



# Identification, spatial extent and distribution of fugitive gas migration on the well pad scale

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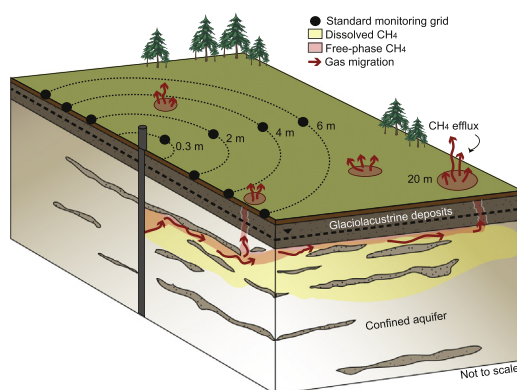
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## HIGHLIGHTS

- Effluxes and stable carbon isotopes identified fugitive CH<sub>4</sub> at 15 of 17 well pads
- Methane effluxes were spatially and temporally variable across well pads
- Fugitive CH<sub>4</sub> was detected >20 m from the well head
- Using standard investigation methods, fugitive gas may go undetected on well pads
- Stable carbon isotopes indicated soil and SCVF gas from a similar thermogenic origin

## GRAPHICAL ABSTRACT



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## ABSTRACT

Global methane (CH<sub>4</sub>) emissions are becoming increasingly important due to the contribution of CH<sub>4</sub> to global warming. Leaking oil and gas wells can lead to subsurface CH<sub>4</sub> gas migration (GM), which can cause both aquifer contamination and atmospheric emissions. Despite the need to identify and quantify GM at oil and gas well pads, effective and reliable monitoring techniques are lacking. In this field study, we used CH<sub>4</sub> and carbon dioxide (CO<sub>2</sub>) efflux measurements together with soil gas stable carbon isotopic signatures to identify the occurrence and to characterize the spatio-temporal migration of fugitive gas across 17 selected well pads in Northeastern British Columbia, Canada. At 13 of these sites, operators had previously reported the occurrence of GM; however, subsequent inspections based on visual, olfactory or auditory evidence only identified GM at two of these sites. Using the soil gas efflux method, evidence for GM was found at 15 of the 17 well pads with CH<sub>4</sub> and CO<sub>2</sub> effluxes ranging from 0.017 to 180 μmol m<sup>-2</sup> s<sup>-1</sup> (0.024 to 250 g CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>) and 0.50 to 32 μmol m<sup>-2</sup> s<sup>-1</sup> (1.9 to 122 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>), respectively. Stable carbon isotopic composition was assessed at 10 of the 17 well pads with 9 well pads showing evidence of GM. The isotopic values indicated that CH<sub>4</sub> in soil gas was from the same origin as CH<sub>4</sub> in the surface casing vent flow gas. There was no correlation between CH<sub>4</sub> effluxes and the distance from the well head; an equal portion of elevated effluxes were detected >10 m from the well head as were detected <5 m from the well head. In addition, CH<sub>4</sub> effluxes varied temporally with values changing by up to an order of magnitude over 2 h. Although the study was carried out in Northeastern British Columbia, the results are applicable on a global scale, suggesting that inspections mostly based on visual evidence (e.g. bubbling at the well head) are not reliable for the identification of GM and, that infrequent survey measurements at

**Abbreviations:** BCOGC, British Columbia Oil and Gas Commission; DIC, dissolved inorganic carbon; GHG, Greenhouse gas; GM, Gas migration; IRGA, infra-red gas analyzer; SCVF, Surface casing vent flow; ND, non-detect; UGGA, ultraportable greenhouse gas analyzer.

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predefined locations close to the well head may overestimate, underestimate or even miss CH<sub>4</sub> effluxes. Repetitive and relatively densely spaced gas efflux measurements using a dynamic closed chamber method proved to be a useful tool for detecting GM.

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## 1. Introduction

Fugitive methane (CH<sub>4</sub>) leakage from faulty oil and gas well casings can lead to greenhouse gas (GHG) emissions and subsurface contamination (Bachu, 2017; Davies et al., 2014; Jackson, 2014; Soeder et al., 2014; Vidic et al., 2013). Compromised well casings most commonly result from cement failure or pipe corrosion. These failures provide pathway (s) for natural gas (comprised mainly of CH<sub>4</sub>) to escape either in the form of surface casing vent flows (SCVFs) or gas migration (GM), an in-depth description on the mechanisms of well failure can be found in Bachu (2017), Dusseault et al. (2000) and Dusseault and Jackson (2014). In the case of a SCVF, gas migrates within the surface casing and is directly released to the atmosphere (Dusseault and Jackson, 2014). With GM, natural gas is released into the formation surrounding the well, causing both lateral and buoyancy-driven upward spreading within the subsurface and possibly leading to groundwater contamination (Sherwood et al., 2016; Vengosh et al., 2014), explosive risks (if soil gas CH<sub>4</sub> concentrations exceed 5% v/v), and releases to the atmosphere (Bachu, 2017; Dusseault and Jackson, 2014; Szatkowski et al., 2002). Atmospheric CH<sub>4</sub> emissions are a concern because CH<sub>4</sub> has a global warming potential 28 to 36 times greater than carbon dioxide (CO<sub>2</sub>) over a 100 year time period (Myhre et al., 2013; Kang et al., 2016). The rise in natural gas production has led to heightened concerns on the risks associated with fugitive CH<sub>4</sub> migration causing groundwater contamination, explosive risks (Jackson et al., 2013; Osborn et al., 2011; Vidic et al., 2013) and GHG emissions (Alvarez et al., 2018; Caulton et al., 2014).

Various regions such as the province of New Brunswick, Canada and countries such as Germany have placed moratoriums on hydraulic fracturing for natural gas until better monitoring techniques are developed (Hays et al., 2015). On the other hand, some regions have experienced a rise in development; for example over the past decade British Columbia, Canada has seen rapid growth in oil and gas production (Fig. 1) (Rivard et al., 2013; British Columbia Oil and Gas Commission (BCOGC), personal communication, 2018). With the rise in production, more attention has been given to address the potential risks related to groundwater contamination (Jackson et al., 2013) and GHG emissions (Alvarez et al., 2018). In 2013, the BCOGC visually inspected for GM at 308 wells. Gas migration was inferred based on visual, olfactory and auditory evidence, mostly related to bubbling in standing water at the well head, vegetation stress, or elevated CH<sub>4</sub> in air measured with a hand-held

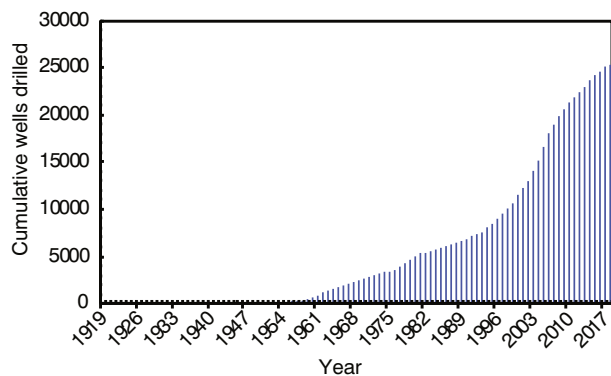


Fig. 1. Cumulative wells drilled in British Columbia from 1919 to 2018 reaching a total of 25,309 wells (BCOGC, personal communication, 2018).

detector. Based on these methods, 11 of these wells showed direct evidence of GM. Considering the low number of wells with identified GM, the study concluded that field screening techniques to detect GM from oil and gas wells were ineffective (BCOGC, 2013). Since 2013, it has been estimated that over 8% of 10,256 active wells in British Columbia have well integrity issues including SCVFs and GM (Boyer, 2016). Similar estimates for well failures have been reported for Alberta (6.56%, n = 446,289) (Bachu, 2017) and Pennsylvania (6.26%, n = 8030) (Davies et al., 2014). However, methods are still lacking to quantify fugitive GM from oil and gas wells. While studies have measured CH<sub>4</sub> emissions from facilities at well sites (Allen et al., 2013; Alvarez et al., 2018) and regionally with aircraft and vehicle measurements (Barkley et al., 2017; Brantley et al., 2014; Caulton et al., 2014; Johnson et al., 2017; Karion et al., 2015; Lan et al., 2015; Schwietzke et al., 2017; Smith et al., 2017), these studies do not isolate fugitive CH<sub>4</sub> associated with GM. To fully characterize GM, the magnitude and spatial extent of CH<sub>4</sub> effluxes needs to be quantified on the well pad scale.

Various studies have identified CH<sub>4</sub> emissions around the well head due to GM, but few have evaluated the spatial distribution of fugitive GM on the well pad scale. Erno and Schmitz (1996) detected GM from wells in Canada by conducting open chamber measurements within a 3 m radius of the well. The authors reported CH<sub>4</sub> effluxes as high as 994  $\mu\text{mol m}^{-2} \text{s}^{-1}$  [1378 g CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>] (reported as 2.1 m<sup>3</sup> m<sup>-2</sup> d<sup>-1</sup>). However, the authors did not measure beyond 3 m to assess the areal extent and distribution of effluxes (Erno and Schmitz, 1996). Szatkowski et al. (2002) identified GM by collecting shallow soil gas samples within 1 m of oil and gas wells in Canada. Also in Canada, Yin et al. (2014) reported suspected GM from five wells based on elevated CO<sub>2</sub> effluxes (up to 28  $\mu\text{mol m}^{-2} \text{s}^{-1}$  [106 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>]), which were attributed to degradation of fugitive CH<sub>4</sub>. However, at the selected sites Yin et al. (2014) did not find direct evidence for CH<sub>4</sub> GM. In the United Kingdom, a survey of soil gas concentrations around abandoned oil and gas wells indicated GM through elevated CH<sub>4</sub> concentrations (compared to control sites) at 31 of 102 wells. Measurements were conducted to assess the spatial distribution of GM by collecting a total of 7 soil gas samples on either side of the well head along a ~40 m transect (Boothroyd et al., 2016). Townsend-Small et al. (2016) also identified CH<sub>4</sub> emissions averaging 336 g CH<sub>4</sub> well<sup>-1</sup> d<sup>-1</sup> from 9 of 138 selected abandoned oil and gas wells in the eastern United States. However, no information was provided on the distribution of fluxes across the well pad. Lyman et al. (2017) conducted flux measurements around natural gas wells in the United States, where CH<sub>4</sub> effluxes were as high as 658  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (reported as 38 g CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup>) 2.5 m from the well head. However, due to the method of site selection and extent of efflux measurements (93% were within 3.1 m of the well head), Lyman et al. (2017) did not assess the spatial distribution of GM around each well pad. These studies demonstrate that soil gas effluxes can be used to detect fugitive GM; however, the studies also reveal knowledge gaps and suggest that further investigation is needed to evaluate the spatial extent and distribution of CH<sub>4</sub> effluxes across well pads.

To this end, we conducted a survey of GM across selected well pads in Northeastern British Columbia, Canada, by measuring soil gas effluxes and stable carbon isotopes. The study provided an opportunity to identify and analyze the spatial distribution of fugitive CH<sub>4</sub> effluxes on the well-pad scale in a region that has historical and active oil and gas development. The objectives of this research were to: 1) identify the occurrence of fugitive GM on well pads, specifically at sites where GM was

previously reported by operators, but where follow-up inspections were unable to identify the occurrence of GM; 2) determine the spatial and to a limited degree temporal distribution of fugitive gas at sites with GM; 3) assess the suitability of the methods used in this study to identify fugitive gas effluxes, and 4) evaluate the ability of common inspection methods and current industry practice to identify GM.

## 2. Materials and methods

### 2.1. Field sites

There are six major gas plays in Northeastern British Columbia; Deep Basin Cadomin, Montney, Jean Marie, Cordova Embayment, Liard Basin, and Horn River Basin (Fig. 2). For this study, a total of 17 active well pads were selected (Table S1). Twelve of these well pads were located above the Late Devonian Jean Marie Formation, a productive carbonate platform hosting several gas pools (Gunnel Creek, Helmet, Sierra, Elleh, Ekwan). The remaining five well pads were located above Mid Devonian shales (Muskwa, Otter Park and Evie Formations) in the Horn River Basin (Fig. 2, Table S1). The Jean Marie Formation and the Horn River Basin are known for having several shallow gas bearing regions (BCOGC, 2013; Hickin et al., 2008). Previous research has suggested that wells drilled in such regions with shallow gas sources are more susceptible to GM (Bachu, 2017; BCOGC, 2013; Dusseault and Jackson, 2014; Jackson, 2014). The Jean Marie Formation and Horn River Basin are therefore regions of particular interest for studying the occurrence and distribution of GM.

At 13 of these 17 well pads, GM had been reported by the operators to the regulator. However, GM was only identified at two of the 13 sites during subsequent inspections (based on visual (e.g. bubbling in

standing water at the well head), olfactory, or auditory indicators). At the remaining 11 sites, inspections were not able to confirm the occurrence of GM at the time of investigation. At four of the 17 well pads, GM had not been reported by the operator and regulatory inspections had not been performed (Table S1).

The lithology in the region of study is expected to influence the sub-surface transport of fugitive gas (see also Section 3.2). Overburden glacial sediments (till) comprise a thick sequence of unconsolidated, layered clay, sand and gravel (BCOGC, 2013; Hickin et al., 2008). While the exact depth to the water table was not known at the sites, the subdued topography and presence of silt-clay surficial material in these regions commonly leads to highly saturated surficial soils with a shallow water table (Ferbey, 2008).

### 2.2. Soil gas effluxes

Surficial CO<sub>2</sub> and CH<sub>4</sub> effluxes were measured using a soil gas survey chamber with an Infra-red gas analyzer (IRGA) (LI-COR Inc., Lincoln, NE, LI-8100 and LI-8100-103, respectively) and a Los Gatos Research (LGR) Ultraportable Greenhouse Gas (CO<sub>2</sub> and CH<sub>4</sub>) analyzer (UGGA) (LGR, Mountain View, CA). The chamber method is based on the measurement of CH<sub>4</sub> and CO<sub>2</sub> accumulation over time in the chamber and sampling circuit. This method allows real-time and simultaneous measurements of both CO<sub>2</sub> and CH<sub>4</sub> effluxes (Sihota et al., 2011, 2013). Soil gas effluxes ( $\mu\text{mol m}^{-2} \text{s}^{-1}$  or  $\text{g C m}^{-2} \text{d}^{-1}$ ) were calculated using well established methods (Jassal et al., 2005; LICOR, 2012; Sihota et al., 2011, 2013; Forde et al., 2018) and were based on linear gas concentration changes measured in the chamber over a specified time interval, providing conservative estimates of gas effluxes (Forbrich et al., 2010; Pihlatie et al., 2013). Detection of CH<sub>4</sub> effluxes was limited by the ability to determine CH<sub>4</sub> concentration changes during the measurement interval ( $\Delta c = 0.2$  ppm, corresponding to a minimum detectable efflux of  $0.010 \mu\text{mol m}^{-2} \text{s}^{-1}$ ).

Soil gas efflux measurements were completed by placing the chamber on polyvinyl chloride (PVC) collars that were positioned radially from the well head. The collars were set up in two perpendicular transects extending from the well head to the perimeter of the well pad (20 to 40 m, depending on well pad size) in 5 to 10 m increments. One measurement was made as close to the well head as possible on one side of the well. At the collar locations, 5 cm of the topsoil was removed and the collars (20 cm ID) were inserted approximately 4 cm into the soil to provide a tight seal. To allow gas effluxes to stabilize before measurements (Law et al., 2001), collars were inserted 24 h before surveying when possible. This was done at 12 sites; however, this was not possible at the remaining five sites (Site 1, 3, 14, 15, and 16) for logistic reasons. At these sites, collars were inserted on the same day with at least a two-hour time period before measurements were conducted. Between 20 and 30 collars were surveyed over approximately 2 h at each site. The measurement interval (duration of chamber closure) was set to 3 min. Two rounds of survey measurements (within 2 h) were completed at every well pad to collect basic information on the temporal variability of soil gas effluxes. Background soil gas effluxes were also measured at three locations off each well pad, at least 100 m from the well head in three directions (at least 100 m from each other).

### 2.3. Soil gas and surface casing vent sampling and stable carbon isotopic analysis

Soil gas samples for stable carbon isotopic analysis were collected from 10 selected well pads, focusing on sites with elevated CH<sub>4</sub> and CO<sub>2</sub> effluxes. The remaining seven well pads were excluded from this analysis for a variety of reasons: CH<sub>4</sub> effluxes were below detection at Site 15; Sites 2, 3, and 12 had saturated soils, preventing gas sample collection; and Sites 4, 6 and 9 had CH<sub>4</sub> soil gas concentrations too low for isotopic analysis. In addition, soil gas samples were collected from at least one background location 100 m off each well pad. Soil gas samples

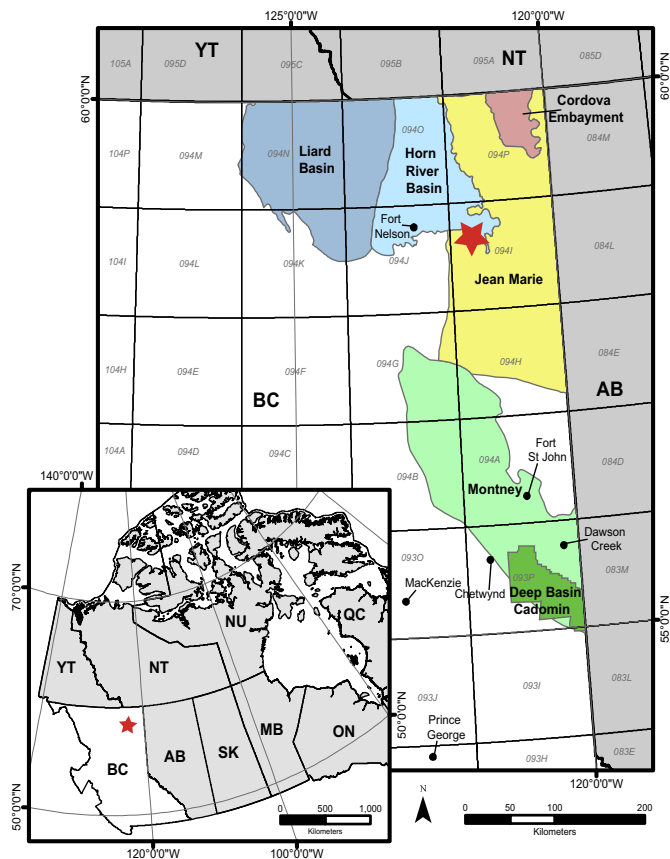


Fig. 2. Gas plays in Northeastern British Columbia, Canada (modified from BCOGC, 2012) with region of study marked by a red star. The grid follows the Canadian National Topographic System (NTS). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

were collected 30 cm below the ground surface by inserting a stainless steel probe (35 cm × 1.2 cm equipped with a 2.5 cm screen) with a slide hammer. Samples were extracted from gas impermeable polyethylene tubing (¼" ID) through a gas-tight fitting equipped with a septum and pressure gauge. During sample collection, three times the volume of the probe and tubing was purged using a 50 mL gas tight syringe (Valco Instruments Co. Inc., Brockville, ON).

SCVF gas samples for stable carbon isotopic analysis were collected from the nine wells that had an identified SCVF. Samples were collected by inserting gas impermeable polyethylene tubing (¼" ID) into the vent and covering the outlet with tape. The end of the tubing was fitted with a septum, which was pierced using a 50 mL gas tight syringe.

All samples were injected and over pressurized into 10 mL and 100 mL pre-evacuated vials (Voigt Global Distributions Inc., Lawrence, KS). The pre-prepared vials were capped with 20 mm septum stoppers (Bellco Glass Inc., Vineland, NJ) that were pre-washed in 0.1 M NaOH and baked for 20 h at 60 °C to ensure a gas-tight seal.

Stable carbon isotopic composition (<sup>13</sup>C) in CO<sub>2</sub> and CH<sub>4</sub> was analyzed at the Biogeochemistry Facility, University of Victoria (British Columbia, Canada) with established methods (Bouchard et al., 2015; Etiope et al., 2016; Niemann, 2006; Niemann and Whiticar, 2017). Stable carbon isotopic signatures are reported in the international standard notation (δ<sup>13</sup>C) relative to Vienna-Pee Dee Belemnite (VPDB). Isotopic analyses on soil gas and SCVF samples were used to determine if high CH<sub>4</sub> and CO<sub>2</sub> effluxes measured on well pads were attributed to fugitive GM. Methane in the subsurface can be of biogenic or thermogenic origin. Biogenic CH<sub>4</sub> is produced microbially from acetate fermentation or CO<sub>2</sub> reduction. Thermogenic CH<sub>4</sub> is formed from thermal maturation of organic matter at high temperatures. Due to limited kinetic isotopic fractionation, thermogenic generation of CH<sub>4</sub> from hydrocarbons produces an isotopic signature close to the parent sedimentary organic matter with δ<sup>13</sup>C-CH<sub>4</sub> values generally less negative than -50‰ (Golding et al., 2013; Schoell, 1988; Whiticar, 1999); however, the signature can be more negative depending on the source (Feinberg et al., 2018; Sherwood et al., 2017). Thermogenic values for δ<sup>13</sup>C-CO<sub>2</sub> are more variable, but tend to range between -4‰ and -20‰ (Dai et al., 2016; Qu et al., 2016). The signature of thermogenic gas may be altered due to mixing with microbially derived CH<sub>4</sub>, which tends to have a more negative δ<sup>13</sup>C-CH<sub>4</sub> signature closer to -60‰ and a δ<sup>13</sup>C-CO<sub>2</sub> value above zero (Scott et al., 1994). The C-isotope fractionation factor (α<sub>CO<sub>2</sub>-CH<sub>4</sub></sub> = [1000 + δ<sup>13</sup>C-CO<sub>2</sub>]/[1000 + δ<sup>13</sup>C-CH<sub>4</sub>]) for CO<sub>2</sub> reduction ranges from 1.06 to 1.09 and from 1.03 to 1.06 for acetate fermentation with lower values (1.005–1.03) associated with CH<sub>4</sub> oxidation (Whiticar and Faber, 1986) and thermogenic gas ranging between 1.02 and 1.04 (Smith et al., 1992).

### 3. Results and discussion

#### 3.1. Occurrence of fugitive GM on well pads

In total 385 efflux measurements were conducted on 17 well pads. Methane effluxes were not detected at any of the background locations (n = 51). On the other hand, CH<sub>4</sub> effluxes were detected on 15 of the 17 well pads at 6% to 58% of the 20–30 measurement points at each site. The 15 sites with measurable CH<sub>4</sub> effluxes included all 13 sites where GM had previously been reported by the operators. The average CH<sub>4</sub> efflux rate was 1.6 μmol m<sup>-2</sup> s<sup>-1</sup> (2.2 g CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>) and ranged from 0.017 to 180 μmol m<sup>-2</sup> s<sup>-1</sup> (0.02 to 249 g CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>) (n = 334). The average CO<sub>2</sub> efflux for all background locations was 2.6 μmol m<sup>-2</sup> s<sup>-1</sup> (9.9 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>), and effluxes ranged from 0.61 to 5.6 μmol m<sup>-2</sup> s<sup>-1</sup> (2.3 to 21 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>) (n = 51). The average CO<sub>2</sub> efflux across all well pads was 3.2 μmol m<sup>-2</sup> s<sup>-1</sup> (12 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>) and values ranged from 0.50 μmol m<sup>-2</sup> s<sup>-1</sup> to 32 μmol m<sup>-2</sup> s<sup>-1</sup> (1.9 to 122 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>) (n = 334). These results suggest the occurrence of CH<sub>4</sub> effluxes at 15 of the 17 well pads could be associated with GM. Elevated CO<sub>2</sub> effluxes, significantly above background (p = 0.004 based on a two-sample t-test with unequal variance) are likely a result of partial CH<sub>4</sub>-oxidation in the subsurface. Ten of these sites were further investigated to identify the CH<sub>4</sub> source by using stable carbon isotopes.

SCVFs were identified at 9 of 16 wells. For wells where a flow rate was measured, rates ranged from 0.10 to 2.2 m<sup>3</sup> d<sup>-1</sup> (BCGOC, personal communication, 2018). SCVF isotopic values for δ<sup>13</sup>C-CH<sub>4</sub> ranged from -51‰ to -39‰, and from -19‰ to -11‰ for δ<sup>13</sup>C-CO<sub>2</sub> (Table 1), in-line with gases of thermogenic origin (Schoell, 1980; Sherwood et al., 2017; Stolper et al., 2015; Whiticar, 1999). The α<sub>CO<sub>2</sub>-CH<sub>4</sub></sub> values for SCVF samples (ranging from 1.02 to 1.04) further suggest a thermogenic origin (Smith et al., 1992). The low value of α<sub>CO<sub>2</sub>-CH<sub>4</sub></sub> (1.02) observed in one SCVF sample (Site 8) may be indicative of partial CH<sub>4</sub> oxidation, leading to an enrichment of <sup>13</sup>C in residual CH<sub>4</sub> (Whiticar and Faber, 1986). Depending on the parent material, mixing of thermogenic gas with biogenic gas in the reservoir or, shallow gas bearing units, could produce δ<sup>13</sup>C-CH<sub>4</sub> values less than -50‰ (Golding et al., 2013; Schoell, 1988), which was generally not the case for the SCVF samples analyzed in this study (with the exception of Site 11, which showed a slightly more negative carbon isotope signature: δ<sup>13</sup>C-CH<sub>4</sub> = -51‰). Isotopic signatures of the SCVF samples were also within range of those observed in other gas bearing regions with δ<sup>13</sup>C-CH<sub>4</sub> and δ<sup>13</sup>C-CO<sub>2</sub> close to -50‰ and -20‰, respectively (e.g. Michigan Basin, USA (Stolper et al., 2015), Alberta, Canada δ<sup>13</sup>C-CH<sub>4</sub> (Lopez et al., 2017), and Mannville Group, Alberta, Canada (Cheung et al., 2010)).

**Table 1**

Effluxes for CH<sub>4</sub> and CO<sub>2</sub> co-located for the ten sites where stable carbon isotopic data (δ<sup>13</sup>C-CH<sub>4</sub> and δ<sup>13</sup>C-CO<sub>2</sub>) was collected for soil gas samples. SCVF flow rates and stable carbon isotopic data are shown from the well head for each site. C-isotope fractionation factors (α<sub>CO<sub>2</sub>-CH<sub>4</sub></sub>) for CO<sub>2</sub> are also shown for each soil gas and SCVF sample.

Site	Distance from well head (m)	CH <sub>4</sub> efflux (μmol m <sup>-2</sup> s <sup>-1</sup> )	CO <sub>2</sub> efflux (μmol m <sup>-2</sup> s <sup>-1</sup> )	Soil Gas δ <sup>13</sup> C-CH <sub>4</sub> (‰)	Soil Gas δ <sup>13</sup> C-CO <sub>2</sub> (‰)	Soil Gas α <sub>CO<sub>2</sub>-CH<sub>4</sub></sub>	SCVF (m <sup>3</sup> d <sup>-1</sup> )	SCVF δ <sup>13</sup> C-CH <sub>4</sub> (‰)	SCVF δ <sup>13</sup> C-CO <sub>2</sub> (‰)	SCVF α <sub>CO<sub>2</sub>-CH<sub>4</sub></sub>
1	40	4.2	5.3	-38	-7	1.03	0.10	-49	ND	
1	30	0.86	3.1	-41	-10	1.03				
1	20	0.56	2.2	-38	-11	1.03				
5	20	0.061	19	-48	-21	1.03	0.10	-49	-15	1.03
5	5	0.053	0.77	-47	-24	1.02				
7	10	0.44	3.1	-37	-22	1.03	0.90	-50	-11	1.04
8	15	0.083	16	-46	-17	1.03	Y-NM	-39	-19	1.02
10	15	7.5	2.8	-42	-24	1.03	0.01	-47	-13	1.03
11	20	3.3	1.3	-39	-31	1.01	Y-NM	-51	-11	1.04
13	5	ND	3.2	-50	-22	1.03	NM	ND	ND	
14	10	0.025	29	-56	-22	1.04	Y-NM	ND	ND	
16	5	0.12	6.3	-46	-23	1.02	Y-NM	-47	-11	1.04
17	5	2.2	5.0	-43	-26	1.02	Y-NM	-46	-11	1.04

ND = non-detectable.

Y-NM = SCVF detected at well head but not measured (flow rate not applicable).

Nine of the 10 well pads selected for stable carbon isotope analysis produced soil gas samples indicative of GM from a thermogenic source similar to the SCVF gas (Table 1, Fig. 3). At these locations, CH<sub>4</sub> and CO<sub>2</sub> effluxes ranged from 0.025 to 7.5  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (0.035 to 10 g CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>) (average 1.6  $\mu\text{mol m}^{-2} \text{s}^{-1}$  [2.2 g CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>]) and 0.77 to 29  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (2.9 to 110 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>) (average 7.3  $\mu\text{mol m}^{-2} \text{s}^{-1}$  [27.8 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>]), respectively. Soil gas stable carbon isotopic signatures at these sites ranged from -50‰ to -37‰ for  $\delta^{13}\text{C}\text{-CH}_4$  and -31‰ to -7‰ for  $\delta^{13}\text{C}\text{-CO}_2$ . At one site (Site 14), soil gas showed a lighter  $\delta^{13}\text{C}\text{-CH}_4$  signature of -56‰, indicating at least in part a biogenic source of CH<sub>4</sub> (Table 1, Fig. 3). At background locations, CH<sub>4</sub> concentrations were below detection limit, while  $\delta^{13}\text{C}\text{-CO}_2$  values ranged from -24‰ to -7‰. The thermogenic signatures of CH<sub>4</sub> detected in soil gas appear to be from the same origin as the SCVF gas but with less negative  $\delta^{13}\text{C}\text{-CH}_4$  values and more negative  $\delta^{13}\text{C}\text{-CO}_2$  values (Fig. 3). The <sup>13</sup>C-CH<sub>4</sub> enrichment in soil gas compared to SCVF gas suggests that CH<sub>4</sub> was at least partially oxidized as it migrated through the soil (Fig. 3). However, the data points do not plot along a single oxidation trend line because the CO<sub>2</sub> produced from CH<sub>4</sub> oxidation can mix with background dissolved inorganic carbon (DIC) that has a variable isotopic signature. Furthermore, the proportion of background DIC versus produced CO<sub>2</sub> likely varies among sampling locations, thereby resulting in different  $\delta^{13}\text{C}\text{-CO}_2$  values affected by DIC. Aerobic oxidation is further suggested by the  $\alpha_{\text{CO}_2\text{-CH}_4}$  for soil gas samples ranging from 1.01 to 1.03 in 9 out of 13 samples (Table 1). Overall, stable carbon isotope results indicate that GM from at least nine of the well pads originated from a thermogenic source, with soil gas isotopic signatures similar to SCVF signatures, albeit with compositions slightly altered by oxidation processes.

### 3.2. Spatial and temporal distribution of fugitive gas

The spatial distribution of effluxes varied for each site and showed no correlation between the magnitude of efflux or the proximity to the well head ( $R^2 = 0.007$ , Fig. S1). Although the highest CH<sub>4</sub> effluxes were measured within 5 m of the well head at five well pads, at the remaining 10 well pads the highest effluxes were measured between 10 m and 40 m from the well head (Table 2). In five instances elevated CH<sub>4</sub> effluxes were measured 10 m or more away from the well head, while measurable effluxes were not seen around the well head (e.g. CH<sub>4</sub> effluxes of 4.8, 0.083, 3.9, 0.12, and 0.025  $\mu\text{mol m}^{-2} \text{s}^{-1}$  [6.7, 0.12, 5.4, 0.17, and 0.035 g CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>] at Sites 2, 8, 11, 16, Fig. 4 and Site 14 Fig. S2). For CO<sub>2</sub>, the highest efflux was within 5 m of the well head at six sites (Sites 3, 4, 8, 13, 16, and 17). These effluxes ranged

**Table 2**

Highest CH<sub>4</sub> effluxes measured with distance from well head with average background and site CO<sub>2</sub> effluxes and, highest CO<sub>2</sub> effluxes measured with distance from well head. Highest CH<sub>4</sub> and CO<sub>2</sub> effluxes were not always co-located. Background samples were collected at least 100 m away from the well head in similar vegetation.

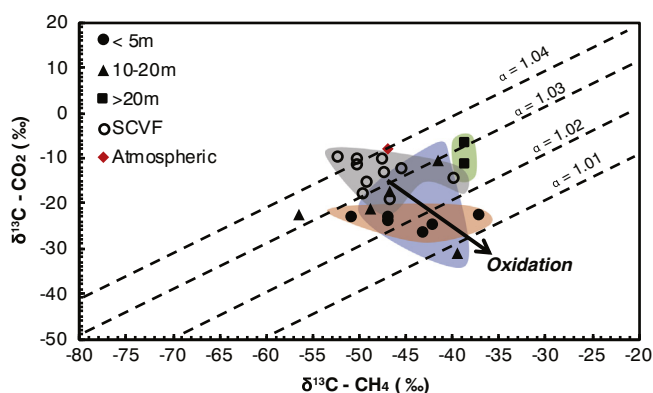
Site	Highest CH <sub>4</sub> efflux ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Distance from well head (m)	Average background CO <sub>2</sub> efflux ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Average site CO <sub>2</sub> efflux ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Highest site CO <sub>2</sub> efflux ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Distance from well head (m)
1	4.2	40	1.6	2.4	7.7	10
2 <sup>a</sup>	4.8	20	5.7	2.9	9.1	20
3	1.4	15	2.1	3.1	16	0
4	0.065	0	1.1	2.6	18	0
5 <sup>a</sup>	1.3	0	0.63	3.2	20	20
6	0.31	0	1.6	2.7	9.3	20
7	0.44	10	1.7	3.9	10	20
8	0.083	15	3.4	6.4	27	5
9	0.34	15	1.1	1.9	3.7	15
10 <sup>a</sup>	7.5	15	0.89	1.2	7.3	20
11	3.9	20	0.79	0.80	8.1	15
12	180	0	0.94	1.8	10.1	10
13	ND	ND	3.8	2.8	7.1	0
14	0.025	10	3.1	12	32	10
15	ND	ND	6.7	6.4	19	15
16	0.12	15	2.2	3.2	9.6	5
17	2.2	5	0.71	1.9	5.9	5

ND = non-detectable.

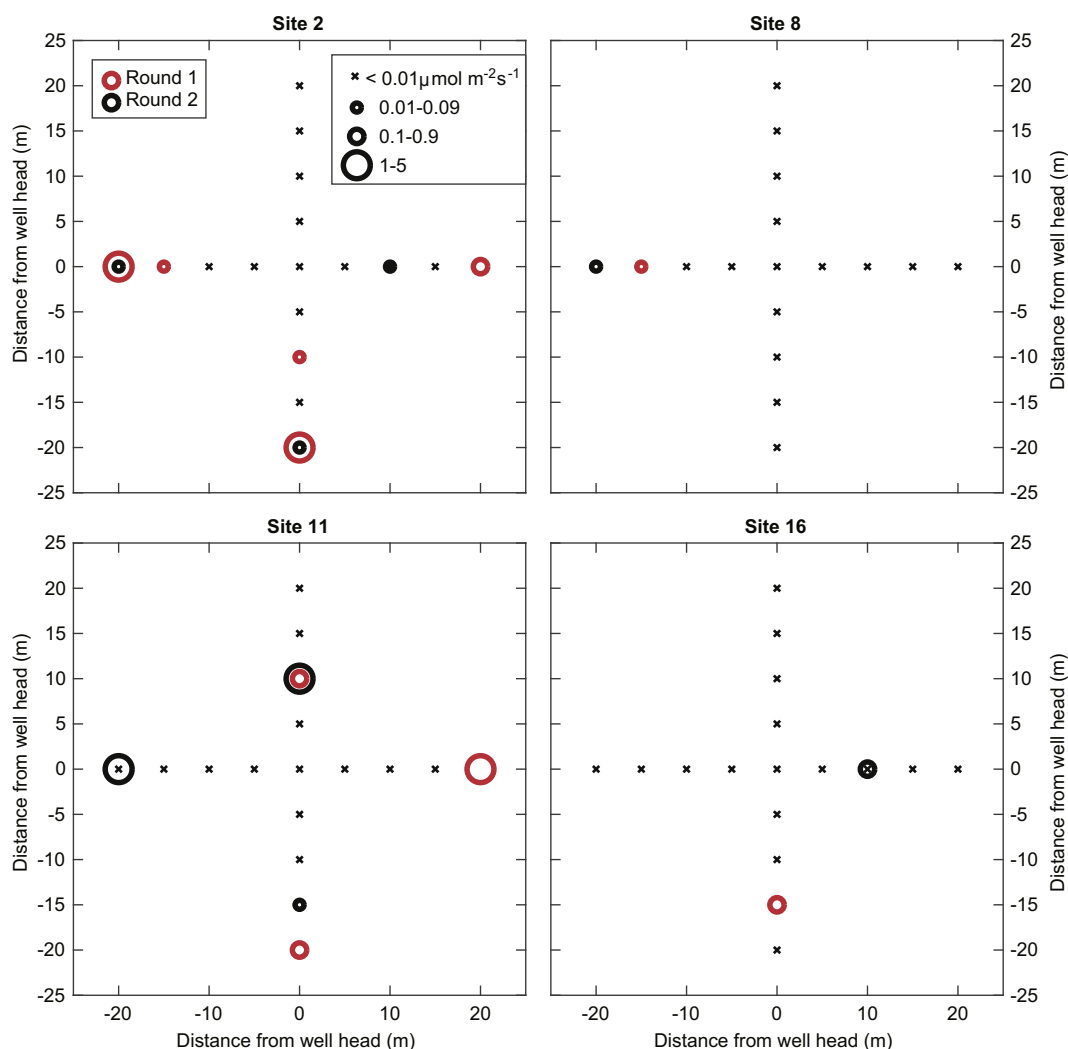
<sup>a</sup> Denotes sites where some effluxes occurred by ebullition.

from 5.9 to 27  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (22 to 103 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>). For the remaining 11 well pads, the highest CO<sub>2</sub> efflux occurred between 10 m to 20 m from the well head and ranged from 3.7 to 32  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (14 to 122 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>) (Table 2). Isotopic data further supports that the occurrence and magnitude of fugitive GM is unrelated to the distance from the well head. An equal number of soil gas samples with thermogenic CH<sub>4</sub> signature were observed >10 m from the well head as <5 m from the well head. In addition, there was no correlation with the distance to the well head and the isotopic signature (e.g. there was no systematic enrichment in <sup>13</sup>C due to oxidation with distance from the well head) (Fig. 3).

The occurrence of effluxes farther away from the well head may be due to the low permeability silt-clay soils at these sites, which likely resulted in lateral gas transport leading to fugitive effluxes along preferential pathways present in the surficial soils. In this region of Northeastern British Columbia, the surficial geology consists of organic materials, silt and clay-rich morainal and glaciolacustrine deposits (Hickin et al., 2008). Lateral subsurface gas transport has been observed at other field sites where low permeability soils prevented vertical GM (Green et al., 2015). For example, at two separate landfill sites, soil gas with elevated CH<sub>4</sub> was measured 35 m (Christophersen and Kjeldsen, 2001) and 90 m (Kjeldsen and Fischer, 1995) from the landfill, providing further evidence for lateral gas transport beneath low permeability soils. Geophysical monitoring of a controlled natural gas injection experiment also demonstrated the occurrence of subsurface lateral CH<sub>4</sub> GM up to 18 m downgradient from the injection location (Cahill et al., 2017; Steelman et al., 2017). In this case lateral transport occurred despite a shallow release depth (4.5 and 9 m below the ground surface) and only modestly heterogeneous soils. It can be expected that for a higher level of heterogeneity and a deeper release of gas into the formation, lateral transport can be more pronounced. Heterogeneities in low permeability soils due to grain size variations or the presence of fractures tends to produce preferential pathways (Delahaye and Alonso Pérez de Agreda, 2002; Šimunek et al., 2003; Tomlinson et al., 2003), which may have led to the occurrence of GM and effluxes at random locations at the surface (Fig. 4). Lateral spreading in CH<sub>4</sub> effluxes was not assessed in other studies on fugitive GM (Erno and Schmitz, 1996; Lyman et al., 2017; Szatkowski et al., 2002), since these studies did not measure fluxes beyond 5 m from the well head. Variations in the distribution of



**Fig. 3.** Stable carbon isotope ratios for CH<sub>4</sub> and CO<sub>2</sub> soil gas and SCVF samples with C-isotope fractionation factors ( $\alpha_{\text{CO}_2\text{-CH}_4}$ ). Soil gas samples are shown with distances from the well head. With one exception, soil gas samples show a signature from the same source as the SCVF gas, subjected to various degrees of oxidation. There is no correlation between thermogenic soil gas and distance to the well head. An equal number of soil gas samples had thermogenic signature >10 m from the well head as those <5 m from the well head.

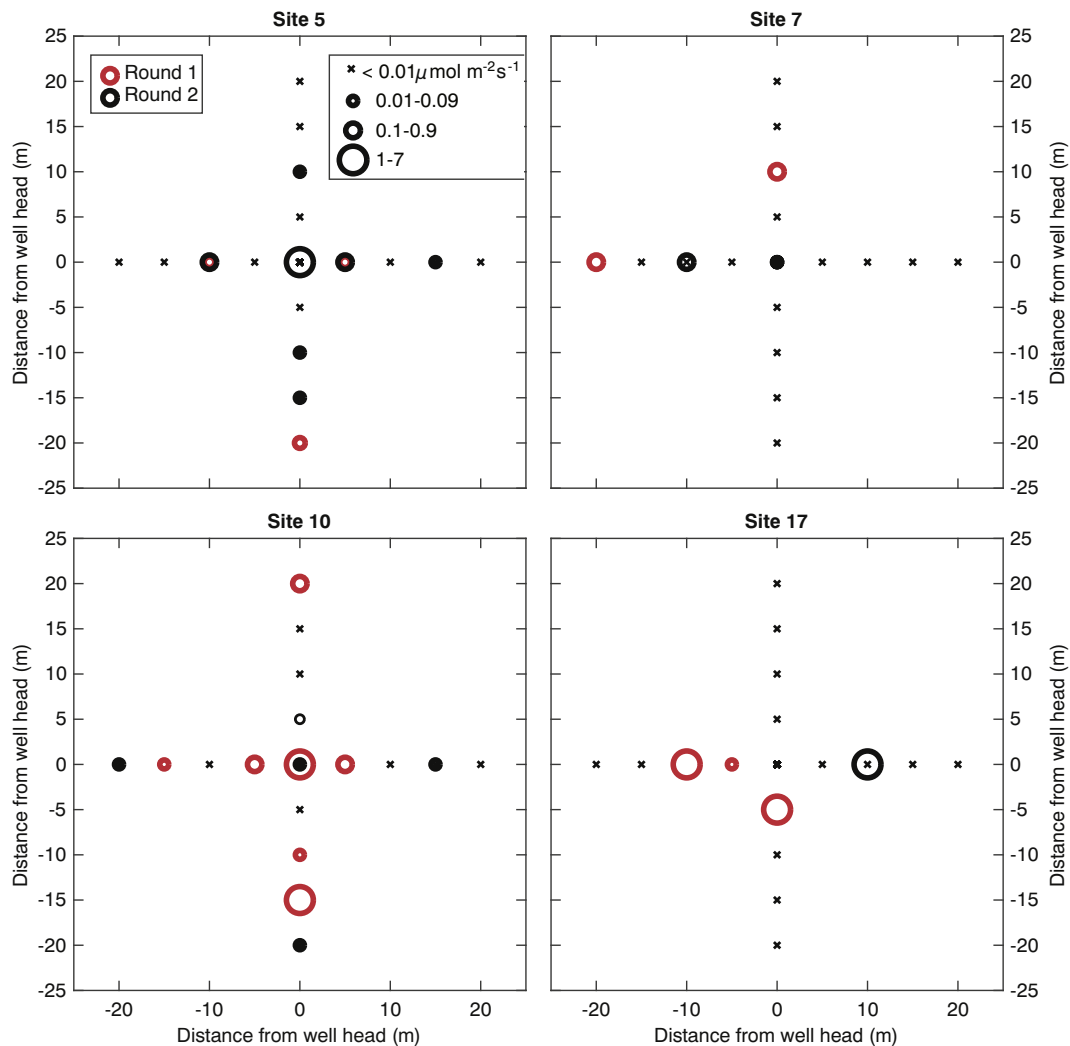


**Fig. 4.** Methane effluxes ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) measured in two rounds at Sites 2, 8, 11, and 16. Sites were selected to show the spatial and temporal variation on the well pad. Legend indicated in the grid for Site 2 applies to all sites. Methane effluxes were only detected  $>10$  m from the well head at all four sites. Crosses correspond to measurements with non-detectable effluxes.

fugitive gas could also be influenced by different well drilling methods, preferential  $\text{CH}_4$  oxidation,  $\text{CH}_4$  exsolution, and/or different lithologies and heterogeneities (presence of more permeable soils and/or soils with more preferential pathways) (Jackson, 2014) at the other field sites.

The magnitude of  $\text{CH}_4$  effluxes was not always the same between both rounds of measurements despite being measured within 2 h of each other (e.g. Sites 5, 7, 10, and 17, Fig. 5 and Table 3). At 10 sites, the highest efflux was at least one order of magnitude greater in one round of measurements compared to the second round of measurement (Table 3). This temporal variability was not always related to the distance or direction from the well head. In some cases, effluxes were seen next to the well head in one round, but then only 10 m away in the second round (e.g. Site 7, Fig. 5). The occurrence of fluxes was also different between measurement rounds. For example, at Site 17  $\text{CH}_4$  effluxes were detected at three locations in the first round, but only at one location in the second round. Locations with varying  $\text{CH}_4$  effluxes were seen between 0 and 20 m from the well head (Fig. 5 and Table 3). Temporal variation between rounds of measurements was not seen for  $\text{CO}_2$ ; instead, effluxes tended to be similar in both rounds of measurements (Table 3). Although other factors such as, moisture content and barometric pressure, can affect the temporal variability of GM, measuring these parameters at each field site was beyond the scope of this study. Therefore, we focus on the known lithology in the region and its effect on gas transport.

Distribution of gas pressure is controlled by various factors including local variations in permeability and water content. Gas can become entrapped in saturated soils with low permeability. Gas breakthrough to the ground surface will occur if the gas pressure (buoyancy forces) overcomes the capillary pressure (Gorody, 2012). As gas pressure builds up, it can result in discontinuous sporadic emissions at surface (Forde et al., 2018; DelSontro et al., 2015). Evidence of discontinuous  $\text{CH}_4$  GM to the surface on short time scales ( $<3$  min, corresponding to the period of chamber closure) was seen in this study during some dynamic closed chamber measurements conducted on the well pads. In most instances, a constant flux of  $\text{CH}_4$  was measured based on a linear concentration increase during a closed chamber measurement (Fig. 6a). On the other hand, three sites had locations where the concentration increased in a stepwise manner (Sites 2, 5 and 10, Table 2). During one event at Site 2,  $\text{CH}_4$  concentrations increased in a stepwise fashion from 3.8 ppm to 10 ppm and then to 22 ppm (Fig. 6b). A step-wise increase in  $\text{CH}_4$  gas concentrations during a closed chamber measurement suggests episodic and rapid buoyancy-driven gas transport from saturated media (ebullition) (Goodrich et al., 2015; Sihota et al., 2013). The episodic nature of these effluxes indicates intermittent releases of over-pressurized gas which likely explains the temporal variability observed in  $\text{CH}_4$  effluxes. Such behavior was also seen at a denatured fuel-grade ethanol contaminated site (Sihota et al., 2013). In addition, localized and temporally elevated  $\text{CH}_4$  effluxes were observed in a controlled natural gas release experiment (Cahill et al., 2017; Forde et al., 2018) and on well pads



**Fig. 5.** Methane effluxes ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) measured at Sites 5, 7, 10 and 17 in two rounds of measurements, each within 2 h of each other. Sites were selected to demonstrate temporal variability. Legend indicated in the grid for Site 5 applies to all sites. Methane effluxes are not consistent between both rounds of measurements. Crosses correspond to measurements with non-detectable effluxes.

**Table 3**

Effluxes in two rounds for  $\text{CO}_2$  and  $\text{CH}_4$  measured at one location for sites 2–17 (Site 1 only had one round). All measurements were conducted within 2 h of each other. Locations on each site were selected to demonstrate variability between rounds of measurements. Fluxes are given with distances from well head at the respective site.

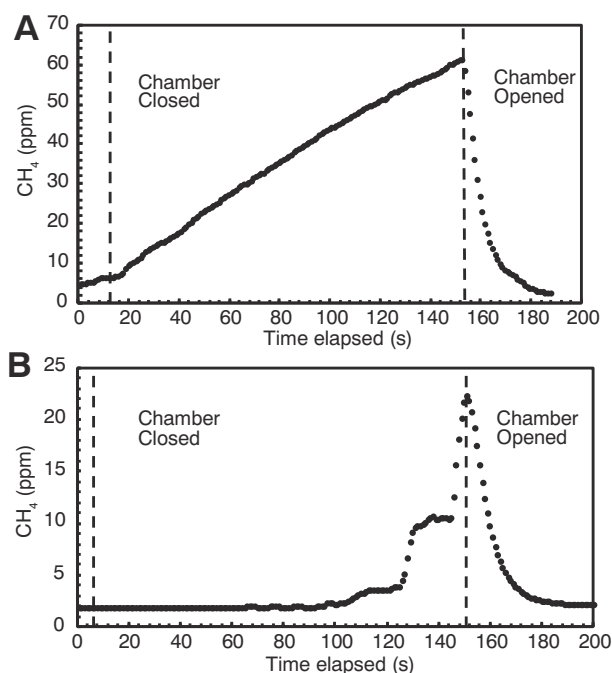
Site	Round 1 $\text{CH}_4$ efflux ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Round 2 $\text{CH}_4$ efflux ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Distance from well head (m)	Round 1 $\text{CO}_2$ efflux ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Round 2 $\text{CO}_2$ efflux ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Distance from well head (m)
2	4.8	0.067	20	9.1	9.1	20
3	0.028	1.4	15	16	11	0
4	0.065	0.028	0	16	18	0
5	1.3	0.96	0	20	19	20
6	0.30	0.31	0	9.3	8.2	20
7	0.44	ND	10	8.7	9.6	20
8	0.083	ND	15	27	28	5
9	0.34	0.07	15	3.7	3.4	15
10	7.5	ND	15	7.3	8.3	20
11	ND	3.9	20	8.1	7.7	15
12	180	171	0	10	10	10
13	ND	ND	ND	7.1	6.9	5
14	0.025	0.017	10	32	31	10
15	ND	ND	ND	19	21	15
16	0.12	ND	15	9.6	8.8	5
17	2.2	ND	5	5.9	5.1	5

ND = non-detectable.

in Utah (Lyman et al., 2017). However, none of these studies demonstrated that  $\text{CH}_4$  effluxes have temporal variability while also extending laterally beyond 5 m from the well head.

### 3.3. Suitability of the methods to detect fugitive gas

The results of our field study demonstrate that effluxes, supported by stable carbon isotope data, can be a meaningful tool to identify GM on well pads, especially if no visual indicators are present. Gas migration farther away from the well head combined with surficial effluxes in unpredictable locations suggests that conducting spatially discrete survey measurements reaching to greater distances from the well head are beneficial to ensure appropriate site characterization. Yin et al. (2014) attempted to capture the spatial distribution of fugitive gas across well pads by using a hand-held gas analyzer to measure  $\text{CH}_4$  concentrations. However, wind speed and direction significantly interfered with measurements, suggesting this technique is not necessarily suitable to reliably detect GM on oil and gas well pads. Flux chambers, on the other hand, are not significantly affected by wind speed and are able to locally measure  $\text{CH}_4$  effluxes directly attributable to GM. Flux chambers have also been used to characterize  $\text{CH}_4$  migration in various field conditions including: on well pads to identify fugitive GM (Erno and Schmitz, 1996; Lyman et al., 2017; Townsend-Small et al., 2016; Yin et al., 2014); at a hydrocarbon contaminated site to delineate contaminant



**Fig. 6.** a) Evidence of a linear increase in CH<sub>4</sub> concentrations to 61 ppm at Site 11. b) Evidence of CH<sub>4</sub> migration by ebullition with concentrations increasing stepwise to 22 ppm at Site 2. Only data from three sites were indicative of ebullition and thus these events did not influence the overall interpretation of effluxes for the study, which was based on the linear approach.

source zones (Sihota et al., 2013); during a subsurface controlled natural gas release (Cahill et al., 2017; Forde et al., 2018); and at landfills to monitor CH<sub>4</sub> migration (e.g. Park and Shin, 2001). Advantages of survey chambers are ease of transport across a site and the opportunity to target multiple measurement locations within one day.

The observed temporal variability of effluxes also suggests that investigations targeting identification and quantification of GM could benefit from more frequent or continuous monitoring. Previous studies have demonstrated that effluxes can vary diurnally and seasonally. Soil gas effluxes tend to be lower during the daytime and in the winter (Baldocchi et al., 2012; Klusman et al., 2000; Korczynski et al., 2010; Sihota et al., 2016). Continuous monitoring can be done with long-term flux chambers connected to gas analyzers (Sihota et al., 2011; Forde et al., 2018). Long-term chambers provide a continuous data set and are well-suited to monitor the temporal variability in GM. The continuous long-term measurements also have the ability to capture irregularities in effluxes, such as ebullition. These events are important to detect as they can emit a significant mass of CH<sub>4</sub> to the atmosphere (DelSontro et al., 2015). Long-term measurements could provide insight on these variations to better inform when detailed monitoring should be conducted. In addition, the results could reveal if fugitive CH<sub>4</sub> effluxes are being under- or overestimated, depending on the time of measurements. However, the chamber method has limitations in fully capturing the spatial distribution of effluxes, especially if measurements are not taken across a well pad and only at select locations. In our study, and others using the chamber method, it is possible that elevated CH<sub>4</sub> effluxes on the well pad were missed because measurements were restricted to select locations. Soil gas effluxes, along with other measurements at or above ground surface, may also not detect fugitive GM if CH<sub>4</sub> oxidation occurs at depth; particularly if well leakage occurs in the saturated zone and is overlain by a deep unsaturated zone. Such observations were made in the Piceance Basin, Colorado, where the authors concluded that CH<sub>4</sub> was oxidized in the unsaturated zone before reaching the ground surface (McMahon et al., 2018). Some studies have used aircraft and vehicle based measurements to achieve a better aerial estimate of fugitive CH<sub>4</sub> across oil and gas regions (Atherton

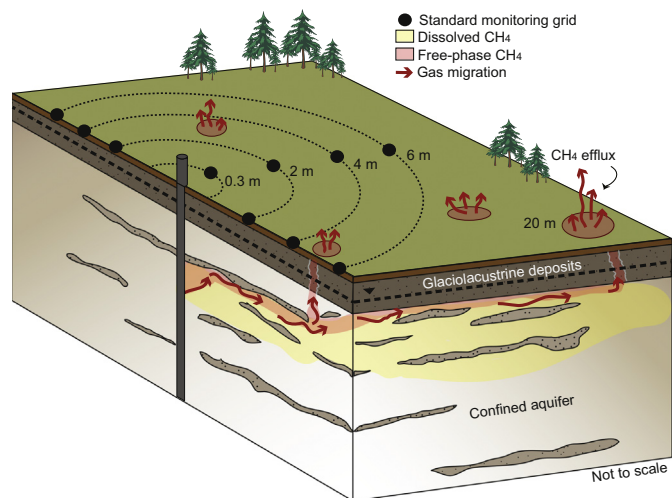
et al., 2017; Brantley et al., 2014; Caulton et al., 2014; Johnson et al., 2017; Lan et al., 2015). The eddy covariance method has also been used to measure CH<sub>4</sub> emissions over extended areas such as in a wetland (Rinne et al., 2007), rice field (Alberto et al., 2014), and the arctic tundra (Wille et al., 2008) and could be applied to oil and gas well pads. However, aerial methods are often based on a few survey campaigns that may not capture high emission events or site specific effluxes (Brandt et al., 2014). Total measured emission rates may also include CH<sub>4</sub> sources from SCVFs, flares, leaky pipelines, oil spills etc. and do not directly target surface gas effluxes due to GM. Soil gas flux chambers can provide a site-specific understanding regarding the extent and variability of surface gas effluxes related to GM. Overall, flux chambers and stable carbon isotopes proved to be a suitable method to detect fugitive gas, provided adequate spatial resolution and could be combined with methods that capture the full aerial extent of emissions.

### 3.4. Ability of methods used by industry to identify GM

GM was identified at 15 of 17 well pads: two with previously identified GM (Site 3 and 11), 11 with GM reported by the operators, but unconfirmed in subsequent inspections, and two with no previous reports on GM (Table S1). The inability to identify and confirm GM at 11 sites with previously reported GM suggests that inspections based on visual, olfactory or auditory indicators may be insufficient to detect GM. Along with the 11 sites with unconfirmed GM investigated in this study, the BCOGC (2013) reported 51 wells where GM was observed at one point, but not again in subsequent inspections. The identification of GM at sites where not previously observed and with the SCVFs below the rate requiring remedial action (<300 m<sup>3</sup> d<sup>-1</sup>) (BCOGC, 2018) has important implications to current industry practice for detecting and monitoring GM at oil and gas production sites.

If GM is identified (usually through bubbling around the well head), operators are requested to complete further field testing. One component of the field testing requires operators to conduct a soil vapour survey around the well head. Inspection and field survey methods often rely on the assumption that GM can be identified through visual (or less likely auditory and olfactory) indicators, such as bubbling at the well head, and will follow a pattern concentrated around the well. Gas samples are collected from 30 cm depth and analyzed on site for hydrocarbons. Samples must be collected 30 cm from the well head in four directions (every 90°) to a minimum distance of 6 m from the well head with spatial increments of 2 m (Fig. 7). If gas is detected at a distance of 6 m, then the sampling must continue until the extent of GM has been identified (BCOGC, 2018). Our study revealed several instances where GM did not occur within the predefined survey area, but was identified at distances 10 m or more from the well head. Our results also show that, although GM can occur near the well head and then dissipate within 6 m from the well head, the spatial extent could still be under predicted as GM may occur at random locations farther away from the well head (Fig. 7), a pattern that was observed at 10 well pads in our study.

Our study demonstrates that spatial and temporal variability could explain inconsistent site monitoring results, further supporting that monitoring methods would benefit in some instances from more frequent or continuous measurements with a greater spatial extent. While these results are applicable to the field locations and regulations in British Columbia, they also have global implications for monitoring GM. For example, to our knowledge, Pennsylvania is the only state in the U.S. that regulates GM. If GM is suspected, the operator must conduct a field survey to determine the location and extent of GM. There is no specification or requirements on the method of surveying the field site (The Pennsylvania Code, 2011). Under certain circumstances, GM testing is required in Alberta, Saskatchewan, and Newfoundland, Canada. These provinces recommend the same soil gas survey protocol



**Fig. 7.** Cross section of a conceptual diagram depicting a well with fugitive GM in a confined aquifer. Regions of low permeability may lead to lateral gas transport until breakthrough via preferential pathways to the ground surface. Methane effluxes can occur in unpredictable locations, potentially far from the well head. Black dots marked with distance from the well head indicate standard industry practice in Western Canada for selecting soil gas measurement locations to check for GM surrounding an oil and gas well.

as in British Columbia (AER, 2003; Government of Saskatchewan, 2015; Pretch and Dempster, 2017).

Both the spatial and temporal variations in effluxes measured in this study demonstrate that surface gas effluxes due to GM may occur in an unpredictable manner that cannot always be delineated through measurements around the well head (Fig. 7). Therefore, monitoring with increased spatial coverage across the entire well pad, and possibly continuously, are approaches that may: enhance identification of GM when there are no visual indicators; provide a more accurate delineation of the lateral extent of GM; and contribute to a better quantification GHG emissions from GM.

#### 4. Conclusions

Survey chamber effluxes and stable carbon isotopes from soil gas and SCVF samples were used to identify the occurrence, origin, spatial and, to a lesser degree temporal variability of fugitive GM from 17 well pads in Northeastern British Columbia, Canada. Our study results provided evidence for GM at 15 of these 17 sites including 11 sites where GM was reported by the operator, but could not be confirmed in subsequent inspections and, two sites where GM had not been reported previously. These results suggest that conventional indicators, such as bubbling in standing water around the well head, may not be sufficient to identify GM.

Observed CH<sub>4</sub> effluxes were spatially variable and temporally episodic across the sites. In five cases, GM was only detected at distances >10 m from the well head, and at 10 sites the highest CH<sub>4</sub> efflux was at least one order of magnitude greater in one round of measurements compared to the other round of measurements. Preferential and discontinuous lateral GM suggests that gas transport was strongly influenced by heterogeneous and low permeability soils. These results imply that surveys in the direct vicinity of the well head may not fully capture the occurrence or extent of GM.

Confirmation of GM at all 13 sites with previously reported GM suggests that chamber-based gas efflux methods can effectively identify GM, in particular if accompanied by stable carbon isotope analyses. Stable carbon isotope signatures indicated a thermogenic signature similar to the signatures seen in SCVFs, yet partially affected by oxidation, at nine out of ten surveyed well pads.

Monitoring fugitive CH<sub>4</sub> emissions at oil and gas production sites is an increasingly important component to quantify and address GHG emissions from the oil and gas sector. Subsurface-derived CH<sub>4</sub> emissions from leaking oil and gas wells may go undetected without the appropriate monitoring techniques. The results of this study are applicable on a global scale, demonstrating that to effectively detect and monitor fugitive GM, spatially discrete measurements across well pads may be beneficial, possibly amended by longer-term continuous measurements. We demonstrate that effluxes and soil gas stable carbon isotopes are useful tools to identify fugitive GM.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2018.10.217>.

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