BC Natural Gas Atlas: Creation of the Geochemical Database for Northeastern British Columbia (Parts of NTS 093, 094)

M.J. Whiticar, University of Victoria, Victoria, BC, whiticar@uvic.ca

C. Evans, University of Victoria, Victoria, BC

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Introduction

Natural gas is an important resource in British Columbia (BC) both as an economic driver and environmental concern. Natural gas is a mixture of hydrocarbon gases, predominantly methane, and typically includes higher hydrocarbons (e.g., ethane through pentane) and frequently nonhydrocarbons, such as carbon dioxide, nitrogen, hydrogen, noble gases and hydrogen sulphide.

BC's history of petroleum activity dates back over 90 years, since the 1920s. About 26 600 oil and gas wells have been drilled in BC (BC Oil and Gas Commission, 2019a). The first commercial production of natural gas in 1948 (Pouce Coupe) delivered gas to Dawson Creek (Figure 1). This was followed by the natural gas discovery in 1956 at Clarke Lake in the Fort Nelson area (Figure 1). Today, the development continues to centre upon BC's reserves of conventional and unconventional natural gas located in the strata forming the edge of the Western Canada Sedimentary Basin (WCSB) in the province's northeast (Figure 1). BC currently produces about 30% of Canada's natural gas (Canadian Association of Petroleum Producers, 2019). In 2017, the unconventional gas types present in BC accounted for 87% of natural gas production, according to the BC Oil and Gas Commission (BC Oil and Gas Commission, 2019b), and includes tight and shale gas. Coalbed gas (coalbed methane) remains a substantial unconventional gas resource in BC, but there has been no production in recent years.

In northeastern BC, the major unconventional gas deposits are in the Montney, Jean Marie and Cadomin plays, the Liard, Horn River and Deep basins, and the Cordova Embayment (Figure 2). They are among the largest shale-gas deposits in North America, equivalent to the original-gas-in-place (OGIP) of the Eagle Ford, Marcellus, Barnett and Haynesville plays of the United States combined (Canadian Association of Petroleum Producers, 2016). These BC deposits are part of the rich, interprovincial oil and gas reserves of the WCSB connecting northeastern BC and Alberta. Of the estimated 94 500 bcm (3337 tcf) OGIP (basin total resource[1]), approximately 82 000 bcm (2900 tcf[2]) are in BC (BC Oil and Gas Commission, 2019c). The estimated ultimate potential marketable resource is 15 000 bcm (532 tcf). The estimated proven reserves (initial raw gas reserves[1]) are considerably less at 1300 bcm (45.9 tcf), i.e., the reserve is only 1.4% of the total resource, of which 250 bcm (8.85 tcf) has already been produced as of 2017 (BC Oil and Gas Commission, 2019b).

The Montney play accounts for the vast majority of drilling activity in BC (92.4%; BC Oil and Gas Commission, 2019b). In 2017, the estimated Montney gas-in-place resource was approximately 55 600 bcm (1965 tcf) compared with the estimated initial raw gas reserve of 1184 bcm (41.8 tcf), i.e., the Montney reserve was 2.1% of the total resource (BC Oil and Gas Commission, 2019b).

In comparison to the Montney play, the other BC unconventional natural gas plays have lower resource and reserve estimates. The most notable is the Liard Basin (Exshaw-Patry shales, Figure 2) with an estimated gas-in-place resource of 24 000 bcm (848 tcf) and initial raw gas reserve of 2.8 bcm (0.1 tcf; BC Oil and Gas Commission, 2019b). The Horn River Basin (Figure 2), which has seen low drilling activity in the past years, has an estimated gas-in-place resource of 12 700 bcm (448 tcf) and initial raw gas reserve of 79 bcm (2.8 tcf; BC Oil and Gas Commission, 2019b).

BC has several other sedimentary basins and regions that have had more limited exploration, including Bowser, Whitehorse Trough, Nechako, Fernie, Georgia, Queen Charlotte, Winona and Tofino (Figure 1). These contain oil and/or both conventional and unconventional gas. The lat-

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[1] *The BC Oil and Gas Commission (2019b) defines 'resources' as an estimate of the amount of natural gas in the region/play that includes proven reserves, produced quantities and unproven resources that may not be recoverable with current technology and economics. 'Reserves' are defined as proven quantities of natural gas that are commercially recoverable, economic and marketable.*

[2] *1 trillion cubic feet (tcf) = 28.32 billion cubic metres (bcm)*

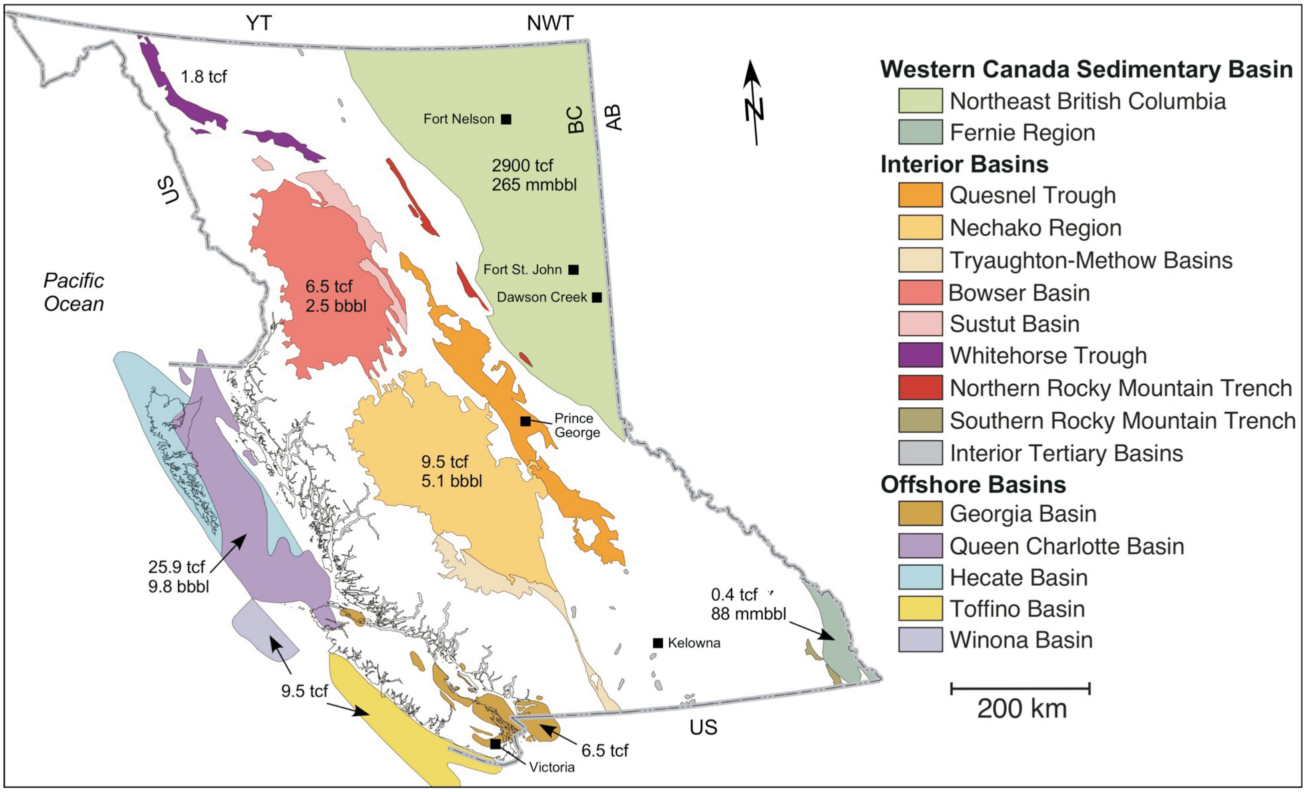

Figure 1. Major natural gas and oil basins of British Columbia (modified after Ferri, 2019, with permission). Gas and oil resource estimates are in trillion cubic feet (tcf) gas-in-place and billion barrels (bbbl) oil-in-place or million barrels (mmbbl) oil-in-place, respectively (BC Ministry of Energy, Mines and Petroleum Resources, 2007). Coalbed gas estimates are not shown. Note: 1 trillion cubic feet (tcf) = 28.32 billion cubic metres (bcm), 1 million barrels (mmbbl) oil = 1.5 x 10^5 cubic metres (m^3) oil, 1 billion barrels (bbbl) oil = 1.5 x 10^8 cubic metres (m^3) oil.

ter includes coalbed methane (CBM; also referred to as coalbed gas, CBG) found in essentially every coalfield throughout the province. The major estimated reserves of CBM include those in the Peace River (northeastern BC), Klappan and Groundhog (northern Nechako Basin), Elk Valley and Crowsnest (southeastern corner of BC), Hat Creek (central interior BC), and Comox and Nanaimo (Vancouver Island portion of Georgia Basin) coalfields. Exploratory wells in the Peace River and Elk Valley coalfields assessed the CBM but currently there is only minor production.

Global atmospheric methane has long been recognized as a major greenhouse gas (GHG), which has doubled in abundance in the troposphere to 1862 ppm since the pre-industrial Holocene (Hopcroft et al., 2017). Methane currently contributes a radiative forcing of approximately 0.5 watts per square metre (W/m^2; approx. 17% of total GHGs; Myhre et al., 2001). Globally, the oil and gas industry contributes an estimated 24% of global anthropogenic methane emissions (Saunois et al., 2016). In the United States, these fugitive emissions are approximately 2.3% of total natural gas production (Alvarez et al., 2018), so they represent a financial loss, as well as an environmental concern.

In Canada, methane emissions in 2017 were 93 Mt CO_2eq (1 Mt CH_4 equals 25 Mt CO_{2eq} [carbon dioxide equivalent on a 100-year time scale]) or 13% of the Canadian total (Environment and Climate Change Canada, 2019a). The oil and gas sector is the largest industrial emitter of methane (44%; Environment and Climate Change Canada, 2018) and in 2017 this sector contributed 195 Mt CO_2eq (27%) to Canada's total GHG emissions (716 Mt CO_2eq; Environment and Climate Change Canada, 2019c). Studies report that 53% of active wells in Alberta are leaking methane (GreenPath Energy Ltd., 2016) and 47% in BC (Atherton et al., 2017). Oil and gas operations in Canada, such as flaring and fugitive emission from equipment and well leaks, contribute approximately 8.5% to total greenhouse gas emissions (Bachu, 2017). After the energy combustion (44.5%) and transportation (28.2%) sectors, fugitive releases (8.5%) are the third largest contributor to Canadian GHG emissions (The Conference Board of Canada, 2013).

New legislation is being introduced to reduce Canadian emissions by 40–45% (Canada Department of Justice, 2019; Environment and Climate Change Canada, 2019b). In BC, the Climate Action Plan (Province of British Columbia, 2008) was created in 2008 to provide stewardship to climate change issues. The BC Climate Leadership Plan (Province of British Columbia, 2016) and then CleanBC

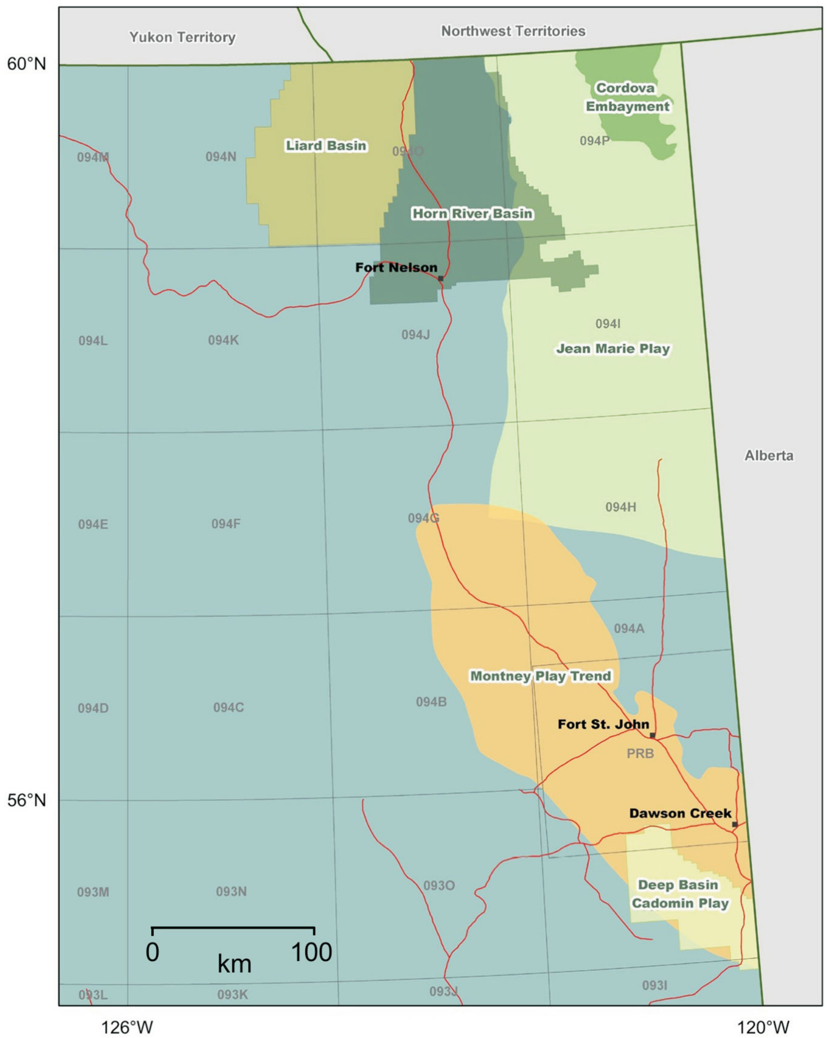

Figure 2. Unconventional hydrocarbon plays and basins in northeastern British Columbia (BC Oil and Gas Commission, 2014, with permission).

(Province of British Columbia, 2018) specifically target methane emissions from upstream natural gas, with the goal of reducing emissions (production and fugitive) by 45% by 2025. The activity focuses on production from the Montney Formation, which accounts for approximately 90% of the gas currently produced in BC (predominantly unconventional gas; BC Oil and Gas Commission, 2019c). There are approximately 5000 active and 4700 inactive/abandoned/restored/orphan wells in the Montney Formation. Initial studies (Atherton et al., 2017) indicate that approximately 47% of the active wells emit approximately 110 kt of methane per year to the atmosphere. Approximately 35% of inactive wells are reported to have fugitive methane emissions (Werring, 2018).

British Columbia Natural Gas Atlas (BC-NGA)

In recognition of the increasing natural gas activity in northeastern BC, Geoscience BC launched the multiyear British Columbia Natural Gas Atlas (BC-NGA) project in 2016. The primary objective is to systematically catalogue the molecular and stable isotope composition of natural gases produced in northeastern BC to establish geochemical fingerprints within a regional geological framework (Evans and Whiticar, 2017). The BC-NGA project provides an open source of comprehensive natural gas data, including searchable datasets (e.g., geochemical), maps and other interpretative tools (www.bcnga.ca).

By providing an integrated compilation of all available natural gas data in northeastern BC, the BC-NGA seeks to improve overall understanding of the distribution and types of natural gas that occur in northeastern BC. The data compilation allows various stakeholders, such as governments, First Nations, industries and other parties to increase their knowledge of existing and potential natural gas activities in the region, for example, by identifying specific geochemical characteristics that delineate more or less productive regions.

By identifying unique natural gas signatures in northeastern BC, the BC-NGA could have the ability to detect and identify the source of fugitive gas emissions (airborne and waterborne) coming from subsurface accumulations in northeastern BC, i.e., from specific geological formations and plays, and from other parts of the natural gas supply chain in the region. This information is critical for distinguishing and apportioning the different methane types being emitted, both natural and anthropogenic, i.e., microbial, thermogenic, pyrogenic, etc. (e.g., Whiticar, 1994). This will potentially aid the responsible development and monitoring of energy resources, while aiding remediation efforts and helping reduce greenhouse gas emissions in BC and contributing to the health of the environment and communities.

The BC-NGA is a compilation of available gas geochemical data from northeastern BC, some of which underwent a quality assurance–quality control (QA-QC) process, leading to the creation of open BC-NGA datasets. The data relies extensively on input from the BCOGC datasets, but also from analyses performed at the University of Victoria on new samples acquired for the BC-NGA project. Currently, if stable isotope analyses of mud gas, headspace gas, produced gas, surface casing vent flow gas, or any other gas

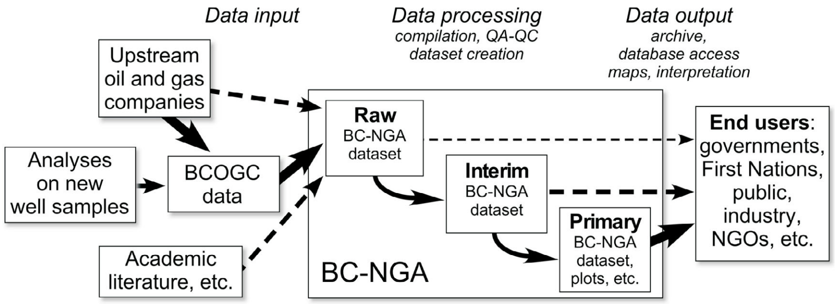

Figure 3. Schematic structure of British Columbia Natural Gas Atlas (BC-NGA) workflow. The thicker arrows indicate the most common pathway. Abbreviations: BCOGC, BC Oil and Gas Commission; NGO, nongovernmental organization; QA-QC, quality assurance–quality control.

associated with production are completed, the BCOGC requires that the information be included in the well data submission, under the requirements outlined in Section 34(5)(b) of the Drilling and Production Regulation (BC Oil and Gas Commission, 2016; Province of British Columbia, 2019). Once any confidentiality is waived, the data can be obtained from the BCOGC and incorporated into the BC-NGA.

BC-NGA Data Sources

The BC-NGA workflow and products comprise several steps. Figure 3 illustrates the various stages from data input, processing to output.

The data input stage includes acquiring the existing molecular and stable isotope data on natural gases in northeastern BC. The predominant source of data is the existing BCOGC dataset. Some of the data entries from the BCOGC dataset are confidential and may not be used until released, whereas other input data have issues that first need to be addressed before a reliable dataset is offered for general use. In many cases, a full suite of gas geochemical parameters was not measured or not available. In some instances, additional data were obtained from other sources, i.e., directly from oil and gas companies, service companies or academic investigators. For example, the BC-NGA received data from Shell Canada Limited and Dr. K. Muehlenbachs (pers. comm., 2018) that was subsequently shared with the BCOGC.

Another source of data was from new natural gas stable isotope analyses performed as part of the BC-NGA scope of work by the Biogeochemistry Facility in the School of Earth and Ocean Sciences at the University of Victoria. The samples were from vertical wells, horizontal wells and surface-equipment in northeastern BC. A brief description of the hydrocarbon gas isotope methodology used is as follows. The $^{13}C/^{12}C$ ratios ($\delta^{13}C$) and, where possible, $^{2}H/^{1}H$ ratios ($\delta^{2}H$) were determined on methane, ethane, propane, *i*-butane, *n*-butane and carbon dioxide. All isotope analyses were made using continuous flow–isotope ratio mass spectrometry (CF-IRMS; Meier-Augenstein, 1999; Whiticar and Eek, 2001; Niemann, 2006). Briefly, the gases are partitioned on a GSQ PLOT column with a Varian, Inc. 3400 GC gas chromatograph, then combusted and transferred online in a Cu/Pt wire micro-combustion oven at 870°C to a Thermo Scientific™ Finnigan MAT Delta XL IRMS. Carbon and hydrogen isotope ratios are reported in the usual delta notation ($\delta^{13}C$, $\delta^{2}H$ in ‰) relative to Vienna Pee Dee Belemnite (VPDB) and Vienna Standard Mean Ocean Water (VSMOW), respectively, according to equation (1), e.g., Coplen (2011):

$$\delta^{13}C_x = \left[\frac{(^{13}C/^{12}C)_{sample}}{(^{13}C/^{12}C)_{VPDB}} - 1\right] \times 10^3, \text{ and}$$

$$\delta^{2}H = \left[\frac{(^{2}H/^{1}H)_{sample}}{(^{2}H/^{1}H)_{VSMOW}} - 1\right] \times 10^3 \qquad (1)$$

BC-NGA Data Structure

The BC-NGA includes three stages of data preparation from raw to final (Primary) for transparency and traceability (Figure 3). The Primary BC-NGA dataset is the level that most users of the data will require, but for those wishing to rework the data in a different manner, or verify the original input data, the Raw and Interim BC-NGA datasets are also available. The datasets offer the user the flexibility to tailor and configure the data from the various stages according to their own needs. Another advantage of the Raw and Interim BC-NGA datasets is that the BC-NGA has developed a script to import future data from the BCOGC, which will assist in keeping the BC-NGA datasets up-to-date.

There are three levels of data in the BC-NGA, with an increasing level of QA-QC, editing and commenting:

1) Raw BC-NGA dataset – original unmodified data, derived from existing data, e.g., BCOGC data or new analytical data. The format of the data here is often inconsistent (i.e., entry errors, replicate entries, dates stored as text, numbers stored as text) and the some of the data requires correction. The purpose of publishing the Raw BC-NGA dataset is not for direct use, rather it provides a verifiable paper trail from the reliable Primary BC-NGA dataset back to the initial raw input data.
2) Interim BC-NGA dataset – this dataset uses the Raw BC-NGA dataset as the data source, but with corrections made for format issues and for replicated entries. In addition, a series of criteria were established to flag the data at this stage for anomalous data entries, e.g., total

gas >100%. Again, this dataset is not intended for use, but continues the paper trail of corrections.

3) Primary BC-NGA dataset – this dataset uses the Interim BC-NGA dataset as the data source. This dataset includes data corrections and edits that were made as part of a QA-QC process. This includes the flagging of replicate sample entries. To clearly identify the QA-QC issues that have been addressed, the status of the same data flags used in the Interim BC-NGA dataset have been updated. In addition, the Primary BC-NGA dataset has a comment field that provides an explanation for any changes made to the Interim BC-NGA dataset.

All three datasets are published on the BC-NGA website as Microsoft® Excel® (.xls) and universal text (.csv) files for unrestricted downloading and use. Users are requested to acknowledge the source of the BC-NGA data used in any presentation or publication. In the future, the datasets will be converted to a Microsoft Access® database management file (.accdb) and hosted on the Geoscience BC website (www.geosciencebc.com). All datasets are presented with a ReadMe file for clarity and explanation of the dataset contents and use.

Raw BC-NGA Dataset

As of October 1, 2019, the Raw BC-NGA dataset had 37 258 sample entries. As described, this is the initial, unmodified raw data, prior to any QA-QC treatment. This dataset still contains replicate sample entries that have not been flagged or removed. In addition, there are numerous errors in some of the entries that have **not** been corrected in this raw level. The dataset has 128 parameter fields (Table 1), which have the basic molecular and stable isotope gas geochemical data, as well as sample identifiers, locations, dates, formations and other metadata on the sample. To aid the user, there is a ReadMe file accompanying the Raw BC-NGA dataset. The data are input as retrieved, without regard for significant digits, etc. Numerous samples do not have entries in some parameter fields. This is evident by gaps in the datasets, which are inherent in a dataset with samples that extend back well over a decade. Figure 4 maps the locations of the samples and colour-codes samples according to their interpreted geological formation (Evans and Hayes, 2018).

Interim BC-NGA Dataset

The Interim BC-NGA dataset had, as of October 1, 2019, 37 258 sample entries. The Interim BC-NGA dataset is generated by running the Raw BC-NGA dataset through a script that simply identifies potential erroneous or anomalous entry values. The objective with the Interim BC-NGA dataset is to create formatted data, identify those with potential QA-QC concerns, and make minor edits (formatting, dates, etc.). The script allows for rapid inspection of the data and can then be automatically applied to future iterations of the Raw BC-NGA dataset. The Interim BC-NGA dataset includes the fields of the Raw BC-NGA dataset and augments them with

- the anomalous value flags,
- calculation from the mol % total gas of the relative abundances of hydrocarbons (hc% for C_1 to C_6) for each of the light hydrocarbon gases (C_1 to C_6), according to the following equation:

$$\text{relative abundance } C_x \text{ (hc\%)} = C_x \text{ (mol \%)} / \Sigma(C_1 \text{ (mol \%) to } C_6 \text{ (mol \%)}) \quad (2)$$

- automatic calculation of some simple ratios using methane (C_1), ethane (C_2) propane (C_3) and butane (C_4) data, (e.g., Whiticar, 1994):

$$\text{Bernard ratio (mol \% / mol \%)} = C_1 / (C_2+C_3) \quad (3)$$

$$\text{wetness ratio (mol \% / mol \%)} = (\Sigma C_2–C_4) / (\Sigma C_1–C_4) \quad (4)$$

$$\text{dryness ratio (mol \% / mol \%)} = C_1 / (\Sigma C_1–C_4) \quad (5)$$

Generally, an entry in the Interim BC-NGA dataset is flagged as anomalous for a specific parameter if the value falls outside ±2 standard deviations (σ) from the mean for all samples of that parameter in the dataset (±2σ is defined as ±2 standard deviations from the average value), as shown in Figures 5 and 6. In a normal distribution, roughly 95% of random variation will be within ±2σ. The ±2σ is a typical cutoff value in hypothesis testing, and is used to set confidence intervals here for setting the flags. The selection of ±2σ to flag parameter values is a conservative approach and only used to easily identify values that may be anomalous or incorrect. It has been assumed that the data population is normally distributed for this classification, which may be incorrect and could lead to some misclassifications and therefore incorrect flags. However, no samples are eliminated from the Interim BC-NGA dataset and all entries and flags are reviewed in the Primary BC-NGA dataset.

Primary BC-NGA Dataset

In contrast to the Raw and Interim BC-NGA datasets, the Primary BC-NGA dataset has undergone line-by-line, close inspection and rigorous QC. The Primary BC-NGA dataset had, as of October 1, 2019, 37 258 sample entries. Each QA-QC change or evaluation has been noted in the file so that replicates, duplicates and samples with suspect data are clearly identified, thus they are transparent and accountable. No samples are added or deleted at this level, however, each data change is detailed in the comments. To aid in quick data assessment, an additional flag is added for each sample showing the overall data quality with three categories: pass (p), fail (f) and conditional (c). Pass indicates that there are no obvious issues with the sample or data entry. Fail means that some data for this sample is a replicate, corrupted and/or cannot be reliably corrected. The conditional flag means that some of the data for the sample ap-

Table 1. List of parameters in the Raw BC-NGA (British Columbia Natural Gas Atlas) dataset.

Parameter name	Parameter name	Parameter name
1 BCNGA_test_index	44 Ar_Argon_mole%	87 Uwi_or_Name
2 WA_num	45 O2_Oxygen_mole%	88 Area_Code
3 Gas_anlyss_base_depth_m	46 O2+Ar_combined_mole%	89 formation
4 Gas_anlyss_top_depth_m	47 CO2_Carbon_Dioxide_mole%	90 Pool_seq
5 Sample_date	48 H2S_Sour_Gas_mole%	91 Drillng_event_seq
6 Formtn_code	49 He_Helium_mole%	92 Sample_point_code
7 Data_filter_flag	50 H2_Hydrogen_mole%	93 Reltv_densty_calc
8 C1_Methane_mole_fraction	51 CO_Carbon_Monoxide_mole%	94 Test_num
9 C2_Ethane_mole_fraction	52 C1_Methane_ppm	95 Test_perf_flag
10 C2H4_Ethene_mole_fraction	53 C2_Ethane_ppm	96 Temp_recvd_C
11 C3_Propane_mole_fraction	54 C2H4_Ethene_ppm	97 Press_recvd_kPa
12 C3H6_Propene_mole_fraction	55 C3_Propane_ppm	98 Ghv_meas
13 C3H4_Propyne_mole_fraction	56 C3H6_Propene_ppm	99 Ghv_calc
14 iC4_iButane_mole_fraction	57 C3H4_Propyne_ppm	100 Vapour_press
15 nC4_nButane_mole_fraction	58 iC4_iButane_ppm	101 Reltv_densty_meas
16 iC5_iPentane_mole_fraction	59 nC4_nButane_ppm	102 Pcp_ppc_kPa
17 nC5_nPentane_mole_fraction	60 iC5_iPentane_ppm	103 Pcp_ptc_K
18 C6+_Hexanes_Plus_mole_fraction	61 nC5_nPentane_ppm	104 Field_lab_flag
19 C7_mole_fraction	62 C6+_Hexanes_Plus_ppm	105 Molclr_wt_of_c7
20 C8_mole_fraction	63 N2_Nitrogen_ppm	106 C5_ml_mol
21 C9_mole_fraction	64 Ar_Argon_ppm	107 Molclr_wt_of_gas
22 C10_mole_fraction	65 O2_Oxygen_ppm	108 Recmbnd_flag
23 N2_Nitrogen_mole_fraction	66 O2+Ar_combined_ppm	109 Project_code
24 Ar_Argon_mole_fraction	67 CO2_Carbon_Dioxide_ppm	110 match_injection_disposal
25 O2_Oxygen_mole_fraction	68 H2S_Sour_Gas_ppm	111 data_source
26 O2+Ar_combined_mole_fraction	69 He_Helium_ppm	112 replicate_report
27 CO2_Carbon_Dioxide_mole_fraction	70 H2_Hydrogen_ppm	113 report_error
28 H2S_Sour_Gas_mole_fraction	71 CO_Carbon_Monoxide_ppm	114 report_MC_units
29 He_Helium_mole_fraction	72 d13C-C1_permil	115 flag_comment
30 H2_Hydrogen_mole_fraction	73 d13C-C2_permil	116 Gas_lab_num_OGC
31 CO_Carbon_Monoxide_mole_fraction	74 d13C-C3_permil	117 Isotech_Lab_No
32 C1_Methane_mole%	75 d13C-iC4_permil	118 Job
33 C2_Ethane_mole%	76 d13C-nC4_permil	119 CoreTrac
34 C2H4_Ethene_mole%	77 d13C-iC5_permil	120 Company_Lab_No
35 C3_Propane_mole%	78 d13C-nC5_permil	121 W_Sample_ID
36 C3H6_Propene_mole%	79 d2H-C1_permil	122 Sample_Time
37 C3H4_Propyne_mole%	80 d2H-C2_permil	123 gas_units
38 iC4_iButane_mole%	81 d2H-C3_permil	124 GC_Date
39 nC4_nButane_mole%	82 d2H-iC4_permil	125 MS_Date
40 iC5_iPentane_mole%	83 d2H-nC4_permil	126 Specific_Gravity
41 nC5_nPentane_mole%	84 d2H-iC5_permil	127 BTU
42 C6+_Hexanes_Plus_mole%	85 d2H-nC5_permil	128 Comments
43 N2_Nitrogen_mole%	86 d13C-CO2_permil	

pears to be unusable, but the remaining data for the sample may still be usable, so the entry is not a complete fail. For example, a sample may have an incorrect isotope ratio entry (e.g., $\delta^{13}C\text{-}CH_4 = –200$ ‰) that cannot be reconciled, yet the molecular data appear correct. Part of the QC process for the Primary BC-NGA dataset involves going to the original data sources, e.g., individual well reports, when available (paper or digital versions) to assess suspect data against the original lab report. Based on the QC work up to October 1, 2019, 16 940 samples passed (p) without obvious issues. There are 18 412 samples with a conditional (c) classification and 1906 that have failed (f). Samples fail or

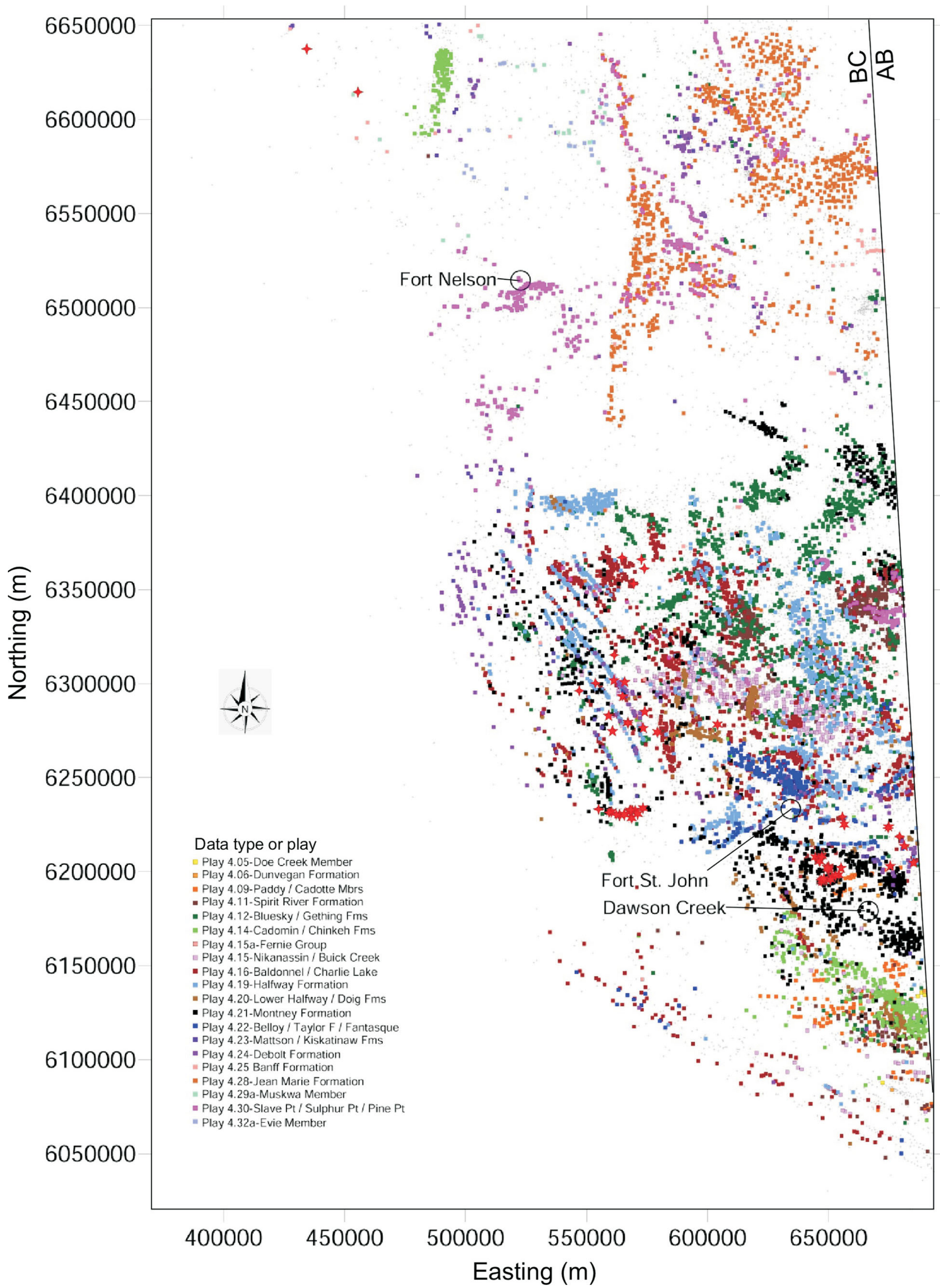

Figure 4. Map showing distribution of sample locations in the BC-NGA (British Columbia Natural Gas Atlas) dataset, colour coded according to geological formation/member. Co-ordinates are in UTM Zone 10, NAD83.

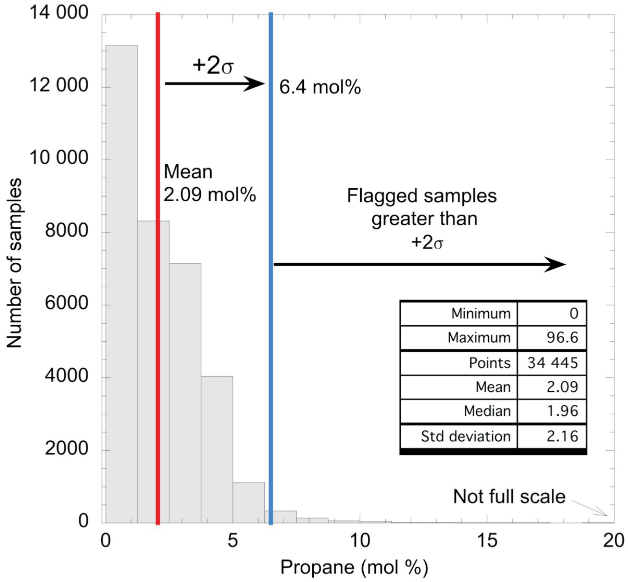

Figure 5. Histogram of propane mol % for entire Primary BC-NGA (British Columbia Natural Gas Atlas) dataset. Note that the horizontal axis is not full scale. The mean and 2 standard deviations (σ) are shown. Values >±2σ are flagged as anomalous and prompted for further inspection. Abbreviation: Std, standard.

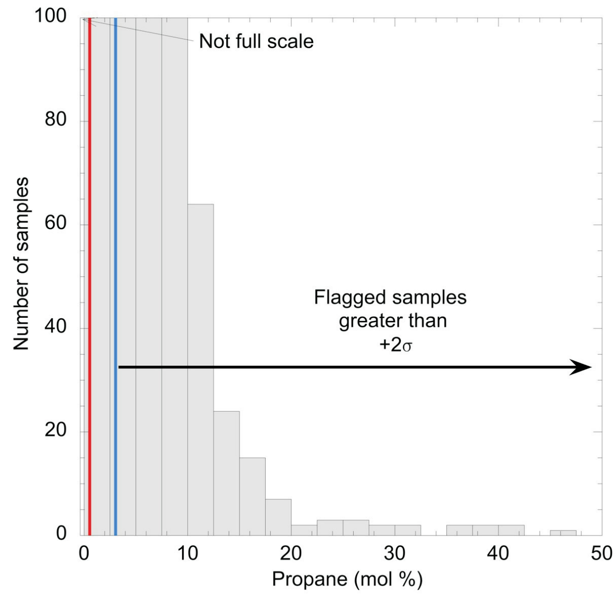

Figure 6. Expanded vertical scale of Figure 5 showing the anomalous samples with propane values flagged for further inspection. Abbreviation: σ, standard deviation.

are conditional for various reasons, including but not limited to the following:

- invalid sample type, e.g., injection well sample;
- corrupted record that cannot be resolved;
- surface casing vent flow (SCVF) or other shallow samples contaminated with air;
- replicate sample entries;
- mud-gas samples with inherently low hydrocarbon content and zero isotope data;
- samples with anomalously high CO_2 or N_2;
- samples of extremely low (e.g., <100 ppm) gas composition and high precision of isotope data;
- isotope data with abnormally high values of noble gases and blank isotope fields;
- isotope data from oil or water samples;
- obvious microbial gas formed during sample storage;
- locations outside northeastern BC;
- a non-injection well with high H_2S that might be an observation well.

Although the failed samples are not eliminated from the Primary BC-NGA dataset, their reliability and utility are questionable. The conditional samples need further user inspection before use, e.g., review of the flags to ensure the user understands the data limitations.

A further feature of the Primary BC-NGA dataset is the calculation and inclusion of additional analytical parameters that are commonly used to assess geochemical signatures. These include ratios such as C_1 to C_4 mol % and differences with stable carbon isotope ($\delta^{13}C_1$ to $\delta^{13}C_3$) data (e.g., Whiticar, 1994; Berner and Faber, 1996; Prinzhofer and Battani, 2003; Tilley and Muehlenbachs, 2013; Niemann and Whiticar, 2017). Parameters included in the BC-NGA for advanced assessment are shown below:

$$C_1\ (\text{mol\%}) / C_2\ (\text{mol \%}) \quad (6)$$

$$C_2\ (\text{mol \%}) / C_3\ (\text{mol \%}) \quad (7)$$

$$i\text{-}C_4\ (\text{mol \%}) / n\text{-}C_4\ (\text{mol \%}) \quad (8)$$

$$C_2\ (\text{mol \%}) / i\text{-}C_4\ (\text{mol \%}) \quad (9)$$

$$N_2\ (\text{mol \%}) / O_2\ (\text{mol \%}) \quad (10)$$

$$\delta^{13}C_2 - \delta^{13}C_1\ (‰) \quad (11)$$

$$\delta^{13}C_2 - \delta^{13}C_3\ (‰) \quad (12)$$

$$\delta^{13}C_1 - \delta^{13}C_3\ (‰) \quad (13)$$

BC-NGA Database Next Steps

With the completion of the Primary BC-NGA dataset the next steps include

- release the datasets as .xls and .csv files for public access at www.bcnga.com;
- port the datasets into Microsoft Access and release the entire BC-NGA database on the Geoscience BC website (www.geosciencebc.com);
- create publicly accessible mapping and interpretative modules in GIS to use with the Primary BC-NGA dataset; and
- publish initial results in scientific journals.

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