Research Project ES-Wells-2021-02 Technical Report

Towards Optimizing Well Plug and Abandonment in British Columbia through Data Analytics, Field Investigations and Predictive Modelling

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Executive Summary

Currently, the integrity of plugged and abandoned (P&A'd) wells in BC, while generally considered to be high, is poorly constrained. To date, no studies have sought to rigorously evaluate historic P&A performance, even though such research could provide insights to guide more effective regulation and optimize ongoing P&A activities. Consequently, significant knowledge gaps persist with respect to how existing P&A's are performing and what constitutes an optimal P&A configuration. Here, we conducted research that sought to evaluate historic P&A performance in BC with a view to informing regulatory policy and optimizing P&A activities during the forthcoming wave of abandonments. The project consisted of 3 synergistic work packages (WP1 – 3), including: 1) Collation and analyses of existing data towards understanding P&A'd well integrity, 2) Field assessment of P&A well integrity in BC, and, 3) Numerical modelling of representative P&A'd well designs.

In WP1, results from recent aerial methane (CH_4) surveys focused on P&A'd wells in BC were reviewed, showing they are representative of the wider P&A'd well population and that the overall incidence rate for integrity failure of surveyed wells is ~5%. Fugitive gas release from integrity compromised P&A'd wells was observed to be generally small in magnitude and likely of limited significance in overall GHG emissions compared to other emission sources (e.g., dairy cattle or similar). It was also shown that prevailing weather conditions such as temperature, wind speed and barometric pressure regimes will likely determine the number of CH_4 detections made during such surveys. Meanwhile, statistical analyses using data associated with survey wells suggests that surface casing vent flow (SCVF) during active life is potentially a key indicator for integrity failure to occur post-abandonment. Consequently, wells known to have suffered SCVF during their active life should be prioritized for monitoring and stewardship post abandonment as they present a greater chance for sub-optimal integrity to develop post-abandonment.

In WP2, we conducted state of the science field investigations at ten P&A'd wells in BC that can broadly be considered as unconventional, finding that two were exhibiting signs of integrity failure and releasing CH_4 into the atmosphere. However, the magnitudes of CH_4 release from these wells was very small, likely contributing minimally to overall GHG emissions in the region. Additionally, it was shown that CO_2 was co-emitting with CH_4 around these wells, likely due to aerobic CH_4 oxidation converting fugitive CH_4 to CO_2 in the shallow soils. This observation highlights the potential for natural CH_4 attenuation in soils to limit GHG emissions associated with integrity-compromised wells. Moreover, we observed highly variable and elevated CO_2 fluxes at several P&A'd wells where no anomalous CH_4 fluxes were detected. The source of this CO_2 is unclear at present but could be linked to some form of P&A'd well integrity failure.

In WP3, we undertook a proof of concept modelling exercise showing that inclusion of defective annular cement (that is expected to be the most likely cause of integrity failure) in model domains can replicate observed CH_4/CO_2 emissions around a potentially integrity compromised P&A'd well. Overall, these results show that integrity of annular cement is a key factor during P&A activities that if understood sufficiently could lead to more effective P&A design and remedial operations. Modelling tools such as demonstrated here could play an important role in the development of a risk-based approach to P&A design and lead to better constraint on the most likely leakage configurations, better

predict and manage resultant environmental risks and aid in design of more optimal and effective P&A scenarios and remedial operations.

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Introduction and Context

British Columbia hosts an extensive historic and ongoing onshore oil and gas industry that has seen some 24,802 energy wells constructed in the province over the past 100 years[1,2]. Currently, some 7,614 (i.e. ~30%) of these wells have been plugged and abandoned (P&A'd); starting more than 60 years ago and continuing at a generally increasing rate up to the present day (Figure 1). A recent study reviewed regulatory data held on wells in BC in the context of P&A, reporting that many varying abandonments have been deployed including in different borehole types (e.g. open, cased, vertical and deviated wells), P&A configurations (e.g. number, type and configuration of plugs) and installation methods (e.g. dump bail, cement circulation etc.)[1]. These data show that approximately 63% of P&A'd wells in BC have one plug (including a bridge plug and cement cap) or two[1], while the remaining 37% of currently abandoned wells have more than 2 plugs of varying lengths and locations within a well. Decommissioning of these wells occurred against a backdrop of evolving regulations and P&A technologies. Consequently, P&A configurations and methods used to P&A a given well will have varied depending on its vintage, due to increasingly detailed guidance which has been generated in a stepwise manner since resource development began. Most notably specific guidance in BC has been provided in key documents released in 1991, 2003, 2010 and most recently 2022, a summary of which is provided in table 1. Further description on the evolution of P&A guidance in BC, including diagrams of how P&A configurations for the same well may have differed with time, is provided in appendix 1. A diagram showing an example of two varying P&A configurations of BC legacy wells to highlight how different some wells may be constructed and then P&A'd is shown in figure 2.

Table 1: Evolution of guidance on P&A in BC.

Year	P&A Guidance/Regulations Document
1991	Energy Resources Conservation Board (ERCB). 1991. Drilling and completions operations guide.
2003	EUB guide. 2003. Well abandonment guide.
2010	Energy Resources Conservation Board (ERCB). 2010. Directive 020.
2022	BC oil and gas commission. 2022. Well decommissioning guidelines.

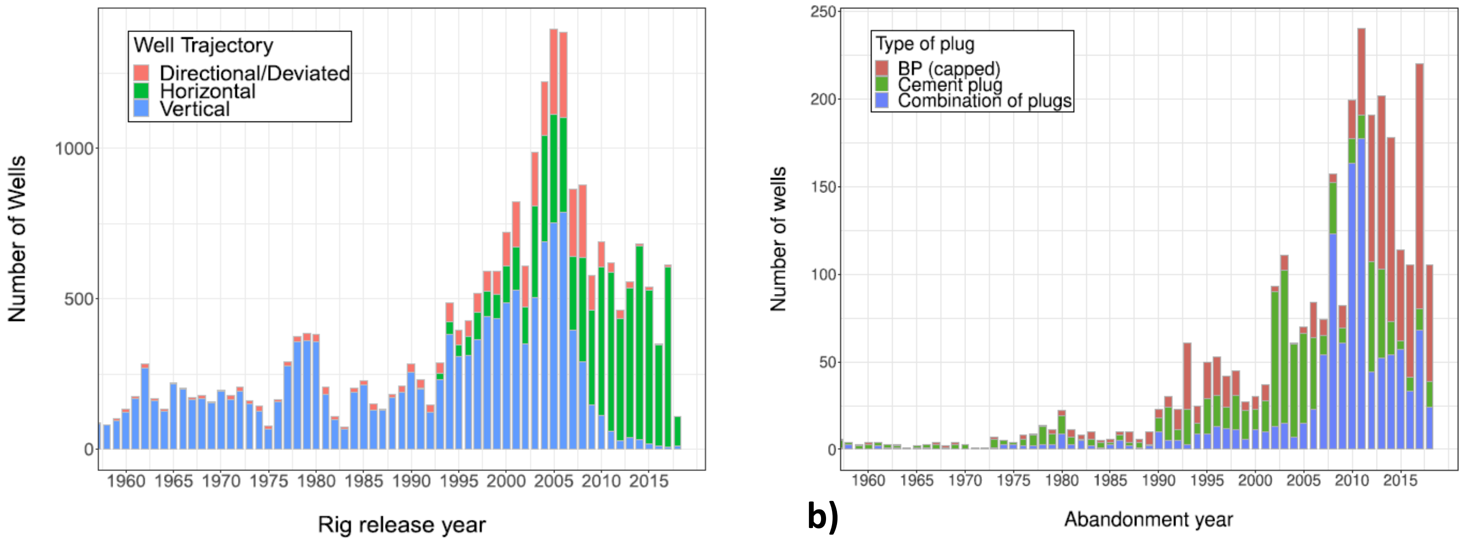


Figure 1: a) From Trudel *et al.* (2019). Wells released per year in BC showing the significant upturn in unconventional development. **b)** P&A's per year in BC and type of plug utilized showing varying configurations, an increasing number of abandonments and increased use of bridge plugs.

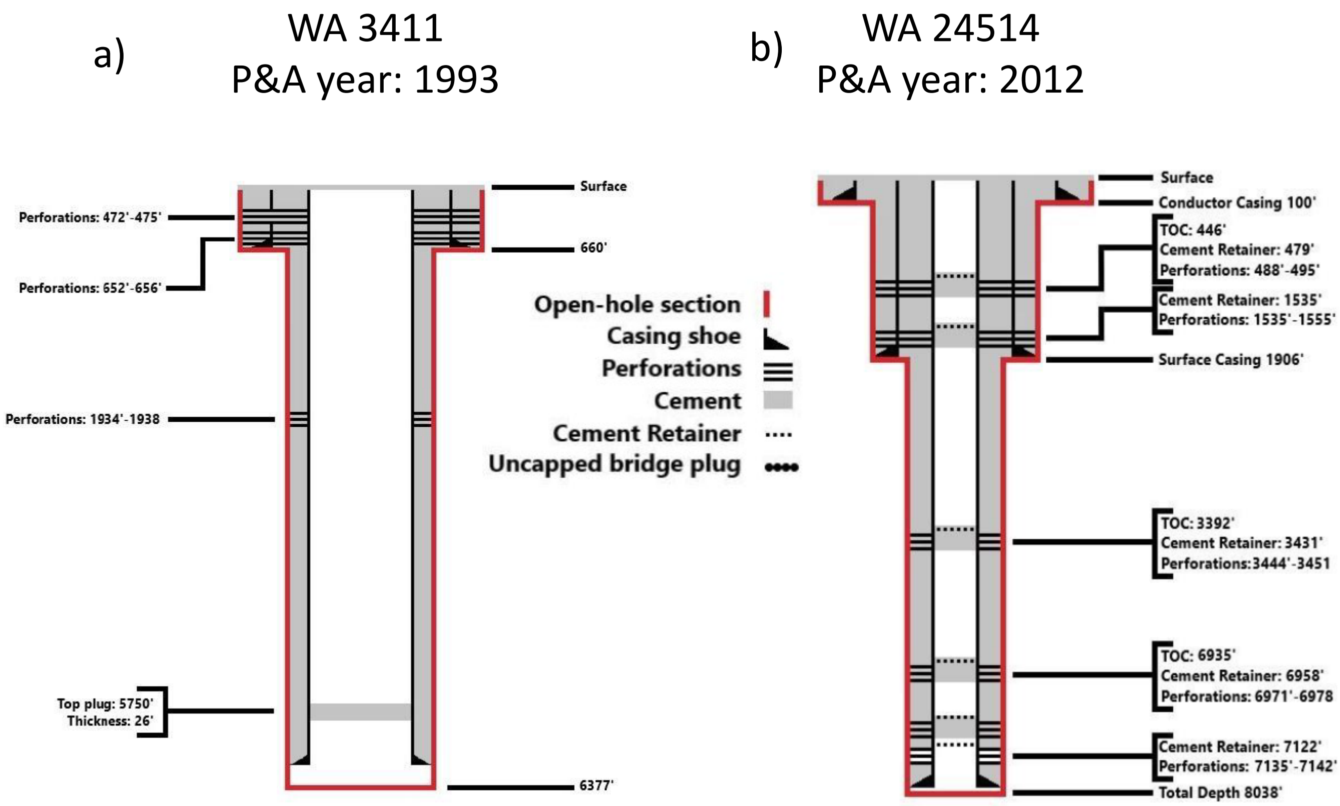


Figure 2: Example of 2 P&A configurations for decommissioned wells in BC of differing vintage, including; a) WA 3411, a gas well completed in 1976 and produced until 1988 before being abandoned in 1993. b) WA 24514, a gas well completed in 2009, going into production the same year before being P&A'd three years later in 2012.

Despite the seemingly large number of P&A's completed in BC to date, the majority of energy wells (i.e. >16,000 or some 70% of the total well population) still remain to be P&A'd in the coming decades. During this unprecedented wave of forthcoming P&A activities a significant proportion of the wells to be P&A'd are what can be considered "unconventional" (i.e. typically horizontal and hydraulically fractured) gas production wells. These wells typically exploited low permeability shales to extract gas and were completed during the unconventional resource boom of the late 1990's to early 2010's (Figure 1). During this time, approximately 14,000 such wells were installed in BC (primarily in the Montney and Horne River Basins), many of which are now approaching the end of their useful lives and will soon need to be efficiently and effectively abandoned[1].

When a petroleum well is P&A'd, the main aim is to fully and totally isolate the well and prevent any fluid flow within, along or outside of it in perpetuity[3]. Interestingly, testing of P&A quality and effectiveness is generally limited considering the long-term perspective of well P&A, typically relying upon a short duration (i.e. 10 minute) positive pressure test, with limited follow up monitoring to ensure the wells remains fully sealed in subsequent years or decades[1]. Despite the colossal scale of decommissioning that will take place in BC in the near future, the performance of varying P&A types and configurations deployed, as well as the overall integrity of decommissioned wells, remains poorly constrained[4-7]. To date, few studies have sought to rigorously evaluate historic P&A performance and decommissioned well integrity with time, even though such research could provide insights to guide more effective regulation and optimize ongoing P&A activities in the coming decades. For example, P&A designs that appear to offer the greatest integrity performance can be replicated or conversely configurations that lead to sub-optimal performance or outcomes can be avoided or re-designed. In addition, where wells have already been P&A'd with configurations that are known to be less effective, they can at least be prioritized for stewardship to ensure minimal environmental impacts occur. Either way, understanding the performance of differing P&A configurations and the general integrity of P&A wells in BC can only aid in more optimal management and regulation of forthcoming P&A activities. The current dearth of research on performance of P&A configurations, as well as general integrity of decommissioned wells in BC, ensures that significant knowledge gaps persist with respect to how existing P&A configurations are performing and what constitutes an optimal and cost-effective design.

Key questions that remain unanswered include:

- How and where has longer-term performance of P&A been assessed (i.e. greater than Certificate of Restoration time scales) and by what methods?
- How have varying P&A configurations and general well integrity performed with time?
- In particular, how are P&A configurations and integrity of newer unconventional style wells performing to date and what lessons can be learned for forthcoming P&A activity?
- What factors contribute to optimal or sub-optimal P&A performance and well integrity? and,
- Can we model P&A performance and general well integrity to support a risk-based P&A design?

In this research project, we attempt to address these questions and evaluate historic P&A performance and general well integrity of legacy wells in BC, with a view to informing regulatory policy and optimizing P&A activities during the forthcoming wave of abandonments.

Project Structure, Aims and Objectives

This research project consisted of 3 synergistic work packages (WP1 – 3) advanced sequentially over the project duration, including:

- **WP1 - Collation and analyses of existing BC regulatory P&A data towards understanding performance of existing P&A's and general decommissioned well integrity.**
- **WP2 - Field assessment of P&A performance and general well integrity in BC**
- **WP3 - P&A and general well integrity performance numerical modelling**

Overall, the projects main aims were to systematically and rigorously evaluate historic P&A performance and general well integrity of legacy wells in BC. This was achieved by; 1) using existing data, 2) collecting new data in the field, and, 3) conducting numerical modeling in order to provide insights on integrity performance of typically deployed P&A configurations and well designs. The overarching objective of this research was to aid optimization of decommissioning and P&A activities in BC in terms of maximizing effectiveness and potentially minimizing costs. Moreover, it was envisioned that a greater general understanding on legacy well integrity achieved by the project could guide future stewardship of legacy infrastructure, as well as inform policy and aid in development of best practice engineering guidelines for ongoing P&A activities.

It should be noted that during the project, the COVID-19 Pandemic took place for which associated restrictions meant that it was not possible to conduct fieldwork and subsequent modelling activities as planned, resulting in a delay of 14 months to project completion. Nonetheless, as soon as travel restrictions allowed, fieldwork was undertaken and subsequent modelling performed with all project deliverables achieved as proposed.

This technical report is divided into sections that outline the specific activities, results and findings from each of the individual work packages (i.e., WP1 – 3). After describing each work package individually, overall project outcomes are summarized in a findings and recommendations section.

WP1: Collation and Analyses of Existing Regulatory Data on Well Integrity towards Understanding Performance of P&A Practices

1. Introduction and Background

Currently, there are no regulations that require monitoring or evaluation of the integrity status of energy wells after P&A and the certificate of restoration (CoR) process. This prevents insights being gained to help understand P&A performance in the longer term, general legacy well integrity, integrity failure incidence rates and causal/triggering factors for integrity failure [8-12]. With many wells soon to be decommissioned [4,13,14], it is important that we understand the integrity status of existing P&A'd wells, the incidence rates at which integrity failure occurs and potential factors, both in terms of engineering and environmental attributes, that may be leading to sub-optimal integrity. Such understanding can facilitate optimization of forthcoming P&A activities and allow any potential risk factors associated with P&A'd wells and their general integrity to be duly considered during prioritization of stewardship of legacy infrastructure in the coming years.

Here in WP1, we seek to evaluate the incidence rate of integrity failure of wells in BC with focus on P&A'd wells, as well as identify contributing or causal factors which may be linked to sub-optimal well integrity. This is achieved by implementing statistical analyses on data obtained from a series of airborne LiDAR CH_4 surveys undertaken across BC from 2017 to 2020, including use of inferential statistical techniques on various relevant well attributes and characteristics, with focus on P&A'd wells. Well attributes and characteristics in this instance refers to how and when a well was drilled, completed and abandoned and the geological environment in which it is hosted. Broadly speaking these attributes can be considered to fall under two types; a) engineering, and, b) environmental aspects. With respect to engineering attributes, these include any aspect of a wells design and construction that will result in its overall integrity, such as total depth, casing configurations and number of plugs etc. With respect to environmental factors, these are generally associated with a wells host geologic and geographic setting and include intersected geology or the presence of over pressurized gas bearing strata among others.

2. Methods

2.1. Aerial P&A Well Integrity Evaluation Surveys

Airborne liDAR data used for this analysis was acquired from four aerial surveys commissioned by the BC OGC between 2017 and 2020, and undertaken by LaSEN Inc. (Las Cruces, NM). During well aerial surveys a helicopter-mounted remote sensing unit and operator console (tuneable diode laser, computer, detectors, high-resolution cameras and GPS) was deployed at 96.5 km/hr from a height of 100 – 300 m to detect CH_4 plumes with an accuracy of ± 5 ppm[15]. The methodology works by tuning the laser to the main absorption band of CH_4 and projecting it at a point of interest (i.e. the ground surface at and around the well). When passing a CH_4 plume or source at or near the well site, a small finite quantity of laser light will be absorbed, allowing quantification of the amount of CH_4 present in the air column (i.e. generating a concentration of ppm of CH_4 per meter of height). Upon detection of CH_4 in excess of background levels (where typical atmospheric/surficial levels are ~2 – 3 ppm) the detection is defined as either small (i.e. CH_4 at 4-24 ppm per m), medium (i.e. CH_4 at 25-49 ppm per m) or large (i.e. CH_4 at >50 ppm per m). More details and specifications of the methodology and its application can be attained from LASEN Inc. [16]. The four aerial surveys used in this research investigation took place from 2017 – 2020, typically in the summer period, where the focus was primarily on fully P&A'd wells. A total of 395 P&A'd (including 5 that were partially or zonally abandoned) plus 11 additional suspended or active wells were examined across the main resource plays of NE BC. Wells for examination for the aerial surveys were selected by the BC OGC somewhat at random, with a general concept to capture wells of all types and vintages, whilst also considering logistics (e.g. flights paths for the helicopter). There was no formal site selection procedure or hypothesis being tested during selection of the survey well sites and to date no analyses have been performed to evaluate how representative of the overall P&A'd well population the surveyed P&A'd wells are. A total of 102, 103, 104 and 97 wells were examined in each respective campaign (i.e. from 2017 to 2020), with any wells presenting an aerial CH_4 indication typically followed up with ground based inspection by OGC Inspectors, which included a site walkover with a hand held CH_4 detector to attempt to validate the CH_4 source observed from above.

2.2. Well Attribute Database Formulation

A key step in this research was to establish a P&A'd well database with information from multiple sources on key well attributes of relevance that could be used in conjunction with results from the aerial CH_4 surveys and ground follow up to evaluate factors potentially correlated with sub-optimal integrity. Firstly, data obtained from the airborne CH_4 surveys (i.e. well ID, abandonment date, program year, aerial CH_4 indication status and ground based CH_4 detection status) was merged with a database created by Sandl, et al. [17], who previously used regulatory data held on all 25,023 energy wells hosted in BC, Canada to explore potential causes of gas migration. Sandl *et al.* defined attributes from the BC Oil and Gas Commission (OGC) Data & Reports online portal [18] and AccuMap software [19] for wells in NE BC that were cased or completed before the end of January 2018 and then filtered for quality control (including identifying inconsistencies, errors or emissions). More detail on this database, its formulation and filtering is provided in the cited published article. Ultimately, this process resulted in a total of 23,859 wells with sufficient quality data being used in the previous gas migration focused analyses. For the current research, this pre-filtered dataset was further filtered to retain only wells with an 'abandoned' status (i.e. having been P&A'd), resulting in a total of 7,079 wells. It was noted that data for 28 wells examined in the airborne surveys were not included as they were not abandoned at the time Sandl *et al.* created their database. Consequently, data for these wells were attained manually using AccuMap® software. Thus, a final main database (henceforth termed **MDB**) for the current research was formulated, comprised of all 7079 wells in BC that are categorized as abandoned, including information on their integrity as provided by the aerial CH_4 surveys and ground follow up.

To allow more detailed analysis to be carried out on wells exhibiting signs of integrity failure (inferred as CH_4 detections greater than background) during the aerial surveys, a refined database (henceforth termed **RDB**) was generated. The RDB was comprised of two different groups consisting of, a) all wells where CH_4 was detected by aerial survey and/or ground follow up, and, b) wells included in the fly over surveys but where no CH_4 was detected. For the RDB, 5 additional attributes of potential relevance for each well were added after manually reviewing in detail well reports from AccuMap®. The generalized concept for formulation of the MDB and RDB, including types of data collated for each well are shown in Figure 3.

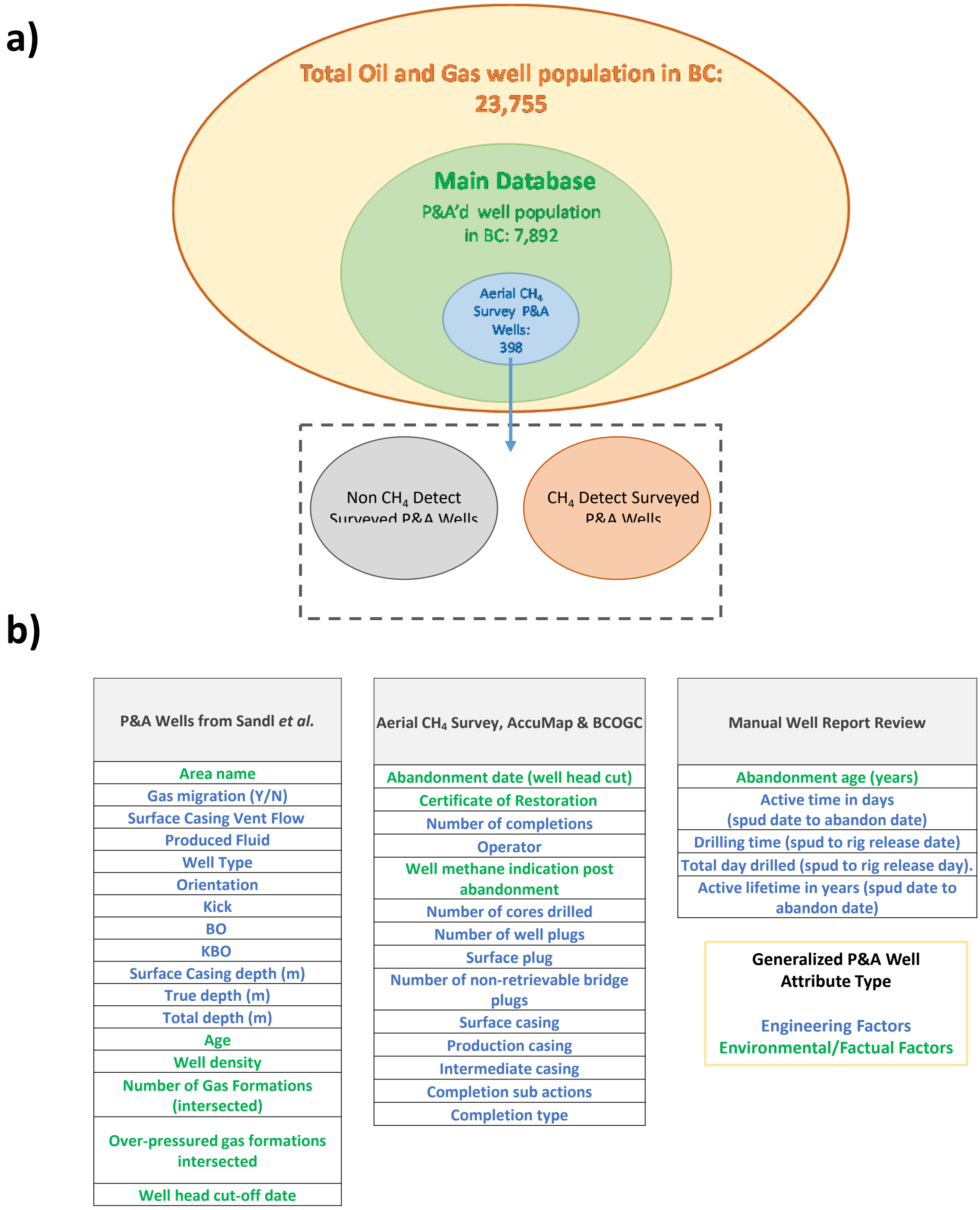


Figure 3: a) Conceptual overview on P&A'd well database formulation including the MDB and RDB, and, b) types of data collated into the database, including engineering and environmental or factual parameters.

A key point to note is that P&A'd well attribute data that forms the database (as shown in figure 3 b) consists of varying data types, which dictates somewhat how the data can be analysed statistically. Here, information on each P&A'd well includes both numeric/quantitative data (including continuous and discrete variables) and categorical/qualitative data (including ordinal and nominal variables) making it a valuable, but somewhat challenging, database to work with.

During this research investigation, it was concluded no other data on P&A performance or well integrity for abandoned wells in BC currently exists or is readily available at the whole population scale. Based on discussions with the BC OGC it was confirmed that no such data is collected or collated into a readily usable format as standard, and, in this case, the only systematic and readily available data on P&A performance and general well integrity comprises the aerial CH_4 survey data used herein.

2.3.P&A Well Demographics and Aerial Survey Sample Representativeness

A critical initial task in the current research involved evaluating whether the P&A'd wells examined in the aerial CH_4 surveys are representative of the wider P&A population such that results from these surveys can be used to infer potential insights onto the greater population. This is an important exercise in any study that involves sampling a subset of a larger population, with a view to understanding the whole. It is critically necessary to evaluate if the examined subsample is representative of the wider population in terms of distribution of the various parameters and attributes. That is, the wider P&A'd well population will have an inherent distribution (i.e. maximum, minimum and mean) for the various engineering and environmental factors that are associated with wells in BC. These parameter distributions need to be somewhat equivilent in a sub-sample; at least if results from examining P&A performance and integrity of that subsample can be considered representative of the wider population. If the sub-sample is not representative in terms of parameter distribution, then a biased result could be attained and no inference should be made on the wider population. If the sub-sample is representative in terms of parameter distribution, the result can be considered unbiased and any insights can potentially be transferrable to the wider population and may be considered in upscaling. Clearly then, evaluating the representativeness of surveyed P&A'd wells is a key task necessary to contextualize results and to determine what inferences it is reasonable to make from them.

In order to determine if the 395 P&A'd wells examined in the airborne survey are representative of the whole abandoned well population, the distribution of data on all attributes were compared. This was done by plotting histograms for quantitative variables and creating contingency tables for nominal and ordinal variables, as available from the MDB, which can reveal the general demographics of P&A'd wells in BC and help determine if the aerial survey wells are representative.

2.4.Evaluation of Factors Associated with Integrity Failure

A key aim of the current WP was to evaluate if there are any factors that appear to be associated with sub-optimal integrity of P&A'd wells. This could be determined by identifying any statistically significant difference between the attributes of CH_4 detect and non-CH_4 P&A'd wells that were part of the aerial surveys and collated into the RDB. The inference would be that any attribute presenting as significantly different, may be a related or causal factor for the development of post abandonment well integrity failure. Firstly, to determine if any difference in spatial correlation was present, both groups (i.e. CH_4 and non-CH_4 detect P&A wells) were evaluated for spatial autocorrelation-using the Global Moran's (I) technique[20] in ArcMap®. This analysis assesses if surveyed P&A's wells (including both CH_4 and non-CH_4 detect wells) are clustered or randomly distributed in the surveyed area and therefore indicate if a given geographic area is more susceptible to sub-optimal integrity or not. Next, since attributes contained in the database have both qualitative categorical (i.e. nominal and ordinal) and quantitative (i.e. discrete and continuous) variables, an initial data split was made to simplify the analysis of both groups. Quantitative data were then evaluated with boxplots, histograms and T-tests while categorical data between groups were evaluated by implementing Chi-squared analyses. The general concept for this statistical evaluation is shown in figure 4.

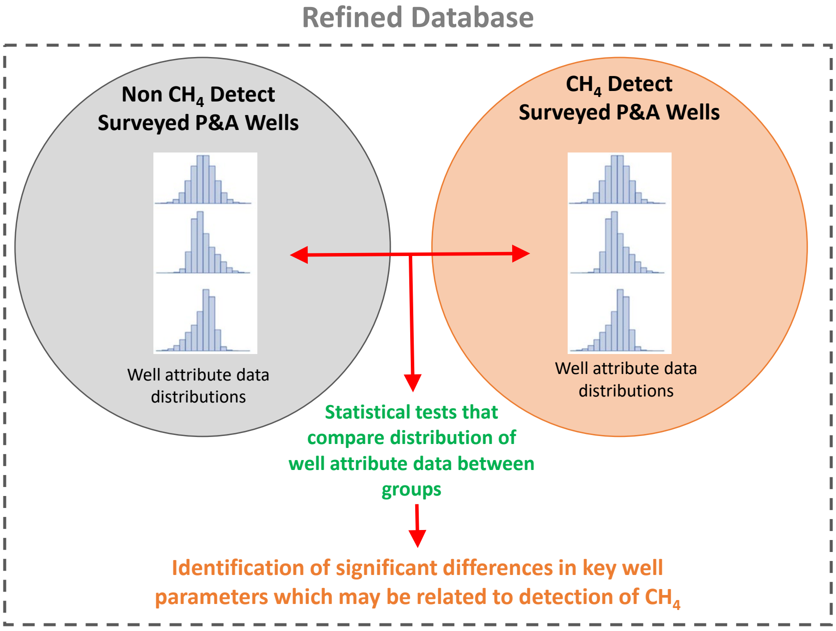


Figure 4: Conceptual figure of inferential statistics methods used to determine any differences in attributes between CH_4 and non-CH_4 detect wells that were part of the aerial surveys.

A T-test is a statistical test that can be used with numerical/quantitative data to compare the means of two groups and determine if there is a statistically significant difference. It is often used in hypothesis testing to determine whether a process or treatment actually has an effect on a population of interest, or whether two groups are different from one another[21]. In our case a T-test (assuming unequal variance and independent groups) was used to evaluate quantitative P&A well attributes and determine if there was a significant difference between wells with CH_4 indications and wells where no CH_4 was detected. T-tests are based on the t-distribution, which describes the distribution of the ratio of the sample mean to the standard error of the mean. The t-statistic value is calculated by subtracting the means of the two groups and dividing the result by the standard error difference and comparing this to the t-distribution (with the appropriate degrees of freedom taken into account). Chi-squared tests were used to compare observed results with expected results for categorical/qualitative data[22]. Results from Chi–squared tests help determine if a difference between observed data and expected data is due to chance, or if it is due to a relationship between the variables being considered (in this case CH_4 detection or not). A chi-squared test is performed by summing the squared differences between the observed and expected frequencies for each category and dividing by the expected frequencies and comparing to the chi-square distribution (again, with consideration of degrees of freedom). More information on these inferential statistics techniques, their underlying theory and application can be attained from any good undergraduate level textbook[23-25].

3. Results

3.1. Integrity of P&A Wells Based on Aerial Survey Results

During the aerial CH_4 surveys and ground based follow up carried out from 2017-2020, a total of 19 wells out of 395 examined (i.e. ~4.8%) were identified as presenting some form of CH_4 indication at

4 ppm or greater in the air column and/or at ground surface around the P&A'd well sites. A total of 9 P&A'd wells exhibited both CH_4 in the air column **and** at ground surface, 8 showed only indications in air column and 2 showed CH_4 only upon ground inspection. In terms of survey year, eight P&A'd wells were detected in 2017 (five of which were partially abandoned as per table 2), two in 2018, six in 2019 and three in 2020. Only two P&A well sites were classed as having "large" CH_4 indications (i.e. > 50 ppm), one as "medium" (i.e. 25-49 ppm) with the rest exhibiting what is considered by the service company performing the surveys as "small" CH_4 indications (i.e. 4 - 24 ppm)[15]. Overall, detection of CH_4 at > 4 ppm in the air column around P&A'd wells is considered anomalous and infers these 19 P&A'd wells are suffering some form of well integrity failure (potentially related to P&A configuration), releasing CH_4 into the environment. Wells surveyed which were positive for CH_4 detection are summarized in table 2, with prevailing climatic conditions and survey dates also indicated. Meanwhile, CH_4 survey wells, including CH_4 and non-CH_4 detect wells, as well as all other P&A wells in the province (i.e. including those not surveyed) are shown in map form in Figure 5.

Table 2: Aerial survey wells identified as exhibiting anomalous CH_4 levels at and/or around the wellhead during aerial CH_4 surveys including survey year, month and prevailing climatic conditions. It should be noted that wells WA 6839, 9533, 11033, 13052 and 16299 are partially (i.e. zonally) abandoned and not fully abandoned.

Aerial Survey Program Year and Prevailing Conditions	WA	Aerial CH4 indication?	CH4 Indication Magnitude	On-site detection of methane?
August 2017 Wind Speed: 2 – 5 mph Ave daily max temp: 21˚c	3156	No	N/A	Yes
	6839	Yes	Small	No
	8818	Yes	Small	No
	9533	Yes	Small	Yes
	11033	Yes	Large	No
	13052	Yes	Small	Yes
	13358	Yes	Small	No
	16299	No	N/A	Yes
October 2018 Wind Speed: 7 – 10 mph Ave daily max temp: 9˚c	4631	Yes	Small	Yes
	4739	Yes	Small	Yes
July 2019 Wind Speed: 8 – 12 mph Ave daily max temp: 21˚c	2107	Yes	Small	Yes
	5308	Yes	Small	No
	7477	Yes	Small	Yes
	8956	Yes	Large	Yes
	19312	Yes	Small	Yes
	25487	Yes	Medium	Yes
September 2020 Wind Speed: 10 – 15 mph Ave daily max temp: 16˚c	2437	Yes	Small	No
	13891	Yes	Small	No
	14001	Yes	Small	No

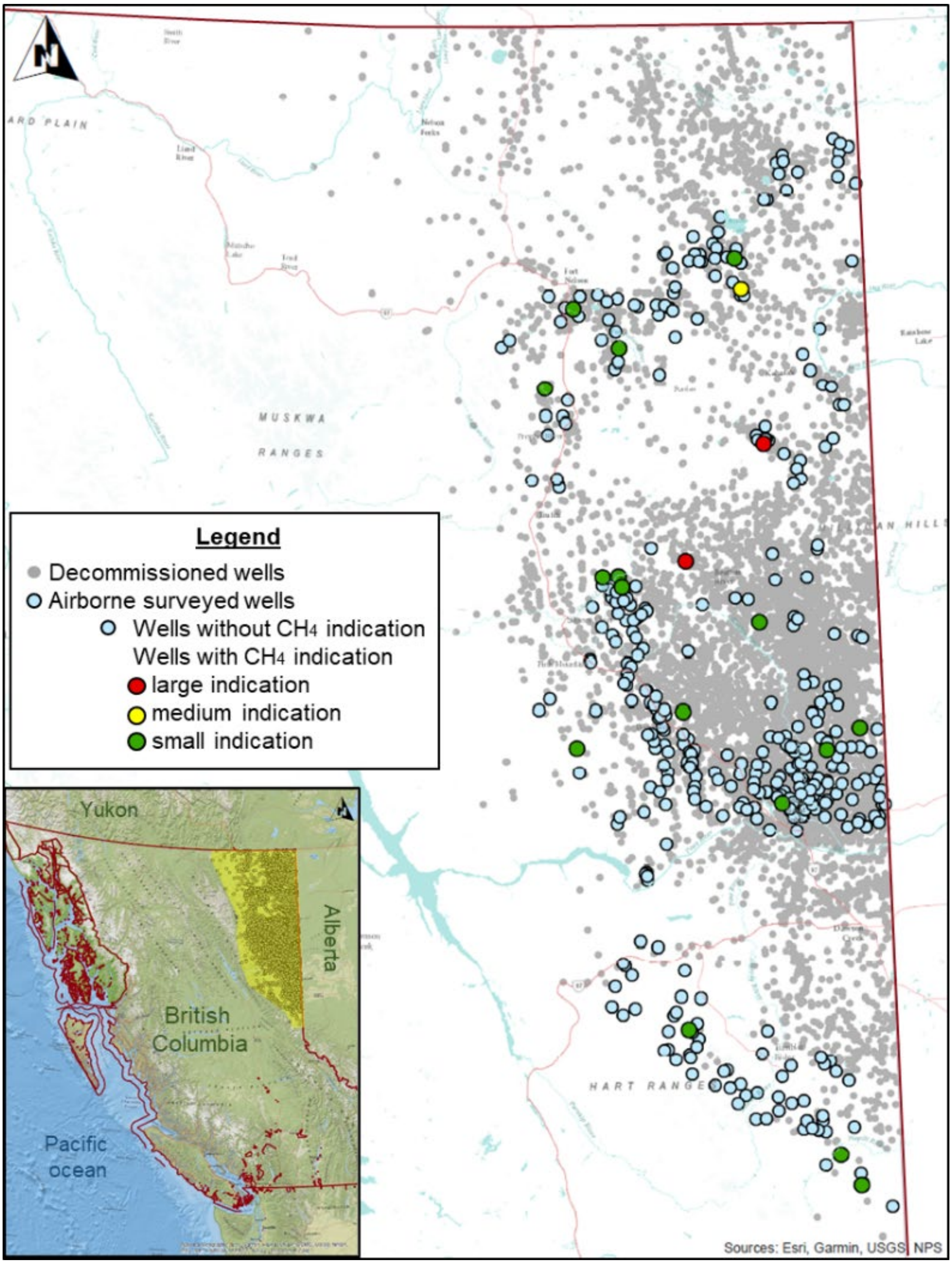


Figure 5: Map of BC showing decommissioned wells surveyed with airborne methods including both CH_4 detects (and indicative size) and non-detects as well as all currently P&A wells in the region (as small grey circles). The overall study area is highlighted (yellow) in the index lower left-corner map.

It should be noted that for the purposes of ongoing inferential statistical analyses that all wells with any indication of CH_4 (i.e. either by aerial and/or ground detection) will be assumed to be suffering some form of integrity failure. In addition, all 395 wells in the aerial surveys will be considered will be described as P&A'd, however it is acknowledged that 5. This approach allows a greater sample size from which to statistically test the significance of relationships. It is however acknowledged that there may be false positives and/or negatives and both aerial and ground based methods are imperfect (as described in more detail in section 4.4).

3.2. P&A'd Well Demographics and Aerial Survey Sample Representativeness

Upon evaluation of the demographics of aerial CH_4 survey wells and the wider P&A'd well population it can be concluded that, for the most part, aerial survey wells are representative of the wider population. This was generally true for most key parameters including overall well and abandonment age, total, true and surface casing depths, number of completions, well density, number of abandonments, number of plugs and number of gas bearing formations intersected, amongst other parameters. Highlights from these results are shown as histograms in Figure 6 and numerically in table 3. Overall these results show that key general attributes for airborne survey wells (totalling 395 wells) are generally similar in distribution to the wider abandoned well population (7,079 wells). Consequently, the observed incidence rates of sub-optimal integrity and inferences on potential causal or related factors can be reasonably applied/scaled to the greater P&A well population.

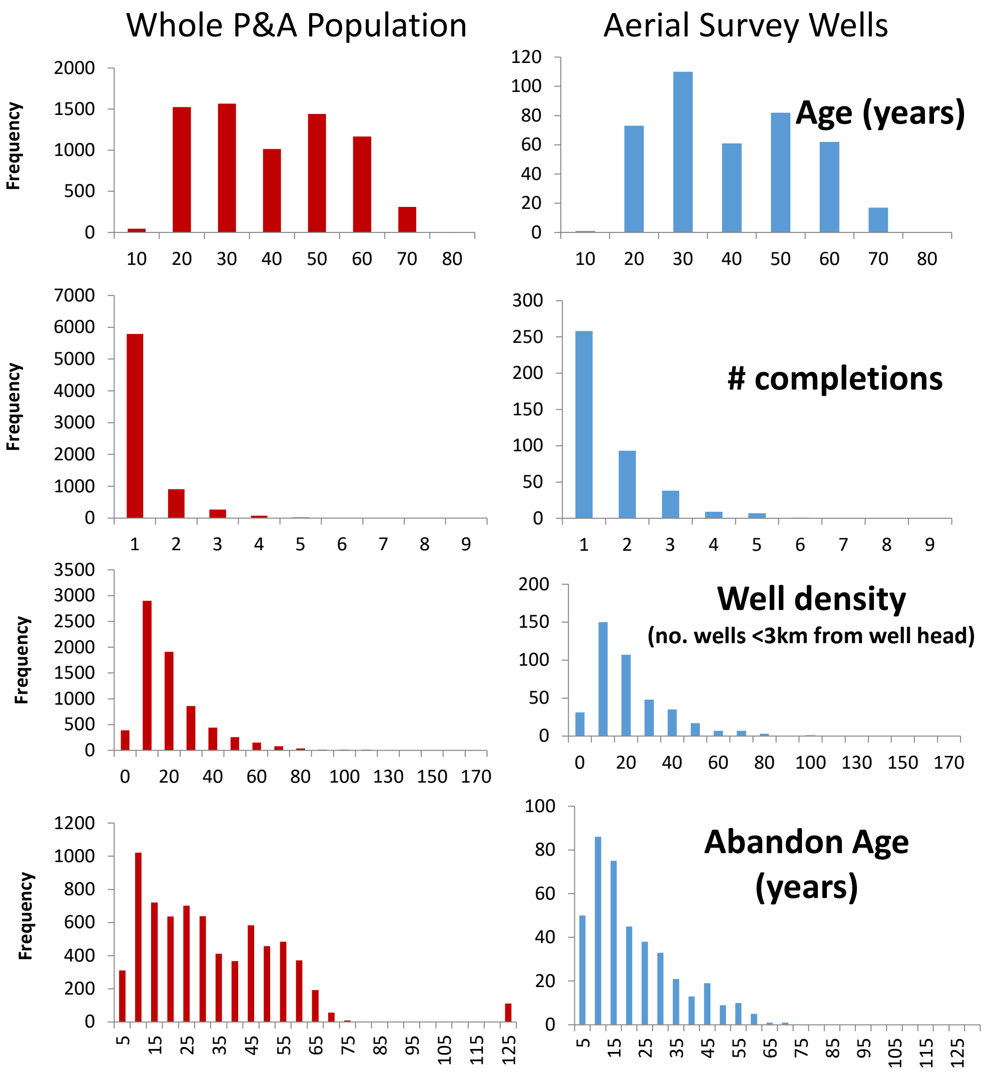


Figure 6: Histograms for key attributes of the whole P&A'd well population and aerial CH_4 survey wells demonstrating representativeness. Because aerial CH_4 survey wells generally represent the total P&A well population in terms of distribution of key attribute data, insights on integrity status can be considered relevant to the greater population.

Table 3: Summary of well attribute data distribution (in terms of mean and standard deviation) for the whole P&A well population and aerial CH_4 survey wells demonstrating general representativeness.

Attribute	All P&A Wells		Aerial Survey Wells	
	Mean	Standard Deviation	Mean	Standard Deviation
Age (years)	35.4	15.2	35.3	14.6
No. completions	1.3	0.6	1.6	0.9
Well Density (wells within 3km radius)	16.2	17	16.5	16
Abandonment Age (years)	30.6	20.9	18.8	13.9
No. Gas Bearing Formations intersected	10.7	5.6	11.1	5.3
Surface Casing Depth (m)	231	110	271	143
Total Depth (m)	1581	682	1880	834
No. of Abandonments	1.1	0.4	1.1	0.3
No. of plugs	2.8	2.3	2.1	2.2
Drilling Days	49	67	37.6	42
Days Active	6182	5763	7980	5402
No. of abandonments	1.1	0.4	1.1	0.3

3.3. Evaluation of Attributes potentially associated with Integrity Failure

3.3.1. Spatial Correlation

Evaluation of potential spatial correlation for wells exhibiting CH_4 detections by Global Moran's (I) technique, shows a negative Moran's index (-0.13) and z-score (-1.24), which indicate the data tends to dispersion instead of clustering. This means that wells with CH_4 detection are not spatially correlated, instead being randomly distributed throughout the survey region. An output from this analyses is shown in Figure 7.

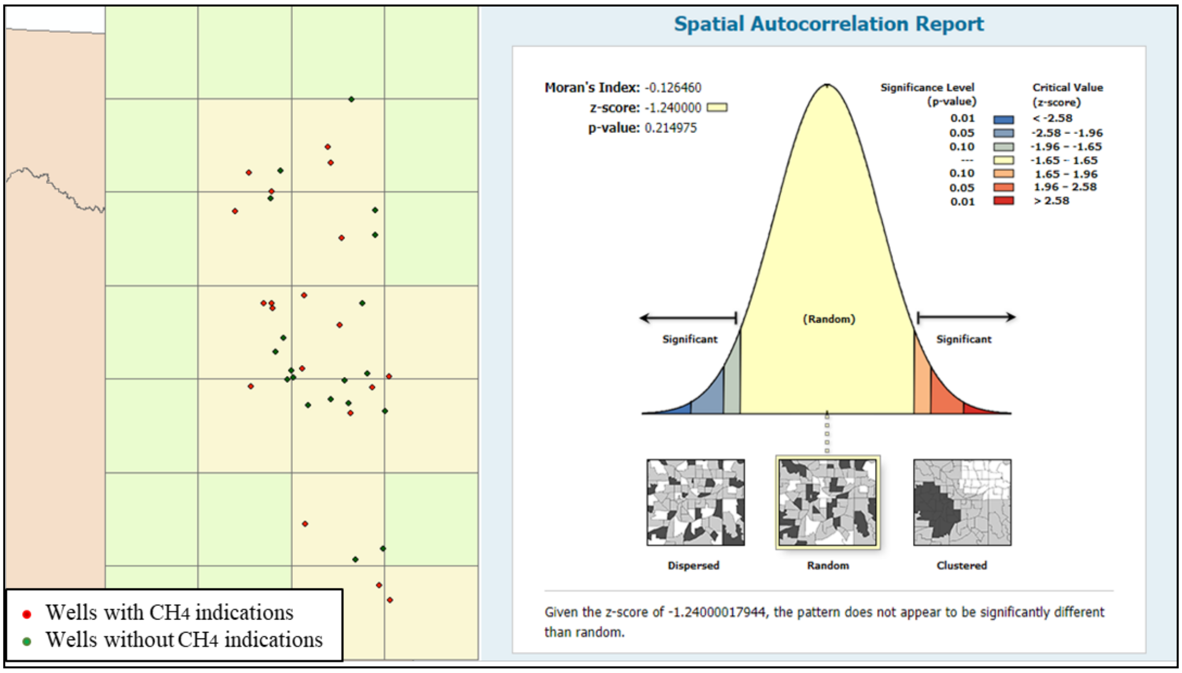


Figure 7: Spatial autocorrelation-Global Moran's (I) Parameters. The test results show a spatially random spatial distribution for the aerial CH_4 survey wells with P&A'd well exhibiting CH_4 detections exhibiting no clustering or spatial correlation.

3.3.2. Quantitative Data Analyses

Here, results from inferential statistical analyses of the RDB (as described in section 2.2) with respect to comparing CH_4 detect and non-detect wells from the aerial CH_4 surveys are presented with a view to identifying any potential causal or related factors associated with sub-optimal integrity. Initially the arithmetic means of the key attribute parameters from CH_4 indication and non-CH_4 well groups were **qualitatively** compared. Here, it was found that wells with CH_4 indications tend to:

a) Be slightly younger (12-54 years) than their counterparts (10-68 years)
b) Be located in an area of lower well density (14 wells vs 17 per 3 km^2 radius from the well head)
c) Intersect less potential gas bearing formations (9 vs 11)
d) Intersect a slightly higher number of over-pressured formations (3 vs 2)
e) Have a greater active lifetime (22 vs 17 years)
f) Involve less drilling days (54 vs 149)
g) Have experienced less time since they were abandoned (9 vs 19 years)

Example box and whisker plots form this qualitative evaluation are shown in Figure 8.

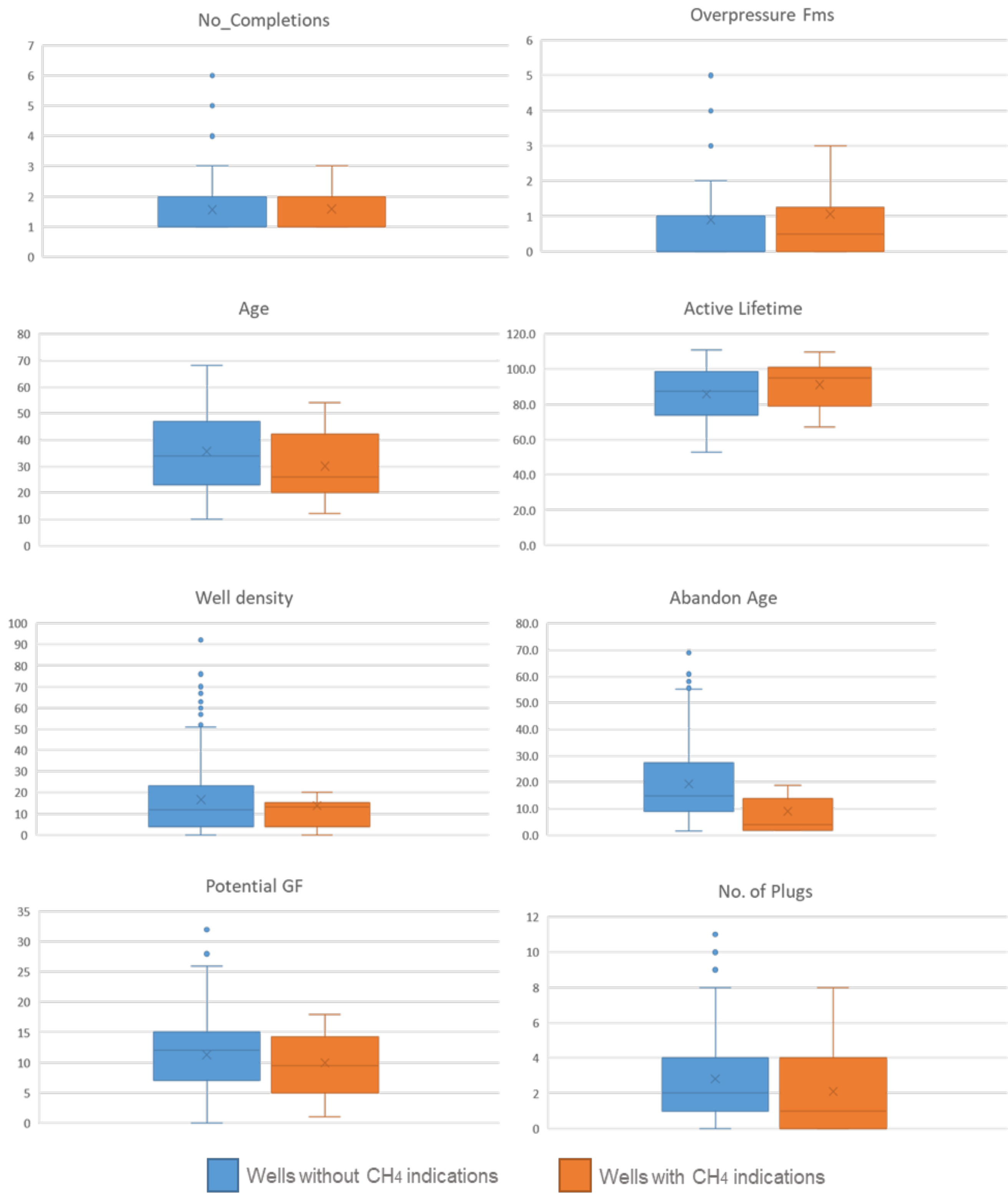


Figure 8: Example of box and whisker plots for CH_4-detect and non-detect wells that were identified during the aerial surveys showing distribution of parameters including equivalency (e.g. no. of completions) and what appear to be significant differences (e.g. abandonment age).

Next, T-tests for evaluating statistically significant differences between attributes of CH_4 and non-CH_4 detect wells (assuming unequal variance) were performed on all 24 quantitative discrete variables, the results of which are shown in Table 4.

Table 4: T-test parameters and test results.

Variable Evaluated by T-test	Statistically significant relationship with CH_4 detection (high: $\alpha = 0.05$, low: $\alpha = 0.1$)	Direction of relationship: CH_4 detect wells compared to non-CH_4 wells
Number of potential gas formations	Yes (High)	Less (i.e.negative)
Number of multiple completions	Yes (High)	Less (i.e. negative)
Abandon age (years)	Yes (High)	Younger (i.e. negative)
Number of open hole completions	Yes (High)	Less (i.e. negative)
Total age	Yes (Low)	Less (i.e. negative)
Total drilling days	Yes (Low)	Less (i.e. negative)
Active time (days)	Yes (Low)	Greater (i.e. positive)
True depth	Yes (Low)	Less (i.e. negative)
Number of surface casings	**None**	**Statistically Equivalent**
Number of well completions		
Number of over pressured formations		
Number of plugs		
Number of production casings		
Well density		
Number of Non retrievable bridge plugs		
Number of intermediate casings		
Number of liners		
Number of dual completions		
Drilling time (days)		
Number of single completions		
Number of cores		
Number of abandonments		
Surface casing depth		
Total depth		

From the T-tests, four attributes were seen to have a potentially strong statistical relationship with CH_4 detection at P&A wells, including; a) the number of potential gas formations intersected, b) number of multiple completions in the well, c) abandonment age in years (from when it was declared abandoned to the present), and, d) the number of open-hole completions. These attributes presented t-statistic values of ranging from -2 to -3 and P-values <0.05, confirming a statistically significant difference between the CH_4 detect and the non-detect wells. Meanwhile a further 4 parameters showed a weaker, but still significant, relationship with CH_4 detection at P&A wells, including; a) total age, b) total drilling days, c) active time at the well (in days , and , d) true depth. Other attributes showed no significant difference for wells where CH_4 was detected and those where it was not and are therefore statistically equivalent.

3.3.3. Categorical Data

Results from Chi-Square tests performed on the categorical attributes are presented in Table 5. These data show a strong statistically significant difference between CH_4 and non-CH_4 indication wells for the presence of SCVF during the wells active life and weaker (but still statistically significant differences) for; a) the presence of GM, b) whether or not a CoR has been attained, and, c) the presence or absence of a surface plug. All other categorical data showed no statistically significant difference between CH_4-detect and non-detect well groups.

Table 5: Chi-square parameters and test results.

Variables for Chi-square test	Difference between CH_4 and non-CH_4 wells
SCVF	Very Strong Difference (MORE than expected)
GM	Weak Difference (MORE than expected)
CoR	Weak Difference (LESS than expected)
Surface Plug	Weak Difference (MORE than expected)
Fractured	**No Difference**
Acidized	
Remedial Treatment	
Kick	
Well Operator	
Well Type	
Area	
Fluid Type	
Well Orientation	
Well Treatment	

4. Discussion

4.1 Aerial Survey Results

Results from the aerial CH_4 surveys and ground follow up showed that a total of 19 P&A'd wells out of 395 examined (i.e. ~ 5%) exhibited signs of sub-optimal integrity, with most of these indicatively quantified as small. Of note was that the number of P&A'd survey wells with CH_4 detected each year was variable with incidence rates ranging from 2% to 9% of wells investigated (in 2018 and 2017 for these minima and maxima respectively). In order to better understand observed incidence rate variation and acknowledging that detection of fugitive gas is affected by prevailing climatic conditions[26-28], data from a weather station located in Fort St. John was attained for the periods of the surveys and analysed in conjunction with number of CH_4 detections made. Results from this analysis are shown in Figure 9.

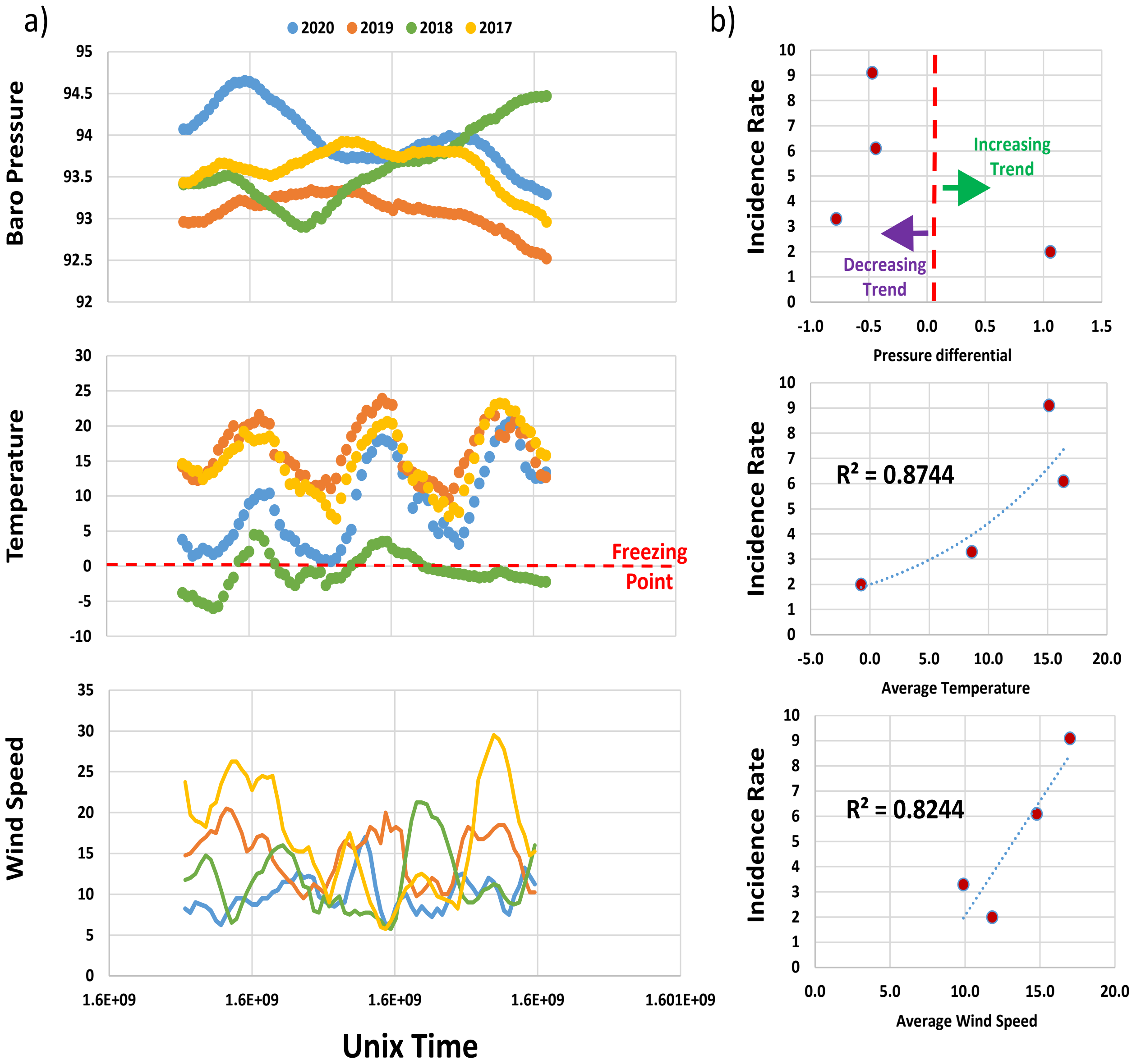


Figure 9: a) Key weather data during a 3-day period over which each of the 4 years of CH_4 aerial surveys were undertaken, and, **b)** influence on incidence rate of CH_4 detection of these parameters.

Here, it was seen that incidence rate appears to be somewhat correlated to prevailing climatic factors during the aerial surveys. In this case, a generally increased incidence rate was observed when surveys were conducted during; a) decreasing barometric pressure regimes, b) warmer temperatures, and, c) higher winds. Temperature in particular seems to have played a key role in the number of CH_4 detections made by aerial survey each year, whereby the least detections were made under freezing conditions (i.e. the survey conducted in 2018 where sub-zero temperatures were in effect most of the survey period). This may be associated with frozen soils limiting the emissions of fugitive CH_4 from the subsurface to the atmosphere[29]. Meanwhile, other years exhibited increasing incidence rates with increasing temperature; leading to an R^2 value of 0.87 (inferring a significant correlation that is unlikely to be by chance).This observation may be associated with warmer temperatures inducing drier soil conditions (increasing effective permeability for gases) which enhances emissions of fugitive gas from the subsurface to atmosphere. Similarly, the greatest incidence rate observed (i.e. 9% in 2017) occurred during a period that experienced the highest winds during any of the surveys. The relationship between incidence rate and wind speed generates an R^2 value of 0.82, which is also statistically significant, suggesting a role of wind in detection of CH_4 in the air column. This may be associated with greater dispersion of CH_4 from surficial soils into the air column during higher winds[30]. Finally, although no clear linear correlation was observed (as with temperature and wind speed) with incidence rate and prevailing barometric pressure regime, there is a tendency for a higher incidence rate when aerial surveys were conducted during falling barometric pressure regimes, as opposed to increasing pressure regimes. As shown previously in a BC context, this is likely a result of barometric pumping during decreasing pressure cycles pulling CH_4 from surficial soils into the air column[26,27,31]. Together, these initial analyses suggest that well integrity failure incidence rate inferred from aerial CH_4 surveys is somewhat controlled by the prevailing weather conditions. These observations highlight that such aerial methods should not be considered as absolute or definitive, and, climatic conditions must be considered when interpreting generated results. Nonetheless, the collection of 4 years of data in varying climatic conditions has allowed an average incidence rate of 5% to be estimated. This at least allows some constraint to be gauged on an overall integrity failure rate for P&A'd wells in BC that seems somewhat reasonable when compared to rates reported in other regions[4]. Overall, these observations show that more work is needed to understand the efficacy of such aerial survey methods and also to define and quantify the effects of prevailing weather conditions on manifestation of well integrity failure.

4.2 Aerial Survey Result Implications

Our analyses shows that despite no prior planning or design, the 395 P&A'd wells included in the airborne surveys are generally representative of the greater abandoned well population in the study area. As it was observed that 19 out of 395 wells (i.e. ~5%) exhibited indications indicative of well integrity failure at the times of sampling, it is reasonable to up-scale this incidence rate to the whole population. Hence, it can be hypothesized that around 350 P&A'd wells from the total population of ~7000 could be suffering some form of sub-optimal integrity and releasing CH_4 into the air column. Eventually, when all wells are P&A'd (i.e. all ~23,000 in BC), a similar incidence rate would infer around 1000 P&A'd wells may suffer integrity failure and release fugitive gases into the atmosphere. The environmental significance and implications of this scale of leakage are currently unknown, however, a key point to note is that most (i.e. > 80%) of the CH_4 detections during the current surveys were classified as small (i.e. only 4 – 24 ppm of CH_4 being detected around the well head location). Consequently, while it is clear that integrity failure is occurring in a relatively small % of P&A'd wells in BC, the magnitude of CH_4 release is likely small. In fact such releases are likely insignificant when compared to other sources of greenhouse gas emissions and may not be a priority cause for concern. More robust field measurements would be needed to better constrain the true magnitude of CH_4 emissions from such integrity-compromised wells and to better evaluate the significance of such leakage.

4.3 Factors Associated with Sub Optimal Integrity Performance

Results from inferential statistical analyses that sought to identify any factors with a relationship to CH_4 detection at P&A'd wells sites indicate that most factors are unrelated. In particular, no factors associated with specific P&A configuration (e.g. number or length of plugs) were highlighted as being related to detection of CH_4 at or around the wells investigated. This in itself suggests that there are no inherent or fundamental flaws with how P&A is carried out currently or in the past, similar to conclusions made by Sandl *et al.* Together, these results emphasize the fact that well integrity failure is a complex multifaceted phenomenon that may be very challenging to understand and predict. Nonetheless, several factors were identified as exhibiting potential linkages to the detection of CH_4 at and around P&A'd wells. Of most note was SCVF, which showed a very strong correlation with detection of CH_4. Here, out of the 19 wells with CH_4 detected during the aerial surveys, 8 were recorded as having exhibited SCVF during their active life (i.e. 42% SCVF incidence rate) in comparison to 59 from 361 that exhibited no CH_4 during the aerial surveys (i.e. 16% SCVF incidence rates). This suggests that exhibiting SCVF during active life could be a risk factor and indicator that a well is more likely to suffer integrity failure post-abandonment than wells where no SCVF was reported. Other factors with strong potential linkages to the presence of CH_4 at aerial survey wells included the number of potential gas bearing formations intersected, the number of multiple and open hole completions as well as age of the well in years. Surprisingly however, these parameters exhibited **negative** relationships with CH_4 detection. Therefore, in this case detection of CH_4 appeared linked to the presence of **less** potential gas bearing formations, **less** multiple and open hole completions and wells being generally **younger**. Such linkages are counter intuitive where it is **positive** relationships with such factors are more typically assumed associated with the development of well integrity failure, making it difficult to explain a rationale behind these findings. Meanwhile, the few other parameters that any showed potential (weak) correlation to detection of CH_4 (e.g. whether or not a CoR has been attained or the presence or absence of a surface plug) were also difficult to explain and highlight the challenges of applying inferential statistics to data sets where the number of CH_4 detect wells is generally low. A small number of wells with a positive result makes meaningful identification of potentially associated parameters particularly difficult. Consequently, it will be necessary to identify a greater number of wells with sub-optimal integrity to allow more conclusive identification of key contributing factors.

4.4 Limitations of Data and Analyses

According to LASEN Inc. [16], the laser used in the airborne survey for this research operates in the Mid infra-red (IR) wavelength (3300 nm) which provides higher sensitivity than other similar technologies (near IR, around 1650 nm), making detection results more precise and accurate. Despite this, it must be accepted that there is uncertainty in sampling conditions and the effectiveness and accuracy of airborne methodologies or what they show, as highlighted by review of climatic data in section 4.1. This uncertainty makes it unclear if the indications are from the well site or other emitting sources nearby and more work would be needed to better constrain true leakage sources. This issue has previously been pointed out by Karion, et al. [32] stating that since there are thousands of potential point sources in typical regions of extensive oil and gas development, it is challenging to claim that a single point source is responsible for a large fraction of the emissions detected. Additionally, emissions registered by different sources can present different magnitudes. For example, Tyner and Johnson [33] found emissions from their aerial survey to be 18 times greater than those found during an optical gas imaging survey. Despite this, airborne studies for analysing GHG emissions are becoming more frequent in industry and research. For example, Ren, et al. [34] mention different airborne studies that have implemented aircraft measurements with a focus on estimating CH_4 inventories from different oil & gas-related sources and areas, some of which have discrepancies between the previously documented emissions. Similarly, other studies implementing airborne methods have shown how a flight-based approach is a valuable tool for estimating CH_4 emissions with reliable results; such as Pekney, et al. [35] in Pennsylvania, focussing on the CH_4 emission contribution from abandoned wells. Therefore, while there are limitations to the use of such aerial surveys and it is not clear what can be delineated from them in terms of incidence rate or casual factors, they remain a useful tool to work towards better constraint on such issues and their continued use should be viewed as beneficial. Nonetheless, there is a clear need to more rigorously evaluate the results of such surveys and validate/calibrate with state of the science ground based methods such that the true incidence rates of failure and their potential causes can be more conclusively determined.

5 Conclusions

Here, we investigated the integrity of P&A'd wells using the only existing data which can indicate integrity and P&A performance at decade timescales post abandonment. This data, in the form of aerial CH_4 surveys conducted at 395 wells from 2017 to 2020, was combined with a custom formulated database containing information on all P&A'd wells in BC which may potentially be associated with development of sub-optimal integrity and detection of CH_4. In particular, these data were used in conjunction with inferential statistical techniques to identify any well factors potentially linked or correlated to the detection of CH_4 at examined aerial survey wells. Firstly, it was shown that the 395 P&A wells included in the aerial surveys were generally representative of the wider population of ~7000 P&A'd wells in BC, thus observed results could be up-scaled to make inferences about the wider population. Next, we described how 19 of the 395 aerial survey wells exhibited signs of anomalous CH_4 in the air column or around the P&A'd well head indicating a failure incidence rate of ~5%. It should be noted that >80% of these CH_4 detections were classed as small (i.e. with 4 – 24 ppm of CH_4 detected, compared to typical background levels of 2 ppm) and likely contribute only a very small amount to overall GHG emissions in the region compared to other sources. The annual variability of incidence rates observed between surveys was subsequently evaluated by considering prevailing climatic factors during each survey year. Here, it was shown that temperature, wind speed and barometric pressure likely play a role in determining the number of CH_4 detects made during an aerial survey and that these conditions need to be better considered when interpreting such results. Next, it was shown that most well attributes appear to be unlinked to the development of P&A'd well integrity failure, concurring with previous studies which have shown that integrity failure typically has a number of nuanced and unique factors that contribute to its development, rather than an obvious few, clear and consistent causes. Nonetheless, a strong association between SCVF during a wells active life and post-abandonment integrity failure was identified that is extremely unlikely to have occurred by chance. This observation suggests that documented inside casing leakage (i.e. SCVF) during a wells active life should be viewed as a risk factor and potential indicator that a given well may have a greater chance to suffer integrity failure during its post abandonment life. This observation seems to manifest irrespectively of the fact that SCVF is typically remediated prior to or during the P&A process.

WP2: Field Assessment of P&A'd Well Integrity in BC

1. Introduction and Background

A key challenge associated with understanding integrity of P&A'd wells in BC and elsewhere is the lack of robust field data from which to infer integrity. To date only limited scope and duration field investigations have been undertaken to assess short-term performance of P&A in BC as part of the Certificate of Restoration (COR) process. Of particular interest is the integrity of more modern wells, often termed unconventional, which form the majority of wells completed in BC (and indeed much of North America) in the last 20 years[1]. This type of well, which is typified by being deviated or horizontal and having been subjected to hydraulic fracturing treatments, will form the majority of forthcoming abandonments that must be performed in the coming decades. Clearly then, understanding how P&A performance and general integrity of these wells will evolve with time is of particular interest to all stakeholders. As described in WP1, the only data currently available on any P&A'd wells and their integrity at scales in excess of the CoR process in BC consists of data collected during recent aerial CH_4 surveys. During these surveys, 17 out of 395 P&A'd wells examined could be considered as modern or unconventional in configuration (i.e. not vertical and hydraulically fractured), two of which exhibited CH_4 indications indicative of integrity failure. However, such top down approaches to evaluating integrity using remotely collected data are associated with significant uncertainty due to issues with limits of detection, efficacy and the potential for false positives and negatives associated climatic conditions or other factors[33,36,37]. With the exception of this very sparse and potentially limited data, no other on the ground, state-of-the-science investigations have yet assessed P&A performance and general well integrity of unconventional wells after the COR process or at scales relevant to permanent abandonment (i.e. after decades and longer). Here, we attempt to address this dearth of data by conducting first of a kind targeted ground investigations at select unconventional wells in BC.

In this work package, state of the science field investigations focusing on unconventional P&A'd wells, for which little data on integrity performance is available, were undertaken. Currently 119 P&A'd modern unconventional exist in BC (Figure 1), while many thousands will soon need to be decommissioned. This subset of P&A'd wells was prioritized for field measurements during which a subset were examined in summer 2022, the results of which are presented herein. Data gained from this WP will provide new insights on general well integrity and P&A performance of unconventional wells in BC over longer timescales than assessed before and serve as input for formulating, calibrating and validating numerical models developed in WP3.

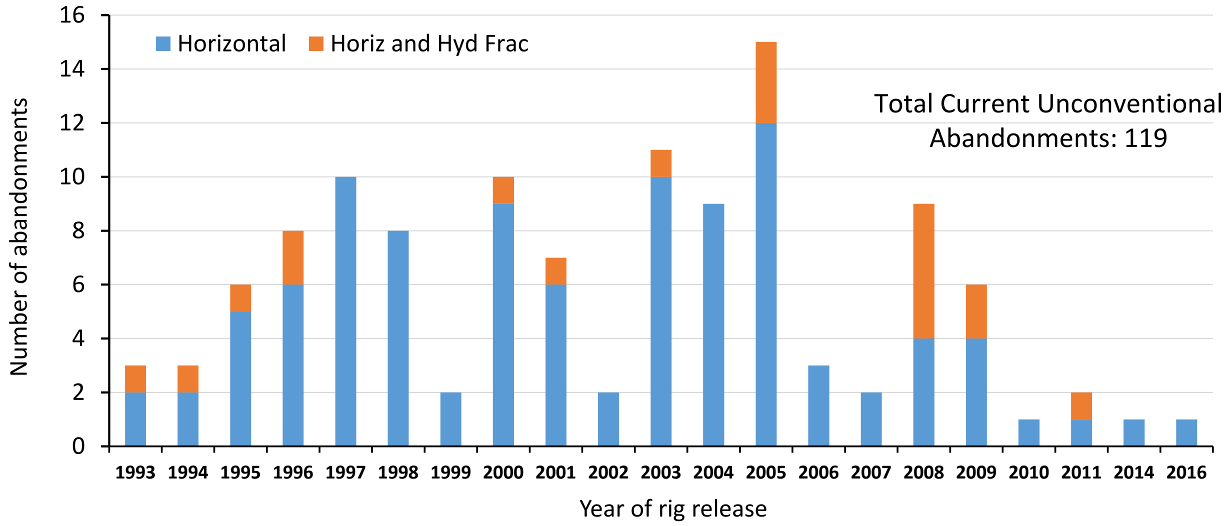


Figure 1: Histogram showing number of existing P&A'd unconventional wells in BC (a total of 119 out of population of 7600) by rig release year including proportions of horizontal only (a total of 100 wells) and horizontal and hydraulically fractured wells (a total of 19 wells).

2. Methods

2.1. Well Site Selection and Field Investigations

Abandoned gas production wells in in and around the Fort St. John area that can be considered modern or unconventional (as described in section 1) were prioritized for field investigations. This means they are: a) deviated or horizontal, and, b) have been subjected to hydraulic fracturing treatments. In addition, investigation logistics, ease of access and input from the relevant license holders was also considered when selecting wells to examine on the ground. During wellsite selection, the database developed in WP1 was filtered for desired target attributes and then potentially suitable modern P&A'd wells for examination near Fort St. John were evaluated in terms of logistics and potential site access (including multiple discussions with various permit holders). In many cases, P&A'd wells that completely conform to the above modern or unconventional criteria were not feasible to investigate due to lack of road access or operator denial, meaning alternative P&A'd wells that deviate from the desired criteria were also considered and selected. A summary of P&A'd wells ultimately selected for field investigation based on these criteria, including their basic attributes are shown in Table 1 and in map form in Figure 2. Field investigations took place during the last week of August and first week of September 2022 and included the deployment of a range of monitoring and measurement methods as described in the proceeding sections.

Table 1: Summary of P&A'd well sites selected for field investigations (all classed as abandoned), most of which generally fall into a type that can be broadly considered as "unconventional" (i.e. not vertical and subjected to hydraulic fracturing treatments). Orientation includes vertical (VERT), multiple (MULT) and deviated (DEV). Well type includes production (PRD), development (DEV) or undefined (UND). Treatments include acidization (A), fracked (F) and remedial (R). The symbol "-" denotes an unknown status or variable. It should also ne noted that WA 10570 is partially abandoned (i.e., zonally), not yet fully P&A'd.

WA	Orientation Name	Well Type	Fluid Type	Treatments	Well Total Age	Time since P&A	No. of Plugs	Total Plug Length
107	VERT	PRD	GAS	A, R	68	15	5	8
6645	MULT	DEV	GAS	F, A, R	35	11	7	159.9
7077	DEV	PRD	OIL	F, A	33	30	1	26
9766	HORIZ	PRD	OIL	R	26	10	2	8
9876	MULT	PRD	OIL	F	26	1	1	259
10570	HORIZ	DEV	OIL	-	25	5	1	126
10512	HORIZ	PRD	GAS	A	25	12	6	24
12660	DEV	-	UND	F	23	22	1	3
14237	DEV	DEV	GAS	F	21	11	4	16
21083	DEV	DEV	UND	F	16	15	2	8
22800	DEV	UND	UND	F	15	15	3	8

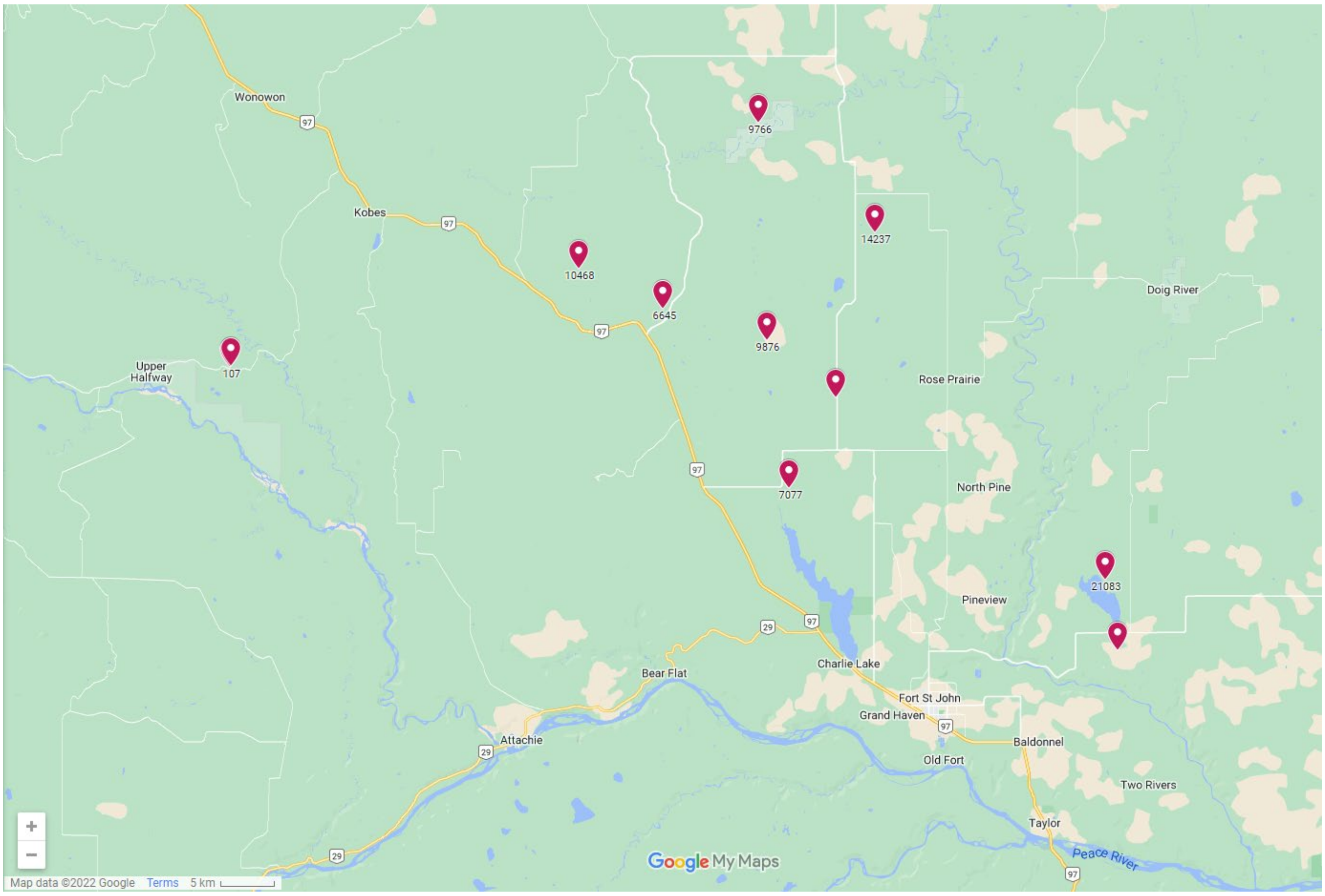


Figure 2: Map showing locations of 11 P&A'd well sites selected for field investigations in and around the Fort St. John Area.

2.2. Well Integrity and P&A Performance Evaluation Methods

During field investigations, candidate wellheads were located according to regulatory held coordinates using a GPS (accuracy to +/- 2m) and visual identification. After locating the well head a sampling grid formed of 9 points in a cross hair pattern (oriented North with each sampling point 2 m apart) was established, centered on the assumed well head location (Figure 3). A dynamic flux chamber system was then used to measure CH_4 and CO_2 efflux from the soils at each sample point above and around the examined P&A'd well in spatial survey mode. The flux chamber was comprised of an Eosense® eosAC Multi-Species Soil Flux Chamber coupled with a tuneable diode CH_4 and CO_2 laser and Campbell Scientific CR1000 data logger. During spatial surveys, the chamber was moved between the different sample points to attain single, short duration (i.e. 5 minute) flux measurements. Prior to flux chamber deployment, a hand auger (12 cm in diameter) was used to penetrate the topsoil and root zone (i.e. to around 20 cm depth) at each measurement location and a cylindrical collar positioned around the shallow hole (i.e. pushed 5 – 10 cm into the soils) to create a more effective seal. The dynamic flux chamber was then deployed on the cylindrical collar, over the top of the shallow auger hole and operated in manual mode, opening and closing upon initiation, while continuously measuring chamber air CH_4 and CO_2 concentrations (Figure 4 and 5). To yield a flux value (in mass/area/time), a regression line was derived from any rate of change in CH_4 or CO_2 concentration observed during chamber closure and combined with the ideal gas volume (derived from ambient temperature and pressure), the chamber volume (0.0021m^3) and cross-sectional area (0.0182m^2). In addition to flux measurements at and around the wellhead location, a background location was also monitored at each wellsite. Background locations were established at least 50 m from the wellhead, ensuring ground and vegetation cover remained representative.

Physical soil-gas samples for laboratory analyses were collected at select locations (i.e. typically at the monitoring grid centre point) using the flux chamber systems peristaltic pump and a 25 ml gas-tight syringe system (SGE 25MDR, Restek Thames, England) with Luer Lock Valve. Here, the 2" syringe needle was placed into the flowing soil gas effluent line, purged several times before a sample was taken and transferred into a 12 ml pre-evacuated sampling tube. In addition to soil gas samples, several atmospheric air control samples were also taken for comparative purposes. Samples were stored upside down and analysed for gas composition (CH_4, CO_2, N_2, O_2, and Ar) and stable-carbon isotope ratios ($^{13}C/^{12}C$) of CH_4 and CO_2 in the Isotope Science Laboratory at the University of Calgary (Alberta, Canada) using a Scion 450/456 gas chromatograph (GC). The lower detection limit for hydrocarbon gases is 1 ppm and for non-hydrocarbon gases 50 ppm. Analytical precision and accuracy for gas composition analysis was ±2.5% of the reported concentrations. Stable carbon isotope ratios $^{13}C/^{12}C$ of CH_4 and CO_2 were also quantified at the ISL using continuous-flow isotope-ratio mass spectrometry. Isotopes were measured using a Thermo Trace GC – GC-IsoLink system interfaced to a Thermo Scientific MAT 253 mass spectrometer via a Thermo Conflo IV. The final isotopic ratio results are expressed as δ values using per mil notation relative to the international V-PDB and V-SMOW standards for ^{13}C with an associated accuracy of ±0.5‰.

Select surficial sediment samples were attained from approximately 0.3 m depth (using a hand auger, double bagged in a soil sediment sample bag and stored in a cooler) in order to characterize parameters that are likely to influence shallow fugitive gas transport. These samples were analyzed for texture (i.e. grain size distribution), moisture content, total organic carbon content (TOC), bulk density, salinity, trace metals and the presence of hydrocarbons (including both volatiles and PAH's) by Bureau Veritas Laboratories using their standard methodologies.

Finally, relevant local climatic factors during the field investigations (i.e. air temperature, barometric pressure and wind speed) were attained from an Environment Canada weather station based in Fort St. John. Together this combination of surficial efflux monitoring, soil gas sampling and sediment characterization in conjunction with meteorological parameter evolution will allow the presence or absence of hydrocarbon gases at anomalous levels (i.e. compared to typical background ranges and measurements attained at background locations) at and in the soil around the select P&A wellheads to be determined. From this information, P&A performance and general well integrity status will be inferred.

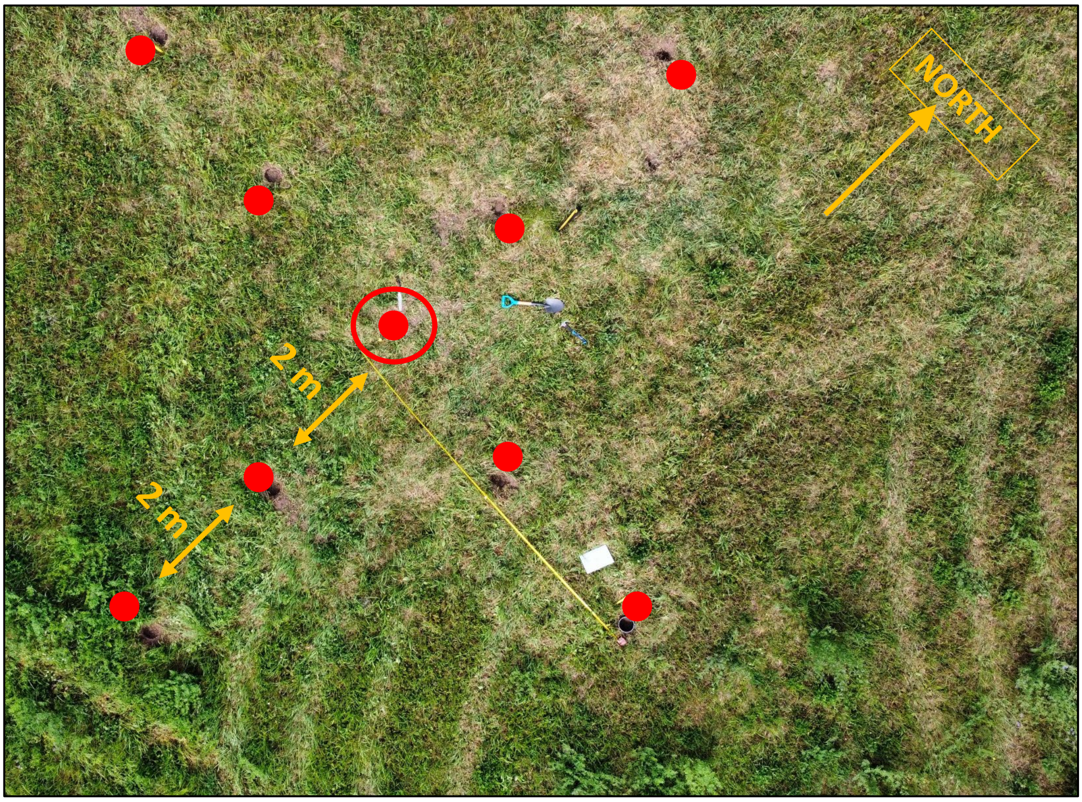


Figure 3: Monitoring grid deployed at each wellsite showing the 9 monitoring points in a cross hair configuration, oriented North, covering an area of 8 m^2 (2 m distance between each point) and centered over the assumed wellhead.

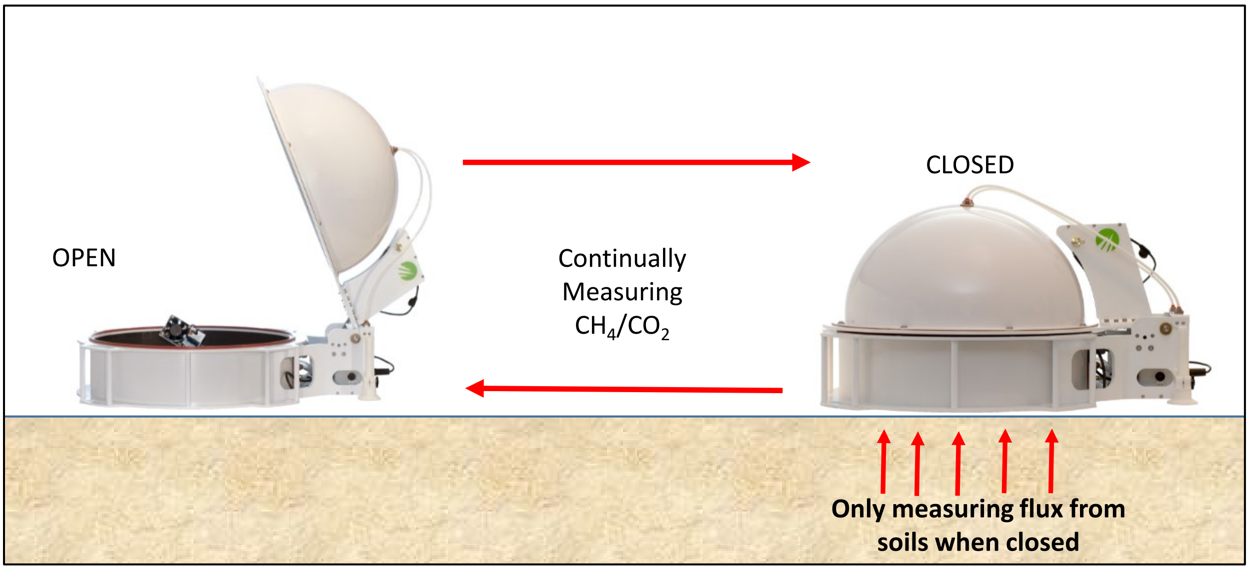


Figure 4: Dynamic flux chamber operational concept showing chamber continually measuring GHG concentrations while opening and closing to estimate fluxes from soils to atmosphere.

Figure 5: Dynamic flux chamber system deployed during field investigations showing the chamber unit installed on a collar connected to the analyzer unit.

3. Results

3.1. Site Locations and Well Status

The investigated well sites presented a variety of soil conditions, from fully reclaimed in pasture or crop fields with no wellhead present (i.e. being cut, capped and buried) to a full wellhead still present with bare soils. Examples of the varying P&A well site conditions encountered are shown in Figure 6. Despite an attempt, it was not possible to reach WA 6645 due to poor road conditions (i.e. fallen trees and large washed out dirt road sections). Consequently, this site was ultimately not examined as was hoped and a total of 10 of the 11 planned P&A'd well sites were visited during field investigations.

Figure 6: Varying conditions encountered at investigated P&A well sites showing; a cut capped and buried well, with reclaimed vegetation in a grazing field (top left), a very recently reclaimed site with no vegetation growth and presence of "pock marks" and bull dozer tracks (top right), a disconnected well head and valve assembly (bottom left) and a fully reclaimed crop field (bottom right).

3.2.Surficial Soils Greenhouse Gas Concentrations and Fluxes

A total of 108 flux measurements were taken across the investigated P&A'd well sites during the investigation period, comprised of 13 background measurements and 95 measurements at and directly adjacent to the well head (i.e. as part of the monitoring grids). A time series of raw CH_4 concentration data (i.e. CH_4 in ppm) during flux chamber operation is shown in Figure 7. A summary of calculated fluxes at each wellsite based on observed concentrations is provided in Table 2. An example of a single flux measurement taken at wellsite WA 22800, where CH_4 flux in excess of natural ranges was detected, is shown in Figure 8. Plan view contour plots (interpolated using the Krigging method) of spatial CH_4 and CO_2 flux during site measurements for select P&A'd wells are shown in Figure 9. It should be noted that typical natural concentration ranges for CH_4 and CO_2 in surficial soils are 2 – 3 ppm and 400 – 800 ppm with typical fluxes usually < 0.05 µmol/m^2/sec and < 5 µmol/m^2/sec respectively.

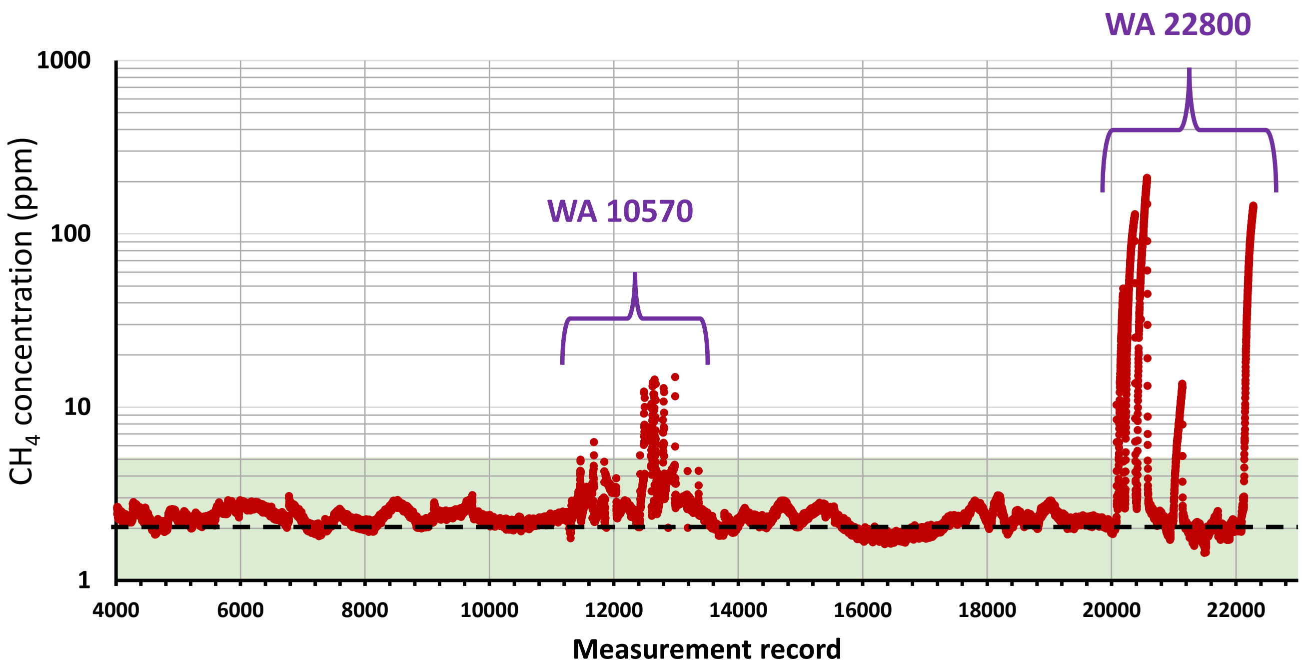


Figure 7: Concentration of CH_4 as measured with the flux chamber system during the whole field investigation campaign (i.e. throughout all site visits for both open and closed chamber status). The green shaded area shows the typical maximum natural range at which CH_4 may be detected in most natural environments relevant to NE BC. Results show CH_4 was typically low in concentration at all sites with the exception of WA 10570 and WA 22800.

Table 2: Calculated flux estimates for each P&A'd well site examined showing number of flux measurements made, average and maximum CH_4 fluxes observed, average CO_2 flux for the wellhead area and background locations as well as an inference on the likely integrity of the P&A'd well based on CH_4 flux observations.

Wellsite	No. of Flux Measurements	Well Head Area fluxes (µmol/m²/sec)			Background fluxes (µmol/m²/sec)		Potential Integrity based on CH_4 Flux
		Ave. CH_4	Max CH_4	Ave. CO_2	Ave. CH_4	Ave. CO_2	
107	10	-0.011	0.011	4.41	0.006	3.43	Likely Intact
7077	6	0.0007	0.041	6.75	N/A	N/A	Likely Intact
9766	11	0.0041	0.046	1.62	0.018	10.85	Likely Intact
9876	11	0.006	0.108	10.93	-1.14	0.519	Likely Intact
10570	12	0.072	0.348	9.74	-0.005	3.53	Sub-optimal
10512	10	0.024	0.165	6.02	0.006	3.43	Likely Intact
12660	13	-0.009	0.012	11.13	-0.032	5.29	Likely Intact
14237	10	-0.003	0.023	3.08	0.023	2,42	Likely Intact
21083	12	-0.017	0.005	14.78	-0.004	5.87	Likely Intact
22800	13	0.73	3.01	16.67	-0.03	3.96	Sub-optimal
6645	Not possible to reach						

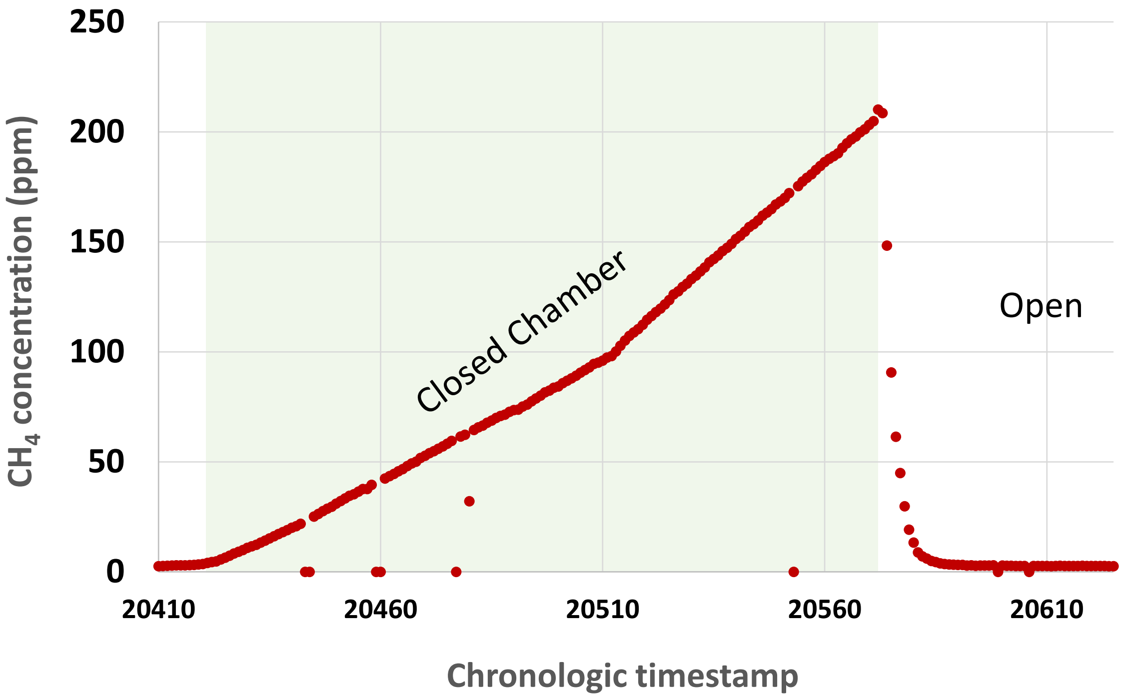


Figure 8: Concentration of CH_4 with time during a single flux measurement taken at the wellhead center of WA 22800. Results show a clear, stable and significant increase in CH_4 from background levels to > 200pm during the closed chamber period of 5 minutes, generating an associated flux estimate of 3 µmol/m^2/sec (compared to a background estimate of -0.03 µmol/m^2/sec attained some 50 m away in the same crop field).

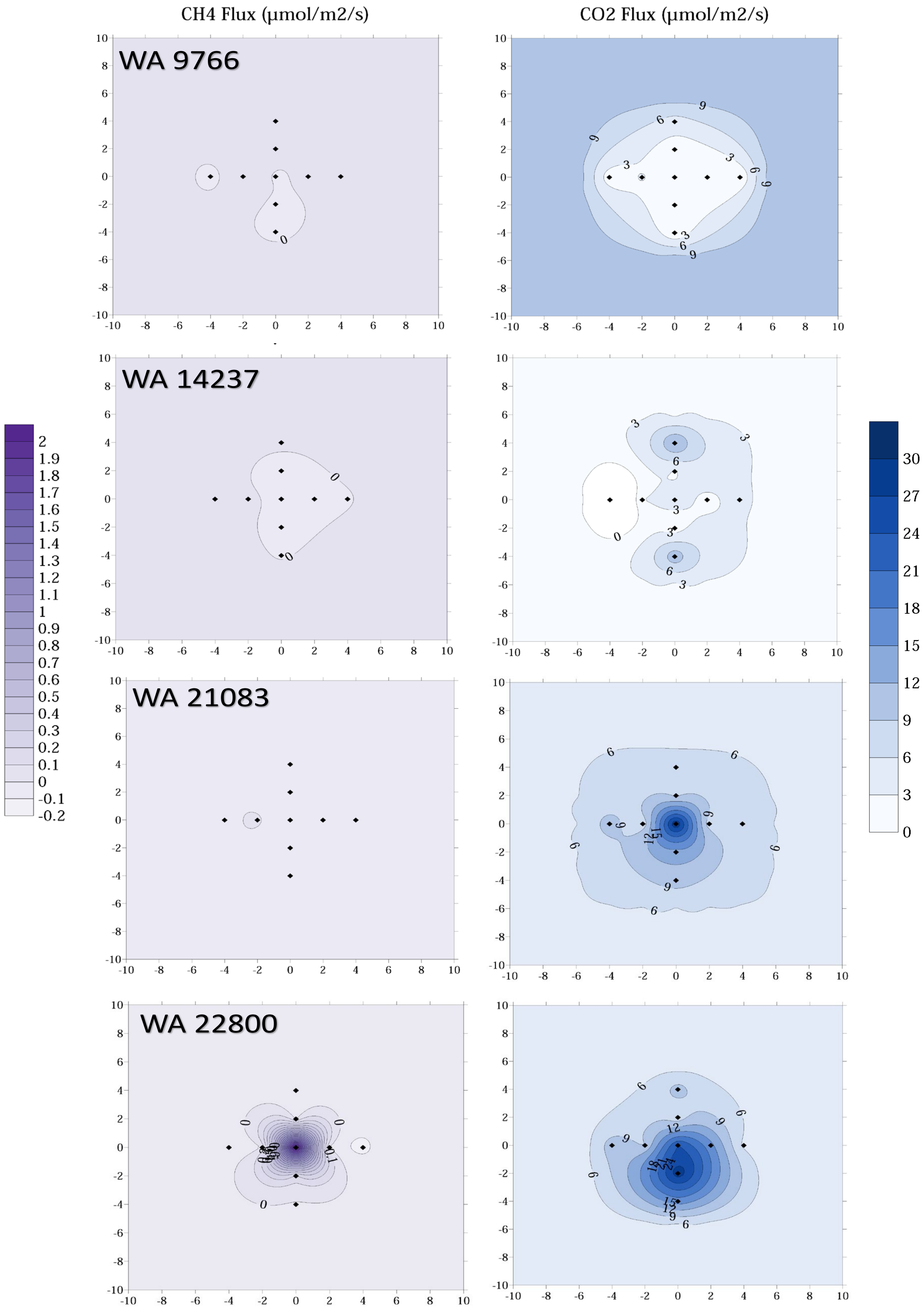


Figure 9: Plan view contour plots of CH_4 and CO_2 flux (interpolated by Krigging) as calculated from rates of change in concentrations detected with the dynamic flux chamber system for select investigated P&A'd well sites.

Results show, that with the exception of well sites WA 10570 and WA 22800, eight out of ten investigated P&A'd well sites exhibited generally normal soil gas CH_4 concentrations (i.e. ~2 – 3 ppm) and fluxes of CH_4 (i.e. +/- 0.01 µmol/m^2/sec) at the soil-atmosphere interface. Based on CH_4 measurements, these P&A'd wells likely maintain full integrity. Exceptionally, well sites WA 10570 and WA 22800 showed CH_4 levels in excess of what can be considered normal in terms of soil gas CH_4 concentrations (exhibiting values of >10 and >200ppm respectively) and CH_4 fluxes to atmosphere (at 0.35 and 3 µmol/m^2/sec respectively) at and around the wellhead. Such values are indicative that fugitive gas leakage from the P&A'd wells is occurring at these sites.

Meanwhile, concentrations and fluxes of CO_2 were much more variable across the examined P&A'd well sites and in some cases anomalously high. Here, well sites with elevated CH_4 (i.e. WA 10570 and 22800) were also shown to be co-emitting CO_2 at anomalously high levels (i.e. average values of 9.7 and 16.6 µmol/m^2/sec respectively compared to background values of 3 – 4 µmol/m^2/sec), likely a result of soil based fugitive CH_4 biodegradation occurring. In addition, several other P&A'd well sites were seen to be exhibiting what could be considered potentially high CO_2 concentrations and fluxes (i.e. in excess of 10 µmol/m^2/sec, compared to typical background values observed of < 5 µmol/m^2/sec). However, interestingly these sites showed no signs of elevated CH_4 concentrations or fluxes.

3.3.Surficial Soil Gas Laboratory Analyses

Results from physical soil gas sample analyses (i.e. concentrations in ppm and $\delta^{13}C$ values corrected to the international VPDB scale, and stated in units of ‰) taken from investigated P&A'd wellsites and sent for laboratory analyses are shown in Table 3. Atmospheric air samples (taken as controls) are shaded in blue with soil gas derived samples shaded green.

Table 3: Physical soil gas sample laboratory analyses results (with concentrations in ppm and $\delta^{13}C$ values corrected to the international VPDB scale, and stated in units of ‰)

Wellsite	Sample Type	Argon	O_2	CO_2	C_1	C_2	C_{3+}	$\delta^{13}C$-CO_2	$\delta^{13}C$-CH_4
107	atm. air	8577	206380	1118	3	0	0	-18.9	na
10570		8732	207683	1061	4	0	0	-16.5	na
12660		8835	208684	1036	2	0	0	-16.3	na
14237		8761	208651	994	3	0	0	-17.1	na
21083		8888	209686	936	3	0	0	-16.2	na
22800		8647	207750	1000	2	0	0	-16.4	na
9766	chamber	8783	207436	1552	3	0	0	-17.4	na
9766		8687	208337	1077	3	0	0	-17.4	na
10570		8748	207857	1506	3	0	0	-19.3	na
10570		8647	207737	1057	3	0	0	-16.8	na
12660		8868	208105	1699	3	0	0	-19.5	na
14237		8711	206874	1529	3	0	0	-18.9	na
14237		8840	207171	1223	3	0	0	-18.0	na
21083		8712	207542	1987	3	0	0	-21.0	na
22800		9816	206684	1986	79	0	0	-30.1	-33.7

Results from laboratory analyses generally confirm observed field concentrations and flux estimates, showing WA 22800 as exhibiting the highest levels of CH_4. However, the sample collected from WA 10570 did not concur with the levels of CH_4 observed in the field (i.e. 10 – 14 ppm), appearing from laboratory analyses at background levels. This could be a result of the extremely windy conditions on the day (see section 3.5), the small level of elevation above background that was manifesting (i.e. only exhibiting values 7 – 10 ppm in excess of baseline) and/or a result of sample vial failure or sampling error. Nonetheless, in general, laboratory results support field concentration and flux estimates for both CO_2 and CH_4.

Only the sample from WA22800 had concentrations of CH_4 high enough to perform a reliable $\delta^{13}C$-CH_4 analysis, which showed a stable carbon isotope ratio value of -33.7 ‰. This value is in a range typical of thermogenic gases (which tend to exhibit values of between -45 and -35 ‰), if not slightly more positive than might be expected. The slightly more positive value observed further corroborates the concept that co-emission of CO_2 at this wellsite is a result of soil based biodegradation of CH_4 during reactive transport through the soils, which would shift the isotope ratio in the positive direction.

3.4.Sediment Analyses

Select results from surficial soil sediment analyses at key P&A'd well sites investigated are shown in Table 4 and Figure 10.

Table 4: Surficial soils organic carbon content, dry bulk density, soil moisture and soil/cover type for examined well sites (units as labelled).

Wellsite	Soil Organic Carbon (%)	Dry Bulk Density (g/cm^3)	Soil Moisture (%)	Soil type/cover
12660	3.5	1.2	11	Grazing field/grass
7077	5.1	1.2	-	Grazing field/grass
22800	3.3	1.3	10	Crop field/wheat
21083-A	5.2	1.1	35	Marsh-like/tall vegetation
21083-B	5.3	1.1	13	
9766	0.96	1.4	-	Wellpad/bare soil
14237	4.3	1.1	-	Wellpad/bare soil
10570	1	1.4	8.1	Wellpad/bare soil
107	1.8	-	-	Wellpad/bare soil
10512	1.6	1.4	-	Wellpad/bare soil

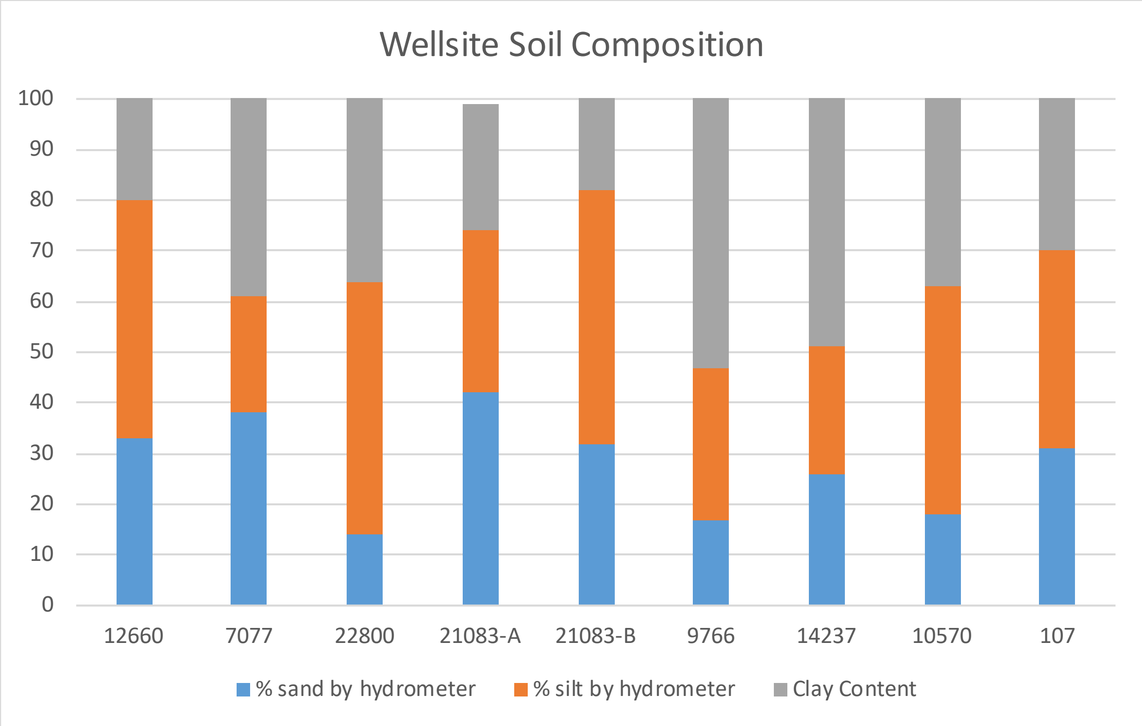


Figure 10: Surficial soil composition as % sand, silt and clay for examined P&A'd well sites.

Results show variable organic carbon content ranging from <1% to > 5% composition, generally corresponding to soil cover type (i.e., with vegetated sites exhibiting higher TOC than bare soils). Soil textural compositions were also highly variable with sand content ranging from 12% to 42%, silt content from 23% to 47% and clay content from 18% to 53% across the P&A'd well sites. Such ranges and mixes in sediment composition infer that these soils will have a range of effective permeabilities for fluid/gas flow. For example, soils at WA 9766 and WA 14237 likely exhibit the lowest permeability with clay contents at ~50% composition, while WA 21083 and WA 12660 may exhibit the highest permeability with sand and silt content at ~80%.

Results for surficial soil alcohols, volatile petroleum hydrocarbons (C6 – C10 +BTEX) and light and heavy extractable petroleum hydrocarbons (including PAH's) returned non-detect results for all parameters at all sites for which samples were analyzed. Soil salinity and soil metals also returned no anomalous results with all analytes of interest being within natural levels for typical soils.

3.5. Meteorological Conditions

Time series of key weather parameters (i.e. air temperature, barometric pressure and wind speed) that prevailed during the field campaign as monitored at a weather station installed in Fort St John area are presented in Figure 11. Days on which individual well sites were investigated are indicated with yellow shading and numeric labels.

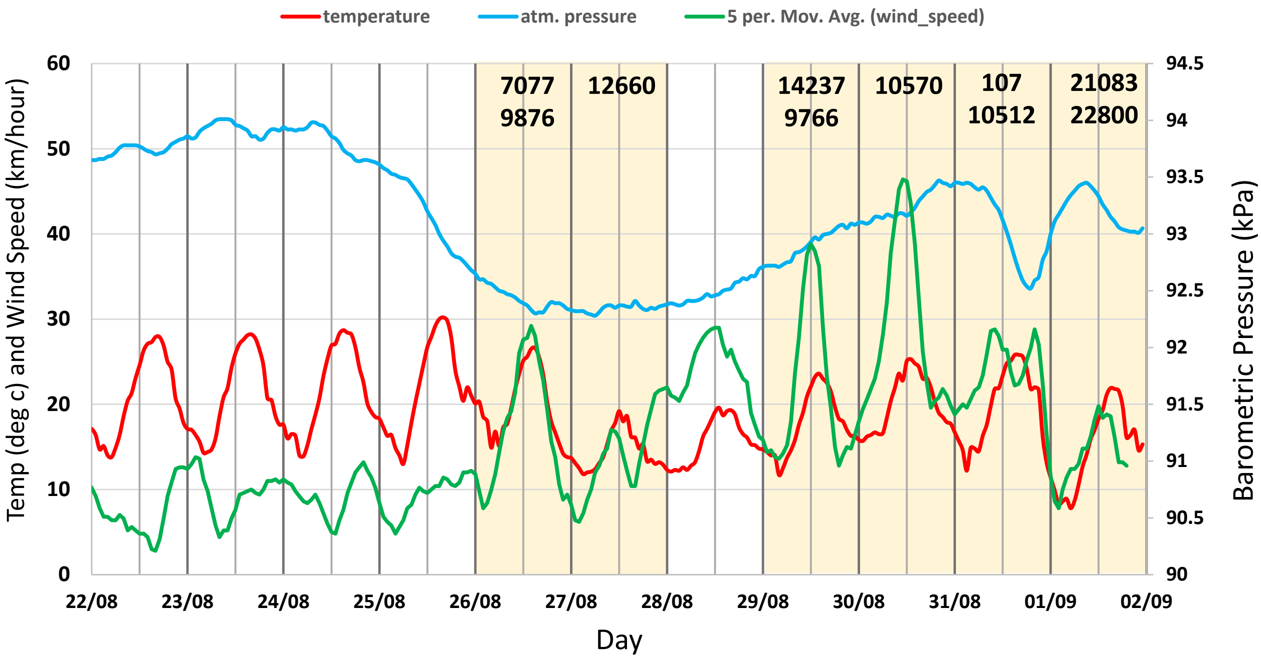


Figure 11: Key weather parameters during field investigations with days each well site was visited indicated in the shaded areas.

Results show prevailing weather conditions were typical of Northeast BC in late August with generally warm (including normal diurnal temperature maxima and minima) and dry conditions (i.e. no rainfall occurred several days before and during the survey period) with fluctuating wind speeds (at times quite high). These data show that conditions were variable by day of the field investigation, which may have had an impact on observed results, and inferences on P&A'd well integrity made (as described in WP1). More specifically, investigations at well sites WA 7077, 9876 and 12660 occurred during a period of stable, lower barometric pressure and generally lower winds (i.e. 10 – 30 km/hr) while wellsite surveys for WA 14237, 9766 and 10570 occurred during a period of steadily increasing barometric pressure and high winds (i.e. 35 – 45 km/hr). The remaining 4 sites examined, i.e. WA 107, 10512, 21083 and 22800, occurred during oscillating pressure cycles with lower winds and temperatures.

4. Discussion

4.1. General Integrity of Examined P&A'd Wells based on CH_4 Measurements

Out of ten candidate well sites ultimately examined, two (i.e. WA 10570 and 22800) were seen to be exhibiting signs of elevated CH_4 at and around the wellhead; a sign indicative of integrity failure. Wellsite WA 22800 was most conclusive with elevated CH_4 concentrations consistently > 200ppm (compared to typical atmospheric levels of 2 – 3 ppm) and fluxes in excess of 3 µmol/m^2/second (compared to typical natural fluxes of slightly net positive or net negative; +/- 0.01 µmol/m^2/sec) consistently observed at the assumed wellhead location. Laboratory analyses confirms this assertion, also showing elevated soil gas CH_4 concentrations at ~80ppm with a $\delta^{13}C$- CH_4 value of -33.7 ‰. This $\delta^{13}C$-CH_4 value is consistent with a thermogenic gas source that has been subjected to some minor biodegradation processes during reactive transport through the soils. Of additional interest to note is that during ground investigations at WA 22800, potential vegetation stress was noted in the form of stunted growth and discoloration of crops in a small radius (i.e. ~2 - 3 m) around the wellhead. This vegetation stress was also visible from the air via drone photography as shown in Figure 12 and is of note as it suggests that evaluation of vegetation health at fully reclaimed well sites could form a useful tool to help identify sub-optimal well integrity.

Figure 12: Aerial photograph at approximately 50 m height, showing areas of the wellhead which appears slightly different than surrounding vegetation as was observed on the ground (with vegetation within 2 m of the wellhead being stunted by at least 50% in comparison to surrounding crops).

For site WA 10570, signs of well integrity failure were less conclusive, but still indicative of fugitive gas release. Here, soil CH_4 concentrations and fluxes were elevated above background levels, but only marginally (exhibiting concentrations of 10 – 15 ppm and ~ 0.35 µmol/m^2/second compared to typical background levels of 2 – 3 ppm and +/- 0.01 µmol/m^2/sec). These elevated values were also observed to be quite erratic in nature with flux measurements and concentrations being highly variable with time (i.e. not stable or consistent as was seen at WA 22800). Laboratory gas sample GC analyses were unable to confirm field observations of marginally elevated CH_4 concentrations (showing values equivalent to baseline at 2 ppm, as opposed to > 10 ppm in the field). Consequently it was not possible to confirm if any CH_4 at this site was of a thermogenic nature (with sample concentrations being below the levels at which reliable stable carbon isotope analyses can be performed, i.e., < 10ppm). However, it was noted on this day that extremely strong winds were present (Figure 11, stable speeds of around 40 – 45 km/hour with gusts of up to 60km/hour), conditions which would undoubtedly impact observed fluxes (acting to dilute or minimize them), as well as making it difficult to obtain a conclusive laboratory sample. In addition, it was hypothesized that WA 10570 may be exhibiting valve leakage from the remaining above ground wellhead infrastructure present at the site. The potential for this was suggested by the Field Supervisor representing the wells license holder (who participated in the site visit), and supported by the presence of a strong bituminous odor around the well and the erratic concentrations observed during the open chamber status. More investigation would be needed to better constrain the integrity status of this well, however, the data collected during this campaign do suggest leakage of CH_4 from the well into the surrounding soils is likely occurring.

Based on CH_4 efflux observations alone, no other investigated P&A'd wells (i.e. the other eight out of ten investigated) appear to be suffering integrity compromise, with soil gas and efflux conditions for CH_4 within natural ranges. Upon evaluation of prevailing weather and soil conditions, CH_4 concentrations and fluxes observed across the different P&A'd well sites on different days appear uncorrelated to any associated factors (i.e. wind speed, barometric pressure, temperature, soil organic carbon etc.). In this case CH_4 fluxes are typically low (either slightly net positive or net negative) regardless of other factors with the exception of fluxes at 22800 and 10570. For these wells, CH_4 levels were in excess of any typical natural ranges for the region, with no linkage to environmental conditions and therefore are clear and robust indicators for sub-optimal integrity.

4.2. Consideration of CO_2 Concentrations and Fluxes

In addition to CH_4 concentrations and fluxes, CO_2 was also monitored during field investigations generating particularly interesting data. As CH_4 is the main component of fugitive natural gas, it typically forms the primary target of well integrity field investigations. However, as is well documented, CH_4 is reactive in shallow soil systems, being readily degraded to CO_2 and H_2O under aerobic conditions. Consequently, it should be expected that when CH_4 is released into shallow soils some portion of it would be converted to CO_2. Thus, quantification of CO_2 concentrations and fluxes when evaluating well integrity is highly beneficial allowing both the occurrence of biodegradation to be confirmed and forming an additional indicator species to aid in evaluation of a P&A'd well integrity status. Consequently, CO_2 flux data for the two P&A'd wells exhibiting elevated CH_4 release (i.e. WA 10570 and WA 22800) were carefully reviewed. These data show clearly that elevated CO_2 fluxes above natural ranges are also occurring at these sites around the wellhead (i.e. average fluxes of 9.7 and 16.6 $\mu mol/m^2/sec$ respectively compared to background values of 3 – 4 $\mu mol/m^2/sec$). This observation strongly supports the concept that microbial oxidation processes are occurring and that some portion of the fugitive natural gas being released from these integrity compromised wells is naturally attenuating via soil microbial communities. From our data it is clear that P&A'd wells suffering sub-optimal integrity will co-emit CH_4 **and** CO_2 and therefore fluxes of both gases should be quantified in order to more effectively detect and better constrain leakage magnitudes. An example of CH_4 and CO_2 co-emission, as detected at P&A'd well WA 22800 is shown in Figure 13.

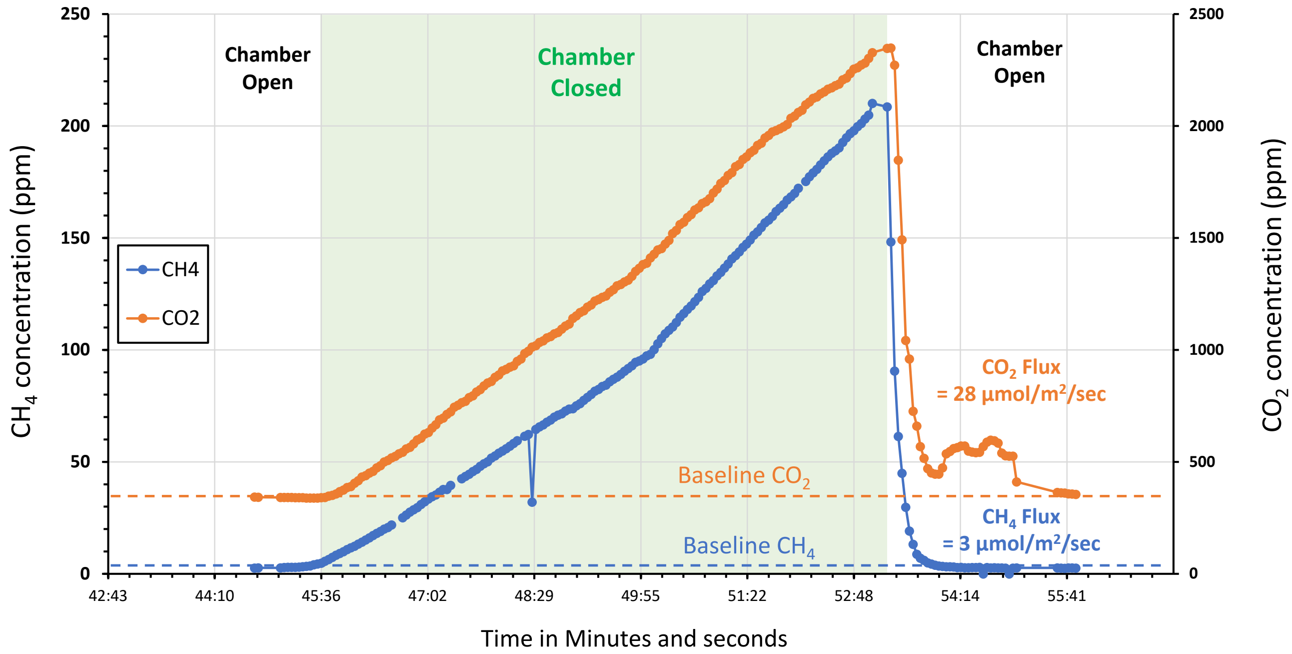


Figure 13: CH_4 and CO_2 concentrations observed during a flux measurement at wellsite WA 22800 showing co-emission indicative of CH_4 oxidation occurring in the surrounding soils.

Meanwhile, average CO_2 fluxes at the other P&A'd well sites examined varied significantly from 1.6 to ~15 µmol/m^2/sec at and around the wellhead locations compared to observed average background levels of 3 – 4 µmol/m^2/sec. This observation is in contrast to CH_4 concentrations which were either very low/close to net zero (where integrity is assumed fully maintained) or clearly elevated (inferred as suffering leakage). To understand this variability these data were reviewed in the context of meteorological (temperature, wind speed and barometric pressure) and soil conditions (organic carbon and moisture content and grain size distribution) that prevailed during data collection. Here, no strong or significant correlations were observed, with the exception of weak or marginal inverse correlations (i.e. not statistically significant) with wind speed ($R^2 = 0.4$) and clay content ($R^2 = 0.58$). This suggests some influence of these parameters in the variability of CO_2 fluxes measured across the sites, with CO_2 fluxes decreasing with increasing wind speed and increasing clay content of soils. However, these potential relationships cannot fully explain the variation in CO_2 concentrations and fluxes observed between sites or the seemingly high levels detected (up to 15 µmol/m^2/sec) at some sites (compared to background conditions of 3 - 4 µmol/m^2/sec). More work is needed to understand this variation and to evaluate the potential source for these elevated levels of CO_2 at and around the P&A'd well heads.

4.3. Implications of Observed Results

Field results suggest that 2 out of 10 unconventional P&A'd wells examined appear to be suffering sub-optimal integrity and releasing small amounts of fugitive gases into the shallow soils and atmosphere. This result, i.e. a potential 20% integrity failure incidence rate, is a reasonable estimate based on other studies and data (including consideration of data from aerial surveys as outlined in WP1) and shows that it is likely that a minority of P&A'd unconventional wells may exhibit leakage post abandonment. Upscaling of this indicative incidence rate would infer that out of the 119 currently P&A'd wells in BC that can be classed as unconventional, some 20 or so could be exhibiting integrity failure. However, it should be noted that the magnitude of CH_4 release is seemingly low (in the case of WA 22800), if not very low (in the case of WA 10570). Here, it is important to acknowledge that based on the field flux measurements made, a reasonable estimate for total volume of CH_4 being emitted at each site would be 23 and 3 liters per day for WA 22800 and WA 10570 respectively (assuming STP conditions, based on a leakage footprint of 4 m^2 with 1 mole of CH_4 equivalent to 22.4 liters volume). This is in comparison to the emissions of CH_4 generated by dairy cattle, which are estimated to be in the range of 250 – 500 liters of CH_4 per day, per animal. Therefore, while leakage was found in 20% of investigated P&A'd unconventional wells, its magnitude was very low and any associated contributions to greenhouse gas emissions and CH_4 budgets for the region are likely minimal if not insignificant compared to other sources.

4.4. Potential Leakage Configurations

In order to identify any potential causes for well integrity failure at WA 10570 and WA 22800, well records were reviewed and in particular, well construction and P&A schematics were evaluated (shown in Figure 14 and summarized in Table 5). Both wells clearly have differing designs and P&A configurations with little in common to explain observed leakage.

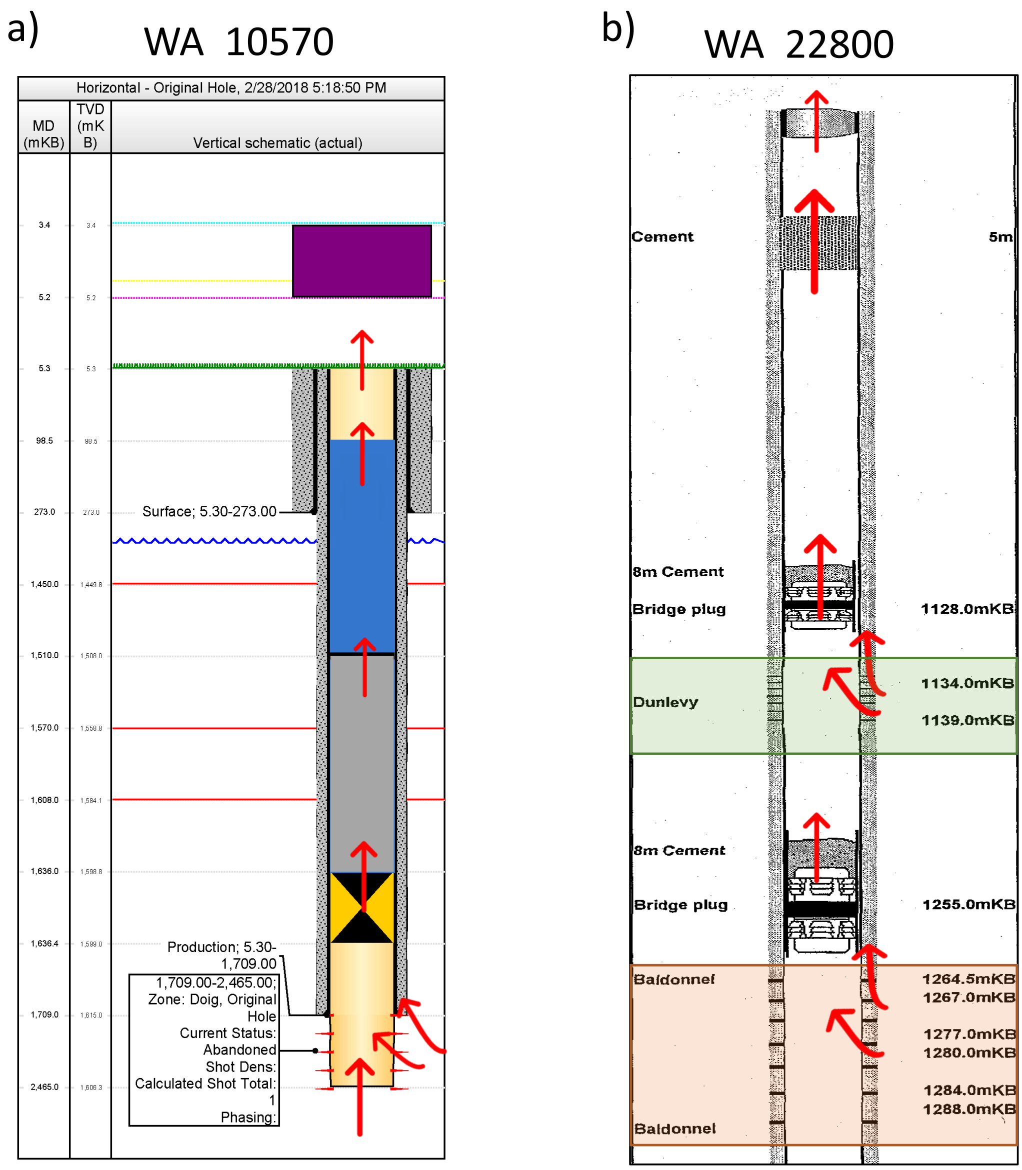


Figure 14: Well completion and P&A schematics for wells identified as potentially suffering integrity failure during field investigations, including potential fugitive fluid migration pathways indicated by red arrows.

Table 5: Summary of attributes for P&A'd wells identified as potentially suffering integrity failure.

WA	Orient	Well Type	Fluid	Length in m (True Depth)	Deviated length	Treatments	Total Age	P&A Age	No. of Plugs	Ave. Plug Length (m)
10570	HORIZ	DEV	OIL	2465 (1606)	784	NA	25	5	1	126
22800	DEV	UND	UND	1440 (1345)	95	F	15	15	3	8

According to records, WA 10570 was a horizontal oil well drilled in 1997, produced for 18 years and abandoned with one single long plug (126 m in length). This well never exhibited SCVF or GM during its active life and was not subjected to hydraulic fracturing treatments. According to records WA 22800 is undefined in its well type and fluid, being drilled in 2007 before being almost immediately P&A'd. It has been P&A'd with 3 plugs and has two perforated sections which have not been cemented that are still connected to gas bearing formations. This well never exhibited SCVF or GM during its active life, however was subjected to both hydraulic fracturing and acid treatments through the casing at the perforated sections. Based on careful review of all currently available data it is not possible to conclusively or meaningfully determine any potential causes for integrity failure to occur at these wells. Further investigation and analyses would be needed to help constrain leakage configuration and causes.

5. Conclusions

Here we investigated the general integrity of 10 unconventional P&A'd wells in BC through state-of-the-science ground-based field investigations. These investigations, which took place from late August into early September 2022, included the use of a dynamic flux chamber, physical soil gas laboratory analyses, surficial soil characterization and data on climatic factors. Together our data suggest that two out of ten P&A'd unconventional wells investigated appear to be releasing CH_4 into surficial soils at and around the well head and are likely suffering some form of integrity failure. Concentrations and fluxes of CO_2 were also elevated beyond natural ranges at the same two well sites, suggesting that CH_4 oxidation is occurring in the surficial soils. This process is performing a natural GHG mitigation function offering a 98% reduction in GHG emissions (i.e., in terms of CO_2 equivalents) for every mole of CH_4 converted to CO_2 (considering a 20-year period). As weather and soil conditions appeared to have no influence on CH_4 flux patterns and only limited influence on observed CO_2 flux patterns, the most likely explanation for our field observations is sub-optimal integrity of the P&A'd well structure at well sites WA 10570 and WA 22800. While two out of ten wells investigated were identified as suffering fugitive gas leakage, it was also noted that the magnitude of leakage at these wells was extremely low. Here, even conservative magnitude estimates suggest the combined release of GHG's from both wells is far less than 10% that created by a single dairy cow per day. In this case it is posited that leakage from these P&A'd unconventional wells is generally insignificant and it may be questionable to re-enter and re-abandon these wells when considering the environmental risks and associated carbon footprint of full remedial action. Review of well records and configurations show these wells are constructed and P&A'd very differently, with the exact causes for leakage not possible to constrain at this point with currently available data. Overall, more work is needed to better constrain the incidence rate, leakage magnitudes and causes of integrity failure at P&A'd wells in BC in general and particularly so for wells classed as unconventional, which will form the majority of wells to be decommissioned in the coming decades.

WP3: Well Integrity and P&A Performance Modelling

1. Introduction and Background

The majority of well plug and abandonment strategies are governed by regulations and guidelines at the local and national levels. These guidelines have traditionally been very prescriptive. In spite of their simplicity of implementation, they typically take a "one-size-fits-all" approach to well P&A design and fail to consider differences in leakage risks between wells [38,39]. Well decommissioning operations, which are typically expensive and involve a large number of wells, have created a need for cost-effective, well P&A design and implementation strategies. As a result of such carefully designed strategies, decommissioning costs could be reduced and environmental standards still met while maintaining high safety standards. Moving away from prescriptive approaches and toward risk-based approaches can boost efficiency and reduce costs of well P&A, which has led to more interest in research in this area [38,40-44].

It is essential to understand the long-term performance of potential P&A design options based on current and possible future well and reservoir conditions in order to formulate a risk-based approach to well P&A design. Obtaining a quantitative understanding of the well P&A system requires a comprehensive model. Researchers at Heriot-Watt University[45] have previously developed a framework for well P&A modelling and design to support a risk-based approach which is explained in the following section. For Work Package 3, we used this framework to model leakage from two P&A'd wells investigated during field investigations undertaken in BC, including WA 22800 and WA 21083. The overall objectives of this modelling exercise were to better understand P&A performance as well as potential leakage configurations and evaluate the potential for optimization of designs through a well-specific risk based approach. In the case of WA 22800, which was shown to be emitting CH_4 from the surrounding soils into the atmosphere, the aim was to constrain the form of integrity failure that could generate fluxes as observed at the site. In the case of WA 21083, which did not exhibit elevated CH_4 fluxes but did show anomalously high CO_2 emissions, the aim was to evaluate if field observations could be associated with integrity failure and if so by which mechanism. Overall, the modelling exercise described herein can act as proof of concept, demonstrating that numerical modelling can help understand potential scenarios of integrity failure, aid in evaluating potential resultant environmental impacts and therefore be used to optimize P&A design and remedial operations as part of a risk-based approach.

2. Methods

2.1. Generalized Modelling Concept

The well P&A modelling framework[45] includes a pre-processing module that renders all the data available as well as engineering knowledge to generate an integrated P&A system, as illustrated in Figure 1. There are three sub-models in this integrated P&A system:

- Sub-model of the well, including all barrier elements and potential fluid flow/leakage pathways,
- Sub-model of the near wellbore and the reservoir layers, and;
- Sub-model of shallower geological layers with significant in-flow or out-flow potential.

A numerical flow simulator, based on finite-difference methods, forms the core of the framework which integrates these sub-models into a single P&A system model. After the simulation has been completed, a post-processing module is used to read and display the simulation results.

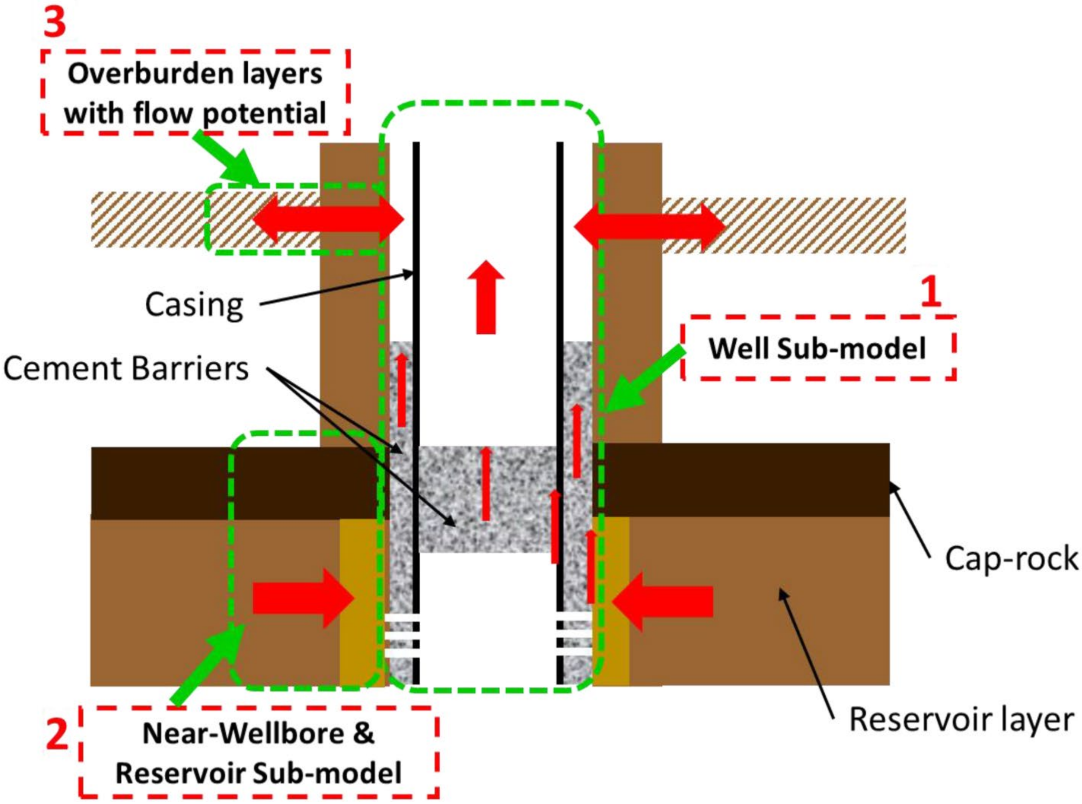


Figure 1: A schematic diagram of the integrated P&A system made up of three sub-models. The arrows indicate the potential flow/leakage pathways for hydrocarbons [45]

Some fundamental input parameters, such as well schematics and reservoir performance data are usually known for P&A system models. Meanwhile, some parameters such as cement barrier quality, including the presence of cement defects and their effective flow properties, are subject to uncertainty. Uncertainties in the input data of the model are handled using conventional probabilistic (e.g. Monte Carlo) techniques. A probability distribution for each uncertain input parameter provides a range of possible leakage rates, as well as their associated probabilities for each P&A design scenario. This allows the framework to compare and rank potential P&A design scenarios, enabling us to make cost-effective decisions on how to allocate time and money. Also, the framework identifies important parameters that influence the risk of future hydrocarbon mobilization, highlighting critical parameters for which greater understanding and constraint is highly beneficial.

The P&A modelling framework covers several P&A design scenarios, as shown in Figure 2, including possible leakage pathways as indicated by red arrows. It is possible for fugitive gas to be mobilized along the following routes: i) Through the bulk cement, cracks/fractures and channels, ii) Through cement-to-casing micro annuli and cement-to-formation interface, and iii) Along gauge cables and hydraulic lines in through-tubing abandonment scenarios.

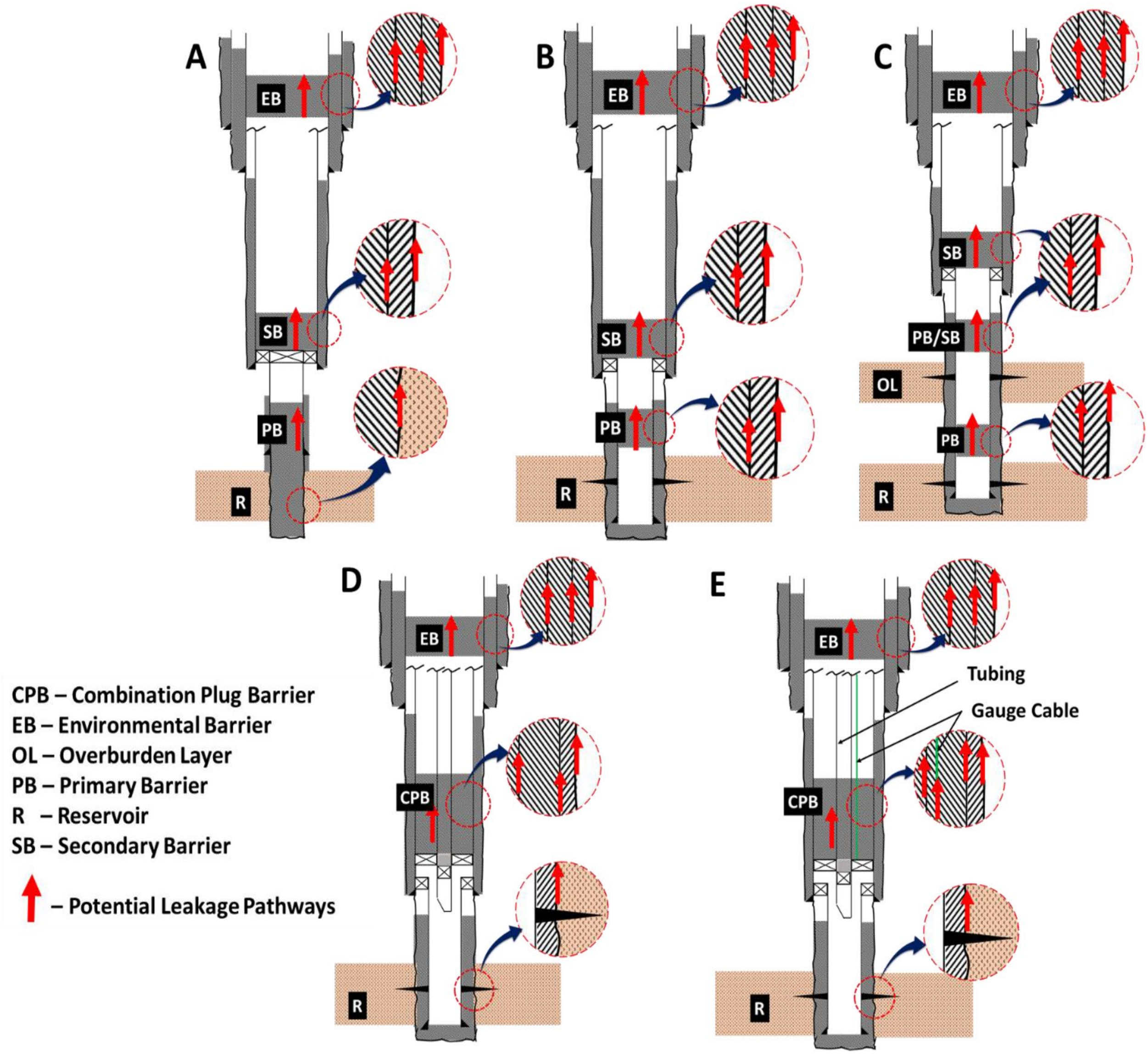


Figure 2: P&A Design scenarios covered by the P&A modelling framework: A) open-hole, single layer, B) cased-hole, single-layer, C) cased-hole, multi-layer, D) through-tubing abandonment without gauge cable and/or hydraulic line E) through-tubing abandonment with gauge cable and/or hydraulic line [45].

In Figure 3, an open-hole P&A design schematic is shown on the left (scenario A in Figure 2) and a cased-hole P&A design is shown on the right (scenario B in Figure 2).

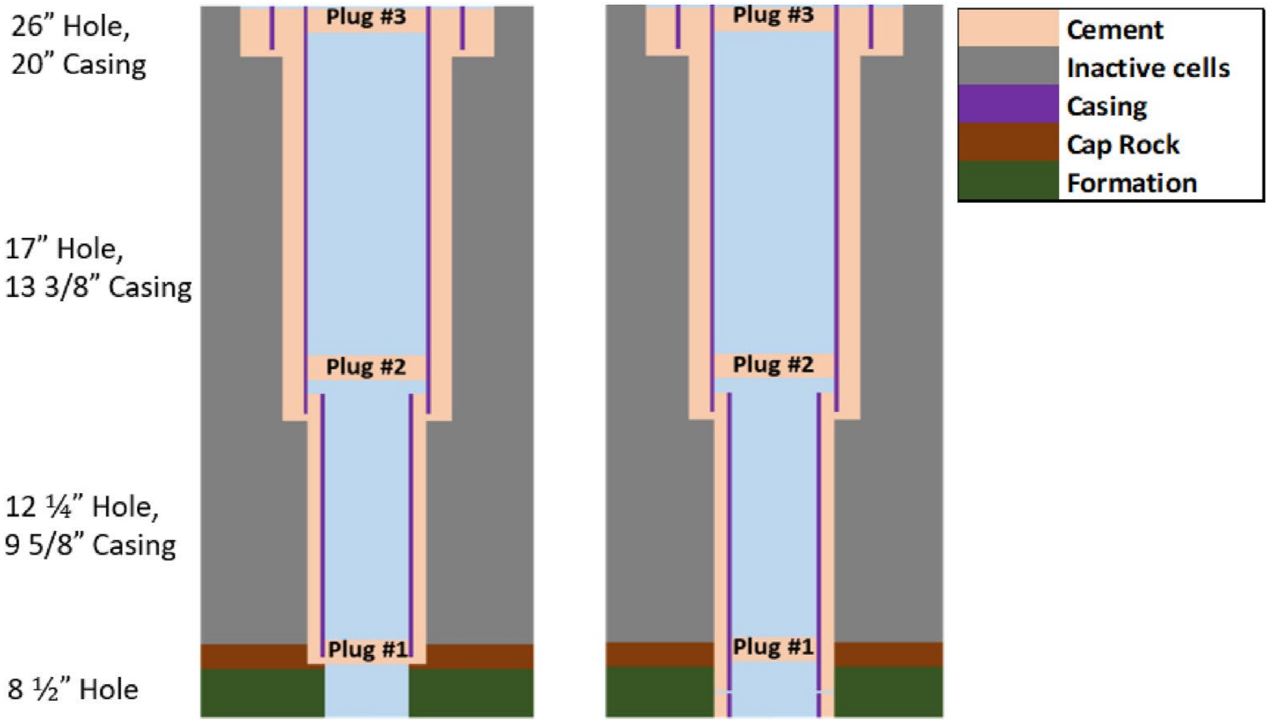


Figure 3: Well schematics for a multiple-plug (Left) open-hole P&A scenario and a (Right) cased-hole P&A scenario [45]

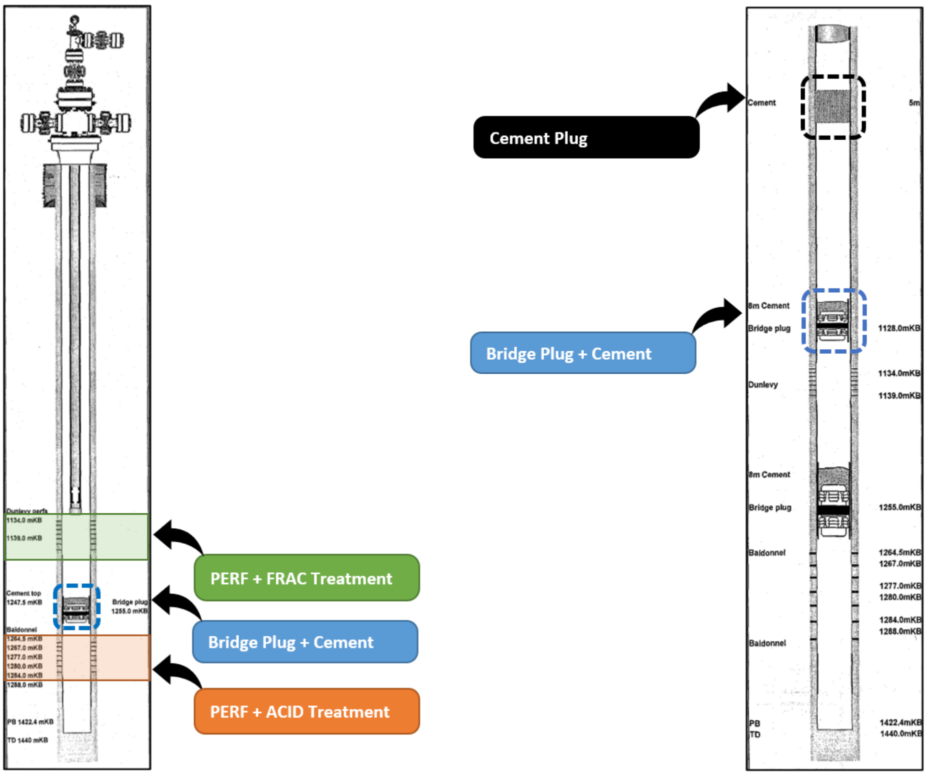
2.2.BC Specific Wells Overview and Modelling Approach

Following the investigation of more than 10 wells in British Columbia as part of the field study WP in this project, two wells were selected to be further examined using the P&A modelling framework to analyze well integrity and identify possible leakage scenarios. These wells are located in the northeastern area of Fort St. John (Figure 4) and are designated as WA 22800 and WA 21083. In the case of WA 22800, which was shown to be emitting CH_4 from the surrounding soils into the atmosphere, the aim of modelling was to constrain the form of integrity failure that could generate fluxes as observed at the site. In the case of WA 21083, which did not exhibit elevated CH_4 fluxes but did show anomalously high CO_2 emissions, the aim was to evaluate if field observations could be associated with integrity failure and if so by which mechanism. Overall, modelling of both wells was envisaged to act as a proof-of-concept exercise, demonstrating that numerical modelling can help understand potential configurations of integrity failure, aid in evaluating potential resultant environmental impacts (i.e. emissions to atmosphere) and be used to aid optimization of P&A design and remedial operations as part of a risk-based approach to decommissioning.

Figure 4: Locations of P&A'd wells WA 22800 and WA 21083 which were examined in field investigations as described in WP2 and were selected for further evaluation by numerical modelling. These wells were selected as, along with their recently collected field data, they offered an opportunity to better understand potential configurations of integrity failure and aid in consideration of optimization.

WA 22800 was drilled and completed in March 2007. The well was first perforated and acid treated in the Baldonnel formation and then isolated using a bridge plug and cement. Afterwards, it was completed in Dunlevy formation by perforation and frac treatment. After a couple of months, the well was abandoned in July 2007 using a second barrier (bridge plug and cement) above the perforated Dunlevy formation, as well as placing a cement plug near the surface. Figure 5 illustrates the completion and abandonment designs for this well.

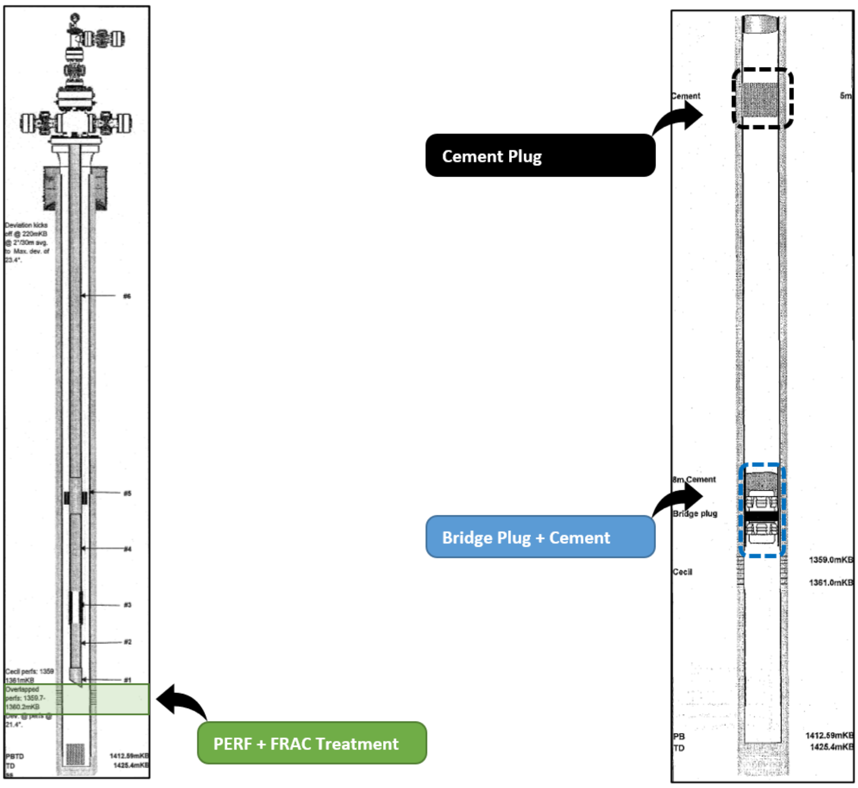
WA 21083 was similarly drilled and completed in 2006. Approximately one year later, it was abandoned by placing a bridge plug and cement above the perforated zone as well as setting a cement plug near the surface approximately three to six meters below ground level. An illustration of the completion and abandonment design can be found in Figure 6.



A-Completion Profile
(14/03/2007)

B-Well Abandonment Profile
(03/07/2007)

Figure 5: Completion (A) & Abandonment Design (B) for WA 22800



A-Completion Profile
(28/07/2006)

B-Well Abandonment Profile
(05/07/2007)

Figure 6: Completion (A) & Abandonment Design (B) for WA 21083

To perform the well P&A modelling for both wells, it is assumed that the reservoir pressure gradient and the wellbore fluid pressure gradient are the same and hold a value of 0.43 psi/ft. Additionally, both completions are presumed to be fully connected to the wellbore. For WA 22800, any fugitive fluids are assumed to be CH_4, and no conversion to other components (such as carbon dioxide) is considered. In contrast, for WA 21083, where only elevated CO_2 fluxes were measured at surface, any leakage of CH_4 is assumed to be totally converted to CO_2 during reactive transport through the subsurface with a 1:1 stoichiometric ratio. That is, any CO_2 fluxes in excess of baseline conditions observed at the site is assumed derived from CH_4 degradation. And, as 1 mole of CO_2 would be produced for every mole of CH_4 originally released due to integrity failure and biodegraded in the soils, the fluxes of CO_2 can be considered equivalent to CH_4 leakage in moles. This approach was taken to evaluate if the anomalous CO_2 seen at this site could feasibly be associated with any potential leakage scenario.

Due to the lack of CBL data, an equivalent micro-annulus (MA) between the cement and casing is considered to be a representative defect or potential cause of integrity failure in this study. This assumption is generally reasonable as it aligns with the hydraulic fracturing operation to which the well was subjected to, a process generally acknowledged to increase the risk for MA development[46,47]. Previous experience shows that bulk cement permeability has a minor effect on the mobility and migration of fugitive fluids within a well structure, hence this parameter was set to 0.02 mD as a conservative assumption. Figure 7 and Figure 8 show the permeability distributions of WA 22800 and WA 21083 well structures in the model domain for both intact and defective (i.e. presence of MA) scenarios. For the defective scenario, an equivalent MA between casing and cement is assumed along the entire section in each scenario. In reality, sections of cement with good and poor bonds are expected to form, however previous studies within the research group at HWU shows that an equivalent size MA along the entire section provides similar long term leakage performance.

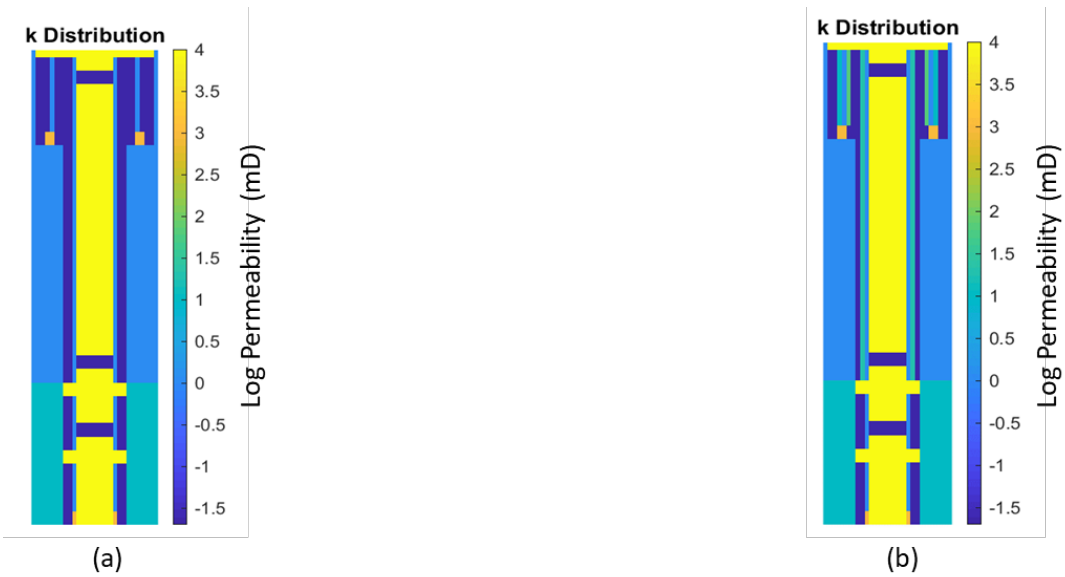


Figure 7: WA 22800 Well P&A Model Permeability Distribution: (a) Intact scenario with full integrity (b) Defective scenario with micro annuli of 13 µm between cement and casing representing the defect.

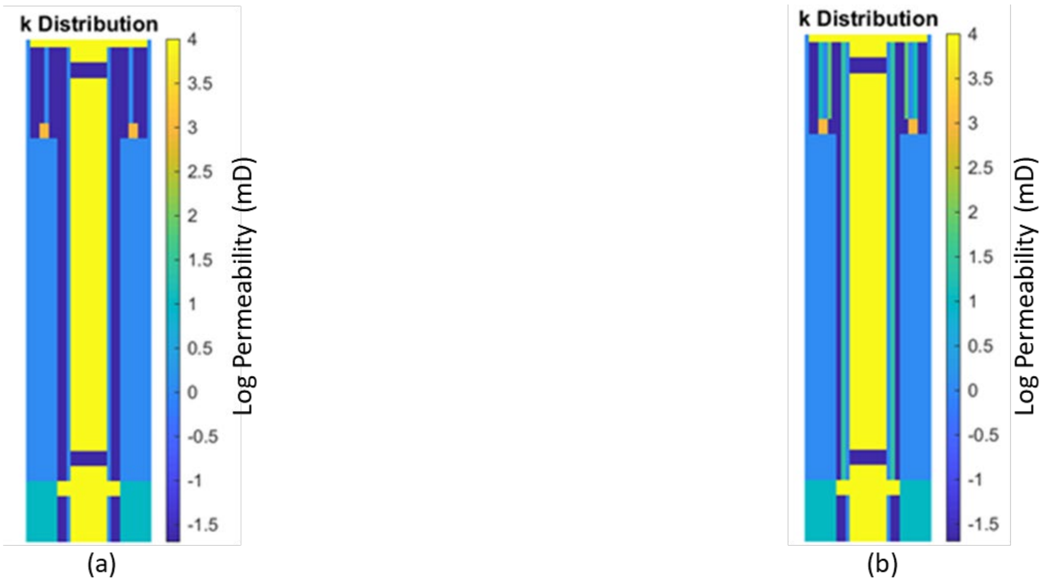


Figure 8: WA 21083 Well P&A Model Permeability Distribution: (a) Intact scenario with full integrity (b) Defective scenario with micro annuli of 13 µm between cement and casing representing the defect.

These models contains two important uncertainties that can significantly affect the simulation results: "bulk cement permeability" and equivalent "micro-annuli (MA) width between cement and casing". For each of these parameters, a range of values is reported in the literature as shown in Table 1. Previous field studies shows that bulk cement permeability has low impact hence we assumed that the bulk cement permeability was fixed at the highest level reported in the literature, i.e. 0.02 mD, as a conservative assumption. The size of MA is then adjusted until the simulated leakage rate matches the measured flux rates during field investigations (considering CH4 fluxes for WA 22800 and CO2 fluxes for WA 21083), as discussed in the following section.

Table 1: Uncertain Parameters and Reported Ranges

Uncertain Parameter	Range (based on literature)
Bulk Cement Permeability	0.001mD - 0.02mD
Micro Annuli (MA) cement and casing	0-60 µm

3. Results

3.1. WA 22800 Leakage Model

The well P&A model for WA 22800 was evaluated against observed CH_4 fluxes as measured in the field by adjusting size of the casing annular cement sheath MA. One intact scenario and four defective scenarios (including an equivalent MA with relative sizes of 8, 10, 15, and 20 µm) were simulated, the results of which in terms of potential leakage rates with time are shown in Figure 9.

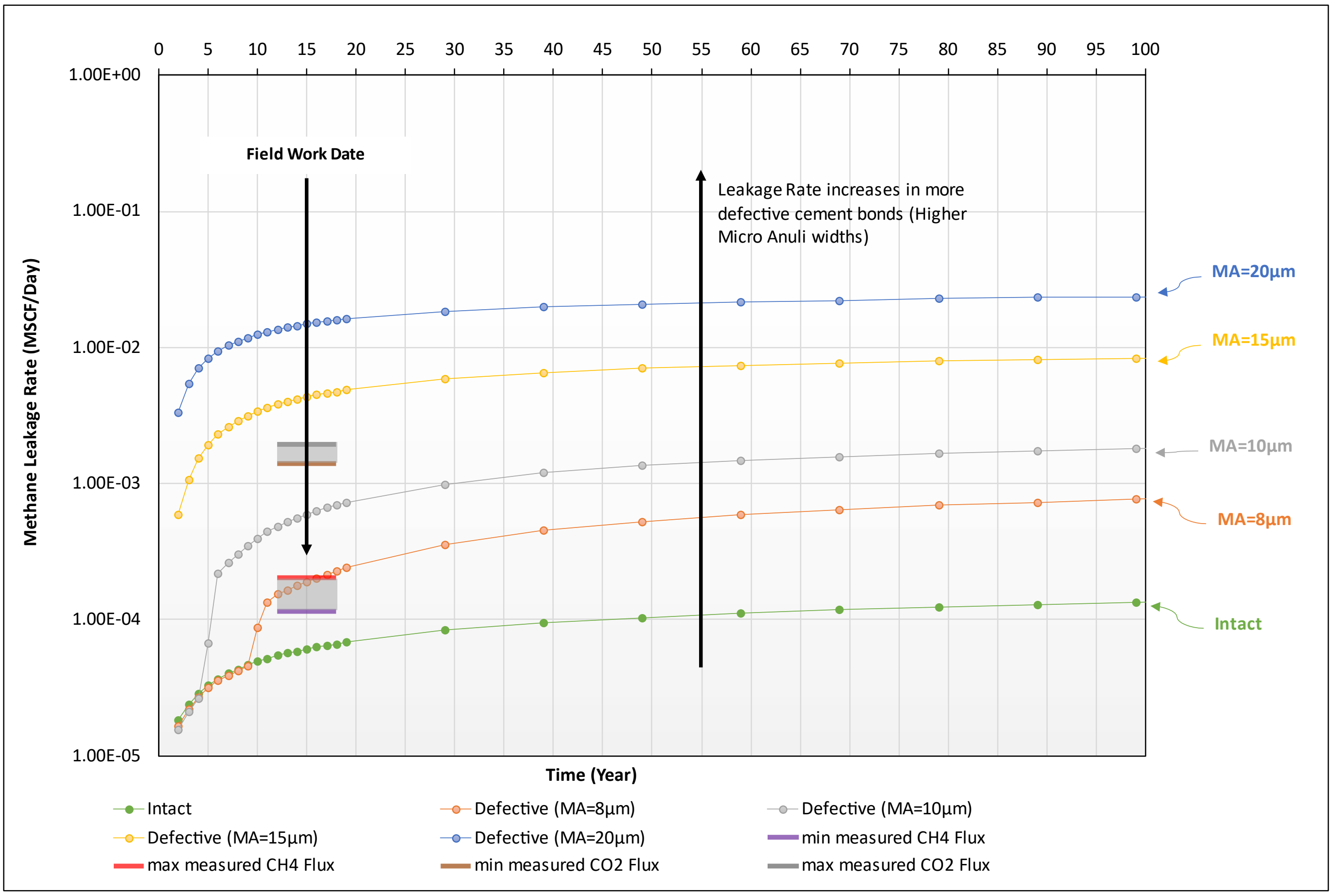


Figure 9: WA 22800 simulated potential leakage rates for varying MA scenarios with time. It should be noted that 1.00E-01 MSCF is equivalent to approximately 3 m^3.

WA 22800 was abandoned in 2007 (nearly 15 years ago) and so this timeframe in particular was of key interest in the model results. As Figure 9 shows, methane leakage occurs in all scenarios and the rate of leakage depends on the level of defect. It should be noted that even the intact cement scenario, still shows a very small amount of leakage (better termed seepage) at a rate of 6E-5 MSCF/Day after 15 years which is due to very low permeability (0.02 mD) of bulk cement. Here it must be recognized that even with 100% integrity maintained there should be an expectation that a small level of seepage will still occur and that no barrier system or P&A design will offer a zero-seepage result. By introducing defects (in the form of increased permeability conceptually associated with the presence of MA), the leakage rate at surface is seen to rapidly and significantly increases by several orders of magnitudes. For example, for MA=8, 15, and 20 µm the leakage rate is 2E-4, 4.33E-3, and 1.48E-2 MSCF/Day, respectively. The observed CH_4 fluxes around the wellhead, as described in WP2, were estimated to be approximately 2E-4 MSCF/Day, a result that can be replicated in the model with an equivalent MA size of 8 µm. Here, the model suggests that the presence of an equivalent MA in the order of just 8 µm along the annular cement can lead to the observed CH4 release patterns observed in the field.

As CO_2 was seen to be co-emitting at WA 22800 and assumed associated with soil-based biodegradation of fugitive CH_4, it is likely the actual CH_4 leakage rate from the well is higher than the observed CH_4 emissions alone (i.e. corresponding to the combination of observed CH_4 and CO_2

fluxes). To further evaluate this hypothesis we assumed any excess CO_2 flux at the site was derived from CH_4 biodegradation and evaluated the size of MA needed to correspond to this higher leakage rate (i.e. assuming the overall CH_4 leakage rate corresponds to the CH_4 and the CO_2 flux combined). Consequently, the range of CO_2 and CH_4 leakage rates measured at the field site are both shown on Figure 9, manifesting as between $1.41E^{-3}$ and $1.96E^{-3}$ MSCF/Day for CO_2 and between $1.14E^{-04}$ and $2.04E^{-04}$ MSCF/Day for CH_4. Thus, the P&A modelling results show that a larger size of equivalent MA of between 10 and 15 μm (i.e. a more defective cement scenario), is required to replicate the observed emissions of CH_4 and CO_2 at well site WA 22800 (assuming excess CO_2 is derived from CH_4 oxidation in the soils).

3.2. WA 21083 Leakage Model

Figure 10 shows the P&A modelling results in terms of potential leakage rates with time for WA 21083. For this well, the observed flux rate of CH_4 in the field (in the range of $2.98E^{-07}$ and $3.83E^{-07}$ MSCF/Day) was negligible in comparison to observed CO_2 fluxes (estimated to be in the range of $3.99E^{-04}$ and $2.28E^{-03}$ MSCF/Day). Assuming that the observed CO_2 is the product of methane oxidation (in a 1:1 mole conversion ratio), the P&A modelling framework was run to evaluate the MA that could replicate corresponding initial CH_4 fluxes of $3E^{-3}$ MScf/Day. As shown in figure 10, an MA size of 14 μm can replicate observed fluxes of CO_2 (assuming they are derived from CH_4 oxidation) and offer a potential explanation for the observed field results as reported in WP2.

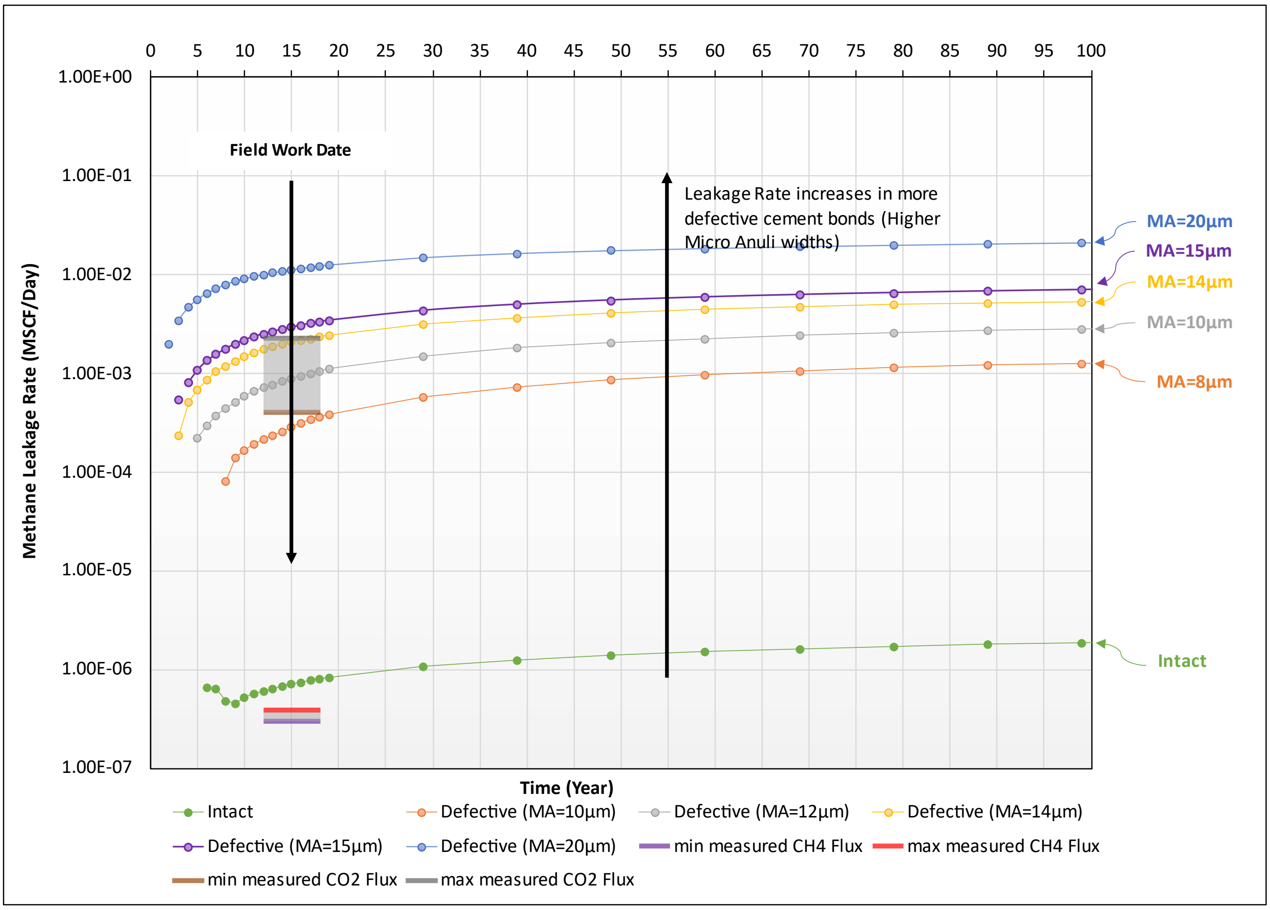


Figure 10: WA 21083 simulated potential leakage rates for varying MA scenarios with time. It should be noted that 1.00E-01 MSCF is equivalent to approximately 3 m^3.

A key advantage of the employed well P&A modelling framework we demonstrate here is that it simulates the dynamic performance of the system (i.e. leakage rate versus time) capturing both transient and steady-state periods. The results show that at early stages of the abandonment (first several years), the intact and defective scenarios all show similar (i.e. close to zero) leakage or seepage rates, as governed by gas flow through bulk of cement with low gas relative permeability due to low gas saturation. The divergence from the base seepage rate is signified by arrival of fugitive gas through defects (such as MA) at surface, which is a function of the size of defect. Such analysis using a dynamic model can support decision making by helping to determine optimal timings for testing a wells integrity (e.g. at least ~10 years post P&A for these wells) and also evaluating the degree to which integrity has been lost.

4. Discussion

4.1. Model Potential for Understanding Integrity Failure and Implications

This proof of concept modelling study shows that a defective annular cement scenario with an equivalent micro annuli size of 8 and 14 μm could potentially predict the field observations for greenhouse gas fluxes (as CH_4 and/or CO_2) into the atmosphere at wells WA 22800 and WA 21083, respectively. Modelling and field measurements are subject to various uncertainties, however, this initial study supports the hypothesis that WA 22800 has experienced integrity failure, as the observed fluxes of CH_4 measured at this site (i.e. ~ $2E^{-4}$ MSCF/Day) are an order of magnitude greater than the expected minimal seepage rate with a fully intact cement scenario (i.e. $6E^{-5}$ MSCF/Day). With respect to WA 21083, although this well was not observed as releasing anomalous CH_4, levels of CO_2 in excess of typical natural ranges and background conditions were detected. Such results could be associated with subsurface leakage of CH_4 and total conversion to CO_2 through soil based reactive transport. Here, a model was developed that was able to show this hypothesis could theoretically occur and if so, an average MA of 14 μm along the annular cement would be able to account for the scale of CO_2 fluxes observed. Both models show that a small degree of defective annular cement can lead to low levels of fugitive gas release into surficial soils and the atmosphere. These models assume that sub-optimal integrity of P&A wells is likely to occur due to a defective annular cement sheath and not necessarily as a result of plug placement or configuration. More well data and further modelling and field studies are required to improve the model's certainty to define the dominant leakage pathways that can generate observed field results. Nonetheless, at this proof-of-concept stage, we show clearly that P&A models, history matched using field measurements, could potentially be a valuable tool to study different scenarios to understand current and future well leakage risks and optimize forthcoming P&A activities.

4.2. Potential For Optimization of P&A

Our initial analysis of wells' data supported by modelling results suggest that the potential sub-optimal integrity of P&A'd wells in BC we investigated (as indicated by CH_4 and/or CO_2 fluxes at surface) may be a result of defective annular cement sheath and not cement plug failure. Consequently, a key step that could aid in uncertainty reduction and optimal decision making during any wells P&A design would be to run cement bond logs (CBL/VDL/USIT) to reduce uncertainty associated with annular cement integrity. If a well can be identified as suffering from annular cement integrity issues, it should then go through remedial operations (e.g. perf-wash-cement) or follow a P&A design that eliminate this potential leakage pathway, such as section milling and placing rock-to-rock cement plug instead of standard inside casing plug. In addition, a more risk-based approach to P&A design should also include careful consideration of any perforated horizons and those subjected to hydraulic fracturing treatments or similar. Such features have been identified in several wells investigated in this study and likely to form a potential weak point for sub-optimal integrity where fracking treatments could decrease overall annular cement integrity. Again, such features may need to be fully investigated and fit-for-purpose remedial operations performed to ensure that an annular pathway for fugitive gas is minimized. In order to further evaluate strategies for optimization of P&A in BC it would be necessary to rigorously identify and rank possible fluid leakage paths, various remedial operations available and perform a formal risk & cost comparison of each option, activities which are beyond the scope of this relatively small research project. However, what is clear at this stage is that annular cement quality is the greatest uncertainty for P&A wells in BC which is likely to develop the most critical leakage pathway. Any optimisation strategy for improving P&A performance in BC needs to first reduce the uncertainty around annular cement integrity to best design an optimal P&A configuration for a given well. Failing information on annular cement integrity being available, then the use of remedial techniques to eliminate this leak path could be immediately considered to ensure optimal outcomes.

5. Conclusions

Here we demonstrated a proof-of-concept modelling methodology to evaluate the potential causes of sub-optimal integrity in two P&A'd wells in BC that showed signs of anomalous CH_4 and/or CO_2 around the well heads. Our modelling approach involved use of a numerical flow simulator, based on finite-difference methods, which integrates 3 sub-models into a single P&A system model followed by a post processing module to read and display the simulation results. By including defective annular cement in each P&A'd well modelled, represented by micro annuli of varying sizes along the whole length of the wells annulus, we were able to replicate observed elevated emissions of CH_4 and/or CO_2 at surface. This finding suggests that such a configuration could be a possible scenario causing fugitive gas release at the wells investigated. It suggests that the quality of annular cement is a key uncertainty that should better constrained in order to design an optimal P&A for a given well. Where annular cement integrity is sub-optimal it may be necessary to consider alternative P&A designs such as section milling or similar in order to eliminate this potential leakage pathways and achieve optimal outcomes. While this may cost more upfront, it could save significant costs and liabilities in the future if integrity failure were to develop and remedial action prescribed. Overall, we show clearly that P&A models, history matched using field measurements, could potentially be a valuable tool to study potential well integrity failure scenarios and better understand current and future P&A'd well leakage risks. Moreover, tools such as those demonstrated here could form part of a risk-based approach to P&A design of wells in BC, which could enhance long-term performance and minimize environmental risk thereby optimizing the process.

Overall Project Findings and Recommendations

As described in each of this research projects three main work packages, the following observations and recommendations can be made with respect to understanding integrity of decommissioned wells and optimizing P&A activities in BC in the coming years:

- Aerial CH_4 surveys conducted to date are the only data currently available that can be used to evaluate the integrity status of P&A'd wells. Such surveys and their results are therefore hugely valuable and should, where possible, be continued/expanded to increase knowledge and understanding on integrity of P&A'd wells across BC. These data can help constrain the incidence rate of failure, quantify any resultant magnitudes of leakage and aid in identification of risk factors associated with development of integrity failure.
- However, here we showed that much uncertainty is associated with such methods and their efficacy and accuracy may be limited. Clearly more work is needed to better understand how representative such surveys and their results are and how best to validate, calibrate and interpret generated results. In particular, we show that prevailing weather conditions (including temperature, wind speed and barometric pressure regimes) during such surveys will likely determine the number of CH_4 detections made. These conditions needs to be more thoroughly considered to ensure results from such aerial surveys are of the greatest value possible.
- Overall, current data from aerial surveys indicates an overall incidence rate for P&A'd well integrity failure of ~5%. Moreover, results suggest that such failures tend to result in only small magnitude releases of CH_4 into the air column which is likely of limited significance in overall GHG emissions compared to other emission sources (e.g. dairy cattle or similar). However, more rigorous validation of these assertions would be beneficial which could be achieved through further ground based quantification of leakage at integrity compromised wells and better understanding on influential climatic factors associated with leakage detection.
- Despite an attempt to identify any causal or linked factors associated with P&A'd well integrity failure, definitive parameters and the mechanisms by which they operate remain poorly constrained or understood. Exceptionally, from this work the presence of SCVF was identified as a potentially key indicator for integrity failure to occur post-abandonment. Our finding suggest SCVF could be used to help predict the likelihood for long term integrity failure and wells known to have suffered SCVF during their active life should be prioritized for monitoring and stewardship post abandonment. It is recommended to further investigate this hypothesis through targeting of P&A'd wells previously identified as suffering SCVF during forthcoming new aerial surveys and also with additional ground based follow up.
- Newly conducted field investigations showed that 2 out of 10 P&A'd wells in BC that can broadly be considered as unconventional were exhibiting signs of integrity failure and releasing CH_4 from the surficial soils into the atmosphere. However, the magnitudes of CH_4 release were generally very small and likely contribute minimally to overall GHG emissions and CH_4 budgets for the region. It is recommended that better constraint on leakage magnitude and causes would be beneficial at these well sites to enhance understanding and implications of integrity failure across the region.
- It was shown that CO_2 is typically co-emitted with CH_4 from soils around wells potentially suffering integrity failure. This is likely a result of reactive transport based aerobic CH_4

oxidation in the soils converting CH_4 to CO_2. This phenomenon is potentially extremely important from a GHG emissions perspective, as it shows potential for significant natural attenuation of fugitive CH_4 in shallow soils that can limit total GHG emissions associated with integrity-compromised wells. More work should be done to better understand the process including its mechanisms, scale/extent, controlling parameters and potential to be used as a remedial strategy for wells suffering integrity failure.

- Linked to the identification of CO_2/CH_4 co-emission at integrity compromised P&A'd wells and recognition of the key role of biodegradation of fugitive CH_4 in shallow soils, we also observed elevated CO_2 at P&A'd wells where no anomalous CH_4 fluxes were detected. The source of this CO_2 is currently unknown but the magnitude of emissions are in excess of typical natural ranges and may be linked to well integrity-derived leakage with full biodegradation of released fugitive CH_4. We recommend further work should be performed to better understand the source of these CO_2 emissions and determine if they are in fact associated with integrity failure.
- A proof-of-concept modelling exercise was undertaken showing that inclusion of defective annular cement can replicate observed CH_4/CO_2 emissions around a P&A'd well. Overall, these results show that such modelling tools could play an important role in the development of a risk-based approach to P&A design and that the integrity of annular cement is a key data gap that if addressed could lead to more effective P&A design. It is recommended that modelling be conducted to better constrain most likely leakage configurations, better predict and manage resultant environmental risks and support optimal design of well P&A and remedial operations.

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