BC Natural Gas Atlas: Description and Visualization Tools of Gas Geochemical Database for Northeastern British Columbia (Parts of NTS 093, 094)

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Whiticar, M.J. and Wiebe, E. (2022): BC Natural Gas Atlas: description and visualization tools of gas geochemical database for northeastern British Columbia (parts of NTS 093, 094); *in* Geoscience BC Summary of Activities 2021: Energy and Water, Geoscience BC, Report 2022-02, p. 61–74.

Introduction

The objective of the British Columbia Natural Gas Atlas (BC-NGA) project, funded by Geoscience BC and the BC Oil and Gas Research and Innovation Society (BC OGRIS), is to create a thorough, searchable and mappable geochemical inventory of natural gases in northeastern BC. This accessible geochemical database will be a valuable resource for a broad range of users, for example, industry, government, non-governmental organizations (NGOs) and the general public. The project output is available at www.bcnga.ca and is the result of extensive efforts by C. Evans (Evans, 2019). For a detailed description of the BC-NGA project, the database and quality assurance–quality control (QA-QC) filters, refer to Whiticar and Evans (2020).

The primary goals of the BC-NGA project are to
1) produce a database of the unique natural gas compositional data assembled from past and active gas operations around northeastern BC (BC-NGA phase 1);
2) characterize and map the geochemical conditions of northeastern BC's major ongoing and future regions of petroleum exploration and production;
3) contribute to understanding the geological framework of natural gas deposits, from field to basin scales;
4) assist development of petroleum system models that help de-risk the exploration and production of plays by providing an understanding and prediction of generation occurrences, histories and potential productivity of natural gas in northeastern BC;
5) provide a robust baseline of gas signatures that help identify and track fugitive emissions of natural gas (into groundwaters and the atmosphere), for example, distinguish microbial gas from thermogenic gas;
6) offer a 'geochemical fingerprint' catalogue for different gas sources, useful in provenance studies at the production, well completion, processing and transport stages; and
7) establish a database to identify and track fugitive gas emissions into surface waters and the atmosphere.

In addition, the BC-NGA project seeks to
1) provide an important, unique, geochemical inventory and assessment of natural gas occurrences in BC;
2) establish a comprehensive, legacy, regional/play, natural gas character framework (e.g., baselines, stratigraphic control, source rocks);
3) enable critical multi-user participation by the energy industry, governments (e.g., First Nations, BC Ministry of Energy, Mines and Low Carbon Innovation, BC Oil and Gas Commission [BCOGC]), not for profit organizations (e.g., Geoscience BC), academic institutions (e.g., BC universities and colleges), NGOs and the public;
4) provide an open-access platform for database query, mapping, plotting and interpretation;
5) integrate BC-NGA into existing Canadian petroleum databases; and
6) contribute diagnostic subsurface gas geochemical data for northeastern BC to groundwater and fugitive gas emissions studies (e.g., Goetz et al., 2021).

The BC-NGA project involved accessing, incorporating and reporting the nonconfidential gas molecular and isotope geochemical data from the BCOGC repository, as well as adding calculated geochemical ratios and other parameters for gas typing and subsurface mapping.

Having detailed information on the geochemical characterization of natural gases, which should routinely include the stable isotope composition of the gases, benefits the operator, potentially allowing them to optimize the gas revenue stream by understanding where certain gas types occur. The systematic cataloguing of BC natural gases in this BC-NGA project will reveal information about the development, migration, segregation and compartmentalization of natural gases within petroleum systems. It will also define

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the distribution of natural gas liquids, which will help gas producers and governments to target higher value assets and natural gas streams.

Additional information may be gained on the effectiveness of regional seals and the impact of geological structure on seal integrity. This information is critical to ensure shallow aquifers are not being compromised during hydraulic fracturing operations. Also, communication between wells (e.g., during hydraulic fracturing) can be tested with diagnostic gas geochemical tracers.

Although new wells are generally drilled with state-of-the-art completion methods and production equipment, there are concerns that the associated drilling, production and transmission activities allow gases to fugitively escape into the atmosphere or shallow groundwater. This includes the release of natural gas from poor well completions, compromised surface-casing cements and pressure cycling during hydraulic fracturing. There are also additional concerns regarding fugitive gas emissions from older, sometimes abandoned, wellbores where cementing practices were less rigorous than required.

The ability to identify a leaking gas source has many benefits for the public and industry. In the case of a leaking wellbore, operators can lower remediation costs by having a higher level of certainty as to the gas source (e.g., depth and location), thereby allowing the operator to quickly and efficiently plan remediation of a leaking wellbore. The identification of gas emission sources can also assist in the remediation of old and abandoned wellbores. The methodology would allow companies and others to pinpoint the horizon(s) that is (are) leaking, thereby reducing fugitive gas emissions, in addition to lost product and revenue.

The detection of fugitive emissions from natural gas upstream activities (exploration, production and transmission) is critical for the responsible development of the resource and for the health and safety of all communities. Cataloguing the geochemical fingerprint of the different types and sources of natural gas in the subsurface is a critical step in the development of a comprehensive air-quality monitoring network.

As new (and previous) wells and oil and gas reservoirs are drilled and tested, natural gas samples are collected for geochemical analyses. By routinely measuring the molecular and isotopic composition of these gases, important details are learned about the character of the gases present, their habitat, origin (e.g., microbial or thermogenic), type of organic source material (e.g., kerogen), maturity or rank levels. Secondary processes, such as degradation, oxidation, mixing and commingling, can also be identified.

In addition to providing a basic gas geochemical database, the BC-NGA is further enhanced with a QA-QC script. This feature improves the reliability of the data and provides quality assessment of the data, while maintaining the transparency of the original database.

In 2021, the BC-NGA database was updated to include the recent addition of data from 86 conventional producing gas wells, provided by Canadian Natural Resources Limited (CNRL). These wellhead data provide a valuable addition to the database of produced, conventional gases. Furthermore, this iteration of the BC-NGA website now offers an interactive, online, data selection and visualization package.

Updated and Enhanced BC-NGA Database

To streamline scripting, improve database performance and to enable interactive user features, the BC-NGA database was reprogrammed. The previous three database levels (Raw BC-NGA dataset, Primary BC-NGA dataset and User BC-NGA dataset) were initially designed to ensure and maintain data treatment transparency. These have been replaced by a single database that merges the three datasets, while maintaining transparency and fidelity. The current revised database is available for download as a .csv file from www.bcnga.ca. The most recent version, updated on October 01, 2021, contains 44 689 individual records (e.g., from wells and horizons). Prior to June 25, 2020, the records were manually compiled and processed and stored on the database; since June 25, 2020, the records have been automatically added and processed with QA-QC scripts within BC-NGA.

The BC-NGA database contains 157 fields (Table 1). It holds 64 basic parameters, such as the BCOGC well authorization number (WA#), location, sampling depth, mol % methane and $\delta^{13}CH_4$, as defined in Table 2. There are also 18 identifier fields, such as BCOGC formation code and data source. In addition, for the automated QA-QC process, there are 103 fields that contain the results of a specific data test (Table 3) and all data are flagged as pass (p), fail (f) or conditional (c). For example, if the mol % for CH_4 is >100%, it is recorded as ‘f’ (fail). However, any data flagged as fail (f) or conditional (c) are not removed from the database. This no-loss data retention is an important feature of the enhanced database. It allows for the easy identification of questionable data, and flags precisely why the data are considered questionable with the defined criteria. However, as the data are not eliminated from the database, this also allows users to custom set or remove the filter criteria (choices of p, f and c values) and/or develop their own filters to independently QA-QC and filter the database. The user can also select to download the entire database as a .csv file for offline work.

The enhanced BC-NGA database now includes a useful online feature that allows users to create individualized data subsets. A data subset is created online by selecting a suite

Table 1. List of 157 parameters in the British Columbia Natural Gas Atlas (BC-NGA) database. See Table 2 for parameter and label abbreviations. See Table 3 for explanation of quality assurance–quality control (QA-QC) control filters (fil).

Parameter name	Parameter name	Parameter name
1 id	54 C2_div_iC4_Mol_percent	106 fil_ao_Dryness_ratio_high
2 BCNGA_test_index	55 C2_div_C3_Mol_percent	107 fil_ap_any_delta_13C_high_or_low
3 WA_num	56 N2_div_O2_Mol_percent	108 fil_aq_any_delta_deuterium_high_or_low
4 data_pass_fail_p_f_c	57 d13C2_minus_d13C1	109 fil_ar_CO2_ISO_13C_low
5 Bottom_Depth	58 d13C2_minus_d13C3	110 fil_as_CO2_ISO_13C_high
6 Top_Depth	59 d13C1_minus_d13C3	111 fil_at_C1_ISO_13C_low
7 corrected_date	60 QA_QC_and_other_comments	112 fil_au_C1_ISO_13C_high
8 formatted_date	61 eastingUTM	113 fil_av_C2_ISO_13C_low
9 BCNGA_play_category	62 northingUTM	114 fil_aw_C2_ISO_13C_high
10 NGA_sample_type	63 Gas_lab_num_OGC_Primary	115 fil_ax_C3_ISO_13C_low
11 Primary_data_source	64 Primary_flag_summary	116 fil_ay_C3_ISO_13C_high
12 C1_Methane_Mol_percent	65 fil_xx_data_not_used	117 fil_az_ISO_C1_C2_difference
13 C2_Ethane_Mol_percent	66 fil_a_C1_low	118 fil_ba_ISO_C2_C3_difference
14 C3_Propane_Mol_percent	67 fil_b_C1_high	119 fil_bb_iC4_ISO_13C_low
15 iC4_iButane_Mol_percent	68 fil_c_C2_low	120 fil_bc_iC4_ISO_13C_high
16 nC4_nButane_Mol_percent	69 fil_d_C2_high	121 fil_bd_nC4_ISO_13C_low
17 iC5_iPentane_Mol_percent	70 fil_e_C3_low	122 fil_be_nC4_ISO_13C_high
18 nC5_nPentane_Mol_percent	71 fil_f_C3_high	123 fil_bf_nC5_ISO_13C_low
19 C6plus_Hexanes_Plus_Mol_percent	72 fil_g_iC4_low	124 fil_bg_nC5_ISO_13C_high
20 N2_Nitrogen_Mol_percent	73 fil_h_iC4_high	125 fil_bh_C1_ISO_D_low
21 O2_and_Ar_combined_Mol_percent	74 fil_i_nC4_low	126 fil_bi_C1_ISO_D_high
22 CO2_Carbon_Dioxide_Mol_percent	75 fil_j_nC4_high	127 fil_bj_C2_ISO_D_low
23 H2S_Sour_Gas_Mol_percent	76 fil_k_iC5_low	128 fil_bk_C2_ISO_D_high
24 He_Helium_Mol_percent	77 fil_l_iC5_high	129 fil_bl_C3_ISO_D_low
25 H2_Hydrogen_Mol_percent	78 fil_m_nC5_low	130 fil_bm_C3_ISO_D_high
26 C1_percent_rel_HC_percent	79 fil_n_nC5_high	131 fil_bn_bad_depth
27 C2_percent_rel_HC_percent	80 fil_o_nC6p_low	132 fil_bo_bad_date1
28 C3_percent_rel_HC_percent	81 fil_p_nC6p_high	133 fil_bp_bad_date2
29 iC4_percent_rel_HC_percent	82 fil_q_C1_low	134 fil_bq_unexpected_date
30 nC4_percent_rel_HC_percent	83 fil_r_C1_high	135 fil_br_unexpected_depth
31 iC5_percent_rel_HC_percent	84 fil_s_C2_low	136 fil_bs_N2_high
32 nC5_percent_rel_HC_percent	85 fil_t_C2_high	137 fil_bt_O2_high
33 C6plus_percent_rel_HC_percent	86 fil_u_C3_low	138 fil_bu_N2_ratio_O2_not_atmospheric
34 d13C_C1_permil	87 fil_v_C3_high	139 fil_bv_injection_or_disposal_well
35 d13C_C2_permil	88 fil_w_iC4_low	140 OGC_Bottom_Depth
36 d13C_C3_permil	89 fil_x_iC4_high	141 OGC_Top_Depth
37 d13C_iC4_permil	90 fil_y_nC4_low	142 NGA_bottom_depth
38 d13C_nC4_permil	91 fil_z_nC4_high	143 NGA_top_depth
39 d13C_iC5_permil	92 fil_aa_iC5_low	144 OGC_sample_date_text
40 d13C_nC5_permil	93 fil_ab_iC5_high	145 OGC_sample_date
41 d13C_CO2_permil	94 fil_ac_nC5_low	146 BCNGA_play_category_2
42 d2H_C1_permil	95 fil_ad_nC5_high	147 PRCL_formation_correlation
43 d2H_C2_permil	96 fil_ae_nC6p_low	148 OGC_Formation_code
44 d2H_C3_permil	97 fil_af_nC6p_high	149 Match_injection_disposal
45 d2H_iC4_permil	98 fil_ag_H2S_high	150 Gas_lab_num_OGC
46 d2H_nC4_permil	99 fil_ah_CO2_high	151 NGA_adjusted_gas_lab_number
47 d2H_iC5_permil	100 fil_ai_alkene_alkyne	152 Isotech_Lab_No
48 d2H_nC5_permil	101 fil_aj_Bernard_low	153 BCNGA_sample_type
49 Bernard_Ratio_C1_div_C2_plus_C3	102 fil_ak_Bernard_high	154 OGC_Sample_Point
50 Wetness_Ratio_sumC2_to_nC4_div_sumC1_to_nC4	103 fil_al_Bernard_error_DIV0	155 data_source
51 Dryness_Ratio_C1_div_sumC1_to_nC4	104 fil_am_Bernard_error_blank_C1	156 dindex
52 C1_div_C2_Mol_percent	105 fil_an_Wetness_ratio_high	157 sample_timestamp
53 iC4_div_nC4_Mol_percent		

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Table 2. Glossary of parameter and label abbreviations used in the British Columbia Natural Gas Atlas (BC-NGA) database (shown in Table 1).

Abbreviation in database	Designation/definition
id	Sequential numbering (for sorting)
BCNGA_test_index	BC Natural Gas Atlas assigned unique identifier text field
WA_num	BCOGC designated well authorization number
data_pass_fail_p_f_c	QA-QC filter status
Bottom_Depth	Bottom of sample collection interval (m)
Top_Depth	Top of sample collection interval (m)
corrected_date	Manual date conversion from various text formats
formatted_date	Formatted date for user
BCNGA_play_category	Sampled geological unit using BC Ministry of Energy, Mines and Low Carbon Innovation (2006) atlas designations
NGA_sample_type	Type of sample collected
Primary_data_source	Origin of the data
C1 or Methane	Methane (CH_4)
C2 or Ethane	Ethane (C_2H_6)
C3 or Propane	Propane (C_3H_8)
iC4 or iButane	iso-Butane (C_4H_{10})
nC4 or nButane	n-Butane (C_4H_{10})
iC5 or iPentane	iso-Pentane (C_5H_{12})
nC5 or nPentane	n-Pentane (C_5H_{12})
C6plus or Hexanes Plus	Hexanes + higher alkanes
N2 or Nitrogen	Nitrogen (N_2)
O2 and Ar combined	Oxygen and argon combined (O_2 + Ar)
CO2 or Carbon Dioxide	Carbon dioxide (CO_2)
H2S or Sour Gas	Hydrogen sulphide (H_2S)
He or Helium	Helium (He)
H2 or Hydrogen	Hydrogen (H_2)
Mol_percent	mol % calculated from total gas with non-numerics removed
HC	Hydrocarbon(s)
Cx_percent_rel_HC_percent	Relative mol % calculated from C_1 to C_6+ hydrocarbons only (100*iC_x mol %/total HC)
d13C_Cx_permil	δ^{13}C, stable carbon isotope ratio of compound (relative to VPDB standard)
d2H_Cx_permil	δ^{2}H, stable hydrogen isotope ratio of compound (relative to VSMOW standard)
Bernard_Ratio_C1_div_C2_plus_C3	mol % C_1 divided by Σ mol % C_2 + mol % C_3, BR = %C_1/(%C_2+%C_3)
BR	Bernard Ratio, BR = %C_1/(%C_2+%C_3)
Wetness_Ratio_sumC2_to_nC4_div_sumC1_to_nC4	Σ mol % C_2 to n-C_4 divided by Σ mol % C_1 to mol % n-C_4
Dryness_Ratio_C1_div_sumC1_to_nC4	mol % C_1 divided by Σ mol % C_1 to mol % n-C_4
Cx_div_Cy_Mol_percent	Division of C_x by C_y (mol % C_x divided by mol % C_y x 100)
d13Cy_minus_d13Cx	Subtraction of $\delta^{13}C_x$ from $\delta^{13}C_y$
QA_QC_and_other_comments	Comment for corrections or changes as a result of filters
eastingUTM	UTM map co-ordinates (easting)
northingUTM	UTM map co-ordinates (northing)
Gas_lab_num_OGC_Primary	Analytical lab reference number
Primary_flag_summary	Concatenation of filtering flags ('fil') as text string
div	Divided by
rel	Relative
No or num	Number
fil_letter (e.g. fil_b_C1_high)	Filter criteria
QA_QC	Quality assurance and quality control
ISO	Isotope
VPDB	Vienna Pee Dee Belemnite (carbon isotope standard)
VSMOW	Vienna Standard Mean Ocean Water (hydrogen isotope standard)
BCOGC or OGC	British Columbia Oil and Gas Commission
PRCL	Petrel Robertson Consulting Ltd.
Isotech	Isotech Laboratories, Inc.

Table 3. Explanation of limits used for the quality assurance–quality control (QA-QC) filters (fil; shown in Table 1) for the British Columbia Natural Gas Atlas (BC-NGA) database. The abbreviation ±2σ used here means the statistical threshold of plus or minus 2 standard deviations from the approximate average value for that parameter over the entire database.

Abbreviation in database	Designation / definition
fil_xx_data_not_used	Report flagged as replicate or other problems (see columns "replicate_report" and "report_error")
fil_a_C1_low	Methane amount in total gas is abnormally <±2σ of 10 mol %
fil_b_C1_high	Methane amount in total gas is abnormally >±2σ of 99.8 mol %
fil_c_C2_low	Ethane amount in total gas is abnormally <±2σ of 0.05 mol %
fil_d_C2_high	Ethane amount in total gas is abnormally >±2σ of 13 mol %
fil_e_C3_low	Propane amount in total gas is abnormally <±2σ of 0.03 mol %
fil_f_C3_high	Propane amount in total gas is abnormally >±2σ of 6 mol %
fil_g_iC4_low	iso-Butane amount in total gas is abnormally <±2σ 0.03 mol %
fil_h_iC4_high	iso-Butane amount in total gas is abnormally >±2σ of 0.8 mol %
fil_i_nC4_low	n-Butane amount in total gas is abnormally <±2σ of 0.03 mol %
fil_j_nC4_high	n-Butane amount in total gas is abnormally >±2σ of 1.6 mol %
fil_k_iC5_low	iso-Pentane amount in total gas is abnormally <±2σ of 0.03 mol %
fil_l_iC5_high	iso-Pentane amount in total gas is abnormally >±2σ of 0.3 mol %
fil_m_nC5_low	n-Pentane amount in total gas is abnormally <±2σ of 0.03 mol %
fil_n_nC5_high	n-Pentane amount in total gas is abnormally >±2σ of 0.5 mol %
fil_o_nC6+_low	Hexane+ (C_6+) amount in total gas is abnormally <±2σ of 0.03 mol %
fil_p_nC6+_high	Hexane+ (C_6+) amount in total gas is abnormally >±2σ of 4 mol %
fil_q_C1_low	Methane relative % to C_1-C_6 hydrocarbons is <±2σ of 77%
fil_r_C1_high	Methane relative % to C_1-C_6 hydrocarbons is >±2σ of 99.8%
fil_s_C2_low	Ethane relative % to C_1-C_6 hydrocarbons is <±2σ of 1%
fil_t_C2_high	Ethane relative % to C_1-C_6 hydrocarbons is >±2σ of 13%
fil_u_C3_low	Propane relative % to C_1-C_6 hydrocarbons is <±2σ of 0.5%
fil_v_C3_high	Propane relative % to C_1-C_6 hydrocarbons is >±2σ of 6%
fil_w_iC4_low	iso-Butane relative % to C_1-C_6 hydrocarbons is <±2σ of 0.3%
fil_x_iC4_high	iso-Butane relative % to C_1-C_6 hydrocarbons is >±2σ of 1%
fil_y_nC4_low	n-Butane relative % to C_1-C_6 hydrocarbons is <±2σ of 0.3%
fil_z_nC4_high	n-Butane relative % to C1-C6 hydrocarbons is >±2σ of 1.9%
fil_aa_iC5_low	iso-Pentane relative % to C_1-C_6 hydrocarbons is >±2σ of <0.01%
fil_ab_iC5_high	iso-Pentane relative % to C_1-C_6 hydrocarbons is >±2σ of 1%
fil_ac_nC5_low	n-Pentane relative % to C_1-C_6 hydrocarbons is <±2σ of 0.3%
fil_ad_nC5_high	n-Pentane relative % to C_1-C_6 hydrocarbons is >±2σ of 0.7%
fil_ae_nC6+_low	Hexane plus relative % to C_1-C_6 hydrocarbons is <±2σ of 0.3%
fil_af_nC6+_high	Hexane + (C_6+) relative % to C_1-C_6 hydrocarbons is >±2σ of 4%
fil_ag_H2S_high	Hydrogen sulphide total gas is abnormally >±2σ of 7 mol %
fil_ah_CO2_high	Carbon dioxide total gas is abnormally >±2σ of 10 mol %
fil_ai_alkene/alkyne	Any unsaturated hydrocarbons amount in total gas is >0.0 mol %
fil_aj_Bernard_low	Bernard ratio $C_1/(C_2+C_3)$ < 0.1
fil_ak_Bernard_high	Bernard ratio $C_1/(C_2+C_3)$ >10 000
fil_al_Bernard_error_DIV0	Bernard ratio $C_1/(C_2+C_3)$ is an error where (C_2+C_3) = zero
fil_am_Bernard_error_blank_C1	Error in C_1 (RAW dB) means the Bernard ratio is not calculated
fil_an_Wetness_ratio_high	Ratio of sum of C_2, C_3, C_4 divided by sum C_1, C_2, C_3, C_4 >0.99
fil_ao_Dryness_ratio_high	Ratio of sum of C_1 divided by all C_1, C_2, C_3, C_4 >0.99
fil_ap_any_delta_13C_high_or_low	All $\delta^{13}C$ fields checked for known natural range of +30 ‰ to -120 ‰ VPDB
fil_aq_any_delta_deuterium_high_ or_low	All $\delta^{2}H$ fields checked for known natural range of 0 ‰ to -500 ‰ VSMOW
fil_ar_CO2_ISO_13C_low	$\delta^{13}C$-CO_2 is abnormally <±2σ of -30.0 ‰
fil_as_CO2_ISO_13C_high	$\delta^{13}C$-CO_2 is abnormally >±2σ of +15.0 ‰
fil_at_C1_ISO_13C_low	$\delta^{13}C$-CH_4 is abnormally depleted <±2σ of -55.0 ‰
fil_au_C1_ISO_13C_high	$\delta^{13}C$-CH_4 is abnormally enriched >±2σ of -33.0 ‰
fil_av_C2_ISO_13C_low	$\delta^{13}C$-C_2 is abnormally depleted <±2σ of -38.3 ‰
fil_aw_C2_ISO_13C_high	$\delta^{13}C$-C_2 is abnormally enriched >±2σ of -25.5 ‰
fil_ax_C3_ISO_13C_low	$\delta^{13}C$-C_3 is abnormally depleted <±2σ of -36.3 ‰

Table 3 (continued). Explanation of limits used for the quality assurance–quality control (QA-QC) filters (fil; shown in Table 1) for the British Columbia Natural Gas Atlas (BC-NGA) database. The abbreviation ±2σ used here means the statistical threshold of plus or minus 2 standard deviations from the approximate average value for that parameter over the entire database.

Abbreviation in database	Designation / definition
fil_ay_C3_ISO_13C_high	$\delta^{13}C-C_3$ is abnormally enriched >±2σ of -22.3 ‰
fil_az_ISO_C1_C2_difference	$\delta^{13}C-CH_4$ minus $\delta^{13}C-C_2$ >1 [positive indicates either error or "reversal"]
fil_ba_ISO_C2_C3_difference	$\delta^{13}C-C_2$ minus $\delta^{13}C-C_3$ >1 [positive indicates either error or "reversal"]
fil_bb_iC4_ISO_13C_low	$\delta^{13}C-iC_4$ is abnormally depleted <±2σ of -36.8 ‰
fil_bc_iC4_ISO_13C_high	$\delta^{13}C-iC_4$ is abnormally enriched >±2σ of -22.5 ‰
fil_bd_nC4_ISO_13C_low	$\delta^{13}C-nC_4$ is abnormally depleted <±2σ of -34.6 ‰
fil_be_nC4_ISO_13C_high	$\delta^{13}C-nC_4$ is abnormally enriched >±2σ of -21.7 ‰
fil_bf_nC5_ISO_13C_low	$\delta^{13}C-nC_5$ is abnormally depleted <±2σ of -33.1 ‰
fil_bg_nC5_ISO_13C_high	$\delta^{13}C-nC_5$ is abnormally enriched >±2σ of -23.4 ‰
fil_bh_C1_ISO_D_low	$\delta^{2}H-CH_4$ is abnormally depleted <±2σ of -298 ‰
fil_bi_C1_ISO_D_high	$\delta^{2}H-CH_4$ is abnormally enriched >±2σ of -151 ‰
fil_bj_C2_ISO_D_low	$\delta^{2}H-C_2$ is abnormally depleted <±2σ of -170 ‰
fil_bk_C2_ISO_D_high	$\delta^{2}H-C_2$ is abnormally enriched >±2σ of -133 ‰
fil_bl_C3_ISO_D_low	$\delta^{2}H-C_3$ is abnormally depleted <±2σ of -250 ‰
fil_bm_C3_ISO_D_high	$\delta^{2}H-C_3$ is abnormally enriched >±2σ of -145 ‰
fil_bn_bad_depth	Depth is blank or unknown
fil_bo_bad_date1	Sample date is blank or unknown
fil_bp_bad_date2	Analysis date is blank or unknown
fil_bq_unexpected_date	Sample date outside range, yyyymmdd format of 19750000 to 20190701
fil_br_unexpected_depth	Depth is outside expected range 400 to 7000 m
fil_bs_N2_high	Nitrogen amount in total gas > atmosphere mixing ratio (78.1 mol %)
fil_bt_O2_high	Oxygen amount in total gas > atmosphere mixing ratio (20.9 mol %)
fil_bu_N2_ratio_O2_not_atmospheric	N_2/O_2 ratio below 3.73 or above 3.74 (ratio of 78.1 to 20.9 mol %)
fil_bv_injection_or_disposal_well	Possible injection or disposal well sample

of one or more parameters, for example, mol % ethane, $\delta^{13}CH_4$ and play category, and then setting the upper and lower limits, range or value for each parameter (Figure 1). The database is filtered by these criteria and the subset created. This data subset can be downloaded as a separate .csv file for offline work or used online for the gas geochemical interpretative plotting routines, described below.

Gas Geochemical Interpretative Plots from BC-NGA Database

Over the past 60 years, geochemists have developed a suite of geochemical parameters that can define and distinguish different natural gases (e.g., Whiticar, 2021). Several review papers have been published on the interpretation of natural gases using geochemical parameters, including the applications of stable isotopes, for example, Schoell (1980), Stahl and Faber (1983), Galimov (1988), Clayton (1991), Whiticar (1994), Prinzhofer and Battani (2003) and Liu et al. (2019). From field and experimental studies, a range of interpretative diagrams have emerged with the broadest utility to classify natural gases and identify primary and secondary effects, such as source rock type, degree of maturation, migration and degradation. Table 4 is an abbreviated list, from Whiticar (2021), of the more common interpretative diagrams used in gas geochemistry.

For the BC-NGA, a selection of these gas geochemistry interpretative diagrams has been created using various combinations of parameters, for example, mol% CH_4, $\delta^{13}CH_4$ and $C_1/(C_2+C_3)$. These plots can be populated using the whole BC-NGA database or using the online-generated data subsets filtered by user criteria. Four examples of the 10 interpretative plots currently available in the online plotting tool are shown in Figures 2 to 5. The data plotted in the figures are an example of a data subset resulting from the chosen data filtering variables (mol % ethane, $\delta^{13}CH_4$, play category) and their respective values, shown in Figure 1.

Figure 2 is commonly termed the 'Bernard Diagram' (Bernard et al., 1976); it plots the relative molecular abundance of the light hydrocarbons C_1-C_3 as the Bernard ratio, that is, $C_1/[C_2+C_3]$ on a volume basis against the stable carbon isotope ratio, $\delta^{13}C_{CH4}$. The Bernard Diagram expands the presence and mixing of microbial gas with thermogenic gas, and is particularly useful for surface sediment studies.

Figure 3 is a modified $\delta^{13}C_{CH4}$ versus $\delta^{2}H_{CH4}$ plot (after Whiticar, 2021) that emphasizes thermogenic natural gases (i.e., associated, humic, etc.). This is a truncated version of the traditional 'CD diagram' or 'Whiticar plot' (e.g., Whiticar, 2020).

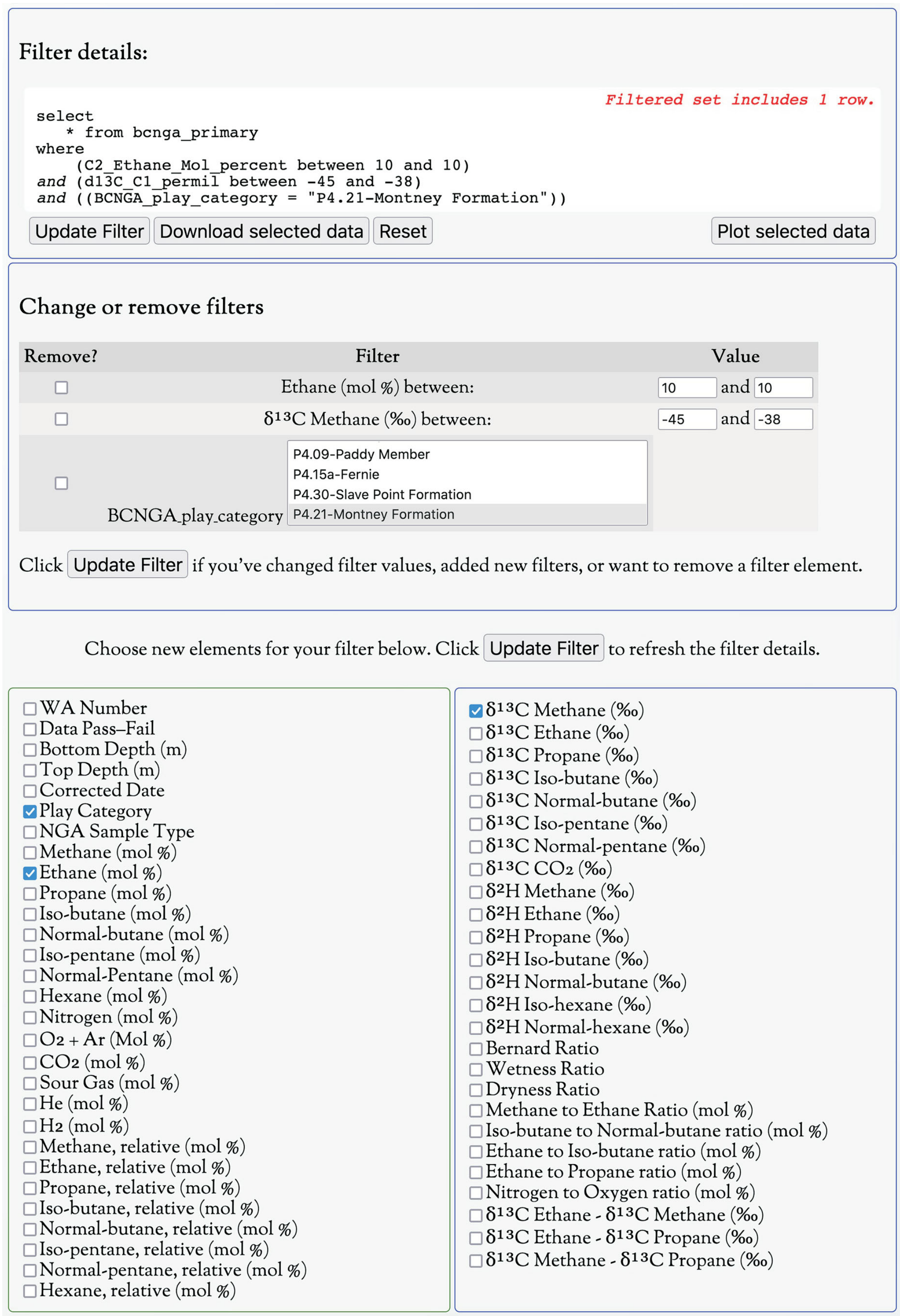

Figure 1. Example of a data subset from the British Columbia Natural Gas Atlas (BC-NGA) database on www.bcnga.ca created using a user-defined selection/filter mask.

Table 4. Examples of interpretative diagrams commonly used in gas geochemistry (from Whiticar, 2021).

Diagram name[1]	Parameters	Basic utility	Reference
Bernard Diagram	$\delta^{13}C_{CH4}$ *vs* $C_1/(C_2+C_3)$	Gas classification of thermogenic and microbial gases; scale emphasizes microbial gas	Bernard et al., 1976
Gas wetness	$\delta^{13}C_{CH4}$ *vs* $\%C_{2+}$ $\%C_2+ = (1-C_1/\sum C_{1-5})\bullet 100$	Gas classification of natural gas types; scale emphasizes thermogenic components	Schoell, 1983
CD diagram (Whiticar plot)	$\delta^{13}C_{CH4}$ *vs* δ^2H_{CH4}	Classification of all types of primary and secondary natural gas types and processes	Whiticar, 1994; Milkov and Etiope, 2018
Faber diagram	$\delta^{13}C_{CH4}$ *vs* $R_o\%$	Estimation of source maturity from methane to propane $\delta^{13}C$ values	Faber, 1987
CC diagram	$\delta^{13}C_{CO2}$ *vs* $\delta^{13}C_{CH4}$	Distinguishing different methanogenic pathways, methanotrophy and identifying biodegradation of oils	Whiticar, 1999; Milkov, 2011
Chung natural gas plot	$\delta^{13}C_{1-5}$ *vs* n/carbon #	Comparison of gases, identifying mixtures and alterations using C_{1-5} alkanes	Chung et al., 1988
Berner-Faber diagram	$\delta^{13}C_{C3H8}$ *vs* $\delta^{13}C_{C2H6}$	Distinguishing gas families, non-thermogenic mixtures and alterations, and estimating maturities	Berner and Faber, 1988, 1996; Rooney et al., 1995
Lorant diagram	$\Delta\delta^{13}C_2-\delta^{13}C_3$ *vs* C_2/C_3 (mol/mol)	Compare primary versus secondary cracking of gas in open and closed systems	Lorant et al., 1998
Delta-delta diagram	$\Delta\delta^{13}C_2-\delta^{13}C_1$ *vs* $\Delta\delta^{13}C_3-\delta^{13}C_2$	Identify mixing of two gases with different molecular and isotope compositions	Jenden et al., 1993
AlphaC-alphaD diagram	α_C *vs* α_D $(\delta^{13}C_{CO2}:\delta^{13}C_{CH4}$ *vs* $\delta^2H_{H2O}:\delta^2H_{CH4})$	Combination of carbon and hydrogen isotopes of methane to distinguish methanogenic pathways	Whiticar, 2020
Isotope rollover diagram	$\delta^{13}C_{C2H6}$ *vs* $\%C_{2+}$	Differentiate normal from high maturity isotope reversals (^{12}C enrichment of $\delta^{13}C_{C2H6}$)	Zumberge et al., 2012; Tilley and Muehlenbachs, 2013
CO_2-delta diagram	$\delta^{13}C_{CO2}$ *vs* $\Delta\delta^{13}C_2-\delta^{13}C_1$	Differentiate microbial-thermogenic gas mixtures from petroleum degradation	Milkov, 2011

[1]The plot names are the unofficial, 'in-house' names used by the author (MJW) and his colleagues over the decades. Some of the diagrams have other variations, names and updates, so apologies for any incorrect designations or attributions, and for the omissions.

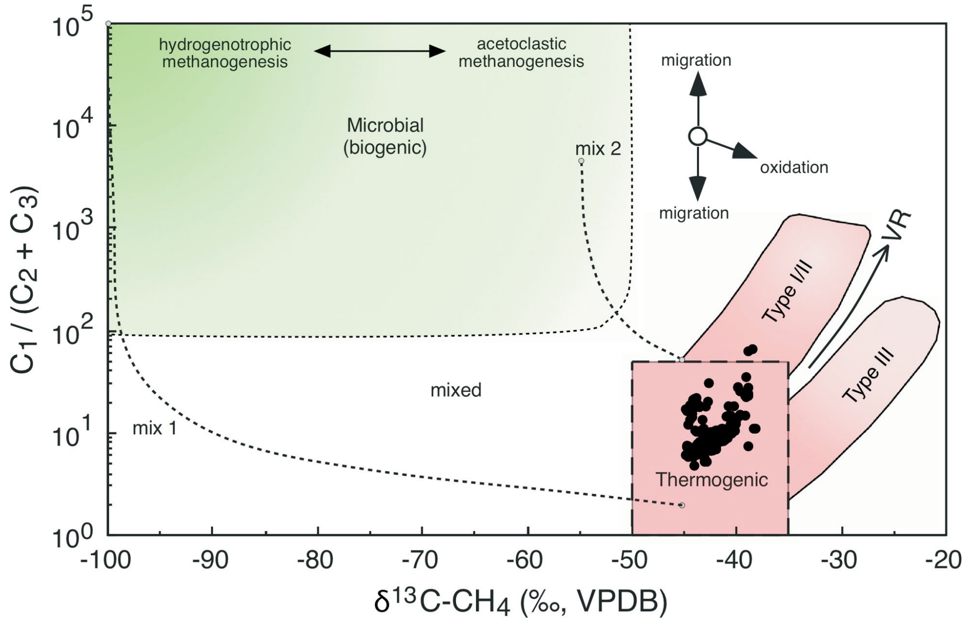

Figure 2. Example of Bernard Diagram (Bernard et al., 1976) created on the www.bcnga.ca website. The data plotted are from a data subset created using the chosen data filtering variables (mol % ethane, $\delta^{13}CH_4$, play category) shown in Figure 1. Abbreviations: VPDB, Vienna Pee Dee Belemnite (carbon isotope standard); VR, vitrinite reflectance (maturity indicator).

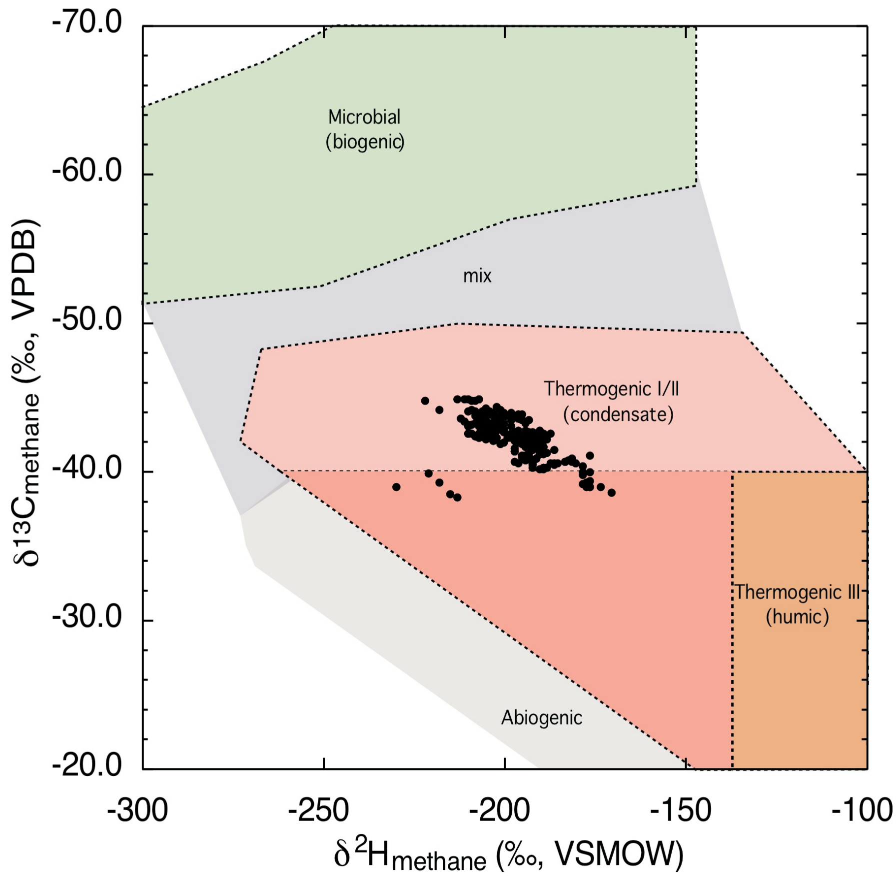

Figure 3. Example of truncated 'Whiticar plot' or 'CD diagram' (Whiticar, 2021) created on the www.bcnga.ca website. The data plotted are from a data subset created using the chosen data filtering variables (mol % ethane, $\delta^{13}CH_4$, play category) shown in Figure 1. Abbreviations: VPDB, Vienna Pee Dee Belemnite (carbon isotope standard); VSMOW, Vienna Standard Mean Ocean Water (hydrogen isotope standard).

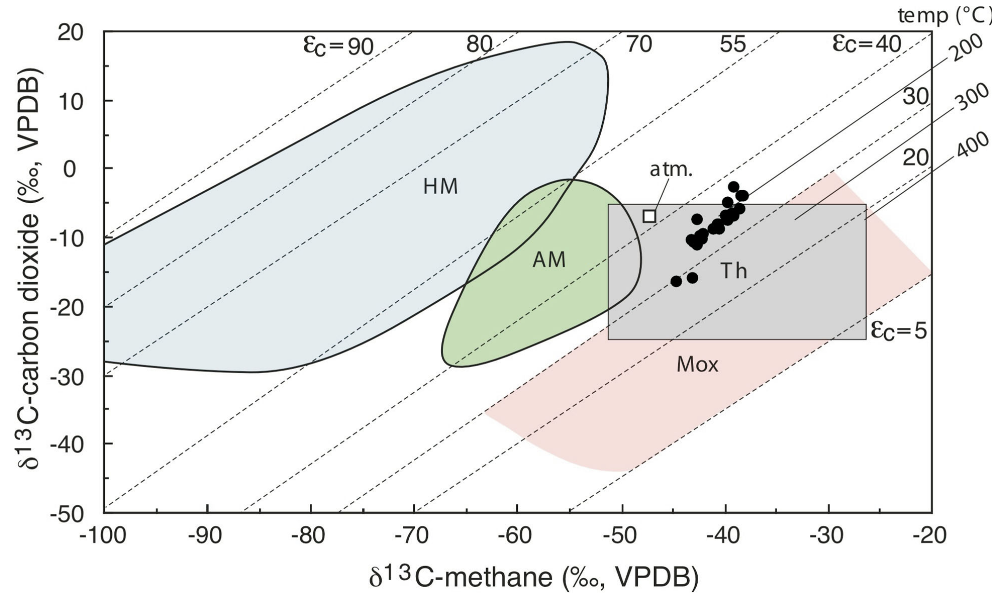

Figure 4. Example of 'CC diagram' (Whiticar, 1999; Milkov, 2011) created on the www.bcnga.ca website. The data plotted are from a data subset created using the chosen data filtering variables (mol % ethane, $\delta^{13}CH_4$, play category) shown in Figure 1. Abbreviations: ε_c, carbon isotope fractionation factor; AM, acetoclastic methanogenesis; atm., average tropospheric methane; HM, hydrogenotrophic methanogenesis; Mox, methane oxidation; Th, thermogenic methane; VPDB, Vienna Pee Dee Belemnite (carbon isotope standard).

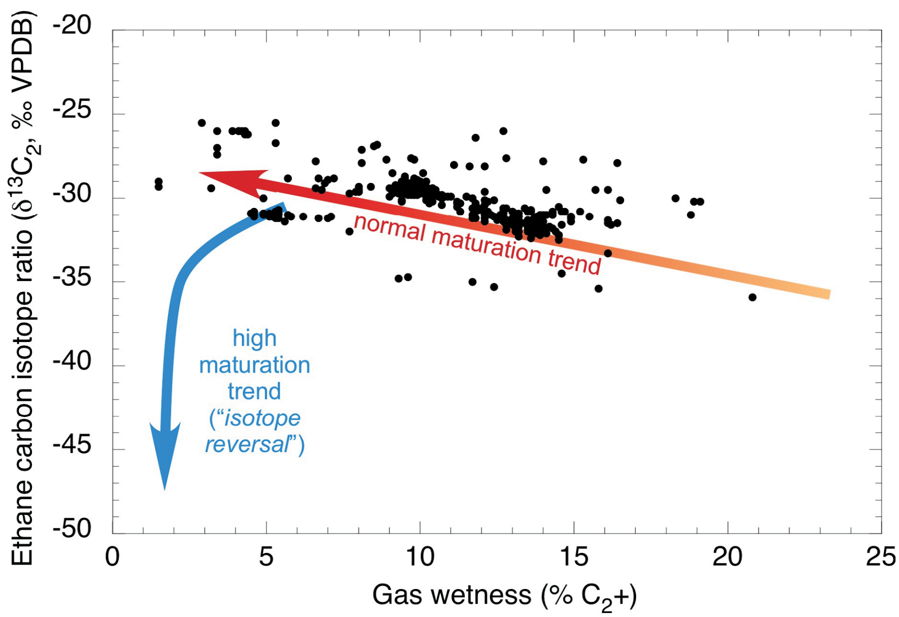

Figure 5. Example of isotope reversal ('rollover') diagram (Zumberge et al., 2012; Tilley and Muehlenbachs, 2013) created on the www.bcnga.ca website. The data plotted are from a data subset created using the chosen data filtering variables (mol % ethane, $\delta^{13}CH_4$, play category) shown in Figure 1. Abbreviation: VPDB, Vienna Pee Dee Belemnite (carbon isotope standard).

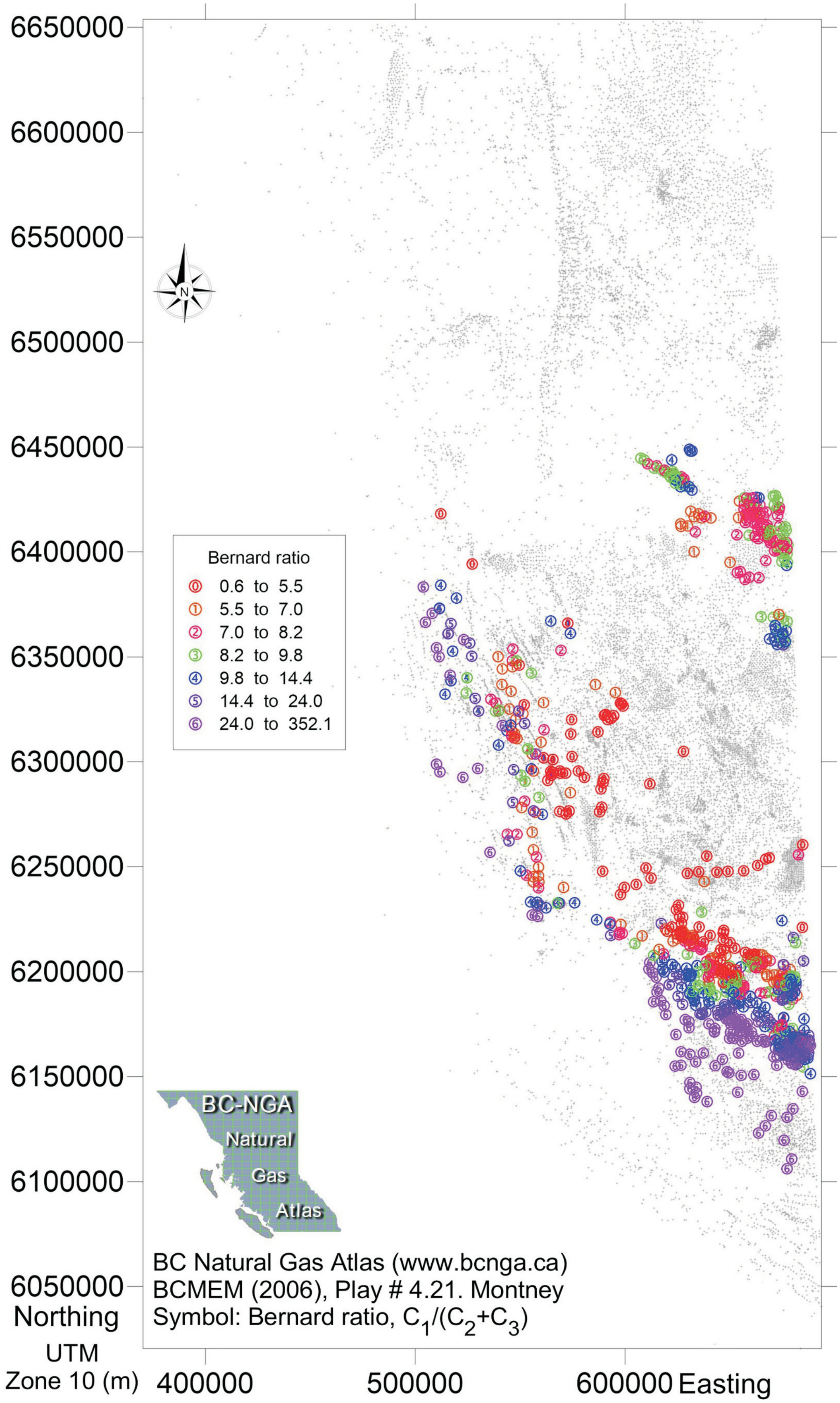

Figure 6. Example from the www.bcnga.ca map catalogue showing Bernard ratio distribution for the Montney Formation in northeastern British Columbia. Small black crosses (+) show the locations of data for the entire database. The map co-ordinates are in UTM Zone 10, NAD 83.

The interpretative plot of $\delta^{13}C_{CO2}$ versus $\delta^{13}C_{CH4}$ or ‘CC diagram’, illustrated in Figure 4 (Whiticar, 1994; Milkov, 2011), is particularly useful in identifying microbial methanogenic and methanotrophic gases and pathways, as well as helping understand the geothermometry and distinguishing thermogenic gas from abiogenic gas.

The final example diagram presented here is termed the ‘isotope reversal’ or ‘isotope rollover’ diagram (Figure 5). It is derived from Zumberge et al. (2012) and Tilley and Muehlenbachs (2013) and plots $\delta^{13}C_{C2H6}$ versus $\%C_{2+}$. This diagram can differentiate normal gas maturation trends or trajectories from the unusual high maturity isotope reversals (^{12}C enrichments of $\delta^{13}C_{C2H6}$).

Mapping of Gas Geochemical Parameters Using the BC-NGA Database

The BC-NGA website (www.bcnga.ca) offers an atlas of 349 geochemical distribution maps. The maps show specific geochemical parameters, such as ppm H_2S, dryness ratio, iC_4/nC_4 ratio and $\delta^{13}CH_4$, for northeastern BC. The maps are catalogued on the website according to the formation/play code (e.g., Dunvegan, Bluesky, Doig, Montney), which is based on the designation in BC Ministry of Energy, Mines and Low Carbon Innovation (2006).

The maps were generated by Evans (2019) using basic kriging with a spherical algorithm and a Gaussian variogram. Declustering was done manually based on the data analysis. Many well test intervals have two or three gas samples analyzed for molecular composition only. These samples are often inadequate to create a production profile and the geographic location is exactly the same. This creates estimation problems for the kriging algorithm and declustering is required. If all samples from a well test interval were flagged equally, only the first sample was used in creating the map. If the first sample was problematic, as identified in the flagging, the second or third sample was chosen. This declustering also applied to gas analysis from multiple legs on a single drilling pad, but instead of using the first sample (usually the motherbore of a horizontal well), the horizontal leg with the longest reach and most frequent testing was used for mapping. Figure 6 provides an example of a www.bcnga.ca map showing the distribution of the Bernard ratio for the Montney Formation in northeastern BC based on the BC-NGA database.

Summary

The British Columbia Natural Gas Atlas (BC-NGA) project and the associated upgraded website, www.bcnga.ca, now features a script to check for new natural gas geochemical data posted on the British Columbia Oil and Gas Commission site. This new nonconfidential data is downloaded and appended to the BC-NGA database, then automatically reformatted and passed through the quality assurance–quality control procedure before being made available to users on www.bcnga.ca. New sorting tools to select, filter and download user-defined data subsets have been created. In addition, to aid interpretation of the gas geochemical data, automated plotting of common interpretative diagrams has been added as a user feature. Maps of the distributions of common natural gas geochemical parameters for northeastern British Columbia are also presented on www.bcnga.ca.

It is anticipated that the BC-NGA database will be periodically updated, and thus will continue to provide a comprehensive and useful geochemical resource for those working on gas geochemical topics and issues in northeastern British Columbia.

Acknowledgments

The British Columbia Natural Gas Atlas (BC-NGA) team would like to thank C. Salas, R. Hughes and L. Wytrykush of Geoscience BC for their proactive support and assistance over the past five years. The support of the BC Oil and Gas Commission, in particular, J. Johnson, S. Venables and M. Hayes, is also recognized. The authors would like to thank S. Verenitch (School of Earth and Ocean Sciences, University of Victoria) and P. Eby (InnoTech Alberta) for conducting the stable isotope ratio analyses. The work of compiling and creating the initial BC-NGA database and manually conducting the quality assurance–quality control of the entries was carefully and tirelessly undertaken by C. Evans. His University of Victoria M.Sc. thesis details much of the gas geochemistry mapping included in the BC-NGA database.

The funding for BC-NGA is generously provided by grants from Geoscience BC and the BC Oil and Gas Research and Innovation Society (BC OGRIS) and is gratefully acknowledged. The authors also thank C. Evans for kindly reviewing and C.J. Dawson, with RnD Technical, for expertly editing the manuscript.

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