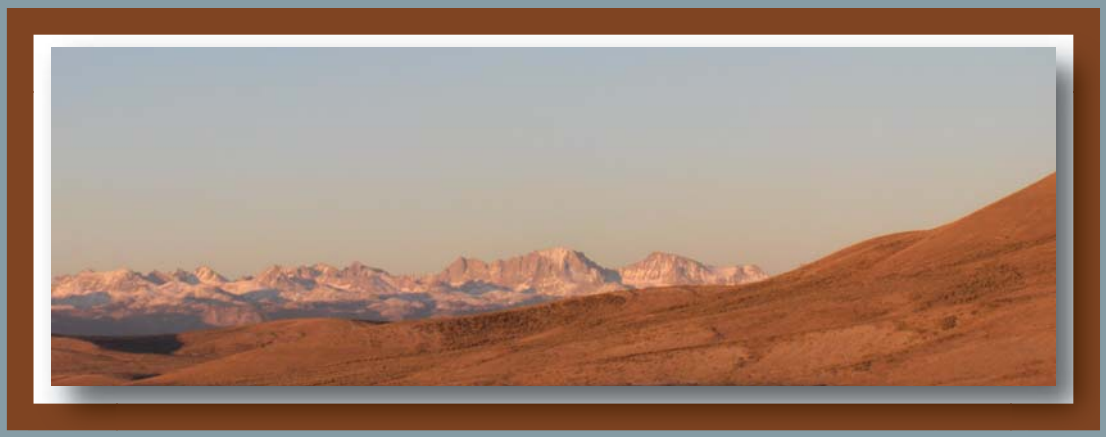
APPENDIX H



Chemical Matrix

APPENDIX H

CHEMICAL MATRIX

1.0 DEVELOPMENT OF THE CHEMICAL MATRIX

This appendix presents a comprehensive matrix summarizing results of chemical analyses performed for this study. The matrix will be referred to as the *chemical matrix*. The intent of this chemical matrix is to present a broad, visual impression of samples that share common properties. The purposes of the chemical matrix are to:

- Present a visual representation of chemical properties that are shared by one or more samples or groups of samples, and
- Present a visual summary of broad trends in the presence or specific range of concentrations of different analytes in individual samples or groups of samples.

The following sections provide an explanation of the columns, rows, and entries in the chemical matrix. An explanation of how indicator matrix tables were developed from the chemical matrix for each potential source material sampled for this study (see **Tables 16** through **22** in main text) is also provided.

1.1 COLUMNS IN CHEMICAL MATRIX

Each column in the matrix represents an individual sample collected and analyzed for this study. Entries in the table indicate those analytes and/or ranges and patterns of results that characterize each sample. If more than one sample was collected for a potential source material, a “material summary” column was added to the table for that potential source material. Entries in the material summary columns summarize those analytes and/or ranges and patterns of results that characterize the potential source material. For example, the material summary for pump installation materials summarizes the characteristics of pipe dope, pipe grease, pipe dope and grease, and Teflon tape sampled for this study, which are collectively referred to as *pump installation materials*. The characteristics of black film were not included in this material summary, because the black film appears to be a mineral substance. Wells with one or more constituent concentrations above Wyoming Department of Environmental Quality (Wyoming DEQ) groundwater standards (i.e., high-level wells) are also highlighted in the chemical matrix.

1.2 ROWS IN CHEMICAL MATRIX

The first three rows of the chemical matrix provide the following sample information: sample type, sample identification or location, and the number of samples collected. Each subsequent row in the chemical matrix represents information for each individual analyte or class of analytes for each sample. Categories for analytes detected, properties assessed, or specific ranges of concentrations that occurred are presented, organized by the following classes of analyses or observations:

- Organics,
- Chromatographic profiles,
- Tentatively identified compounds (TICs) by chemical group,
- Inorganics (subdivided further as general water quality parameters and metals),
- Stable isotope values of water and methane,
- Hydrocarbon gas composition, and
- Hydrocarbon gas component ratios.

The sections below describe the information presented in the rows of the matrix and describe the rubric used to categorize results for each of these categories of analyses and observations.

1.2.1 Sample Information

Well/Sample Type identifies the sample type for potential source material samples (e.g., drill mud) or well type for groundwater samples (e.g., SAP study well for wells sampled as part of implementing the sampling and analysis plan).

Site Name identifies the sample identification of the potential source material sample (e.g., JEN 1A MUD), the well pad location for a sample collected from a natural gas well (e.g., RS 11-14), the well pad location for groundwater samples collected from industrial water supply wells (e.g., AN 15-23), or the well identification for groundwater samples collected from study wells (e.g., T-1-SW).

Number of Samples identifies the number of samples collected in association with the *Site Name.* For material summaries, this identifies the number of samples collected for each type of potential source material (e.g., three samples were collected of drill mud for this study). Typically only one groundwater sample was collected from each water well for this study (i.e., this excludes quality control samples collected from water wells), with the following exceptions:

- Two groundwater samples were collected from water wells RS 11-25 and RS 15-12 in 2010. One sample was collected from the top of the water column, and one sample was collected from the middle of the perforated interval in each of these wells.
- Groundwater samples were collected from the following water wells in both 2010 and 2012: SP 5-20, MS 14-16, MS 12-28, RS 11-14, RS 1-4, BO 12A-33, WB 8-6, WB 7-5, T-4-RWa and T-4-RWb. The groundwater samples collected in 2010 were analyzed for the full-suite of parameters specified for this study (see Table 2 in main text); follow-up samples collected in 2012 were analyzed for a select list of parameters (given in Section 3.2.4.6 of main text).
- Two samples of LNAPL were collected; however, results for the volatile fraction were reported from one sample and results for the semivolatile fraction were reported from the other sample.

1.2.2 Organics

Method 8015 Detections represent the volatile (purgeable) and semivolatile (extractable) fractions detected using EPA Method 8015. Results are shown for the following fractions*:*

- Total purgeable hydrocarbons (*TPgH*);
- Total petroleum hydrocarbons – gasoline range organics (*TPH-GRO*);
- Total extractable hydrocarbons (*TEH*); and
- Total petroleum hydrocarbons (*TPH-DRO*).

TEH after SGT represents the result for TEH when the sample was re-analyzed following silica gel treatment.

Results for the percent of TPH-GRO that makes up TPgH (*% TPH-GRO of TPgH*) and the percent TPH-DRO that makes up TEH (% *TPH-DRO of* TEH) are indicated for specified ranges to indicate how much of the volatile fraction comprised gasoline-range organics and how much of the semivolatile fraction comprised diesel-range organics.

The volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) listed under *VOC Detections* and *SVOC Detections,* respectively, were confined to only those that were detected in either a groundwater sample or potential source material. Phthalates were not included in the chemical matrix under *SVOC Detections* because these compounds are likely present due to cross-contamination. The organic constituents listed under *Confirmation of Tentatively Identified Compounds [TICs]*) are those TICs that were tentatively identified in groundwater samples collected in 2010 and 2011 and subsequently selected for follow-up sampling and quantitation by EPA Methods 8260 and 8270 in 2012.

For individual samples, organic constituent detections are indicated by a solid circle (●) in the chemical matrix. If the constituent was detected in all potential source material samples of a certain type, a solid circle (●) was placed in the material summary for that potential source material. For example, benzene was detected in all four flowback fluid samples collected for this study; thus, benzene is represented by a solid circle (●) in the material summary for flowback fluid in the chemical matrix. If the organic constituent was detected in some, but not all, of the potential source materials of a certain type, an open circle (○) was placed in the material summary for that potential source material. For example, phenol was detected in only two of the four flowback fluid samples; thus, phenol is indicated by an open circle (○) in the material summary for flowback fluid. Adamantane was reported as a TIC in the LNAPL sample, and was quantified in a groundwater sample upon follow-up sampling and analysis. This association is indicated in the chemical matrix by the symbol ☼.

A blank entry in the chemical matrix indicates that a constituent was either not detected (i.e., benzene entry for drill mud sample, JEN 1A MUD, is left blank because benzene was not detected in this sample) or the result was not within the range specified (i.e., the percent TPgH that is TPH-GRO was not greater than 85% in drill mud sample JEN 1A MUD, and thus the entry is left blank). An entry that is shaded gray in the chemical matrix indicates that the constituent was not analyzed

in the sample for this study or required results were not generated for the indicated observation or ratio. For example, the entry for TPgH is shaded gray in the chemical matrix for the natural gas samples, because the natural gas samples were not analyzed for TPgH. Moreover, the percentage of TPgH that is TPH-GRO could not be calculated for these samples, thus these entries are also shaded gray in the chemical matrix.

This general rubric for symbology and shading is followed throughout the chemical matrix for the other constituents and analytical groups.

1.2.3 Chromatographic Profile

The appearance of the profiles in GRO and DRO chromatograms generated from analyses by EPA Method 8015 were described by a series of specific attributes in order to provide a rough mental image of the chromatographic profile. Chromatographic profiles were also assessed with respect to whether they were diagnostic, non-diagnostic, or variable between potential source materials of the same type. This evaluation is described further below.

1.2.3.1 Specific Attributes

For descriptive purposes, the appearance of a chromatographic profile was assessed based on:

- Whether the chromatographic profile was *narrow* or *broad*, *symmetrical* or *asymmetrical*, and/or *spiky*; and
- Whether *early eluting peaks* (gases with less than five carbon numbers), *distinct individual peaks* (constituents with five or more carbon numbers), an unresolved complex mixture (*UCM*), or *little to no response* were present in the chromatogram.

Profiles were described as *narrow* or *broad* based on the breadth of the retention time window during which the majority of the chromatographic response is observed. Most of the response in a narrow chromatographic profile is present within a relatively short retention time window, roughly 6 to10 minutes in length. This type of profile typically exhibited a defined “hump,” which was observed in DRO chromatograms for drill mud (**Figures F-1** and **F-2** of **Appendix F**). The response exhibited for broad chromatographic profiles generally extended over a longer retention time window (e.g., greater than 8 to 10 minutes in length) and did not exhibit a defined hump. A broad chromatographic profile can manifest itself as an unresolved complex mixture (UCM), as in the DRO chromatogram for the LNAPL sample (**Figure F-10** of **Appendix F**), or as numerous spiky peaks across a broad retention time range, which was observed in the GRO and DRO chromatograms for condensate (**Figure F-2** of **Appendix F**). A chromatographic profile characterized as containing distinct individual peaks generally has peaks that are not linked together, which is consistent with that of a spiky profile in a chromatogram. For example, the GRO chromatograms for produced water samples display distinct, individual peaks (**Figures F-3** through **F-5** of **Appendix F)**.

Attributes of profiles specific to the GRO chromatogram from individual samples are indicated by an open square (□) in the chemical matrix. Attributes of profiles specific to the DRO chromatogram from individual samples are indicated by a solid square (■) in the matrix. Attributes that are similar in both GRO and DRO chromatograms from individual samples are indicated by a black, open square with a thick border in the matrix (◘). For example, little to no response was observed in both

GRO and DRO chromatograms from the groundwater sample collected from water well BO 1-32 (**Figure F-21** of **Appendix F**). For material summaries, only those specific attributes of chromatographic profiles that were observed in all potential source materials of the same type are indicated based on the symbology above. If a specific attribute is not consistently present in the chromatographic profiles of potential source material samples of the same type, the entry in the material summary column is left blank.

1.2.3.2 General Assessment

An assessment was also made of whether one or both chromatographic profiles for a groundwater sample or potential source material samples of the same type (e.g., material summary) were:

- *Diagnostic*,
- *Variable,* and/or
- *Non-diagnostic*.

For potential source material samples, the chromatographic profiles are considered *diagnostic* if the specific attributes of the chromatographic profiles are consistent among potential source material samples of the same type. For example, the DRO chromatograms for drill mud samples exhibit a consistent appearance among samples (i.e., a narrow, spiky, symmetrical hump) and are considered diagnostic (**Figures F-1** and **F-2** of **Appendix F**). Chromatographic profiles are deemed *variable* when specific attributes of the chromatographic profiles are not consistent among potential source material samples of the same type. For example, the profiles in DRO chromatograms for flowback fluid samples ranged from little to no response to narrow and symmetrical, to broad, symmetrical and spiky (**Figures F-6** and **F-7** of **Appendix F)**. Thus, it is difficult to make a determination of source based on the varying chromatographic profiles of DRO chromatograms in flowback fluid.

For groundwater samples, a profile is diagnostic if it resembles the profile of a potential source material sampled or standard reference chromatogram. For example, the narrow, symmetrical hump observed in the profile of the DRO chromatograms generated from groundwater samples collected from RS 11-25 are similar to the profile in DRO chromatograms from drill mud samples (**Figure F-18** of **Appendix F**). A non-diagnostic profile in a groundwater sample does not closely resemble a profile of a potential source material sample or a standard reference chromatogram. In these samples, the chromatographic response does not definitively point to source (e.g., groundwater sample from water well BO 1-32; **Figure F-21** of **Appendix F**).

The symbology for the assessment of a chromatographic profile as diagnostic or variable and/or non-diagnostic is the same as that used for the specific attributes of chromatograms. Assessments based on the GRO chromatogram are indicated by an open square in the matrix (□), whereas assessments made based on the DRO chromatogram are indicated by a solid square (■). Assessments that are the same for both the GRO and DRO chromatograms are indicated with an open square with a thick border (◘) in the matrix.

1.2.4 Tentatively Identified Compound (TIC) Groups Represented

TICs were placed in the following chemical groups to facilitate comparisons between samples in the chemical matrix:

Alkanes	*Alkylbenzenes*	*Alcohols*
Branched Alkanes	*Indan/Indane/Indene Compounds*	*Ketones*
Alkynes	*Naphthalenes*	*Aldehydes*
Cycloalkanes	*Decalins*	*Phenols*
Alkylcycloalkanes	*Tetralins*	*Silanes*
Cycloalkenes	*Terpenoids*	*Siloxanes*
Alkenes	*Organic Acids*	*Sulfur*
Branched Alkenes		

The symbology for detections in TIC chemical groups follows that for organic constituents (see **Section 1.2.2** of main text). For potential source material summaries, the same individual TIC within a TIC chemical group does not need to be detected in all samples of a particular potential source material, as long as one TIC from the respective chemical group is detected in all potential source material samples of the same type. For example, at least one alkane was detected in every produced water sample collected; thus, the alkane TIC chemical group is represented by a solid circle (●) in the material summary for produced water, although the identical alkane compounds were not detected in all of these samples.

The number of TICs detected in each sample is also provided (*Total Number of Individual TICs*) in the matrix. This total represents the number of different, individual TICs reported in a sample or for all samples where multiple samples were collected (e.g., total number of TICs reported for the two groundwater samples collected from RS 15-2 and RS 11-25). For material summaries, this total represents the number of different, individual TICs detected in all potential source material samples for that sample type, and is therefore not a sum of the number of TICs reported in each sample for that sample type.

1.2.5 Inorganics

Numerous inorganic constituents were detected in the samples of potential source materials and groundwater collected for this study. Because of the ubiquitous nature of these constituents in samples, the detections of these constituents in groundwater samples may not indicate the influence of a potential source material. Conversely, the detected constituents in potential source material samples may not serve as a useful indicator of a potential source material if concentrations are low or the presence of constituents and the magnitude of concentrations are similar among potential source materials.

The presence of an inorganic constituent, either a *general water quality parameter* or a *metal* in a groundwater or potential source material sample was indicated by a solid circle (●) in the chemical matrix only if the constituent was detected at a concentration greater than 10 times (10xs) the

laboratory reporting limit in that sample. If this constituent was detected at a concentration greater than 10 times the reporting limit in all potential source materials of that type, the material summary column for that constituent has a solid circle (●) in the matrix. If the inorganic constituent was detected at a concentration greater than 10 times the reporting limit in some, but not all, of the potential source materials of the same type, detection is indicated by an open circle (○) is placed in the chemical matrix.

Thus, a blank entry in the chemical matrix may indicate that the inorganic constituent either was not detected or was detected, but at a concentration less than 10 times the laboratory reporting limit. Identifying constituents present at 10 times the reporting limit was the first step in filtering results for inorganic constituents detected in groundwater samples that are likely representative of background conditions and not necessarily influenced by the presence of a potential source material. This process was also the first step in filtering inorganic constituents detected in potential source material samples that were not present at concentrations sufficient to cause elevated levels in groundwater or high enough such that the constituent could be used to help identify or narrow down a potential source.

Some inorganic constituents in potential source material samples were detected at concentrations *greater* than 10 times the reporting limit *and* appeared to be elevated with respect to concentrations reported in groundwater samples for this study. These constituent detections in potential source material samples are indicated by a solid diamond (♦) in the matrix. For example, the potassium concentration in produced water sample AN 1-9 PDW was 115 milligrams per liter (mg/L), which is greater than 10 times the reporting limit for potassium in that sample (1 mg/L) and more than an order of magnitude higher than potassium concentrations reported in groundwater for this study (up to 3 mg/L). If inorganic constituent detections met this criterion in all potential source material samples of a certain type, a solid diamond (♦) was placed in the respective material summary column for that constituent. If the inorganic constituent detections met this criterion in some, but not all, of the potential source material samples of a certain type, an open diamond (◊) was placed in the respective material summary column for that constituent. Inorganic constituents that met these criteria in potential source material samples could serve as potential indicators of a source if elevated levels of that constituent are observed in groundwater.

Some inorganic constituents in potential source material samples were detected at concentrations *less* than 10 times the reporting limit *but* were still elevated with respect to concentrations reported in groundwater samples for this study. These results are indicated by the symbol (**X**) in the matrix. For example, bromide concentrations in produced water samples ranged from 66 to 123 mg/L. These concentrations were less than 10 times the reporting limit for bromide in produced water samples (50 mg/L), but one to two orders of magnitude higher than bromide concentrations reported in groundwater for this study (up to 1.2 mg/L). Thus, bromide in produced water samples and the material summary for produced water is indicated by the symbol (**X**) in the matrix.

1.2.6 Stable Isotopes

The range in values for stable isotopes of water [*oxygen (^{18}O)*, *hydrogen (^{2}H),* and *dissolved inorganic carbon (^{13}C)*] in produced water and groundwater samples and the range in stable isotope values of methane, [*carbon (^{13}C)* and *hydrogen (^{2}H)*] in gas samples collected from natural gas wells (natural gas samples) and in dissolved gas samples collected from water wells

are indicated in the chemical matrix. The specified ranges for carbon (^{13}C) isotope values of methane in the matrix follow the ranges in isotope values typically associated with a particular gas origin: thermogenic, microbial or intermediate. The symbology for the ranges in which isotope values were detected follows that described in **Section 1.2.2**.

1.2.7 Hydrocarbon Gas Detections and Component Ratios

The hydrocarbon gas components represented by rows in the matrix are those that were analyzed in both the dissolved gas analyses for groundwater samples and gas analyses for natural gas samples (C_1 through C_6), as well as benzene, toluene, ethylbenzene, and xylenes (BTEX), which were only analyzed in the natural gas samples. Symbology with respect to detections of these hydrocarbon gas components follows that described in **Section 1.2.2**. The detection of C_{3+} gas components and BTEX in a sample indicates the presence of gas with a thermogenic origin. Detection of only methane (C_1) likely indicates the presence of microbial gas.

Ratios of *methane to ethane + propane* ($C_1/C_2 + C_3$), *isobutane to butane* ($isoC_4/nC_4$), and *isopentane to pentane* ($isoC_5/nC_5$) were calculated from the hydrocarbon gas components detected in both the dissolved gas analyses for groundwater samples and gas analyses for natural gas samples. The $C_1/C_2 + C_3$ ratio is an indicator of gas origin, where higher ratios can indicate a microbial origin (i.e., more methane relative to ethane and propane), and lower ratios are typical of thermogenic gas (i.e., less methane relative to ethane and propane). The $isoC_4/nC_4$ and $isoC_5/nC_5$ ratios provide an indication of the alteration of gas, whereby a preferential depletion of n-alkanes relative to isoalkanes (i.e., ratios greater than 1) indicates alteration of gas. The specified ranges of these ratios were selected to facilitate comparisons between and among groundwater and natural gas samples. Ratios could not be calculated in many groundwater samples, because either some or all of the hydrocarbon gas components were not detected. In a few samples, the gas component ratio could not be calculated because isoalkane(s) were detected, but n-alkane(s) were not detected. This complete depletion of n-alkanes with respect to isoalkanes indicates that highly altered gas is present; samples where this occurs are indicated by an asterisk (*) in the matrix (i.e., groundwater samples HWY 7, RS 11-14, and RB 16-30).

1.2.8 Presentation of the Chemical Matrix

A visual scan of individual columns in the chemical matrix provides an impression of whether samples or groups of samples have similar or distinct chemical signatures. For example, a glance of the columns shows that a majority of the LEL wells contained predominantly volatile organic fractions, whereas semivolatile organic fractions were predominantly detected in the control wells. Similarly, the greatest variety of TICs was reported in produced water, drill mud, and flowback fluid samples, whereas very few TICs were reported in samples of pump installation materials.

A visual scan of rows shows how commonly individual analytes or groups of analytes are detected in different samples or sample groups or to what degree specific patterns or ranges of results occur. For example, the chemical matrix shows clearly that many individual VOCs and SVOCs were detected in most potential source material samples, but in very few groundwater samples. Numerous TICs were reported, and several TIC chemical groups are represented, in most potential source material samples, but in very few groundwater samples. The hydrocarbon gas component detections and component ratios in natural gas samples are different from those in dissolved gas from groundwater samples analyzed in this study.

2.0 DEVELOPMENT OF INDICATOR MATRIX TABLES

To more easily compare chemical signatures in groundwater samples to chemical signatures in each potential source material, the chemical matrix was used to develop a separate table, or "indicator matrix," specific to each potential source material sampled for this study. The following indicator matrix tables are presented in the main text of the report:

- Condensate (**Table 16**);
- Produced Water (**Table 17**);
- Flowback Fluid (**Table 18**);
- Drill Mud (**Table 19**);
- Pump Installation Materials (**Table 20**);
- LNAPL (**Table 21**); and
- Natural Gas (**Table 22**).

2.1 ROWS IN INDICATOR MATRIX TABLES

The rows in each indicator matrix table represent the results of the chemical matrix for each individual groundwater sample collected and analyzed for this study, as well as groundwater samples collected and analyzed for the HDG investigation (i.e., HDG study wells). The symbology in the indicator matrix tables is obtained directly from the chemical matrix. The first row in each indicator matrix table presents a summary of the results for the potential source material of interest. For example, the first row in **Table 16** contains the results for the condensate sample from the chemical matrix. If more than one sample was collected per source material type, the results of the material summary for that potential source material type from the chemical matrix are shown. For example, the results of the material summary for produced water from the chemical matrix are displayed in the first row of **Table 17**.

Each indicator matrix table is differentiated from the other indicator matrix tables by the following attributes:

- The potential source material of interest; and
- The columns or "potential indicators" included in the table that are characteristic of the potential source material of interest and for which results are included for the groundwater samples.

2.2 COLUMNS IN INDICATOR MATRIX TABLES

Those parameters (e.g., constituent detections, ratios, percentages, etc.) from the chemical matrix for a particular source material that might serve to differentiate it from another potential source material, or that are considered an integral part of the chemical signature of a potential source material, were selected as "potential indicators" for each potential indicator table. Potential indicators were typically those parameters that were consistently detected among potential source

material sample types or those that are characteristic of that material in comparison to other potential source materials. In most cases, these parameters would not be definitive indicators alone, but a number of these parameters combined result in a chemical signature characteristic of one potential source material. In some instances, what was not detected in a potential source material was more of an indicator than what was detected, and these parameters (conspicuous by their absence) were included in the indicator matrix when appropriate.

2.2.1 Organics and Chromatographic Profiles

Potential indicator matrix tables for all potential source materials except natural gas include columns for the following potential indicators:

- *EPA Method 8015 Detections*;
- *% TPH-GRO of TPgH* and *%TPH-DRO of TEH*; and
- *General* and *Specific Attributes* of *GRO & DRO Chromatographic Profiles.*

These columns are not included for natural gas samples, which were not analyzed for these parameters or parameters could not be calculated (**Table 22**). These columns were included in all of the other tables as these organic constituents provide a general indicator of the fractions detected (i.e., volatile versus semivolatile), and chromatogram pattern matching was integral in assessing differences in the characteristics of the potential source materials (and correspondingly characteristics of groundwater samples).

In general, only those individual VOCs and SVOCs detected, and those TIC chemical groups reported, for the potential source material sample(s) are displayed in columns of their respective indicator matrices. For example, benzene, toluene, ethylbenzene, and xylenes (BTEX) were the only VOCs detected in the condensate sample; naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene were the only SVOCs detected. Thus, these constituents are represented in columns of the indicator matrix for condensate (**Table 16**). The exception to this rubric was for pump installation materials, in which BTEX were included as columns in the indicator matrix, but only xylenes were detected in the samples. The absence of VOC detections in pump installation materials is characteristic of this potential source material compared to the others, in which these constituents were generally detected.

Columns for *Confirmation of Tentatively Identified Compounds (TICs)* were included in the potential indicator matrix tables only for flowback fluid (**Table 18**) and the LNAPL sample (**Table 21**). No TICs that were reported in groundwater samples and quantified upon follow-up sampling and analysis were reported as TICs in potential source materials, except in the case of LNAPL. Thus, these columns are included in this indicator matrix (**Table 21**). These columns were also included in the indicator matrix for flowback fluid because most of these TICs targeted for quantitation (i.e., non-hydrocarbon TICs) would most likely be associated with flowback fluid. However, a review of **Table 18** shows that these non-hydrocarbon TICs are not potential indicators of the flowback fluid currently generated in the PAPA, as these constituents were not reported as TICs in the flowback fluid samples collected for this study.

2.2.2 Inorganics

Columns containing the detections of general water quality parameters were included in the indicator matrices for produced water and flowback fluid because these parameters were only analyzed in these two types of potential source materials (**Table 17** and **18**). All general water quality parameters were included in **Tables 17 and 18** because what was not detected was often more informative than what was detected based on the criteria outlined in the chemical matrix (i.e., parameter concentrations greater than 10 times the reporting limit and/or parameter concentrations that were elevated with respect to the range of concentrations observed in groundwater in this study). For example, general water quality parameters are typically detected above the criteria outlined in the chemical matrix in both potential source material samples and groundwater samples; thus, the magnitude of the detection of the general water quality parameter in groundwater is more important in source identification as compared to a mere detection. In addition, if varying groundwater types are observed, as is the case in the PAPA, the concentration at which a general water quality parameter in groundwater is considered to be influenced by a potential source material may vary based on geographic location. Alternatively, a general water quality parameter that is detected in a potential source material, but generally not in a groundwater sample, may serve as a better indicator than a general water quality parameter that is detected in samples of potential source materials and groundwater, where the relative magnitude of concentrations would need to be evaluated with respect to what is typical for groundwater in the area.

Columns containing the detections of metals were included in the indicator matrix tables for produced water, flowback fluid, and drill mud because these parameters were only analyzed in these potential source materials. However, in contrast to general water quality parameters, only those metals detected based on criteria outlined in the chemical matrix were included in the columns in these potential indicator matrix tables. The same considerations apply to metals when evaluating the influence of potential sources in groundwater that were used for general water quality parameters.

2.2.3 Stable Isotopes

Columns containing the range in values of stable isotopes of water are included in the indicator matrix for produced water because these parameters were only analyzed in this potential source material sample (**Table 17**). The ^{2}H and ^{18}O isotope values in produced water are clearly different from the values observed in groundwater. As such, stable isotope of water values may be useful in identifying the influence of produced water on groundwater quality.

Columns containing the range in values of stable isotopes of methane are presented in the indicator matrix for natural gas samples (**Table 22**). Stable isotope values of methane provide an indication of the origin of the gas.

2.2.4 Hydrocarbon Gas Detections and Component Ratios

Columns containing the detections of hydrocarbon gas components and gas component ratios are presented in the indicator matrix for natural gas samples (**Table 22**). The stable isotopes of methane, detections of hydrocarbon gas components, and gas component ratios were used to

make a determination of chemical signature in the natural gas samples and the dissolved gas in groundwater.

2.3 PRESENTATION OF INDICATOR MATRIX TABLES

Based on the potential indicators or characteristics that make up the chemical signature of a potential source material, one can read down the respective table and see if that chemical signature matches the chemical signature in any of the groundwater samples. In each indicator matrix table for a particular potential source material, the chemical signature of that material is shaded a specific color. In addition, the row for any groundwater sample that displays that signature, or most closely displays that chemical signature, is shaded the same color. For example, the chemical signature of drill mud closely resembles the chemical signature in groundwater samples collected from water wells RS 11-25 and RS 15-12. Thus, the results for these groundwater samples in **Table 19** are shaded the same color as the results for drill mud at the top of the table.

Of all potential source materials sampled, the chemical signature in most low-level wells most closely resembles pump installation materials, as indicated in **Table 20**. However, the low-level, non-diagnostic response observed in groundwater samples could also be attributed to the presence of well installation materials or naturally occurring organic matter, which were not sampled for this study. The shading in **Table 20** provides further evaluation with respect to the possible influence of these potential source materials in groundwater samples.

The evaluation of the source of the chemical signatures observed in dissolved gas samples collected from water wells is also indicated by shading in **Table 22**. When using multiple lines of evidence, the source of dissolved gas can be identified even though the source of this gas could not be directly sampled. For example, the stable carbon isotope value and C_1/C_2+C_3 ratio in dissolved gas from LEL wells AN 11-10D, HWY 7, and RS 11-14 are similar to gas samples collected from natural gas production wells; however, the gas component ratios are clearly different and indicate the gas has been altered with respect to natural gas produced in the PAPA. Although the source of this altered thermogenic gas was not directly sampled for the study, an interpretation can be made based on the chemical signature of the gas, which is shown by shading in **Table 22**.

Table 23 presents a summary of the sources or likely sources of organic constituents detected in each of the water wells sampled for this study, which is based on the analysis of chemical signatures as displayed in **Tables 16** through **22**.

Chemical Matrix
Low-Level Petroleum Hydrocarbon Evaluation
Sublette County, Wyoming
Appendix H

Site Name[2]	Material Summary	RS 11-14	WB 7-4	WB 7-15D	BO 12A-33	WB 7-5	AN 1-9	CGF-3-C	Material Summary	AN 1-9 PDW	MS 14-16 PDW	RN 16-30 PW	RS 15-12 PW	SP 13-33 PDW	WB 7-15 PW	Material Summary	JEN 1A MUD	MS 12-16 MUD	RIV 4-10 MUD	Material Summary	MS3-27-FBF	MS3C-33D FBF	MSD2-21 FBF	RS 9-2 FBF	Pump Installation Materials Summary
Well/Sample Type[1]	natural gas from natural gas production wells							condensate	produced water							drill mud				flowback fluid					Pump Installation Materials Summary
Number of Samples[3]	6	1	1	1	1	1	1	1	6	1	1	1	1	1	1	3	1	1	1	4	1	1	1	1	17
Organics																									
Method 8015 Detections: TPgH								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○
TPH-GRO								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○
TEH								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○
TPH-DRO								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○
TEH after SGT																									
% TPH-GRO of TPgH: > 85									●	●	●	●	●	●	●										
50 to 85								●												○	●			●	○
25 to 50																				○			●		○
< 25																●	●	●	●	○		●			○
% TPH-DRO of TEH: > 85																●	●	●	●	○		●	●		
60 to 85									○						●					○				●	
~ 40 to 60									○	●	●	●		●	●					○	●				
< 40								●	○				●												●
VOC Detections (EPA Method 8260): Benzene								●	●	●	●	●	●	●	●					●	●	●	●	●	
Toluene								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Ethylbenzene								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Xylenes								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○
Methyl Ethyl Ketone																				○	●	●			
SVOC Detections[4] (EPA Method 8270): 2-4-Dimethylphenol									●	●	●	●	●	●	●					○	●			●	
Phenol									●	●	●	●	●	●	●					○	●			●	
1-Methylnaphthalene								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
2-Methylnaphthalene								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Naphthalene								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Fluorene									○		●	●	●		●										
m- & p-Cresols									●	●	●	●	●	●	●					○	●			●	
o-Cresol									●	●	●	●	●	●	●					○	●			●	
Phenanthrene									○		●		●		●	●	●	●	●						
Pyrene																○		●	●						
Follow-Up Analysis for TICs[5] (EPA Methods 8260 & 8270): n-Hexadecanoic acid																									
2-Ethyl-hexanoic acid																									
2-Ethyl-1-hexanol																									
Hexanal																									
Nonanal																									
Acetone																									
2-4-Dimethyl-3-pentanone																									
2-Methyl-1-pentene																									
1-Heptene																									
Adamantane																									
Chromatographic Profile[6]																									
GRO & DRO Chromatographic Profile Method 8015 – General: Diagnostic[7]								◘	□							■									■
Variable[8] / Non-Diagnostic[9]									■							□				◘					□
Specific Attributes: Narrow (Hump Present)																■	■	■	■			■			
Broad (Hump Absent)								◘	■	■	■	■	■	■	■								■	■	■
Symmetrical																■	■	■	■			■	■		■
Asymmetrical																									
Early Eluting Peaks (<C_5 gases)											□	□	□	□						□	□	□	□	□	
Distinct Individual Peak(s) (>C_5)									□	□	□	□	□	□	□					□	□	□	□	□	
Spiky								◘	■	■	■	■	■	■	■	■	■	■	■				■	■	
UCM																									■
Little to No Response																□	□	□	□		■				□
TIC Chemical Groups Represented																									
Tentatively Identified Compound (TIC) Groups (EPA Methods 8260 & 8270): Alkanes								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○
Branched Alkanes								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○
Alkynes																									
Cycloalkanes								●	●	●	●	●	●	●	●					○	●		●	●	
Alkylcycloalkanes								●	●	●	●	●	●	●	●	○	●		●	●	●	●	●	●	○
Cycloalkenes																				○			●	●	
Alkenes																				○	●			●	○
Branched Alkenes																				○			●		
Alkylbenzene								●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Indan/Indane/Indene Compounds																●	●	●	●						
Naphthalenes																○		●		○	●		●	●	
Decalins																○		●	●	○	●				○
Tetralins									○	●		●	●	●	●	●	●	●	●	○		●	●	●	
Terpenoids																									
Organic Acids																				○	●			●	
Alcohols									○		●									○	●		●		
Ketones									○	●		●		●						○	●		●		○
Aldehydes																									
Phenols																				○				●	
Silanes																									
Siloxanes																									○
Sulfur																									○
Total Number of Individual TICs								53	82	35	53	39	41	44	36	55	31	26	41	113	22	29	77	46	26
Inorganics																									
Detections of General Water Quality Parameters at Concentrations greater than 10x the Reporting Limit: Total Alkalinity as $CaCO_3$									●	●	●	●	●	●	●					●	●	●	●	●	
Total Alkalinity as HCO_3									●	●	●	●	●	●	●					●	●	●	●	●	
Total Alkalinity as CO_3																									
Chloride									♦	♦	♦	♦	♦	♦	♦					♦	♦	♦	♦	♦	
Sulfate																									
Fluoride									●	●	●	●	●	●	●					●	●	●	●	●	
Bromide									X	X	X	X	X	X	X					X	X	X	X	X	
Nitrate + Nitrite (as nitrogen)									○				●							○				●	
Ammonia (as nitrogen)									◊	♦	♦	♦		♦	♦					♦	♦	♦	♦	♦	
Phosphorus (total)									◊						♦					X	X	X	X	X	
Total Dissolved Solids									♦	♦	♦	♦	♦	♦	♦					♦	♦	♦	♦	♦	
Detections of Total Metals at Concentrations greater than 10x the Reporting Limit: Aluminum																♦	♦	♦	♦	○	●	●		●	
Antimony																									
Arsenic																				○	●				
Barium									♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	
Beryllium																									
Boron									X	X	X	X	X	X	X					◊	♦		♦	♦	
Cadmium																									
Calcium									♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	
Chromium																X	X	X	X	○		●		●	
Cobalt																				○		●			
Copper																X	X	X	X	○		●		●	
Iron									●	●	●	●	●	●	●	♦	♦	♦	♦	●	●	●	●	●	
Lead																				○		●			
Magnesium									○				●			♦	♦	♦	♦	●	●	●	●	●	
Manganese									●	●	●	●	●	●	●	♦	♦	♦	♦	●	●	●	●	●	
Mercury																									
Nickel																				○				●	
Potassium									♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	
Selenium																				○		●			
Silicon									○				●			●	●	●	●						
Silver																									
Sodium									♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	
Strontium									●	●	●	●	●	●	●	♦	♦	♦	♦	♦	♦	♦	♦	♦	
Thallium																									
Titanium																X	X	X	X	○	●				
Vanadium																X	X	X	X						
Range in Water Isotope Values																									
Dissolved Inorganic Carbon (^{13}C) (per mil): < -20																									
-20 to -10																									
-10 to 0									○	●		●	●	●											
> 0									○		●				●										
Hydrogen (^2H) (per mil): < -150																									
-100 to -150									○		●														
> -100									○	●		●	●	●	●										
Oxygen (^{18}O) (per mil): < -20																									
-20 to -10																									
-10 to 0									●	●	●	●	●	●	●										
Range in Methane Isotope Values																									
Hydrogen (^2H) (per mil): > ~ -200	●	●	●	●	●	●	●																		
-200 to -240																									
-240 to -275																									
< -275																									
Carbon (^{13}C) (per mil): < -64 microbial-type																									
-50 to -64 intermediate-type																									
> -50 thermogenic-type	●	●	●	●	●	●	●																		
Gas Composition																									
Detections of Hydrocarbon Gas Components: Methane	●	●	●	●	●	●	●																		
Ethane	●	●	●	●	●	●	●																		
Propane	●	●	●	●	●	●	●																		
n-Butane	●	●	●	●	●	●	●																		
Isobutane	●	●	●	●	●	●	●																		
n-Pentane	●	●	●	●	●	●	●																		
Isopentane	●	●	●	●	●	●	●																		
n-Hexane or Hexanes+	●	●	●	●	●	●	●																		
Benzene	●	●	●	●	●	●	●																		
Ethylbenzene	●	●	●	●	●	●	●																		
Toluene	●	●	●	●	●	●	●																		
Xylenes	○	●			●	●	●																		
Gas Component Ratios																									
Ratio of Methane to Ethane + Propane ($C_1/C_2 + C_3$): > 1,000 microbial type																									
~ 50-1,000 intermediate-type																									
< 50 thermogenic-type	●	●	●	●	●	●	●																		
Ratio of Isobutane to n-Butane[10] ($isoC_4/nC_4$): > 5.0 altered																									
1.3 to 5.0 slightly altered																									
~ 1.0 to 1.2 unaltered	●	●	●	●	●	●	●																		
Ratio of Isopentane to n-Pentane[10] ($isoC_5/nC_5$): > 5.0 altered																									
1.6 to 5.0 slightly altered																									
~ 1.0 to 1.5 unaltered	●	●	●	●	●	●	●																		

Site Name[2]	BO 1-32-1	Mesa 14-16-1	MS 12-28-1	MS 12-28-2	RS 11-14-Pump-2	RS 15-12-Pump	WB 16-5-Pump-2	WB 7-15-Pump	WB 7-5-1	WB 7-5-2	PD-Baseline	Mesa 15-16-1	WB 16-5-Pump	RS 1-4-Pump	BO 1-32-2	RS 11-14-Pump	MS 14-16-2	AN 1-16 PHC
Well/Sample Type[1]	pipe dope											pipe grease		pipe dope/ grease	black film		teflon tape	LNAPL
Number of Samples[3]	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
Organics																		
TPgH	●	●	●		●	●	●	●		●	●	●		●			●	●
TPH-GRO	●					●		●		●	●			●				●
TEH	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●
TPH-DRO	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	●
TEH after SGT																		
% TPH-GRO of TPgH: > 85																		
50 to 85								●		●	●							
25 to 50														●				
< 25	●					●												●
% TPH-DRO of TEH: > 85																		
60 to 85																		●
~ 40 to 60																		
< 40	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	
Benzene																		
Toluene																		
Ethylbenzene																		
Xylenes								●						●				
Methyl Ethyl Ketone																		
2-4-Dimethylphenol																		
Phenol																		
1-Methylnaphthalene																		
2-Methylnaphthalene																		
Naphthalene																		
Fluorene																		
m- & p-Cresols																		
o-Cresol																		
Phenanthrene																		
Pyrene																		
n-Hexadecanoic acid																		
2-Ethyl-hexanoic acid																		
2-Ethyl-1-hexanol																		
Hexanal																		
Nonanal																		
Acetone																		
2-4-Dimethyl-3-pentanone																		
2-Methyl-1-pentene																		
1-Heptene																		
Adamantane																		☼
Chromatographic Profile[6]																		
Diagnostic[7]																		■
Variable[8] / Non-Diagnostic[9]																		□
Narrow (Hump Present)																		
Broad (Hump Absent)	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■
Symmetrical	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	
Asymmetrical																		■
Early Eluting Peaks (<C_5 gases)																		
Distinct Individual Peak(s) (>C_5)			■		■			■	■	■	■							
Spiky																		
UCM	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■
Little to No Response	□	□	□	□	□	□	□	□	□	□	□	□	□	□	◘	◘	□	□
TIC Chemical Groups Represented																		
Alkanes	●					●			●					●				
Branched Alkanes	●					●												●
Alkynes																		
Cycloalkanes																		●
Alkylcycloalkanes	●					●												●
Cycloalkenes																		
Alkenes														●				
Branched Alkenes																		
Alkylbenzene																		
Indan/Indane/Indene Compounds																		
Naphthalenes																		
Decalins	●					●												●
Tetralins																		
Terpenoids																		●
Organic Acids																		
Alcohols																		
Ketones																	●	●
Aldehydes																		
Phenols																		
Silanes																		
Siloxanes								●			●							
Sulfur					●										●	●		
Total Number of Individual TICs	11	0	0	0	1	17	0	2	4	0	2	0	0	5	1	1	1	17

(No entries are printed in the pipe dope, pipe grease, pipe dope/grease, black film, teflon tape and LNAPL columns for the Inorganics, Range in Water Isotope Values, Range in Methane Isotope Values, Gas Composition and Gas Component Ratios rows.)

Site Name[2]	AN 15-23	BO 1-32	MS 15-16	RB 13-29	RS 2-24	SP 11-34	AN 11-10D	AN 1-16	BO 12A-33	HWY 7	RS 11-14	WB 7-4	WB 7-5	HWY 11	MS 12-28	MS 14-16	RB 16-30	RS 11-25	RS 1-4	RS 15-12	SP 11-33	SP 5-20	WB 16-5	WB 7-15D	WB 8-6
Well/Sample Type[1]	Control						LEL							PHC											
Number of Samples[3]	1	1	1	1	1	1	1	1	2	1	2	1	2	1	2	2	1	2	2	2	1	2	1	1	2
Organics																									
TPgH							●	●		●	●		●		●		●	●		●		●		●	●
TPH-GRO							●	●		●							●	●						●	
TEH	●	●	●	●		●		●	●	●		●	●	●	●	●	●	●	●	●	●	●		●	●
TPH-DRO	●		●	●				●					●		●	●	●	●	●	●				●	●
TEH after SGT																									
% TPH-GRO of TPgH: > 85																								●	
50 to 85							●																		
25 to 50								●		●															
< 25																	●	●							
% TPH-DRO of TEH: > 85																		●		●					
60 to 85	●							●					●		●		●								●
~ 40 to 60				●												●			●						
< 40			●																						
Benzene																								●	
Toluene								●	●							●	●	●	●					●	
Ethylbenzene																		●						●	
Xylenes																		●						●	
Methyl Ethyl Ketone																									
2-4-Dimethylphenol																									
Phenol																									
1-Methylnaphthalene																		●							
2-Methylnaphthalene																		●							
Naphthalene																									
Fluorene																									
m- & p-Cresols																									
o-Cresol																									
Phenanthrene																									
Pyrene																									
n-Hexadecanoic acid																			●						
2-Ethyl-hexanoic acid																									
2-Ethyl-1-hexanol									●						●										●
Hexanal																									
Nonanal																						●			
Acetone																									
2-4-Dimethyl-3-pentanone																									
2-Methyl-1-pentene																									
1-Heptene																									
Adamantane																									
Chromatographic Profile[6]																									
Diagnostic[7]							□	□		□	□							■		■				□	
Variable[8] / Non-Diagnostic[9]	◘	◘	◘	◘	◘	◘	■	■	◘	■	■	◘	◘	◘	◘	◘	◘	□	◘	□	◘	◘	◘	■	◘
Narrow (Hump Present)																		■		■					
Broad (Hump Absent)								■																	
Symmetrical																		■		■					
Asymmetrical								■																	
Early Eluting Peaks (<C_5 gases)							□	□		□	□						□							□	
Distinct Individual Peak(s) (>C_5)									■						■		■	□	◘			□		□	■
Spiky																		■		■					
UCM	■		■	■				■					■			■			■						■
Little to No Response	□	◘	□	□	◘	◘	■		□	■	■	◘	□	◘	□	□				□	◘	■	◘	■	□
TIC Chemical Groups Represented																									
Alkanes							●	●	●	●	●	●	●					●		●				●	
Branched Alkanes							●	●	●	●	●	●	●					●		●				●	
Alkynes																	●								
Cycloalkanes							●	●		●			●				●							●	
Alkylcycloalkanes							●	●		●	●	●	●				●	●						●	
Cycloalkenes																	●								
Alkenes																	●								
Branched Alkenes																	●			●					
Alkylbenzene																		●		●					
Indan/Indane/Indene Compounds																		●		●					
Naphthalenes																		●							
Decalins																									
Tetralins																		●							
Terpenoids																									
Organic Acids																			●						
Alcohols									●		●				●		●								●
Ketones																●			●						
Aldehydes													●		●	●	●					●			
Phenols																									
Silanes													●							●					●
Siloxanes																									
Sulfur	●	●		●			●	●		●	●	●					●	●	●						●
Total Number of Individual TICs	1	1	0	1	0	0	11	13	3	14	13	7	13	0	2	2	24	54	4	27	0	2	0	21	3
Inorganics																									
Total Alkalinity as $CaCO_3$	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Total Alkalinity as HCO_3	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Total Alkalinity as CO_3							●	●		●													●	●	
Chloride	●	●		●	●		●	●	●	●		●	●	●		●	●	●					●		●
Sulfate	●	●		●		●	●				●			●	●	●	●		●		●	●	●		
Fluoride	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Bromide																									
Nitrate + Nitrite (as nitrogen)																									
Ammonia (as nitrogen)																									
Phosphorus (total)		●										●				●			●						
Total Dissolved Solids	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Aluminum				●		●										●			●						
Antimony																									
Arsenic																									
Barium				●																					
Beryllium																									
Boron																									
Cadmium																									
Calcium		●														●									
Chromium																									
Cobalt																									
Copper							●												●						
Iron	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Lead																									
Magnesium																									
Manganese			●	●		●	●		●	●					●	●	●		●		●		●		●
Mercury																									
Nickel							●																		
Potassium																									
Selenium																									
Silicon	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Silver																									
Sodium	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Strontium																									
Thallium																									
Titanium																									
Vanadium																									
Range in Water Isotope Values																									
DIC (^{13}C): < -20												●													
-20 to -10	●	●	●	●	●	●	●							●	●	●	●			●	●	●	●	●	
-10 to 0									●		●		●					●	●						●
> 0								●		●															
Hydrogen (^2H): < -150	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
-100 to -150		●																							
> -100																									
Oxygen (^{18}O): < -20			●		●	●					●				●	●			●	●	●	●			
-20 to -10	●	●		●			●	●	●	●		●	●	●			●	●					●	●	●
-10 to 0																									
Range in Methane Isotope Values																									
Hydrogen (^2H): > ~ -200																									
-200 to -240							●	●		●	●													●	
-240 to -275									●			●	●										●		
< -275					●													●							●
Carbon (^{13}C): < -64 microbial-type					●													●							
-50 to -64 intermediate-type									●			●	●										●		●
> -50 thermogenic-type							●	●		●	●													●	
Gas Composition																									
Methane	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Ethane				●	●		●	●	●	●	●	●	●		●		●	●					●	●	●
Propane							●	●	●	●	●	●	●				●	●						●	
n-Butane							●	●	●			●	●											●	
Isobutane							●	●	●	●	●	●	●				●							●	
n-Pentane							●	●				●	●											●	
Isopentane							●	●		●		●	●				●							●	
n-Hexane or Hexanes+							●	●		●	●	●	●				●	●						●	
Benzene																									
Ethylbenzene																									
Toluene																									
Xylenes																									
Gas Component Ratios																									
$C_1/C_2 + C_3$: > 1,000 microbial type					●													●					●		●
~ 50-1,000 intermediate-type				●					●			●	●		●										
< 50 thermogenic-type							●	●		●	●						●							●	
$isoC_4/nC_4$: > 5.0 altered							●	●		*	*						*								
1.3 to 5.0 slightly altered									●			●	●												
~ 1.0 to 1.2 unaltered																								●	
$isoC_5/nC_5$: > 5.0 altered							●	●		*	*						*								
1.6 to 5.0 slightly altered												●	●											●	
~ 1.0 to 1.5 unaltered																									

Site Name[2]	T-1-SW	T-1-RW	T-2-RW	T-3-SW	T-3-RW	T-4-SW	T-4-RWa	T-4-RWb	T-5-RW	X-1-A	X-1-SW	X-2-A	X-2-SW	X-3-A	X-3-SW	X-4a-A	X-4-SW	X-4-RW	X-5-A	X-5-SW	T-6-SW	T-6-RW	T-7-SW	T-7-RW	T-8-A	T-8-SW	T-9-RW
Well/Sample Type[1]	SAP Study Well									HDG Study Well																	
Number of Samples[3]	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Organics																											
TPgH				●	●		●	●																			
TPH-GRO				●	●		●	●																			
TEH	●	●	●	●	●	●	●	●	●		●		●		●				●			●		●	●		●
TPH-DRO		●				●	●	●	●						●										●		●
TEH after SGT		●	●		●			●	●						●										●		●
% TPH-GRO of TPgH: > 85					●																						
50 to 85				●				●																			
25 to 50							●																				
< 25																											
% TPH-DRO of TEH: > 85									●						●												●
60 to 85							●																		●		
~ 40 to 60		●				●		●																			
< 40																											
Benzene				●	●																						
Toluene			●	●	●																						
Ethylbenzene					●																						
Xylenes				●	●																						
Methyl Ethyl Ketone																											
2-4-Dimethylphenol																											
Phenol																											
1-Methylnaphthalene																											
2-Methylnaphthalene																											
Naphthalene																											
Fluorene																											
m- & p-Cresols																											
o-Cresol																											
Phenanthrene																											
Pyrene																											
n-Hexadecanoic acid																											
2-Ethyl-hexanoic acid																											
2-Ethyl-1-hexanol																											
Hexanal																											
Nonanal																											
Acetone																											
2-4-Dimethyl-3-pentanone																											
2-Methyl-1-pentene																											
1-Heptene							●																				
Adamantane							●																				
Chromatographic Profile[6]																											
Diagnostic[7]				□	□		□	□	■						■										■		■
Variable[8] / Non-Diagnostic[9]	◘	◘	◘	■	■	◘	■	■	□	◘	◘	◘	◘	◘	□	◘	◘	◘	◘	◘	◘	◘	◘	◘	□	◘	□
Narrow (Hump Present)									■						■										■		■
Broad (Hump Absent)								■																			
Symmetrical									■						■										■		■
Asymmetrical		■						■																			
Early Eluting Peaks (<C_5 gases)				□	□		□	□																			
Distinct Individual Peak(s) (>C_5)			□	□	□																						
Spiky																											
UCM		■						■	■						■							■			■		■
Little to No Response	◘	□	■	■	■	◘	■		□	◘	◘	◘	◘	◘	□	◘	◘	◘	◘	◘	◘	□	◘	◘	□	◘	□
TIC Chemical Groups Represented																											
Alkanes		●		●	●		●	●																			
Branched Alkanes				●	●		●	●																			
Alkynes																											
Cycloalkanes				●	●		●	●																			
Alkylcycloalkanes				●	●		●	●																			
Cycloalkenes																											
Alkenes																											
Branched Alkenes							●																				
Alkylbenzene				●			●	●																			
Indan/Indane/Indene Compounds					●																						
Naphthalenes																											
Decalins																											
Tetralins																											
Terpenoids							●	●																			
Organic Acids																											
Alcohols																											
Ketones																											
Aldehydes																											
Phenols																											
Silanes																											
Siloxanes																											
Sulfur		●																									
Total Number of Individual TICs	0	5	0	17	19	0	15	12	0																		
Inorganics																											
Total Alkalinity as $CaCO_3$	●	●	●	●	●	●	●	●	●																		
Total Alkalinity as HCO_3	●	●	●	●	●	●	●	●	●																		
Total Alkalinity as CO_3			●				●	●	●																		
Chloride			●		●	●	●	●	●																		
Sulfate	●	●	●			●																					
Fluoride			●	●	●		●	●	●																		
Bromide																											
Nitrate + Nitrite (as nitrogen)																											
Ammonia (as nitrogen)																											
Phosphorus (total)		●	●	●	●		●	●	●																		
Total Dissolved Solids	●	●	●	●	●	●	●	●	●																		
Aluminum		●	●	●	●		●	●	●																		
Antimony																											
Arsenic																											
Barium																											
Beryllium																											
Boron																											
Cadmium																											
Calcium	●					●																					
Chromium																											
Cobalt																											
Copper																											
Iron		●	●	●	●		●	●	●																		
Lead																											
Magnesium	●																										
Manganese	●	●	●		●		●	●	●																		
Mercury																											
Nickel																											
Potassium																											
Selenium																											
Silicon	●	●	●	●	●	●	●	●	●																		
Silver																											
Sodium	●	●	●	●	●	●	●	●	●																		
Strontium																											
Thallium																											
Titanium			●		●		●	●	●																		
Vanadium																											
Range in Water Isotope Values																											
DIC (^{13}C): < -20																											
-20 to -10	●	●	●	●	●	●		●	●																		
-10 to 0							●																				
> 0																											
Hydrogen (^2H): < -150	●	●	●	●	●	●		●	●																		
-100 to -150							●																				
> -100																											
Oxygen (^{18}O): < -20		●	●																								
-20 to -10	●			●	●	●	●	●	●																		
-10 to 0																											
Range in Methane Isotope Values																											
Hydrogen (^2H): > ~ -200				●	●																						
-200 to -240							●	●																			
-240 to -275																											
< -275									●																		
Carbon (^{13}C): < -64 microbial-type									●																		
-50 to -64 intermediate-type																											
> -50 thermogenic-type				●	●		●	●																			
Gas Composition																											
Methane	●	●	●	●	●		●	●	●																		
Ethane				●	●	●	●	●	●																		
Propane				●	●		●	●																			
n-Butane				●	●		●	●																			
Isobutane				●	●		●	●																			
n-Pentane				●	●		●	●																			
Isopentane				●	●		●	●																			
n-Hexane or Hexanes+				●	●		●	●																			
Benzene																											
Ethylbenzene																											
Toluene																											
Xylenes																											
Gas Component Ratios																											
$C_1/C_2 + C_3$: > 1,000 microbial type									●																		
~ 50-1,000 intermediate-type																											
< 50 thermogenic-type				●	●	●	●	●																			
$isoC_4/nC_4$: > 5.0 altered							●	●																			
1.3 to 5.0 slightly altered																											
~ 1.0 to 1.2 unaltered				●	●																						
$isoC_5/nC_5$: > 5.0 altered							●	●																			
1.6 to 5.0 slightly altered				●	●																						
~ 1.0 to 1.5 unaltered																											

Notes:
1 - Control = well with no history of detectable petroleum hydrocarbons; LEL = well with history of detectable combustible gas in well casing; PHC = well with history of petroleum hydrocarbon detections; SAP Study Well = study well sampled for this study; HDG Study Well = study well sampled for hydrogeological data gaps investigation.
2 - AN = Antelope; RB & RN = Rainbow; BO = Boulder; RS & RIV = Riverside; MS = Mesa; SP = Stewart Point; T and X = Study Well; HWY = Highway; WB = Warbonnet; JEN = Jensen; CGF = Central Gathering Facility.
Samples were analyzed for constituent groups shown using methods specified in Table 2.
3 - Two groundwater samples were collected from water wells, RS 15-12 and RS 11-25, in 2010. One sample was collected from the middle of the perforated interval; one sample was collected from the top of the water column. The remaining wells with two samples indicated had one sample collected in 2010 (full suite of analytes) and one sample collected in 2012 (follow-up sample for select analytes).
4 - Phthalate detections not included because cross-contamination is likely source.
5 - Tentatively identified compounds (TICs) reported in initial samples that were calibrated for and quantified upon follow-up sampling.
6 - Appearance of chromatographic profiles in GRO chromatogram primarily in gasoline range organics (2-methylpentane to 1,2,4-trimethylbenzene) and in DRO chromatogram primarily in diesel range organics (C_{10} to C_{28}).
UCM = unresolved complex mixture.
7 - Diagnostic: resembles a profile of a potential source material sampled or standard reference chromatogram.
8 - Variable: a profile that is not consistent between samples of a potential source material. Not applicable to condensate and LNAPL (only one sample).
9 - Non-diagnostic: does not resemble a profile of a potential source material sampled or a standard reference chromatogram. Response does not definitively point to source.
10 - Unaltered ratios are gas component ratios observed in natural gas samples collected from natural gas production wells. Gas component ratios that are generally above 1.3 to 1.5 indicate that gas that has been altered or slightly altered by depletion of n-alkane(s) with respect to isoalkane(s).

Symbols and Shading:
Note: *Detected* in this matrix means analyte was detected at concentration at or above practical quantitation limit (PQL), also referred to as laboratory reporting limit.
(white) Blank entry indicates parameter not detected or not detected within range specified.
(grey) Parameter not analyzed for this study, or percentage or component ratio could not be calculated.
☼ TIC was reported in the potential source material and quantified in a groundwater sample.
(orange) Well with high-level detections of organic constituents in this study.

- ● Parameter detected or detected within range specified. For the material summaries, this parameter or range was consistently detected among samples.
- ○ Parameter not consistently detected or not consistently detected within specified range among samples.
- ♦ General water quality parameter or metal detected at concentration elevated with respect to typical groundwater.
- ◊ For material summaries, general water quality parameter or metal not consistently detected at concentration elevated with respect to typical groundwater.
- X Parameter has been identified as a potential indicator because its concentration is elevated with respect to typical groundwater; however, parameter concentration in the sample was not greater than 10x the reporting limit.
- ◘ Characteristic of both GRO and DRO chromatograms.
- ■ Characteristic of DRO chromatogram only.
- □ Characteristic of GRO chromatogram only.
- * Gas component ratio could not be calculated because isoalkane(s) were detected but n-alkane(s) were not detected. This complete depletion of n-alkane with respect to isoalkane indicates alteration of gas.