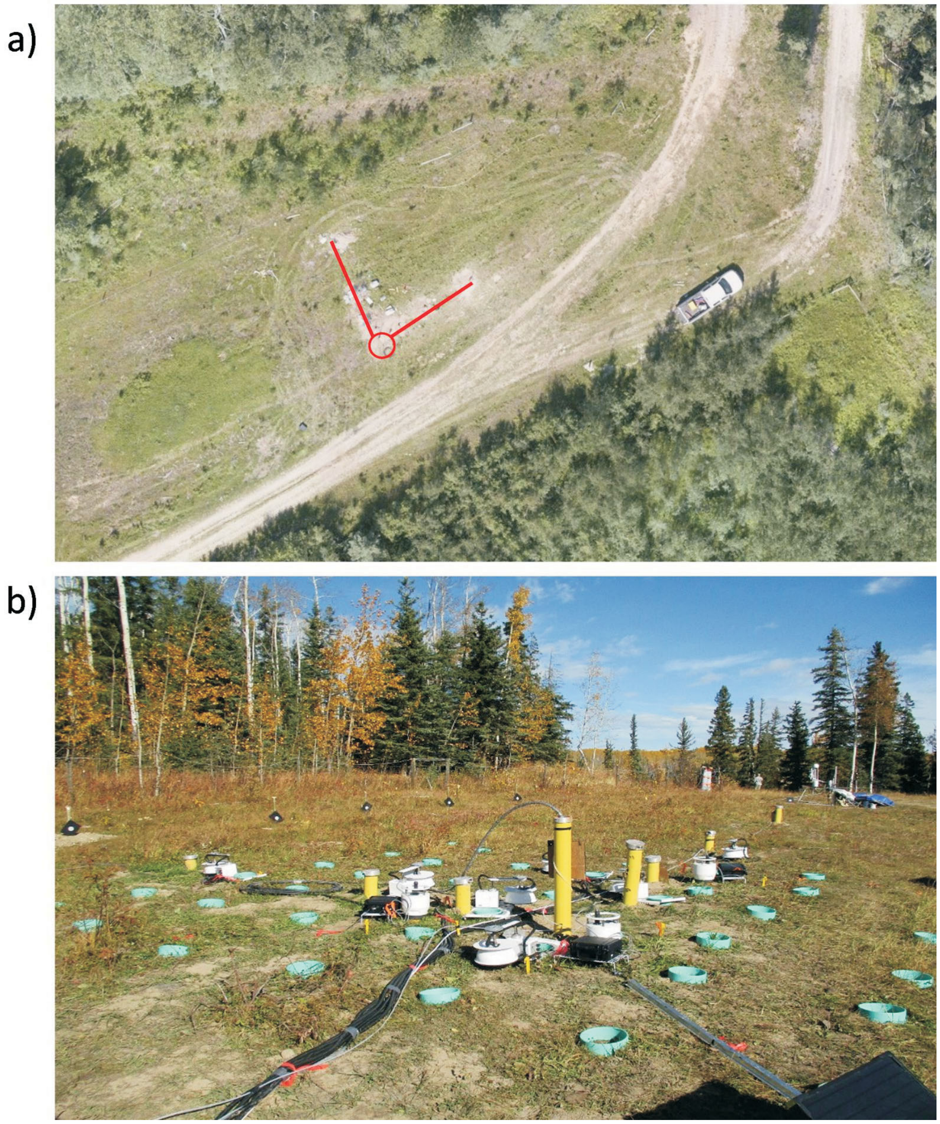

**Figure 4. a)** Aerial drone photograph of unsaturated zone field research site, during infrastructure installation/site investigations, showing injection zone (gas injected at 12 m depth) as red circle and red lines delineating transect profiles of multilevel soil gas monitoring wells. **b)** Site fully instrumented prior to injection of 29 $m^3$ of natural gas at a constant rate over five days, initiated on September 25, 2017. Monitoring is still ongoing as of November 2017 with initial results being processed.

shown in Figure 6. Less than 400 m from the site is an orphaned gas well (Figure 6; coalbed methane well drilled in 1994), which is defined as infrastructure that does not have any legally responsible or financially able party to deal with its abandonment and reclamation. Proximity to an orphaned well demonstrates the relevance of the setting in which these controlled release investigations are being undertaken.

## Ongoing Work

Two separate but closely located field sites were chosen as the locations of controlled gas releases. Consequently, UBC EERI is now poised to advance knowledge on fugitive gas, as set out in the multiple successful proposals completed. A short-term gas injection experiment has been undertaken at the USZ FRS and is currently in the final stages of monitoring. This experiment alone has already generated a huge dataset and will form an important standalone study with many insights set to be gained with respect to fugitive gas. The results from the USZ FRS study will also be used to help steer and maximize results obtained from the SZ FRS study planned to take place in 2018. This will increase the likelihood that the SZ FRS study will be successful and infers many new insights will be made as proposed. A project workshop was held on November 29, 2017, at which recently gained results and plans for ongoing work were discussed.

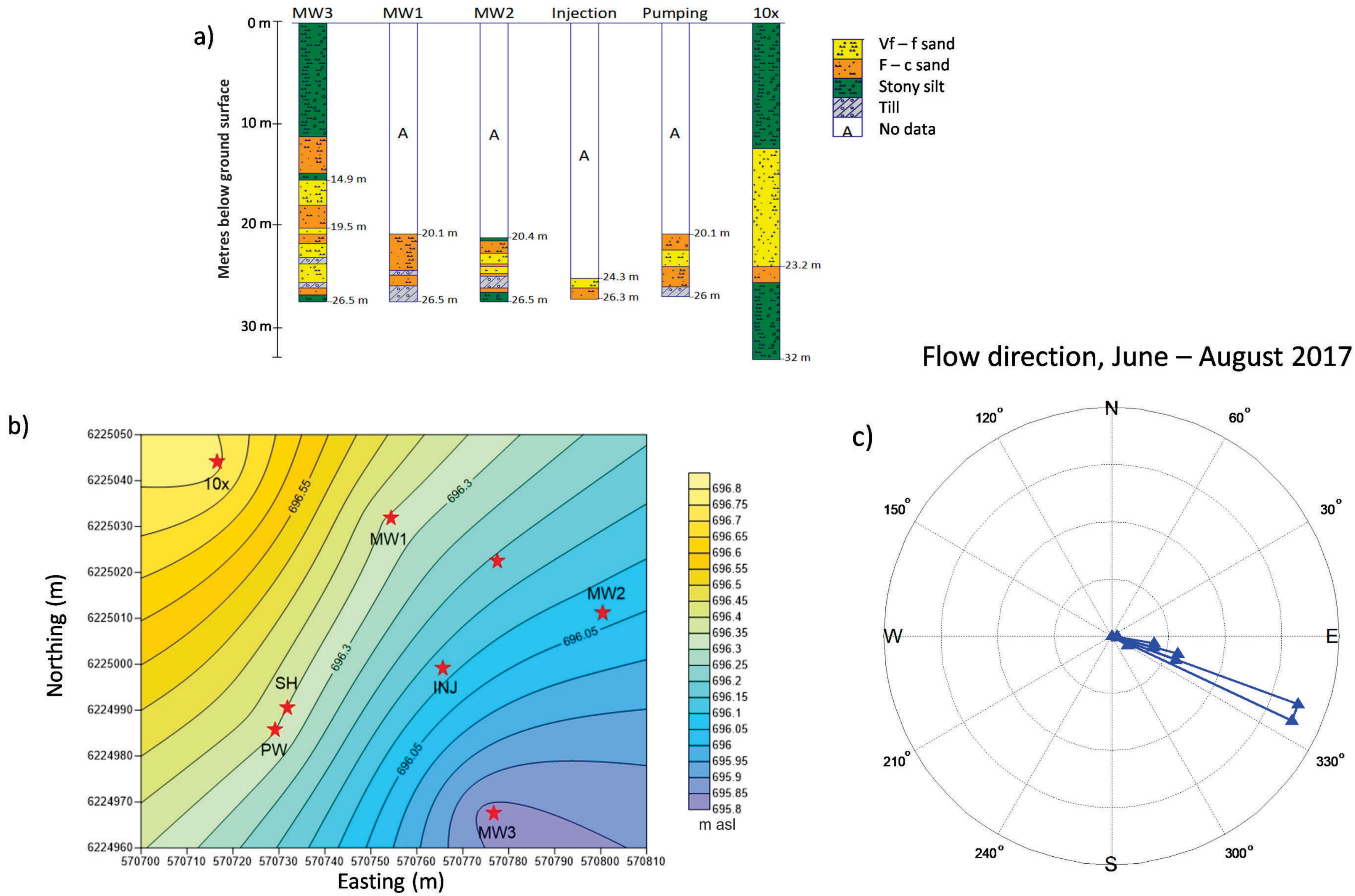


**Figure 5.** Saturated zone field research site: **a)** geological logs from boreholes cored during initial site investigation show a heterogeneous, confined sandy aquifer; **b)** locations of boreholes drilled in area of interest and groundwater elevation contours across the site for August 11, 2017 and **c)** groundwater flow direction rose diagram for June to August, 2017, showing flow direction is generally consistently southeast. Abbreviations: c, coarse; f, fine; vf, very fine.

**Table 2.** Geochemical compositions of baseline shallow groundwater samples from saturated zone field research site. Abbreviation: EC, electrical conductivity; TDS, total dissolved solids.

| Property/composition | MW1 | MW2 | MW3 | Inj | PW | 10x |
|---|---|---|---|---|---|---|
| EC (µS/cm) | 1120 | 955 | 1100 | 1125 | 1100 | 1131 |
| pH | 7.35 | 7.58 | 7.43 | 7.48 | 7.052 | 7.4 |
| Cl (mg/L) | 2.75 | 6.35 | 2.75 | 4.2 | 2.1 | 2.25 |
| $SO_4$ (mg/L) | 220.8 | 201.9 | 241.5 | 213.4 | 156.8 | 8.3 |
| $NO_3$ (mg/L) | 0.08 | 0.11 | 0 | 0 | 0.07 | 0 |
| Alkalinity (mg/L) | 520 | 500 | 520 | 520 | 580 | 180 |
| Li (mg/L) | 0.0248 | 0.0375 | 0.0267 | 0.0246 | 0.0247 | 0.0029 |
| B (mg/L) | 0.1080 | 0.1470 | 0.1020 | 0.0976 | 0.1170 | 0.0213 |
| Na (mg/L) | 73.77 | 100.15 | 62.21 | 53.26 | 61.11 | 7.89 |
| Mg (mg/L) | 80.24 | 47.28 | 66.53 | 76.11 | 80.06 | 11.44 |
| Al (mg/L) | 0.2790 | 0.0408 | 0.1150 | n/a | 0.4660 | 0.0579 |
| Si (mg/L) | 7.44 | 7.79 | 7.7 | 7.3 | 8.75 | 4.41 |
| K (mg/L) | 4.8 | 6.23 | 6.07 | 6.53 | 4.64 | 7.32 |
| Ca (mg/L) | 94.88 | 87.76 | 103.07 | 101.29 | 85.85 | 30.7 |
| Mn (mg/L) | 0.0444 | 0.3500 | 0.3050 | 0.7700 | 0.0666 | 0.0549 |
| Fe (mg/L) | 0.9930 | 0.3940 | 0.4720 | 0.0148 | 0.9150 | 0.5140 |
| As (mg/L) | 0.0046 | 0.0030 | 0.0021 | 0.0012 | 0.0039 | 0.0011 |
| Sr (mg/L) | 0.6590 | 0.7940 | 0.6100 | 0.6030 | 0.6350 | 0.1140 |
| Calculated TDS (mg/L) | 728 | 620.75 | 715 | 731.25 | 715 | 735.15 |

**Table 3.** Dissolved gas compositions of baseline shallow groundwater samples from saturated zone field research site.

| Well no. | $CH_4$ (mg/L) | Total C2 (mg/L) | Total C3 (mg/L) | Total $CO_2$ (mg/L) | Total $N_2$ (mg/L) | Total $O_2$ (mg/L) |
|---|---|---|---|---|---|---|
| MW1 | 0.00814 | 0.00086 | 0.00000 | 29.87 | 36.59 | 0.62 |
| MW2 | 0.03080 | 0.00371 | 0.00081 | 13.9 | 57.26 | 3.18 |
| MW3 | 0.01330 | 0.00200 | 0.00041 | 21.09 | 57.2 | 7.32 |
| Inj | 0.00634 | 0.00143 | 0.00041 | 20.05 | 42.34 | 7.63 |
| PW | 0.00791 | 0.00160 | 0.00350 | 36.16 | 62.03 | 4.8 |
| 10x | 0.00735 | 0.00057 | 0.00000 | 28.18 | 48.98 | 2.89 |

## Summary of Progress

The following forms a summary of the progress made to date with respect to UBC EERI's controlled methane release investigation project:

- UBC EERI have undertaken significant leveraging activities, which have resulted in 3.4:1 additional funding above that initially provided by Geoscience BC. The total project cash budget is now in excess of $2.2 million.
- Through this additional funding, the project scope has been vastly increased and will now include a highly multidisciplinary team encompassing examination of fugitive gas from perspectives of geology, hydrogeology, soil gas and surface efflux processes, microbiology, isotope geochemistry, geophysics, eddy covariance and airborne sensing.
- Two sites (saturated and unsaturated) have been identified in the Peace region near Hudson's Hope, BC, at which natural gas has been and will be released in the subsurface and at surface in a controlled manner. These sites have been subjected to comprehensive intrusive investigations and detailed baseline site conceptual models are being developed.
- A short-term natural gas injection experiment has been initiated at the USZ FRS whereby 29 $m^3$ of compressed natural gas has been injected at 12 m depth and gas migration monitored in a multidisciplinary fashion. Monitoring of injected gas is ongoing.
- Setup and infrastructure installation at the SZ FRS is underway and plans are on track for a long-term injection experiment to be undertaken in 2018.

a)

b)

**Figure 6. a)** Drone aerial image of saturated zone field research site and surrounding area. The area of investigation, including the injection site, is indicated by the red square. The blue star indicates the site of an orphaned gas well (coalbed methane well drilled in 1994 but never produced). **b)** The orphaned gas well during winter drilling. Proximity to an orphaned well demonstrates relevance of setting in which the controlled releases investigations are being undertaken.

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