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Gas and Isotope Chemistry of Thermal Features in Yellowstone National Park, Wyoming

U.S. Department of the Interior
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By Deborah Bergfeld, Jacob B. Lowenstern, Andrew G. Hunt, W.C. Pat Shanks III, and William C. Evans

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
Volume		
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
Mass		
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32

Vertical coordinate information is referenced to the North American datum of 1983 (NAD 83).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

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Abstract

This report presents 167 gas analyses and 59 related water analyses on samples collected from thermal features at Yellowstone between 2003 and 2012. An overview of previous studies of gas emissions at Yellowstone is also given. The analytical results from the present study include bulk chemistry of gases and waters and isotope values for water and steam ($\delta^{18}O$, δD), carbon dioxide ($\delta^{13}C$ only), methane ($\delta^{13}C$ only), helium, neon, and argon. We include appendixes containing photos of sample sites, geographic information system (GIS) files including shape and kml formats, and analytical results in spreadsheets. In addition, we provide a lengthy discussion of previous work on gas chemistry at Yellowstone and a general discussion of the implications of our results. We demonstrate that gases collected from different thermal areas often have distinct chemical signatures, and that differences across the thermal areas are not a simple function of surface temperatures or the type of feature. Instead, gas chemistry and isotopic composition are linked to subsurface lithologies and varying contributions from magmatic, crustal, and meteoric sources.

Introduction

Yellowstone National Park hosts an active hydrothermal system with more than 10,000 individual thermal springs, pools, and fumaroles (Fournier, 1989). These thermal features exist because of heat generated by intrusion and crystallization of magma beneath the Yellowstone Caldera and its surroundings coincident to an abundant water supply (Lowenstern and Hurwitz, 2008). The heat that is transferred upwards into voluminous groundwater reservoirs produces hydrothermal fluids that may boil on ascent, feeding surface hot springs and fumaroles. Gases in hot springs and fumaroles are sufficient in volume and flux that significant magmatic input is required, at least for the carbon dioxide (Werner and Brantley, 2003; Lowenstern and Hurwitz, 2008). The different gas species have a variety of potential sources in addition to magma (see, for example, Giggenbach and Poreda, 1993; Minissale and others, 1997; Lowenstern and Janik, 2003), including descending meteoric waters, as well as reactions with volcanic and nonvolcanic wallrocks and organic

material. The water and gas chemistry is also affected by high-temperature interaction with silicate rocks (Giggenbach, 1984; Hurwitz and others, 2010) and by biological activity at the surface, including respiration by thermophilic organisms that reside within and around the thermal features (see, for example, Nordstrom and others, 2006; Shock and others, 2010). The chemistry of gas emanations provides important clues about the history and ongoing process of magma degassing, metamorphism, water-rock interaction, hydrothermal reservoir conditions, and biological activity.

This report presents a database of gas and isotope chemistry for 167 samples collected from fumaroles, pools, and "frying pans" from areas within and around Yellowstone National Park. Some of the 167 analyses represent replicate samples collected back-to-back in different bottles on the same day, and others are samples collected from the same location in different years. All of the samples were collected in August or September from 2003 to 2012. This report focuses on gas-phase samples because they provide information on the underlying magmatic system and various crustal rocks. Dissolved gas concentrations, by contrast, are more likely to reflect solubility constraints at near-surface conditions, rather than conditions established deep in the system. Following a discussion of previous work, we present a brief discussion of the general geochemistry of the collected gases. We also provide sufficient metadata (locations, photographs, and temperatures) to aid with interpretation of the chemical characteristics of the gases. Finally, we consider the systematic variations in gas concentrations and ratios and their significance for understanding the gas sources. Future publications will further develop interpretations and will discuss the implications for magmatism, crustal metamorphism, and hydrothermal processes.

Background and Previous Work

Early Work

Early trappers and explorers in the Yellowstone region recognized sulfurous odors and brimstone (sulfur-bearing) deposits, plus the "soda gas" (CO_2) emerging at Mammoth Hot Springs (fig. 1). Indeed, C.L. Heizmann, the chemist for

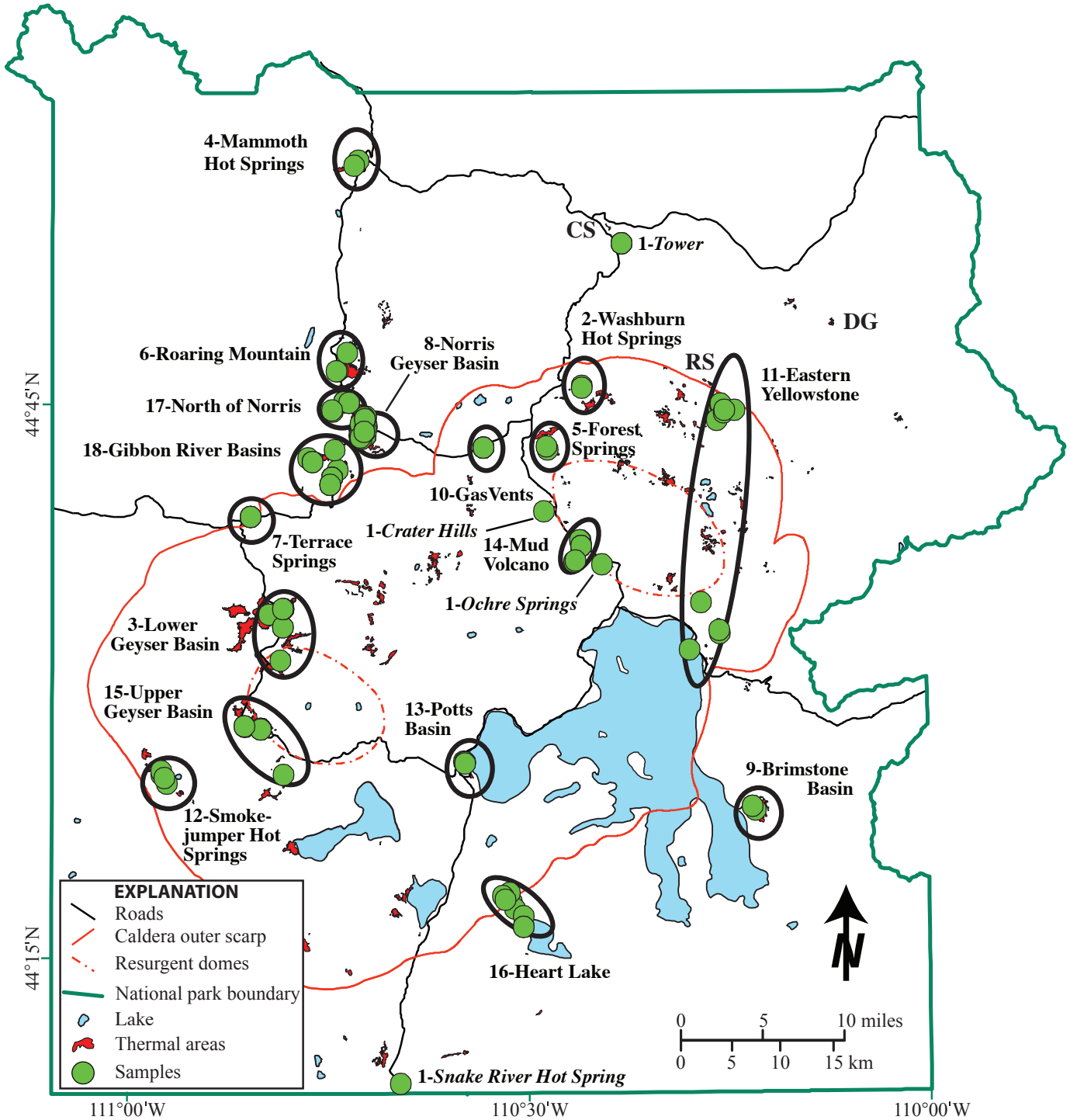**Figure 1.** Map showing sample locations (green dots) within this database and other locations mentioned in the text. Sample groups 2–18 are circled by bold black lines and are labeled with the group name and group number as listed in table 1. Sample group 1 contains miscellaneous samples located in four areas that are shown in italicized text. CS=Calcite Spring, DG=Death Gulch, RS=Rainbow Springs.

the 1873 Jones Expedition was able to confirm the presence of both sulfur and carbonic gases (Jones, 1875). Gooch and Whitfield (1888) published a remarkable set of analyses of thermal waters, but they made no attempt to analyze gas bubbles emerging from the waters or nearby soils. Weed (1889) described gas vents along Cache Creek, dubbing the area "Death Gulch" (fig. 1) for the dead animals (including six deceased bears) that were found at the time to have succumbed to the effects of noxious gas. Jaggar (1899) later revisited and documented the gas vents of "Death Gulch," and Traphagen (1904) analyzed the gases, finding lethal amounts of both CO_2 and H_2S within cracks and near ground level.

In his paper "Origin of the Thermal Waters in the Yellowstone National Park," Hague (1911) reported gas analyses by F.C. Phillips of Pittsburgh, Pennsylvania. Most samples appear to have been contaminated by significant amounts of air, but many were dominated by CO_2 and some contained H_2S and CH_4. Hague (1911) argued that the thermal waters of Yellowstone were meteoric in origin and had descended a sufficient distance to acquire heat and solutes before ascending back to the surface. The waters were believed to be acidic at depth and subsequently neutralized through degassing of H_2S and CO_2.

It was not until the monumental work of Allen and Day (1935) that a detailed study of gases from Yellowstone National Park was completed. Their 525-page treatise presented detailed summaries of most of Yellowstone's thermal areas, including water chemistry, flow rates, and heat discharge. Many of their measurements, especially with respect to spring and stream discharge, have not been redetermined in the subsequent 75 years. With respect to gas chemistry, Allen and Day (1935) provided analyses for most of the major species from 40 locations and showed that CO_2 dominated other gases, CO was essentially absent, and H_2S was the next most abundant gas after steam and CO_2. They recognized that little water flowed from the acid terrains, whereas considerable water flow could be found in the alkaline, Cl-rich thermal areas. They also noted more abundant gas associated with the acid waters; they were able to collect 1 liter of gas in about 6 minutes from acid waters, whereas it could take more than ten times that long to collect the same volume of gas from alkaline waters (Allen and Day, 1935, p. 90). Finally, Allen and Day (1935) noted that gases from alkaline waters were much richer in N_2 and other air-sourced gases. Their thinking was fundamentally different from that of Hague (1911), because they hypothesized that magmatic gas rose straight to the surface and was composed of superheated steam and CO_2 with minor amounts of H_2, CH_4, N_2, Ar, and H_2S. They thus believed that fumaroles, or steam vents, were features that discharged gases from depth. Alkaline waters issued in topographically low areas where groundwater was most abundant and could minimize the mass of rising acid gas. Higher areas with deeper groundwater were overwhelmed by fumarolic emanations, resulting in acid waters and acid-altered terrains. This model represented a great departure from that of Hague (1911), who envisioned that both acid and alkaline

waters were ultimately meteoric in origin, with alkaline waters as degassed or reacted equivalents of acid waters.

Conceptual Models of the Yellowstone Geothermal System

White (1957) provided a new conceptual view that differed from those of previous workers and could be applied to a variety of Yellowstone's acid sulfate regions (his terminology) located close to areas bearing alkaline waters. He believed the acid sulfate waters (those acid waters high in sulfate but low in chloride) represented the steam boiled off alkaline waters. Condensation of the steam and shallow oxidation of H_2S (the latter also discussed by Allen and Day, 1935) created hot, acid-altered terrain. This theme was later expanded upon in White and others (1971), using abundant data from Yellowstone, including lessons learned from scientific drilling in Yellowstone during the late 1960s (White and others, 1975). Truesdell and Fournier (1976) and Fournier (1989) focused their efforts mainly on the neutral chloride fluids, finding evidence that most of the waters in and near the Yellowstone Caldera could be derived from a single parent fluid at 340°C and with ~400 mg/l Cl⁻. Waters boiled off this fluid would rise in acid sulfate regions. Divergent mixing, cooling, and boiling paths would result in the diversity of neutral to alkaline waters in the geyser basins.

Morgan and others (2003) and Morgan and Shanks (2005) suggested that lava flows exert a fundamental control on the locations of thermal basins through lateral flow of deep-seated waters in basal breccias, resulting in venting at edges of lava flows in drainage basins. Hurwitz and others (2007, 2010) noted the pronounced differences in river chemistries around the caldera, attributing the variability to significant (shallow) lateral migration of originally deep Cl-rich geothermal fluids that emerge at the surface primarily at low elevations along the Firehole, Gibbon, and Snake rivers, near Heart Lake, and at West Thumb. The acid-sulfate terrains, mostly concentrated in the eastern part of the caldera, reflect areas of deep boiling and gas discharge (Fournier, 1989). Nordstrom and others (2006, 2009) discussed the detailed geochemistry of H_2S oxidation in acid sulfate systems, the formation of abiogenic sulfur mounds, and oxidation and reduction reactions, some biotic, that form sulfuric acid, thiosulfate, polythionate, and sulfate. Nordstrom and others (2009) classified acid sulfate waters as "MG," reflecting their inferred origin as meteoric (M) waters fluxed with hot gas (G).

Gas Isotope Signatures and Fluid Origins

With the development of tools in nuclear isotope geochemistry following World War II, many researchers began to apply isotopic analyses to understanding the origins of the geothermal waters and gases of Yellowstone. Craig (1953) looked at the isotopes of carbon from numerous gases, carbonates, organic materials, and other sources in an overview of the systematics of carbon at Yellowstone. The $\delta^{13}C$ value of

CO_2 in Yellowstone gases averaged –2.8 per mil, which was similar to values from limestone but greater than that seen in igneous rocks (at that time thought to be < –20 per mil), causing him to conclude that the gases were likely sourced primarily from limestone. Later work on hydrogen and oxygen isotopes (Craig and others, 1956) showed that water and steam from Yellowstone were almost entirely of meteoric origin. Gas ratios determined by Mazor and Wasserburg (1965) and later by Gunter and Musgrave (1966) also pointed to a clear meteoric origin of the waters, because noble gas ratios displayed atmospheric values. Excess He was attributed to radioactive decay of crustal materials. Later studies on gases from geothermal drillholes in Yellowstone confirmed the presence of radiogenic He and Ar, but no evidence was found for crustal or magmatic sources of H_2O (Mazor and Fournier, 1973).

Craig and others (1978) were the first to document high $^3He/^4He$ ratios in Yellowstone gases, finding R/R_a values (the $^3He/^4He$ ratio of the sample relative to that of air) as high as 15 and attributing this to the hotspot setting. They also remarked that in some areas (for example, Mud Volcano) there was minimal influence of continental crust on the mantle-derived He isotope signatures. Further evidence for a diversity of gas sources came from subsequent studies of noble gases. Kennedy and others (1985, 1987) undertook a detailed study of the noble gas isotope systematics, and they found evidence for three primary end members—atmospheric, crustal and magmatic, the latter best exemplified by gases from Mud Volcano. The crustal endmember had $^{40*}Ar/^{4*}He$ of 0.245 (the * denoting radiogenic origin), consistent with a K/U source ratio of about 14,000 (Kennedy and others, 1985). Results from Werner and others (2008) extended the K/U ratio to a value as low as 2,000 for gas from the Hot Spring Basin region, consistent with derivation from limestone or quartz-rich sedimentary rocks.

More local studies undertaken on the Lower Geyser Basin (Kennedy and others, 1987) and in Shoshone Geyser Basin (Hearn and others, 1990) found that R/R_a values were correlated with bicarbonate concentrations in spring waters. Both groups concluded that degassing of the waters lowered their He (and bicarbonate) concentrations, allowing greater influence of mixing with crustal (radiogenic) He (see also Fournier and others, 1994). The most magmatic He-isotope signatures were retained by samples that cooled without considerable boiling during upflow. Evans and others (2006) undertook a detailed study of the chemistry of waters and gases from springs northeast of the Yellowstone Caldera, searching for evidence of an inferred CO_2-rich gas body thought to be located between Norris Junction and Hebgen Lake (Husen and others, 2004). The low flux of dead (old) carbon and low R/R_a provided little evidence for the accumulation of magmatic or metamorphic gas in that region.

Hydrocarbon Gases

Other workers have focused on the origin of organic gases such as methane (CH_4) and higher hydrocarbons. Such gases at Yellowstone are especially abundant in eastern areas of the park, including those known to produce small seeps of liquid petroleum (Love and Good, 1970). Des Marais and others (1981) demonstrated convincingly that the decomposition of sediments containing organic material was responsible for generating methane. They noted that the ratio of methane to higher hydrocarbons was far lower than would be predicted by full equilibration of C-O-H gases under geothermal conditions and were consistent with disequilibrium breakdown of organic matter in wallrocks. Clifton and others (1990) studied "hydrothermal" petroleum and inferred Eocene mudstone sources for Rainbow Springs (fig. 1), whereas petroleum found at Calcite Spring was inferred to be derived from the Permian Phosphoria Formation and recent sediments filling the valley of the Yellowstone River. Lorenson and others (1991) published hydrocarbon gas and isotopic analyses from these and a variety of other springs and seeps throughout the park.

Gas Chemistry

After Allen and Day (1935), few subsequent studies have reported complete analyses of gas compositions. Hearn and others (1990) published nine full analyses of gases from hot springs and fumaroles sampled at Shoshone Geyser Basin in 1982 and 1986. Sheppard and others (1992), using results from sites sampled between 1974 and 1986, demonstrated that gases obtained from large pools were unlikely to yield reliable results because of differential gas solubility in the near-surface water. They concluded that most Yellowstone gases represent a mixture of gas derived from air-saturated meteoric water with gas containing a He-rich crustal endmember, consistent with the findings of Kennedy and others (1985). Werner (2002) and Werner and Brantley (2003) provided 15 full analyses of gases from Yellowstone in conjunction with calderawide estimates of CO_2 flux. Goff and Janik (2002) compared nine of these samples and three others from Yellowstone with those from the Valles and Long Valley calderas and concluded that at Yellowstone, gas was derived from air-saturated meteoric water and a He-rich endmember that could originate from either mantle or crustal materials. Relative CH_4 abundances were higher than in gases from the Valles and Long Valley calderas. Werner and others (2008) demonstrated that Hot Spring Basin gases were relatively rich in rock-derived crustal components such as He, CH_4, and H_2.

Objectives

Three different types of features—fumaroles, "frying pans," and thermal pools (fig. 2)—were sampled to provide a comprehensive overview of gas geochemistry in Yellowstone National Park and to provide information on the gas geochemistry of the hydrothermal and magmatic systems. We sought fumarole samples (steam and gas vented through cracks or holes in the ground) whenever possible, because they provide the best samples of deep-seated gases. Fumaroles only exist where the temperature of the thermal feature equals
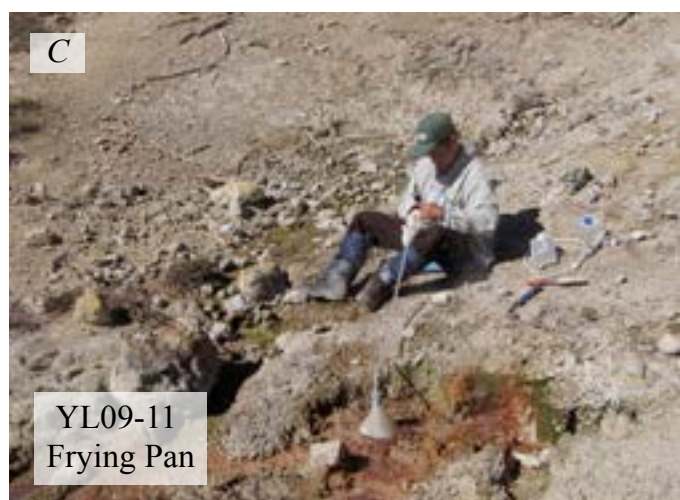
Figure 2. Photos showing examples of sampled thermal features represented in this gas geochemistry database. *A*, Fumaroles are features where steam/gas emerges from dry ground or through a crack. *B*, Pools and springs are features where water issues from the ground (with associated gas bubbles) or where gas rises through standing water. *C*, "Frying pans" are areas of sizzling ground with abundant steam/gas discharge and small amounts of liquid water.

or exceeds that of the local boiling point of water. In thermal areas where the subsurface is water saturated, one often finds a terrain of "frying pans" (sizzling ground), features whose temperatures are close to the boiling point. In locations where there were no fumaroles (or locations where an existing fumarole could not be sampled) frying pans provided the next-best sampling point. Some areas lack fumaroles and frying pans and instead have pools, where gas bubbles emerge from the surface of liquid water. Though some pools are connected to flowing springs, other pools lack outlet channels and consist of stagnant or convecting water. Gases rising through such pools and through frying pans cannot be attributed simply to boiling of the water in the pools but must come from depth.

Locations for gas samples are shown in figure 1, a map of Yellowstone National Park with dots for individual samples and showing sample groups as defined in table 1 and keyed to the remainder of the tables and figures in the manuscript. For the purpose of this report, water types of specific thermal areas are defined as follows: (1) acid sulfate waters are waters with pH < 5 and sulfate as the primary anion, (2) neutral Cl waters have pH > 5 and Cl as the primary anion, and (3) Na and Ca carbonate waters have carbonate as the dominant anion, with either Na or Ca as the primary cation. Thermal areas with more than one water type are denoted as "various" in table 1. Other papers (for example, Fournier, 1989; Nordstrom and others, 2009) provide more detailed descriptions of water chemistry. Photographs and summary tables for each gas sample are provided in appendix 1. Appendixes 2 and 3 contain KML and shape files to be used with Google Earth and ArcGIS software programs, respectively.

Methods

Sampling

Gas, water, and steam-condensate samples were collected and analyzed using standard field and laboratory methods. Sampling sites at locations with multiple features were selected on the basis of comparison of vent temperatures and the strength of gas outflow. At all locations, temperatures were measured using a K-type thermocouple and digital thermometer. At warm and cold springs, pH was measured using a calibrated meter, and indicator strips were used at hot springs and pools.

Bulk gas composition was determined following methods outlined in Fahlquist and Janik (1992). Fumarole samples were collected via a titanium tube, whereas a funnel fitted with flexible tubing was used to collect gas from frying pans and pools (fig. 2). Silicone tubing was used to connect the funnel or titanium tube to the sample bottle for all samples before the 2005 field season. Tygon tubing was used for some samples in 2005, and in all subsequent years. At fumaroles, a separate aliquot of condensed steam was often collected into glass bottles for stable-isotope analysis. The steam was condensed by adding a length of Tygon tubing to the sampling

Table 1.   Details concerning sample groupings and water types as discussed in the text.

Group	Group Name	No. Samples	Water Type
1	Miscellaneous	8	Various
2	Washburn Hot Springs	2	Acid Sulfate
3	Lower Geyser Basin	6	Neutral Cl
4	Mammoth Hot Springs	2	Ca Carbonate
5	Forest Springs	2	Acid Sulfate
6	Roaring Mtn/Amphitheater Springs	5	Acid Sulfate
7	Terrace Springs	3	Na Carbonate
8	Norris Geyser Basin	35	Various
9	Brimstone Basin	3	Acid Sulfate
10	Gas Vents, Norris-Canyon Road	4	Acid Sulfate
11	Eastern Yellowstone	14	Acid Sulfate
12	Smokejumper Hot Springs	4	Acid Sulfate
13	Potts Basin	3	Neutral Cl
14	Mud Volcano	9	Acid Sulfate
15	Upper Geyser Basin	10	Neutral Cl
16	Heart Lake	8	Neutral Cl
17	North of Norris Geyser Basin	9	Various
18	Gibbon River Basins	13	Various
19	Shoshone	11	Various
20	Highland Hot Springs	5	Acid Sulfate

apparatus and placing it in a bucket or beaker of cold water until a sufficient amount of steam emerging from the fumarole had condensed within the line. For gas-rich samples we used a small hand pump to facilitate a continuing flow of steam into the line. The condensed steam was gravity-fed into the sample bottle.

Gases collected for analysis of noble gas concentrations and isotopic ratios were collected from the titanium tube or funnel into copper tubing that was then sealed at both ends using refrigerator clamps. For these types of samples Tygon tubing was used for all connections in all years.

Water samples for bulk chemistry were collected through a 0.45-μm filter into plastic bottles that were first prerinsed with filtered water. Samples for cation analyses were preserved with high-purity nitric acid by dropwise addition until a pH < 2 was obtained. Other nonfiltered water samples were collected in glass bottles for alkalinity titrations and stable isotope analyses of δD and $\delta^{18}O$.

Analytical

Gas samples were analyzed for their bulk composition at the USGS Volcano Gas Geochemistry Laboratory in Menlo Park, California. The head-space gases H_2, He, Ar, O_2, N_2, CH_4, and other hydrocarbons were analyzed using a Varian gas chromatograph with a dual-injection system using Ar and He carrier gases. Concentrations of the absorbed soluble gases were determined by wet-chemical techniques, including ion chromatography (Dionex ICS-2000) for HCl, HF, and H_2S (after conversion to sulfate), ion selective electrode (NH_3),

and direct measurement of CO_2 on a vacuum extraction line, following acidification of the NaOH solution. Replicate analysis of NaOH blanks (that is, from prepared bottles with no sample added) provided background concentrations of CO2, Cl-, F-, and SO_4^{2-} that were used to correct measured values. The background concentrations of Cl- and SO_4^{2-} were larger in 2003–5 than in subsequent years when we began using commercially prepared ion exchange columns. Until 2006, CO_2 concentrations were quantified by pipetting an aliquot of the NaOH solution and 0.5 ml of H_2O_2 into an extraction vessel and evolving the CO_2 using phosphoric acid, following the standard procedure of McCrea (1950). The amount of CO_2 was quantified by a mercury manometer, and the sample was then transferred to a bottle for isotopic analysis. In 2006 we changed the procedure so that immediately after the sample bottle was opened an aliquot of NaOH was drawn into a syringe and then injected through a septum into an evacuated bottle. The syringe was weighed before and after injection, providing an accurate measure of the NaOH content. An additional 0.5 ml of H_2O_2 was similarly injected, and the sample was allowed to sit overnight. The following day a sufficient amount of 5 N H_2SO_4 was added to liberate the CO_2. The gas was purified and quantified using a digital pressure gauge on an extraction line using standard cryogenic techniques, and the CO_2 was then transferred to a bottle for stable isotope analysis. This procedure reduced the exposure time of the NaOH sample solution to the atmosphere and improved quantification of the amount of NaOH over the pipette method.

On average the blank NaOH solutions contained 6 mmol of CO_2 per ml NaOH. The CO_2 content of the blanks most

likely reflects exposure of the solution to atmospheric CO_2 during bottle preparation. Results of five analyses of the blank-generated CO_2 had $\delta^{13}C$-CO_2 values between –21.1 and –17.6 per mil, the low $\delta^{13}C$ values resulting from kinetically controlled isotopic fractionation when atmospheric CO_2 ($\delta^{13}C \approx$ –8 per mil) diffuses into the NaOH (Fritz and others, 1985). For most samples the influence of this small amount of atmospherically derived CO_2 on the final carbon isotope composition is not detectable. Comparison of $\delta^{13}C$-CO_2 values from replicates where one sample is collected in NaOH and a second sample is collected in an evacuated bottle show that, at CO_2 concentrations greater than 50 µmol per ml NaOH, there is no discernable isotopic shift. All samples with CO_2 isotope data in table 2 have concentrations above this cutoff value.

Starting in 2008, an aliquot of the head-space gas from samples with sufficient CH_4 was reserved for carbon isotopic analysis. Water and CO_2 were removed from the bulk gas using standard cryogenic techniques. The remaining gas, mostly N_2 and CH_4, was introduced to a section of the vacuum line containing a copper-oxide furnace and the temperature raised to 800°C (Kiyosu and Krouse, 1989). To ensure total conversion of CH_4 to CO_2 the gas was held at 800°C for 2 hours. Upon completion, the temperature was lowered and the furnace cooled slowly to 400°C. After cooling, the volume of produced CO_2 was determined and the sample was sent to the USGS lab in Reston, Virginia, for $\delta^{13}C$ analysis.

Isotope analyses were preformed at several laboratories. Carbon isotope analyses were performed at USGS laboratories in Menlo Park and Reston. The $^3He/^4He$ determination was run at the USGS Noble Gas Laboratory in Denver, Colorado, as discussed in Werner and others (2008). δD and $\delta^{18}O$ analyses of waters (δD_w, $\delta^{18}O_w$) and condensed steam (δD_s, $\delta^{18}O_s$) were performed at the USGS laboratory in Denver. During 2003-8 the water and steam isotope analyses were performed using techniques outlined in Coleman and others (1982) and Epstein and Mayeda (1953). In 2009 these analyses were performed by laser cavity ring-down spectroscopy.

Anion concentrations were determined using ion chromatography (Cl^-, F^-, SO_4^{2-}) and titration (HCO_3^-). Cation concentrations were determined using either inductively coupled plasma mass spectroscopy (Perkin Elmer ELAN 6000, 2003-7) or inductively coupled plasma optical emission spectroscopy (Thermo Scientific icap 6000, 2008-9) at USGS laboratories in Menlo Park.

Data Formats and Uncertainties: Table 2 Gas Analyses

Below we outline the data columns in table 2 and information relevant for interpretation of values and their related uncertainties.

Sample: Alpha-numeric codes begin with YL followed by a two-digit year code (03 for 2003, for example), a hyphen, and a sample number for that year.

Location: Informal name for the sampled feature. The name could be a defined thermal feature or could indicate simply that the sample was taken in the same general location. When we sampled an actual thermal feature denoted in the Yellowstone Thermal Features database (http://www.rcn.montana.edu/Features/Search.aspx), we list the name of that feature in the "YNP Thermal Features Database" column.

Group: One of twenty groups defined for the purpose of explication and plot generation. Except for group 1 (Miscellaneous) and group 11 (Eastern Yellowstone), samples in a group are generally closely located. The groups shown below are also described and categorized in table 1.
1. Miscellaneous
2. Washburn Hot Springs
3. Lower Geyser Basin
4. Mammoth Hot Springs
5. Forest Springs
6. Roaring Mountain/Amphitheater Springs
7. Terrace Springs
8. Norris Geyser Basin
9. Brimstone Basin
10. Gas Vents (Norris-Canyon Road)
11. Eastern Yellowstone
12. Smokejumper Hot Springs
13. Potts Basin
14. Mud Volcano
15. Upper Geyser Basin
16. Heart Lake
17. North of Norris Geyser Basin
18. Gibbon River Basins
19. Shoshone
20. Highland Hot Springs

Date Sampled: In month/day/year format (mm/dd/yyyy).

Feature: Split into three types: (1) fum (fumarole), (2) fry (frying pan), and (3) pool (pools and springs). Some fumaroles may be steaming ground or subboiling gas seeps.

Temp: Temperature in degrees Celsius. Temperature can be reproducibly measured to within 0.1°C, but accuracy may be limited to ~0.5°C because of temperature variability within the feature and instrumental variations.

Easting: East-west location in Universal Transverse Mercator (UTM) coordinate system, Zone 12. Datum is NAD83 (nearly identical to WGS84). Units are in meters. Uncertainties are generally ~3 m.

Northing: North-south location in Universal Transverse Mercator (UTM) coordinates, Zone 12. Datum is NAD83 (nearly identical to WGS84). Units are in meters. Uncertainties are generally ~3 m.

Xg%: Mole percent gas relative to gas plus steam. A sample with no steam would have a value of 100 (for example,

Table 2. Sample collection parameters, volume % normalized gas compositions, and isotope ratios for gas collected within and around Yellowstone National Park, Wyoming during 2003 through 2012 (part 1).

[Gas for compositional analyses and δ13C-CO2 (C) was collected in tubes containing NaOH, gas for 3He/4He ratios and δ13C-CO2 (E) collected in empty tubes; a blank cell indicates that an analysis was not attempted]

Sample number	Location	Group	Date	Feature	Temp °C	Easting meters	Northing meters	Xg (%)	CO2 mol%	H2S mol%	NH3 mol%	He mol%	H2 mol%	Ar mol%	O2 mol%	N2 mol%	CH4 mol%	C2H6 mol%	CO mol%	C3H8 mol%	C4H10 mol%	C5H12 mol%
YL03-01A	Lone_Star	15	09/04/2003	fry	94.0	515429	4918413	0.11	87.6	3.68	0.081	0.0041	0.770	0.1583	0.49	6.3	0.8768	0.00183				
YL03-02A	Fountain_Paint_Pot	3	09/05/2003	fum	111.1	515386	4933083	0.48	94.3	0.45	0.02	0.0051	0.008	0.1014	0.28	4.0	0.8543	0.00103				
YL03-03A	Black_Sands1	15	09/05/2003	fry	92.2	511542	4923256	0.50	95.3	0.25	0.028	0.0019	0.023	0.0959	0.48	3.4	0.4218	0.0005				
YL03-04A	Black_Sands2	15	09/05/2003	pool	76.1	511628	4923190	82.4	77.6	0.22	0.002	0.0093	<0.00003	0.4473	2.7	17.4	1.66	0.00226				
YL03-05B	Near_DB	8	09/06/2003	fum	94.7	523214	4952111	0.05	75.1	7.6	0.037	0.0021	0.598	0.348	1.7	14.5	0.1444	0.00041				
YL03-06B	Green_Dragon	8	09/06/2003	pool	88.6	523196	4951898	37.7	84.5	0.4	0.002	0.0045	0.091	0.343	0.60	13.8	0.2981	0.00115				
YL03-07	Son_of_Green_Dragon	8	09/06/2003	fum	94.1	523208	4952035	0.15	90.2	3.94	0.007	0.0012	0.318	0.121	0.48	4.8	0.0858	0.00011				
YL03-08	Dishwater	8	09/06/2003	pool	89.4	523384	4952086	9.4	91.0	0.6	0.005	0.0024	0.376	0.1733	0.59	6.8	0.1654	0.00058				
YL03-09B	Beryl_Spring	18	09/07/2003	fum	99.6	520077	4947298	1.1	98.3	0.83	0.009	0.0011	0.141	0.0176	0.0005	0.73	0.0183	0.0001				
YL03-10B	Black_Growler	8	09/07/2003	fum	93.6	523502	4952728	0.30	93.6	2.91	0.139	0.0016	0.388	0.0716	0.009	2.8	0.1032	0.00041				
YL03-11B	Black_Pit	8	09/07/2003	pool	82.3	523588	4952139	80.5	94.0	0.69	0.0006	0.0023	0.649	0.0954	0.52	3.9	0.1557	0.00063				
YL03-12A	Porcelain_Terrace1	8	09/07/2003	fum	93.9	523746	4953112	1.0	96.9	2.0	0.0012	0.0045	0.333	0.0134	0.0008	0.47	0.2849	0.00063				
YL03-13A	Nymph_Lake_new_feature	17	09/08/2003	fum	93.6	521471	4955495	0.93	97.7	0.92	0.021	0.0041	0.232	0.0257	0.013	1.0	0.0641	0.00014				
YL03-14B	Terrace_Springs	7	09/08/2003	pool	63.3	512184	4944102	86.6	99.8	<0.002	<0.0002	0.0003	0.001	0.0054	0.036	0.17	0.0003	<0.00001				
YL03-15A	W_Nymph_Lake_Thermal_Area1	17	09/09/2003	pool	82.0	520335	4954609	43.6	97.7	0.4	<0.0002	0.008	0.187	0.0389	0.028	1.5	0.1363	0.00018				
YL03-16A	W_Nymph_Lake_Thermal_Area2	17	09/09/2003	fry	92.0	520244	4954683	2.8	98.5	0.73	0.001	0.0039	0.161	0.0125	0.0002	0.52	0.0712	0.00009				
YL03-17A	Conoco	15	09/10/2003	fum	94.5	513205	4922954	0.20	91.3	1.55	0.039	0.0021	0.074	0.1468	0.81	5.6	0.4836	0.0008				
YL03-18A	Smokejumper1	12	09/12/2003	pool	85.0	503793	4917530	75.5	83.0	1.06	0.001	0.0146	5.27	0.2254	0.30	8.7	1.43	0.00323				
YL03-19A	Smokejumper2	12	09/12/2003	fum	92.1	503260	4918509	0.47	89.5	3.86	0.02	0.0069	2.28	0.0924	0.0032	3.5	0.6940	0.00175				
YL03-20	Smokejumper3	12	09/12/2003	fum	92.1	503273	4918792	0.36	89.0	4.09	0.008	0.0058	2.63	0.0846	0.013	3.6	0.5705	0.00143				
YL03-21A	Smokejumper4	12	09/12/2003	fry	92.1	503559	4918096	0.29	88.3	4.44	0.026	0.0072	3.13	0.0841	0.032	3.3	0.6862	0.00175				
YL04-01	Black_Pit	8	09/13/2004	fum	92.6	523588	4952139	0.68	97.6	0.59	0.058	0.0022	0.484	0.0268	0.0016	1.1	0.1423	0.00073				
YL04-02	nr_Gibbon_R1	8	09/13/2004	pool	84.0	523658	4954007	4.7	96.5	1.44	0.008	0.0037	0.546	0.024	0.0005	0.94	0.2855	0.00884				
YL04-03	nr_Gibbon_R2	8	09/13/2004	pool	72.8	523680	4954101	93.3	97.5	1.29	<0.0002	0.0031	0.324	0.0121	0.0028	0.50	0.3367	0.02172				
YL04-04	Nymph_Lake_new_feature	17	09/13/2004	fry	93.0	521444	4955530	1.2	97.8	0.67	0.007	0.0045	0.195	0.0278	0.0009	1.2	0.0729	0.00014				
YL04-05	Conoco	15	09/14/2004	fum	94.3	513182	4922973	0.20	93.3	1.05	0.011	0.0022	0.088	0.1245	0.10	4.8	0.5016	0.00055				
YL04-06	Bison_Kill	8	09/14/2004	pool	8.5	523471	4954042	61.4	96.1	0.04	<0.0002	0.0013	0.0003	0.0683	0.68	3.0	0.1406	0.00446				
YL04-07	Bison_Flat1	8	09/14/2004	fum	92.9	523527	4953778	2.9	97.1	1.87	<0.0002	0.0046	0.023	0.0158	0.0013	0.66	0.2939	0.00564				
YL04-08	Back_Basin1	8	09/15/2004	fum	nm	523182	4952090	0.21	94.3	2.17	0.008	0.002	0.268	0.0739	0.006	3.0	0.1190	0.00026				
YL04-09	Back_Basin2	8	09/15/2004	pool	67.4	522963	4952193	91.7	93.8	0.39	<0.0002	0.0015	0.011	0.1537	0.024	5.5	0.1008	0.0002				
YL04-10	Green_Dragon	8	09/15/2004	pool	76.8	523197	4951894	3.1	93.9	0.92	0.001	0.0026	0.43	0.0661	0.057	4.4	0.1679	0.00075				
YL04-11	Steamboat_mud_volcano	8	09/15/2004	fum	92.8	523502	4952272	0.56	96.7	2.31	0.082	0.0021	0.386	0.0098	0.0035	0.38	0.1401	0.00208				
YL04-12	Porcelain_Terrace2	8	09/15/2004	fum	92.6	523732	4953033	1.0	97.1	1.29	0.001	0.0041	0.498	0.0206	0.0006	0.80	0.2616	0.00144				
YL04-13	Hundred_Springs_Plain	8	09/15/2004	pool	89.1	523113	4953330	23.4	93.9	0.23	0.0003	0.0057	0.556	0.118	0.047	4.8	0.3261	0.00172				
YL04-14	Beryl_Spring	18	09/16/2004	fum	93.1	520093	4947311	0.76	95.6	0.7	0.015	0.0007	0.083	0.0604	0.017	3.5	0.0101	0.00001				
YL04-15	Devils_Den	1	09/16/2004	[1] fum	27.2	549077	4971336	89.3	98.0	1.08	0.0002	0.0006	0.002	0.0071	0.0030	0.30	0.5873	0.01778				
YL04-17	Sylvan_Springs1	18	09/17/2004	pool	22.4	517878	4949941	87.3	98.6	0.16	<0.0002	0.0034	0.134	0.0253	0.0049	1.1	0.0226	0.0002				
YL04-19	Sylvan_Springs2	18	09/17/2004	fum	97.8	518326	4949582	6.5	99.0	0.47	0.0004	0.0035	0.142	0.0075	0.0005	0.32	0.0216	0.0002				
YL04-20	Sylvan_Springs3	18	09/17/2004	fry	91.9	518326	4949582	3.9	98.9	0.45	<0.0002	0.0033	0.117	0.0114	0.0005	0.48	0.0206	0.0002				
YL04-21	Gas_Vents_Norris_Canyon_Rd	10	09/18/2004	fum	92.1	535329	4951004	1.5	97.3	1.33	0.0003	0.0048	0.031	0.0258	0.0016	1.0	0.3216	0.00154				
YL04-22	Artist_Paintpot	18	09/18/2004	fry	91.7	520838	4948760	0.16	87.9	0.66	0.005	0.0013	0.079	0.1971	2.7	8.4	0.0393	0.00065				
YL05-01	Black_Pit	8	09/13/2005	fum	91.7	523589	4952144	0.92	97.7	0.73	0.025	0.0032	0.624	0.0124	0.0007	0.45	0.2074	0.00159				
YL05-02	Terrace_Springs	7	09/13/2005	pool	62.3	512184	4944102	55.0	99.7	0.01	<0.0002	0.0004	0.0001	0.0086	0.058	0.25	0.0003	0.00015				
YL05-03	Frying_Pan_Spring	17	09/14/2005	fry	91.8	521979	4955476	1.5	98.7	0.49	0.006	0.0042	0.368	0.0101	0.0006	0.38	0.0866	0.00051				
YL05-04	Gibbon_River_Bridge	18	09/14/2005	fum	93.4	520295	4947980	3.0	99.3	0.34	<0.0002	0.0016	0.195	0.0039	0.0005	0.17	0.0286	0.00038				
YL05-05	Conoco	15	09/14/2005	fum	92.5	513181	4922972	0.18	96.0	0.72	<0.0002	0.0026	0.119	0.0744	0.005	2.5	0.6078	0.00266				
YL05-06	Back_Basin3	8	09/15/2005	fum	92.6	523170	4952046	0.09	93.4	2.74	<0.0002	0.002	0.345	0.1088	0.011	3.2	0.1243	0.01314				
YL05-07	Back_Basin4	8	09/15/2005	pool	87.4	523011	4952171	82.2	91.1	0.72	<0.0002	0.0021	0.001	0.2227	0.0017	7.8	0.0985	0.00181				
YL05-08	Black_Growler	8	09/15/2005	pool	93.6	523496	4952728	0.53	97.7	1.11	0.011	0.0029	0.529	0.0141	0.0011	0.49	0.1742	0.00146				
YL05-09	Bison_Flat2	8	09/16/2005	fum	93.9	523538	4953830	1.7	97.6	1.53	<0.0002	0.0052	0.122	0.0113	0.0006	0.41	0.3246	0.00726				
YL05-10	Nymph_Lake_new_feature	17	09/16/2005	fum	93.5	521456	4955507	2.7	98.9	0.45	0.0008	0.0044	0.224	0.0081	0.0004	0.30	0.0727	0.00034				
YL05-11	Chocolate_Pots	18	09/16/2005	fum	52.5	520496	4950780	93.1	98.5	0.002	<0.0002	0.0013	0.0001	0.0401	0.014	1.4	0.0328	0.00044				
YL05-12	Sulphur_Caldron1	14	09/17/2005	pool	68.9	544992	4941758	93.5	99.3	0.16	<0.0002	0.0021	0.139	0.0077	0.016	0.36	0.0313	<0.00001				
YL05-13	Mud_Geyser	14	09/17/2005	fum	112.9	545055	4941205	10.6	99.5	0.14	0.0008	0.0022	0.078	0.0035	0.0002	0.21	0.0423	0.00011				
YL05-13A	Mud_Geyser	14	09/17/2005	fum	112.9	545056	4941209	14.0	99.5	0.15	0.0003	0.0022	0.075	0.0032	0.0001	0.20	0.0411	0.0001				
YL05-14	Roaring_Mountain1	6	09/19/2005	fum	92.7	520861	4958599	2.9	98.9	0.61	<0.0002	0.0104	0.086	0.0091	0.0002	0.32	0.0456	0.00047				
YL05-15	Narrow_Gauge	4	09/19/2005	fum	74.8	522880	4979593	96.1	99.5	0.25	<0.0002	0.00003	0.0003	0.0049	0.0043	0.19	0.0021	0.00017				
YL05-17A	Quagmire	3	09/21/2005	fry	93.4	515413	4934949	0.12	93.0	2.81	0.008	0.0081	0.511	0.0878	0.007	3.0	0.5680	0.00533				
YL05-17B	Quagmire	3	09/21/2005	fry	93.4	515402	4934942	0.13	94.0	2.22	0.012	0.0078	0.471	0.0761	0.0026	2.7	0.5221	0.00446				
YL05-18A	Gibbon_River_Bridge	18	09/21/2005	fum	93.2	520295	4947980	2.6	99.3	0.38	<0.0002	0.0015	0.188	0.0035	0.0005	0.14	0.0271	0.0003				
YL05-18B	Gibbon_River_Bridge	18	09/21/2005	fum	93.2	520295	4947980	2.2	99.3	0.32	<0.0002	0.0014	0.183	0.0036	0.0002	0.16	0.0260	0.00023				
YL05-18C	Gibbon_River_Bridge	18	09/21/2005	fum	93.2	520295	4947980	2.3	99.3	0.35	<0.0002	0.0014	0.175	0.0047	0.0012	0.16	0.0249	0.00023				
YL05-18D	Gibbon_River_Bridge	18	09/21/2005	fum	93.2	520295	4947980	2.3	99.1	0.3	<0.0002	0.0014	0.177	0.0103	0.0003	0.42	0.0255	0.00026				
YL06-01A	HSB1	11	08/27/2006	fum	91.9	558800	4954767	1.4	93.2	2.33	0.003	0.008	3.53	0.0051	0.007	0.17	0.7683	0.01643				

[1] Site is a cold gas seep; listed as a fumarole for simplicity.

[2] Carbon isotope composition is different than reported in Werner and others, 2008.

[*] Values are revised from the previous version of this report.

Table 2.
Sample collection parameters, volume % normalized gas compositions, and isotope ratios for gas collected within and around Yellowstone National Park, Wyoming during 2003 through 2012 (part 1).—Continued

[Gas for compositional analyses and δ¹³C-CO₂ (C) was collected in tubes containing NaOH, gas for ³He/⁴He ratios and δ¹³C-CO₂ (E) collected in empty tubes; a blank cell indicates that an analysis was not attempted]

Sample number	Location	Group	Date	Feature	Temp °C	Easting meters	Northing meters	Xg (%)	CO₂ mol%	H₂S mol%	NH₃ mol%	He mol%	H₂ mol%	Ar mol%	O₂ mol%	N₂ mol%	CH₄ mol%	C₂H₆ mol%	CO mol%	C₃H₈ mol%	C₄H₁₀ mol%	C₅H₁₂ mol%
YL06-02	HSB2	11	08/29/2006	pool	91.9	558553	4953761	81.8	94.0	3.35	0.0004	0.0056	1.34	0.0124	0.0028	0.48	0.7679	0.01051				
YL06-03	HSB3	11	08/29/2006	fry	91.4	558752	4954838	2.4	90.0	2.08	0.006	0.0083	6.97	0.005	0.010	0.16	0.7583	0.01546				
YL06-04	HSB4	11	08/29/2006	fum	93.4	558890	4955349	3.7	90.7	1.82	0.146	0.0079	5.76	0.0041	0.0040	0.10	1.45	0.04646				
YL06-05	HSB5	11	08/29/2006	pool	76.9	558925	4955398	88.1	91.1	1.76	<0.0002	0.009	3.98	0.0365	0.010	1.5	1.54	0.04767				
YL06-06	HSB6	11	08/30/2006	fry	90.1	559263	4954529	0.74	91.2	3.09	0.749	0.0045	4.36	0.0061	0.0061	0.20	0.3615	0.01008				
YL06-07	HSB7	11	08/30/2006	fum	90.9	560345	4954787	0.70	92.1	4.31	0.006	0.0029	0.049	0.0296	0.0044	2.3	1.15	0.02742				
YL06-08	HSB8	11	08/30/2006	pool	68.1	559347	4954788	97.2	94.7	3.54	<0.0002	0.0018	0.065	0.0166	0.0009	0.64	0.9577	0.03554				
YL06-09	Black_Pit	8	09/01/2006	fum	94.5	523589	4952144	0.44	96.9	1.73	0.052	0.0025	0.528	0.0155	0.0025	0.56	0.1684	0.00244				
YL06-10	Back_Basin5	8	09/01/2006	fum	92.1	523155	4952043	0.21	94.9	3.39	0.009	0.003	0.658	0.021	0.010	0.82	0.2156	0.00785				
YL06-11	Guardian	8	09/01/2006	fum	92.5	523477	4952724	0.56	96.7	2.31	0.082	0.0021	0.386	0.0098	0.0035	0.38	0.1401	0.00208				
YL06-12	Behind_Congress	8	09/01/2006	pool	92.7	523655	4952727	0.22	96.0	2.33	0.024	0.0033	0.531	0.0234	0.006	0.90	0.2191	0.00471				
YL07-01	Gas_Vents_Norris_Canyon_Rd	10	09/12/2007	fum	91.1	535328	4951009	1.8	96.6	2.4	<0.0002	0.0052	0.025	0.0135	0.0005	0.56	0.3580	0.00188		0.0004	<0.00001	<0.002
YL07-02	Sulphur_Caldron2	14	09/12/2007	fum	98.2	544961	4941790	11.1	99.4	0.24	<0.0002	0.0021	0.142	0.003	0.0008	0.20	0.0276	<0.00001				
YL07-03	Mud_Geyser	14	09/12/2007	fum	114.7	545055	4941202	9.5	99.5	0.14	0.005	0.002	0.074	0.0029	0.0003	0.19	0.0369	0.00004				
YL07-04	Behind_Inkpot	2	09/13/2007	fum	92.4	545106	4956992	2.3	90.4	3.33	1.108	0.0009	1.93	0.001	0.0049	0.20	3.00	0.00374		0.0006	0.00012	<0.002
YL07-05	Washburn	2	09/13/2007	fum	93.2	545135	4957173	1.7	83.0	2.58	1.093	0.0007	4.64	0.0089	0.012	0.43	8.18	0.01062		0.0022	0.00056	<0.002
YL07-06	Pocket_Basin	3	09/14/2007	fum	93.7	513979	4934350	0.15	95.7	1.99	<0.0002	0.005	0.341	0.043	0.008	1.6	0.3549	0.00236		0.0005	<0.00001	<0.002
YL07-09	Guardian	8	09/14/2007	fum	92.1	523477	4952724	0.32	96.5	2.02	0.086	0.0032	0.703	0.0107	0.0029	0.45	0.2050	0.00083				
YL07-10	Steamvalve	8	09/15/2007	pool	68.8	523494	4952561	87.5	97.0	0.6	<0.0002	0.003	0.545	0.0414	0.0010	1.6	0.1956	0.00081				
YL07-11	Bison_Flat	8	09/15/2007	fum	92.1	523548	4953837	1.3	95.4	3.82	<0.0002	0.0043	0.151	0.0084	0.0011	0.33	0.2962	0.00665		0.0025	0.00095	0.00062
YL07-12	Roaring_Mountain2	6	09/16/2007	fum	92.4	520703	4958588	0.46	97.5	1.76	<0.0002	0.0097	0.147	0.0135	0.0019	0.54	0.0443	0.00037				
YL07-13	Mud_Geyser	14	09/16/2007	fum	nm	545055	4941202	8.7	99.5	0.15	0.002	0.0021	0.079	0.0033	0.0009	0.21	0.0411	0.00007				
YL07-14	Fountain_Paint_Pot	3	09/17/2007	fum	92.0	515376	4933087	0.22	95.7	0.35	0.047	0.0056	0.008	0.0762	0.005	2.9	0.1754	0.00022		0.0002	<0.00001	<0.002
YL07-15	Beryl_Spring	18	09/17/2007	fum	92.5	520077	4947298	0.79	98.7	0.8	<0.0002	0.0015	0.195	0.0059	0.0015	0.26	0.0260	0.00007				
YL07-17	Crater_Hills	1	09/18/2007	fum	90.9	541392	4944637	3.0	98.4	1.27	<0.0002	0.0026	0.016	0.0047	0.25	0.0560	0.0004					
YL07-18.1	Devils_Den	1	09/18/2007	¹fum	23.7	549070	4971350	85.9	78.1	1.11	<0.0002	<0.00003	0.011	0.2134	2.6	17.6	0.2865	0.01075		0.0027	0.00067	0.04400
YL07-18.2	Devils_Den	1	09/18/2007	¹fum	23.7	549070	4971350	74.4	79.2	1.03	<0.0002	<0.00003	0.001	0.2026	2.4	16.9	0.2711	0.01034				
YL08-02	Steamboat_Point	11	09/17/2008	fum	93.4	555848	4930907	0.21	91.9	3.46	0.724	0.0239	0.441	0.044	0.0020	1.6	1.80	0.00484		0.0006	<0.00001	<0.002
YL08-03	Potts_Basin1	13	09/17/2008	pool	68.8	533421	4919761	81.4	94.2	<0.002	<0.0002	0.0037	0.001	0.1148	0.42	4.3	0.9077	0.00134		0.0003	<0.00001	<0.002
YL08-04	Potts_Basin2	13	09/17/2008	pool	87.5	533505	4919689	43.8	92.9	<0.002	<0.0002	0.0007	0.003	0.1601	0.36	6.3	0.2327	<0.00001				
YL08-04B	Potts_Basin2A	13	09/17/2008	pool	87.5	533505	4919689	79.8	88.5	<0.002	<0.0002	0.0013	0.002	0.2448	0.74	10.2	0.3184	0.00053				
YL08-05	Potts_Basin3	13	09/17/2008	pool	45.3	533505	4919547	98.1	88.5	0.003	<0.0002	0.0079	0.026	0.1806	1.3	1.84	1.84	0.00278		0.0006	<0.00001	<0.002
YL08-07B	Snake_River_HS	1	09/18/2008	pool	81.4	527133	4887672	87.4	53.2	<0.002	<0.0002	0.0424	0.012	1.0219	0.68	44.7	0.3825	0.00357		0.0015	0.00034	<0.002
YL08-08	Conoco	15	09/18/2008	fum	93.5	513195	4922978	0.15	95.9	1.09	<0.0002	0.0025	0.119	0.0671	0.0047	2.3	0.5509	0.00143		0.0002	<0.00001	<0.002
YL08-09	Forest_Springs1	5	09/19/2008	fum	91.0	541730	4951154	3.5	98.6	0.96	<0.0002	0.0021	0.212	0.0031	<0.0001	0.14	0.0789	0.0055		0.0003	<0.00001	<0.002
YL08-10	Forest_Springs2	5	09/19/2008	fry	87.6	541609	4951154	3.8	98.6	1.01	<0.0002	0.0018	0.191	0.0029	<0.0001	0.13	0.0728	0.00042	0.00002	0.00005	<0.00001	<0.002
YL08-11	Ochre_Spring	1	09/19/2008	fum	91.7	547154	4979397	2.5	98.8	0.15	<0.0002	0.0024	0.162	0.0155	0.0002	0.16	0.2012	0.0018		0.0002	<0.00001	<0.002
YL08-12	Poison_Spring	4	09/20/2008	pool	39.3	522453	4979039	89.7	96.1	0.03	<0.0002	0.0051	<0.00003	0.0669	0.22	3.5	0.0732	0.00276		0.0007	0.00017	<0.002
YL08-13	Amphitheater_Springs	6	09/20/2008	fry	88.3	521782	4960436	1.8	85.6	2.88	<0.0002	0.0031	0.37	0.1412	0.28	10.6	0.0515	0.00118				
YL08-14	Obsidian_Pool_fry	14	09/21/2008	fry	90.2	544411	4939629	10.9	99.4	0.16	0.0004	0.0023	0.107	0.0037	0.0003	0.24	0.0437	0.0002				
YL08-14B	Obsidian_Pool_fry	14	09/21/2008	fry	90.2	544411	4939629	10.3	99.4	0.15	0.0019	0.0028	0.116	0.0041	0.0005	0.26	0.0444	<0.00001				
YL08-15	Obsidian_Pool	14	09/21/2008	fum	89.2	544530	4939794	9.2	98.9	0.11	<0.0002	0.002	0.094	0.0144	0.077	0.79	0.0361	0.0003				
YL08-16	Back_Basin6	8	09/21/2008	fum	93.7	523119	4952036	0.11	94.5	2.8	<0.0002	0.0038	0.851	0.0458	0.013	1.6	0.2207	0.00132				
YL08-17	Steamvalve	8	09/21/2008	pool	71.4	523494	4952561	83.8	96.0	0.43	<0.0002	0.0029	0.481	0.0701	0.010	2.8	0.1768	0.00103				
YL08-18	Brimstone1	9	09/25/2008	pool	6.6	562143	4915346	75.0	99.0	0.70	0.0015	0.0104	0.007	0.0066	0.0003	0.23	0.0753	0.0008		0.0003	0.00013	0.00009
YL08-19	Brimstone2	9	09/25/2008	pool	16.3	562447	4914975	79.7	98.9	0.58	<0.0002	0.0113	0.00003	0.0105	0.0016	0.37	0.0925	0.00083		0.0003	0.00012	0.00008
YL08-20	Brimstone3	9	09/25/2008	pool	nm	562134	4914977	83.1	99.0	0.64	<0.0002	0.0106	0.00008	0.0081	0.006	0.24	0.0758	0.00081		0.0003	0.00012	0.00009
YL09-01	Conoco	15	09/08/2009	fum	93.3	513206	4922948	0.08	94.3	1.61	<0.0002	0.0038	0.116	0.0898	0.009	3.1	0.7027	0.00357				
YL09-02	Black_Sands1	15	09/08/2009	pool	90.0	511542	4923259	0.90	97.8	0.007	0.022	0.0012	0.015	0.0446	0.22	1.6	0.2529	0.00041				
YL09-03A	Gas_Vents_Norris_Canyon_Rd	10	09/08/2009	fum	92.9	535321	4951008	1.7	96.8	2.16	<0.0002	0.0051	0.061	0.0151	0.0003	0.64	0.3373	0.00239				
YL09-03B	Gas_Vents_Norris_Canyon_Rd	10	09/08/2009	fum	92.9	535321	4951008	1.7	96.8	2.08	<0.0002	0.0054	0.046	0.017	0.0007	0.72	0.3571	0.00236		0.0001	0.00003	<0.002
YL09-04	Frying_Pan_Spring	17	09/08/2009	fry	92.3	521972	4955470	1.6	98.1	1.09	0.006	0.0051	0.344	0.0088	0.0022	0.35	0.0856	0.00027				
YL09-05	Heart_Middle	16	09/11/2009	pool	89.9	538455	4905116	3.9	96.6	0.04	0.005	0.0048	0.002	0.0751	0.13	2.3	0.6275	0.00217		0.0004	0.00009	<0.002
YL09-06	Heart_Fissure	16	09/11/2009	fum	92.9	538183	4905810	0.18	95.5	0.75	0.072	0.0144	0.1	0.075	0.009	2.2	1.24	0.00517		0.0013	0.00034	<0.002
YL09-07B	Heart_Lower	16	09/11/2009	fum	84.0	539343	4904383	62.3	64.8	0.02	<0.0002	0.0184	0.005	0.4226	6.7	27.1	1.01	0.00416				
YL09-08	Heart_Rustic	16	09/11/2009	fum	93.0	539330	4903255	0.06	83.1	0.66	0.366	0.0667	0.023	0.3101	0.039	10.5	4.53	0.01532		0.0052	0.00160	<0.002
YL09-09	Heart_North	16	09/12/2009	fum	92.9	537947	4906671	0.30	93.2	0.61	0.03	0.0201	0.076	0.1004	<0.0001	3.7	2.07	0.00888		0.0035	0.00100	0.00046
YL09-10	Heart_White_Gulch	16	09/12/2009	fum	92.7	537259	4906392	0.38	93.7	0.64	<0.0002	0.013	0.059	0.1037	0.0021	3.7	1.87	0.00884		0.0035	0.00100	0.00061
YL09-11	Heart_Upper	16	09/12/2009	fry	92.0	537568	4906016	0.17	93.5	1.15	<0.0002	0.0137	0.173	0.0933	0.0049	3.4	1.57	0.00759		0.0027	0.00068	<0.002
YL09-12	Heart_Rustic	16	09/12/2009	fum	93.4	539330	4903255	0.06	86.1	0.77	0.217	0.0426	0.031	0.2332	<0.0001	8.7	3.88	0.01408		0.0049	0.00140	<0.002
YL09-13	Rabbit_Creek	3	09/15/2009	fum	93.2	515107	4929792	0.06	95.6	0.6	<0.0002	0.0047	0.015	0.0951	0.013	3.0	0.4057	0.00102				
YL09-14	Quagmire	3	09/15/2009	fum	93.5	515415	4934948	0.18	95.3	1.26	<0.0002	0.008	0.417	0.0648	0.007	2.4	0.5037	0.00304		0.0010	0.00032	<0.002
YL09-15	Terrace_Springs	7	09/15/2009	pool	63.3	512184	4944102	99.0	99.8	<0.002	<0.0002	0.0003	0.0001	0.0061	0.037	0.18	0.0002	0.00002				
YL09-16	Turbid_Lake_upper	11	09/16/2009	fum	91.1	558905	4932535	5.8	97.8	1.08	0.083	0.0041	0.209	0.0035	<0.0001	0.13	0.6226	0.01453		0.0018	0.00031	0.00014
YL09-17	Bear_Creek	11	09/16/2009	pool	92.3	558816	4932859	4.6	97.7	1.21	0.059	0.0042	0.207	0.0037	0.0004	0.14	0.6536	0.01561		0.0019	0.00036	0.00014
YL09-18	Pelican_Creek_Trail	11	09/16/2009	pool	6.7	557027	4935598	83.6	96.1	0.56	<0.0002	0.0112	<0.00003	0.0298	0.0010	1.2	2.14	0.00762		0.0013	0.00034	0.00022

¹Site is a cold gas seep; listed as a fumarole for simplicity.

²Carbon isotope composition is different than reported in Werner and others, 2008.

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Table 2. Sample collection parameters, volume % normalized gas compositions, and isotope ratios for gas collected within and around Yellowstone National Park, Wyoming during 2003 through 2012 (part 1).—Continued

[Gas for compositional analyses and δ^{13}C-CO$_2$ (C) was collected in tubes containing NaOH, gas for ^{3}He/^{4}He ratios and δ^{13}C-CO$_2$ (E) collected in empty tubes; a blank cell indicates that an analysis was not attempted]

Sample number	Location	Group	Date	Feature	Temp °C	Easting meters	Northing meters	Xg (%)	CO$_2$ mol%	H$_2$S mol%	NH$_3$ mol%	He mol%	H$_2$ mol%	Ar mol%	O$_2$ mol%	N$_2$ mol%	CH$_4$ mol%	C$_2$H$_6$ mol%	CO mol%	C$_3$H$_8$ mol%	C$_4$H$_{10}$ mol%	C$_5$H$_{12}$ mol%
VHZDB11-01	Big 102	14	09/12/2012	soil gas		546322	4940154															
YL11-02	Conoco	15	09/09/2011	fum	93.9	513199	4922960	0.2	95.6	1.10	0.030	0.004	0.107	0.0702	0.0037	2.4	0.5688	0.00135	0.0033	0.0004	<0.00001	<0.002
YL11-03	Mud_Geyser	14	09/10/2011	fum	113.4	545054	4941203	12.0	99.5	0.15	0.002	0.002	0.084	0.0035	<0.0001	0.23	0.0453	0.00003	0.0001			
YL11-04	Back_Basin6	8	09/10/2011	fum	93.2	523119	4952036	0.15	94.8	3.29	0.045	0.003	0.570	0.0249	0.010	0.87	0.1846	0.00139		<0.00001	<0.00001	<0.002
YL11-05	Steamboat_mud_volcano	8	09/10/2011	fum	93.6	523502	4952272	1.4	97.0	2.04	0.005	0.002	0.501	0.0081	0.0005	0.30	0.1548	0.00086				
YL11-06	Gibbon_River_Bridge	18	09/10/2011	fum	94.1	520295	4947980	2.1	99.0	0.56	0.005	0.001	0.188	0.0045	0.0006	0.20	0.0277	0.00013	0.0003			
YL11-07	Shoshone_01	19	09/12/2011	fum	92.6	516273	4911441	0.23	91.4	5.81	0.027	0.003	0.272	0.0482	0.023	1.8	0.5314	0.00162	0.0012	0.0001	<0.00001	<0.002
YL11-11	Shoshone_03	19	09/12/2011	pool	86.5	516447	4911596	87.0	89.9	0.72	<0.0002	0.004	1.97	0.1427	<0.0001	6.6	0.6765	0.00218	0.0001			
YL11-13	Shoshone_04	19	09/13/2011	fum	92.8	516153	4911145	0.4	92.2	3.69	0.020	0.004	1.29	0.0545	<0.0001	2.1	0.6310	0.00176	0.0009			
YL11-14	Shoshone_05	19	09/13/2011	fum	92.7	516308	4911063	0.23	92.3	4.72	0.013	0.003	0.166	0.0547	0.0041	2.1	0.6118	0.00168	0.0030	0.0001	<0.00001	<0.002
YL11-15_1	Shoshone_06	19	09/13/2011	fum	94.7	516224	4911474	0.32	91.6	5.01	0.009	0.003	0.203	0.0553	0.0016	2.5	0.5870	0.00174	0.0009			
YL11-15_2	Shoshone_06	19	09/13/2011	fum	94.7	516224	4911474	0.32	91.8	4.96	0.012	0.002	0.309	0.0527	<0.0001	2.2	0.5567	0.00166	0.0008			
YL11-16	Shoshone_07	19	09/14/2011	fum	91.6	515879	4911472	0.20	96.8	0.03	0.093	0.002	0.005	0.0773	0.20	2.5	0.2160	0.00051	0.0013	<0.00001	<0.00001	<0.002
YL11-17_1	Shoshone_08	19	09/14/2011	pool	87.6	515863	4911232	39.0	89.7	<0.002	0.009	0.007	0.051	0.2413	0.19	8.8	0.8038	0.00184				
YL11-17_2	Shoshone_08	19	09/14/2011	pool	87.6	515863	4911232	7.5	90.1	0.01	<0.0002	0.006	0.048	0.2323	0.19	8.5	0.7744	0.00185				
YL11-18	Shoshone_09	19	09/14/2011	pool	76.5	515954	4910960	63.0	65.7	0.05	<0.0002	0.003	0.023	0.4078	6.2	27.0	0.4444	0.00123				
YL11-19	Shoshone_10	19	09/14/2011	pool	85.2	516121	4911400	77.0	92.0	0.14	<0.0002	0.005	0.848	0.1652	<0.0001	6.0	0.8297	0.00224	0.0002	0.0002	<0.00001	<0.002
YL11-27	Shoshone_11	19	09/15/2011	pool	84.9	516196	4911471	91.0	92.4	0.62	<0.0002	0.003	1.71	0.1113	<0.0001	4.4	0.7055	0.00219	0.0002			
YL11-31	Shoshone_12	19	09/15/2011	fum	92.3	516277	4911554	0.4	92.8	4.37	0.025	0.002	1.06	0.0358	0.0012	1.4	0.3725	0.00108				
YL12-01	Gas_Vents_Norris_Canyon_Rd	10	07/10/2012	fum	92.4	535355	4950974	1.2	96.4	2.72	<0.0002	0.004	0.018	0.0115	0.0022	0.55	0.2854	0.00159		0.00002	<0.00001	<0.002
YL12-02	Mary_Bay	11	07/11/2012	fry	92.9	555264	4933613	0.52	89.5	5.08	0.037	0.008	1.97	0.0473	0.005	2.0	1.38	0.00321		0.0002	<0.00001	<0.002
YL12-03	Butte_Springs	11	07/11/2012	fry	95.1	557460	4929966	0.06	90.7	2.94	1.169	0.028	0.650	0.0870	0.038	3.2	1.16	0.00258		0.0006	<0.00001	<0.002
YL12-04	Cinder_Pool	8	07/14/2012	pool	84.2	522980	4953269	13.0	96.8	1.63	<0.0002	0.002	0.001	0.0353	0.0012	1.5	0.0901	0.00037		0.00002	<0.00001	<0.002
YL12-05	Amphitheater_Springs	6	07/15/2012	fum	~92	521490	4960810	0.9	96.5	2.96	0.002	0.008	0.049	0.0099	0.014	0.40	0.0823	0.00144				
YL12-06	Helen's_Cool_Pool	14	07/25/2012	pool	23.2	545673	4941001															
YL12-07	Monument_Fumarole	18	09/06/2012	fum	114.2	519532	4947894	4.3	99.2	0.49	0.003	0.002	0.131	0.0028	0.0007	0.13	0.0196	0.00010	0.0001			
YL12-09	Highland #1	20	09/08/2012	fum	90.8	530167	4939875	0.8	80.0	14.91	<0.0002	0.004	0.094	0.0682	0.0020	4.6	0.3017	0.00006	0.0004			
YL12-10	Highland #2	20	09/08/2012	fum	91.5	530298	4939495	0.06	63.6	30.18	<0.0002	0.004	0.466	0.0977	0.052	5.4	0.2246	0.00011	0.0046			
YL12-11	Highland #3	20	09/09/2012	fum	92.5	530540	4939141	0.16	50.1	20.52	0.002	0.002	0.492	0.3491	0.018	28.3	0.1606	<0.00001	<0.0001			
YL12-14	Highland #4	20	09/09/2012	fum	92.3	530698	4938710	0.3	74.3	19.64	<0.0002	0.005	0.156	0.0768	0.023	5.6	0.2154	0.00004	0.0004			
YL12-15	Highland #5	20	09/09/2012	fum	92.3	530716	4938613	0.3	55.1	13.15	<0.0002	0.006	0.080	0.3876	0.019	31.1	0.1395	<0.00001	0.0002			
YL12-19	Nymph_Lake_new_feature	17	09/13/2012	fum	92.7	521452	4955523	2.1	98.5	0.97	<0.0002	0.005	0.104	0.0078	0.0015	0.32	0.0737	0.00025	0.0002	<0.00001	<0.00001	<0.002
YL12-20	Nymph_frying_pan	17	09/13/2012	fry	91.4	521481	4955449	1.9	98.3	0.94	<0.0002	0.006	0.313	0.0096	0.0029	0.38	0.0887	0.00024				
YL12-21	Obsidian_Creek_Pool_gas	6	09/13/2012	pool	68.8	520644	4959557	150.0	97.0	0.03	<0.0002	0.006	0.058	0.0501	0.75	2.0	0.0521	0.00075	0.0002	0.0001	0.00004	<0.002
YL12-22	Gibbon_River_Bridge	18	09/13/2012	fum	93.3	520295	4947980	2.3	99.1	0.56	<0.0002	0.001	0.176	0.0031	0.0012	0.15	0.0264	0.00043	0.0002			
YL12-24	Sulfur_Hills_Fumarole #1	1	09/14/2012	fum	103.4	553792	4938184	0.24	80.4	6.60	0.461	0.006	8.63	0.0344	0.013	1.6	0.7420	0.00160	0.0019	0.0002	0.00007	<0.002
YL12-25	Sulfur_Hills_Fumarole #2	1	09/14/2012	fum	114.3	554027	4938193	0.17	77.9	10.95	0.058	0.007	8.67	0.0511	0.083	1.6	0.6426	0.00783	0.0023			

[1] Site is a cold gas seep; listed as a fumarole for simplicity.

[2] Carbon isotope composition is different than reported in Werner and others, 2008.

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Table 2. Sample collection parameters, volume % normalized gas compositions, and isotope ratios for gas collected within and around Yellowstone National Park, Wyoming during 2003 through 2012 (part 2).—Continued

[Gas for compositional analyses and δ¹³C-CO₂ (C) was collected in tubes containing NaOH, gas for ³He/⁴He ratios and δ¹³C-CO₂ (E) collected in empty tubes; a blank cell indicates that an analysis was not attempted]

Sample number	HCl mol%	R/Ra	Rc/Ra	Ne2022	Ne2122	Ar3836	Ar4036	F⁴He	HeNe_Air	⁴He/⁴⁰Ar*	δ¹³C-CO₂ (C) per mil	δ¹³C-CO₂ (E) per mil	δ¹³C-CH₄ per mil	δ³⁴S-H₂S per mil	* CO₂-³He	δD per mil	δ¹⁸O per mil	N₂/Ar	YNP Thermal Features Database
YL03-01A	<0.001	7.32	7.37	9.952	0.0291		284		32						2.1E+09	-173	-21	40.0	
YL03-02A	<0.001	6.11	6.13	9.888	0.0293		287		84		-3.2				2.2E+09	-175	-22.7	39.3	Fumarole
YL03-03A	<0.001										-3.4					-178	-21.1	35.2	
YL03-04A	<0.001										-3.4							38.9	
YL03-05B	<0.001	6.85	7.17	9.919	0.0292		291		5						3.7E+09	-172	-20.2	41.6	
YL03-06B	<0.001										-3.0							40.2	Green Dragon Spring
YL03-07	<0.001	6.87	7.04	9.992	0.0293		284		10						7.8E+09	-167	-20.2	40.0	Son of Green Dragon Spring
YL03-08	0.26										-2.7							39.1	Dishwater Spring
YL03-09B	<0.001	12.34	12.40	10.013	0.0293		278		53					-1.0	5.2E+09	-178	-21.1	41.5	GGCGNN073
YL03-10B	<0.001	7.29	7.35	10.018	0.0295		281		29		-4.7				5.7E+09	-168	-20.8	39.4	Black Growler
YL03-11B	<0.001										-2.7							41.1	Black Pit Spring
YL03-12A	<0.001										-3.3					-171	-20.8	34.9	
YL03-13A	<0.001	4.93	4.94	10.07	0.0303		287		124		-3.0			0.2	3.5E+09	-167	-19.8	39.8	
YL03-14B	<0.001	7.92	7.93	9.761			292		186		-4.3				3.0E+10			31.3	GTSANN003
YL03-15A	<0.001	6.32	6.32	9.905	0.0289		299		220		-3.0			-1.2	1.4E+09			39.1	
YL03-16A	<0.001	6.26	6.26	10.014			325		740						2.9E+09			41.3	
YL03-17A	<0.001	7.72	7.82				294		19		-3.6				4.0E+09	-171	-22	38.1	
YL03-18A	0.01										-4.0							38.4	
YL03-19A	<0.001	5.49	5.50	9.987	0.0294		292		95		-4.9				1.7E+09	-163	-20.6	38.1	
YL03-20	<0.001										-4.9							42.0	
YL03-21A	<0.001	5.62	5.64	9.968	0.0294		302		95		-4.8				1.6E+09	-162	-21.7	39.0	
YL04-01	0.002										-3.7							40.1	Black Pit Spring
YL04-02	0.20										-2.0							39.3	
YL04-03	0.01										-1.9							40.9	
YL04-04	0.02	4.74	4.75	10.306			312		1021		-3.5				3.3E+09	-159	-19.3	42.6	
YL04-05	0.01	7.39	7.45	10.102			293		100		-3.5				4.1E+09	-174	-23.3	38.7	
YL04-06	0.002	3.26	3.28	10.36			289		159		-2.6				1.6E+10			43.3	
YL04-07	0.003										-3.2					-176	-23.4	41.9	
YL04-08	0.02										-4.1					-174	-22.4	40.8	
YL04-09	0.004	7.66	7.81	9.947			285		48		-2.7				5.8E+09			36.0	NBBNN032
YL04-10	0.002										-2.5							66.8	Green Dragon Spring
YL04-11	<0.001										-3.4					-175	-23.4	38.8	
YL04-12	0.01	4.48	4.48	10.363			299		635		-3.1				3.8E+09	-169	-22	39.0	
YL04-13	0.04	6.20	6.22	9.896			292		205		-2.6				1.9E+09			40.7	
YL04-14	0.01	11.57	12.13	9.871			297		20		-4.1				8.4E+09	-171	-20.7	58.0	
YL04-15	0.01	0.84		9.855			294		1.3		-2.3				1.4E+11			41.7	
YL04-17	0.001	7.25	7.32	10.458			286		101		-3.0				2.9E+09			41.5	
YL04-19	<0.001	7.13	7.14	10.168			345		714		-3.2				2.8E+09	-164	-21.3	43.2	GSSGNN060
YL04-20	0.003										-3.2					-149	-18.8	42.4	GSSGNN060
YL04-21	0.01	5.07	5.08	9.978			314				-2.9				2.9E+09	-162	-21.6	39.4	GSSGNN076
YL04-22	0.03	10.02	10.40	10.073			345								4.8E+09			42.7	
YL05-01	0.22	6.48	6.48	10.5			335		2106		-3.8				3.4E+09	-163	-21.7	36.5	Black Pit Spring
YL05-02	0.01										-4.8							29.3	GTSANN003
YL05-03	<0.001										-3.8					-143	-16.3	37.1	NMCNN036
YL05-04	0.01	12.14	12.15	11.4			383		2476		-3.6				3.7E+09	-163	-22	43.3	GGCGFM002
YL05-05	0.01										-4.6					-166	-22.1	33.7	
YL05-06	<0.001	7.26	7.31	10.4			301		148						4.6E+09	-162	-20.1	29.5	
YL05-07	0.002										-3.7							35.2	
YL05-08	<0.001										-3.9					-161	-20.7	34.9	Black Growler
YL05-09	<0.001										-3.4					-166	-21.8	36.6	
YL05-10	<0.001	4.71	4.71	10.1			329		1533		-3.2				3.4E+09	-164	-20.5	37.4	
YL05-11	<0.001										-4.1							34.0	GCPNN006
YL05-12	0.001	14.97	14.98	11.3			397		1441		-2.7				2.3E+09			47.1	
YL05-13	0.01	15.29	15.29	10.6			606		4354		-2.9				2.1E+09			60.0	
YL05-13A	<0.001										-2.9							61.9	
YL05-14	<0.001	1.87	1.87	10.1			480		9832		-4.2				3.6E+09	-155	-20.1	34.7	
YL05-15	<0.001										-4.4							38.4	Narrow Gauge Spring and Terrace
YL05-17A	<0.001	3.48	3.48	10.3			344		722						2.4E+09	-171	-22.2	34.5	
YL05-17B	<0.001																	35.6	
YL05-18A	<0.001										-3.2					-164	-21.4	40.6	GGCGFM002
YL05-18B	<0.001										-3.2					-160	-22.2	43.1	GGCGFM002
YL05-18C	<0.001										-3.2							33.6	GGCGFM002
YL05-18D	<0.001										-3.2	-2.7						41.0	GGCGFM002
YL06-01A	<0.001	5.52	5.52	10.08	0.036		418		12006	* 22.5	²-4.2				1.5E+09	-148	-15.7	33.5	

¹Site is a cold gas seep; listed as a fumarole for simplicity.

²Carbon isotope composition is different than reported in Werner and others, 2008.

*Values are revised from the previous version of this report.

Table 2. Sample collection parameters, volume % normalized gas compositions, and isotope ratios for gas collected within and around Yellowstone National Park, Wyoming during 2003 through 2012 (part 2).—Continued

[gas for compositional analyses and δ¹³C-CO₂ (C) was collected in tubes containing NaOH, gas for ³He/⁴He ratios and δ¹³C-CO₂ (E) collected in empty tubes; a blank cell indicates that an analysis was not attempted]

Sample number	HCl mol%	R/Ra	Rc/ Ra	Ne2022	Ne2122	Ar3836	Ar4036	F⁴He	HeNe_Air	⁴He/⁴⁰Ar*	δ¹³C-CO₂ (C) per mil	δ¹³C-CO₂ (E) per mil	δ¹³C-CH₄ per mil	δ³⁴S-H₂S per mil	* CO₂-³He	δD per mil	δ¹⁸O per mil	N₂/Ar	YNP Thermal Features Database
YL06-02	0.002	6.73	6.73	9.925	0.029		367		1961	* 11.5	[2] -3.8				1.8E+09			38.5	
YL06-03	<0.001										[2] -4.0							31.0	SCANN196
YL06-04	0.001	5.10	5.10	10.117	0.036		466		12634	* 23.9	[2] -3.9				1.6E+09	-159	-18.6	25.1	
YL06-05	0.01										[2] -3.7							40.4	
YL06-06	<0.001	5.67	5.69	10.129	0.031		369		5002	* 21.7	[2] -4.3				2.6E+09			33.4	
YL06-07	0.01	4.63	4.71	10.556	0.03		287		48		[2] -4.2				4.9E+09	-158	-17.5	78.5	
YL06-08	0.01										[2] -4.0							38.7	
YL06-09	<0.001										-3.7					-159	-21.2	36.2	Black Pit Spring
YL06-10	<0.001																	39.0	
YL06-11	<0.001	7.43	7.43	10.019	0.027		315		1321	* 11.2	-3.5				4.4E+09	-168	-21.4	38.8	Guardian Geyser
YL06-12	<0.001										-4.1							38.6	
YL07-01	<0.001										-2.8							41.1	
YL07-02	<0.001	15.28	15.29	10.346	0.0308	0.22	531	2457	3543	1.7	-2.7				2.2E+09			65.7	
YL07-03	<0.001	16.48	16.49	10.473	0.0305	0.183	593	2803	3924	1.6	-2.8				2.2E+09			66.2	
YL07-04	<0.001	4.91	4.91	10.044	0.0298	0.199	332	504	1495	2.3	-3.4				1.5E+10			202.0	WHSNN014
YL07-05	<0.001	4.78	4.78	9.768	0.03	0.208	403	2497	3767	3.9	-5.0				1.8E+10			47.8	
YL07-06	<0.001	2.95	2.95	9.873	0.0296	0.217	298	138	438		-3.5				4.6E+09			37.2	
YL07-09	<0.001										-3.5							42.1	Guardian Geyser
YL07-10	0.003	8.76	8.79	9.916	0.029	0.199	303	166	285		-3.1				2.6E+09			39.4	Steam Valve Spring
YL07-11	<0.001										-2.9							39.5	
YL07-12	<0.001										-4.3							39.6	
YL07-13	<0.001										-2.9							64.5	
YL07-14	<0.001	6.06	6.07	9.904	0.03	0.224	308	120	308	1.6	-3.2				2.0E+09			38.4	Fumarole
YL07-15	<0.001	12.19	12.22	10.09	0.031	0.183	311	222	377	2.3	-3.4				3.9E+09			44.4	GGCGNN073
YL07-17	<0.001	10.37	10.37	10.11	0.0302	0.2	351	801	1354	2.4	-2.9				2.6E+09			52.1	
YL07-18.1	0.01										-1.4							82.5	
YL07-18.2	0.01																	83.3	
YL08-02	<0.001	0.76	0.76	9.912	0.0292	0.196	325	1328	4525	7.4	-3.6		-45.5		3.6E+09	-148	-19.8	37.0	BSRNN033
YL08-03	0.002										0.2		-37.9					37.7	
YL08-04	0.01	4.35	4.73	9.97	0.0291	0.186	294	8.5	10		-3.4		-43.6		2.2E+10			39.6	
YL08-04B	0.003										-3.0		-43.5					41.5	
YL08-05	0.003										0.4		-38.7					45.1	
YL08-07B	0.01	0.81	0.80	9.958		0.192	296	96	266		-13.3		-28.3		1.1E+09			43.7	
YL08-08	0.03												-28.3			-164	-21.7	33.8	
YL08-09	<0.001	11.65	11.65	10.007	0.0345	0.191	309	796	2560		-3.0	-2.9	-23.9		2.9E+09			45.2	
YL08-10	<0.001	11.93	11.93	10.044	0.0302	0.195	332	726	1641	3.3	-4.1	-2.9	-24.3		3.3E+09			44.8	
YL08-11	0.002	12.17	12.19	9.921	0.0306	0.194	317	350	563	2.7	-2.4	-2.3	-33.6		2.4E+09	-161	-23.5	42.6	Ochre Spring
YL08-12	<0.001	7.71	7.74	9.848	0.0296	0.198	303	160	218		-3.3	-3.2	-44.4		1.8E+09			52.8	Poison Spring
YL08-13	<0.001										-4.5	-4.3						75.2	APTNN011
YL08-14	<0.001	16.28	16.28	10.443	0.0323	0.192	351	1470	4584	4.4	-2.5	-2.4	-23.4		1.9E+09			64.9	MVNN003
YL08-14B	<0.001										-2.5		-23.5					63.4	MVNN003
YL08-15	<0.001										-2.4	-2.4	-24.6					54.9	Obsidian Pool
YL08-16	<0.001	7.28	7.30	10.04	0.03	0.192	302	240	516	1.6		-4.1	-31.8		2.4E+09	-162	-19.8	34.1	
YL08-17	0.002										-2.8		-31.8					40.5	Steam Valve Spring
YL08-18	<0.001	3.03	3.03	10.086	0.0351	0.232	736	8447	21636	3.2	-3.0		-42.8		2.3E+09			34.8	
YL08-19	<0.001	2.98	2.99	10.235	0.0379	0.19	307	501	308	7.1	-2.9		-46.4		2.1E+09			35.2	
YL08-20	<0.001										-3.0		-43.3					29.6	
YL09-01	<0.001	6.05	6.30	9.858			321	78	21	0.5					2.9E+09	-165	-21.9	35.0	
YL09-02	<0.001	7.58	8.10	9.84			318	58	14	0.43	-1.7				7.7E+09			36.5	
YL09-03A	<0.001	4.53	4.55	9.752			414	1029	158	1.45	-2.7		-28.2		3.0E+09	-152	-20.2	42.4	
YL09-03B	0.01										-2.8		-28					42.4	
YL09-04	<0.001	5.60	5.65	9.977			425	1070	95	1.37	-3.4		-25.4		2.5E+09			39.8	NMCNN036
YL09-05	0.17	1.20	1.21	9.888			314	124	32	1.13	-4.7		-44.2		1.2E+10			30.5	
YL09-06	<0.001	1.14	1.14	9.811			347	525	122	1.68	-3.4		-44.1		4.2E+09			29.3	
YL09-07B	0.01										-4.4	-2.4						64.0	
YL09-08	0.40	1.09	1.09	9.869			335	348	78	1.47			-43.2		8.2E+08			33.7	HLRNN018
YL09-09	0.18	1.81	1.81	9.817			323	415	123	2.55	-3.0	-1.4	-40.5		1.8E+09	-167	-23.9	37.2	
YL09-10	<0.001	2.67	2.70	9.795			316	267	75	2.19	-2.0	-1.6	-36.8		1.9E+09	-155	-21.8	35.2	
YL09-11	<0.001	2.91	2.94	9.812			331	227	59	1.08			-36.5		1.7E+09			36.9	
YL09-12	<0.001												-43.2					37.5	HLRNN018
YL09-13	0.23	7.18	8.82	10.173			347	31	5	0.1	-3.3				2.0E+09	-163	-22	32.0	
YL09-14	<0.001										-2.9							37.5	
YL09-15	<0.001										-4.0							29.5	GTSANN003
YL09-16	0.01	4.00	4.02	10.135			600	2560	121	1.4	-3.0		-32.4		4.3E+09	-158	-19	37.1	
YL09-17	<0.001	4.19	4.23	10.409			625	3108	78	1.57	-3.0		-32.5		4.0E+09			37.8	
YL09-18	0.002	2.40	2.41	9.784			374	1136	255	2.4	-3.0		-37.3		2.6E+09			39.9	

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Table 2. Sample collection parameters, volume % normalized gas compositions, and isotope ratios for gas collected within and around Yellowstone National Park, Wyoming during 2003 through 2012 (part 2).—Continued

[Gas for compositional analyses and δ¹³C-CO₂ (C) was collected in tubes containing NaOH, gas for ³He/⁴He ratios and δ¹³C-CO₂ (E) collected in empty tubes; a blank cell indicates that an analysis was not attempted]

Sample number	HCl mol%	R/Ra	Rc/Ra	Ne2022	Ne2122	Ar3836	Ar4036	F⁴He	HeNe_Air	⁴He/⁴⁰Ar*	δ¹³C-CO₂ (C) per mil	δ¹³C-CO₂ (E) per mil	δ¹³C-CH₄ per mil	δ³⁴S-H₂S per mil	* CO₂-³He	δD per mil	δ¹⁸O per mil	N₂/Ar	YNP Thermal Features Database
VHZDB11-01		3.61	6.19																
YL11-02	0.11	7.60	7.64	9.858	0.0290	0.1896	300	76	197			-2.3	-28.0		2.3E+09	-186	-25.4	34.6	
YL11-03	0.004	15.96	15.97	10.430	0.0358	0.1804	600	2401	5146	1.3	-2.9	-2.3	-21.2		2.2E+09	-161	-21.0	64.9	
YL11-04	0.19	7.10	7.13	9.891		0.1845	306	309	240	5.1					3.2E+09	-164	-19.4	35.0	
YL11-05	0.02										-3.1		-27.3					37.3	
YL11-06	0.005	12.26				0.1797	373	844		1.8	-3.0	-2.8	--		5.8E+09	-167	-22.0	44.8	
YL11-07	0.08	4.20	4.21	9.876	0.0290	0.1850	301	106	352		-3.8	-2.3	-27.5		5.2E+09	-155	-19.9	37.1	
YL11-11	0.02	7.49	7.56	9.899	0.0291	0.1891	297	58	104		-2.2	-1.7	-32.9		2.1E+09			45.9	SBSGNN009
YL11-13	0.05	7.91	7.94	9.822	0.0290	0.1853	299	91	222		-2.8	-2.2	-27.0		2.1E+09	-158	-20.9	37.7	
YL11-14	0.04	3.18	3.19	9.826	0.0290	0.1836	301	76	231		-3.4	-2.2	-25.8		6.9E+09	-162	-21.3	37.5	
YL11-15_1	0.03	7.58	7.60	9.843	0.0266	0.1896	297	136	381		-3.0	-2.4	-27.5		2.9E+09	-164	-21.4	45.4	
YL11-15_2	0.03										-2.9		-27.2					42.4	
YL11-16	0.11	8.59	8.60	9.893	0.0290	0.1898	299	386	1008						4.0E+09	-177	-24.2	32.5	
YL11-17_1	0.01	8.92	8.99	9.859	0.0290	0.1919	300	46	121		-3.9				1.0E+09			36.5	
YL11-17_2	0.01										-3.8							36.5	
YL11-18	0.03	8.60	8.89	9.852	0.0290						-5.1				1.8E+09			66.2	SCGNN006
YL11-19	0.02	8.66	8.72	9.868	0.0290	0.1888	297	60	131		-2.5	-2.3	-29.0		1.5E+09			36.3	SMMGNN014
YL11-27	0.01			9.858	0.0290						-2.6	-2.0	-32.2					39.3	
YL11-31	<0.001										-2.9		-23.0					37.9	
YL12-01	<0.001	5.14	5.15	10.380	0.0302	0.1993	324	660	1	3.8	-3.2		-27.4		3.4E+09			48.1	
YL12-02	<0.001	4.75	4.76	9.748	0.0301	0.1880	308	373	1	4.9	-5.7		-37.8		1.7E+09			41.6	
YL12-03	<0.001			192.9														37.3	
YL12-04	<0.001										-2.9		-28.4					41.0	
YL12-05	<0.001										-4.6							40.3	
YL12-06		16.43	16.43									-2.3							
YL12-07	<0.001	12.31	12.31	10.060	0.0312	0.1945	372	1378	5	3.0	-2.9	-2.6			2.9E+09	-161	-21	45.5	
YL12-09	<0.001	8.45	8.59	10.160	0.0306	0.1962	293	114	0.06		-3.3	-2.7	-23.6		1.7E+09	-193	-27	67.4	
YL12-10	<0.001	8.47	8.55	10.350	0.0297	0.1943	295	113	0.10			-2.6			1.3E+09	-169	-21.8	55.4	
YL12-11	<0.001	7.62	8.73	9.753	0.0292	0.2022	296	7	0.01			-2.7			2.4E+09	-159	-20.1	81.1	
YL12-14	<0.001	8.03	8.22	10.430	0.0301	0.2009	287	95	0.04			-2.7			1.3E+09	-177	-24.4	72.5	
YL12-15	<0.001	5.17	5.65	9.800	0.0290	0.1952	287	21	0.01			-2.7			1.3E+09	-172	-22.7	80.3	
YL12-19	<0.001										-3.1	-2.8	-24.8			-162	-20.9	40.5	
YL12-20	<0.001										-3.1		-25.2					39.1	
YL12-21	<0.001										-3.2							40.0	
YL12-22	<0.001										-2.9	-2.8				-163	-22.7	48.8	
YL12-24	1.5	7.48	7.48	9.942	0.0295	0.2007	304	319	1.00			-2.5	-37.2		1.3E+09	-147	-18.3	46.6	
YL12-25	0.12	6.97	6.98	9.798	0.0302	0.1881	308	316	0.74	4.1		-2.7			1.1E+09	-151	-18.5	30.3	

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typically pools have higher Xg because the steam condenses as it bubbles through the water). The value for a gas-free sample would approach zero. Our expected accuracy is 10 percent relative; that is, an Xg of 10 should be between 9 and 11 mol percent gas.

CO_2: Mole percent carbon dioxide relative to all other gases (H_2O-free). One-sigma uncertainty is 0.2 mol percent (absolute) based on replicate analysis of individual samples. Uncertainty based solely on counting statistics is less than 0.1 mol percent.

H_2S: Mole percent hydrogen sulfide relative to all other gases (H_2O-free). In samples from 2003 through 2006, sulfate concentrations were not corrected (for the blank), and samples with very low H_2S from those years may have slightly higher reported values than their actual concentrations. One-sigma uncertainty is ~5 percent relative, based on replicate analysis of individual samples.

NH_3: Mole percent ammonia relative to all other gases (H_2O-free). One-sigma uncertainty is 10 percent relative based on replicate analysis of individual samples.

He: Mole percent helium relative to all other gases (H_2O-free). One-sigma uncertainty based on replicate analysis of samples is ~1 percent relative.

H_2: Mole percent hydrogen relative to all other gases (H_2O-free). One-sigma uncertainty based on replicate analysis of samples is ~1 percent relative.

Ar: Mole percent argon relative to all other gases (H_2O-free). One-sigma uncertainty based on replicate analysis of samples is ~1 percent relative.

O_2: Mole percent oxygen relative to all other gases (H_2O-free). Most samples had very little O_2. For samples with low O_2 contents, the one-sigma uncertainty is 50 percent relative, based on replicate analysis of individual samples. Most variability is from small amounts of air entrained during sampling. Samples with more than 0.1 mol percent O_2 have much lower uncertainty, and their values should be accurate to within 5 percent relative.

N_2: Mole percent nitrogen relative to all other gases (H_2O-free). One-sigma uncertainty based on replicate analysis of samples is ~2 percent relative. As with O_2, most variation is due to small variations in entrained air.

CH_4: Mole percent methane relative to all other gases (H_2O-free). One-sigma uncertainty based on replicate analysis of samples is ~1 percent relative.

C_2H_6: Mole percent ethane relative to all other gases (H_2O-free). One-sigma uncertainty based on replicate analysis of samples is ~15 percent relative.

HCl: Mole percent hydrogen chloride relative to all other gases (H_2O-free). In reality, nearly all Cl^- in the gas sample is not from HCl-bearing gas, but comes from small droplets of Cl^--bearing thermal water that enter into the gas stream at bubbling pools and frying pans. Samples with high apparent HCl may also have anomalous H_2S by the same process. The one-sigma analytical uncertainty is 5 percent relative, but the random appearance of Cl^- (through entrainment of thermal water) within replicate samples implies that reproducibility is low.

R/R_a: $^3He/^4He$ ratio of sample divided by that in air (1.399×10^{-6}). One-sigma analytical error is 0.01.

R_c/R_a: $^3He/^4He$ ratio of sample divided by that in air (1.399×10^{-6}) and corrected for any air that may have been mixed into the sample.

Ne2022: $^{20}Ne/^{22}Ne$ ratio in the gas. One-sigma analytical error is 0.003.

Ne2122: $^{21}Ne/^{22}Ne$ ratio in the gas. One-sigma analytical error is 0.0001.

Ar3836: $^{38}Ar/^{36}Ar$ ratio in the gas. One-sigma analytical error is 0.004.

Ar4036: $^{40}Ar/^{36}Ar$ ratio in the gas. The air ratio is 298.6. One sigma uncertainty is 2.

F^4He: $^4He/^{36}Ar$ in sample divided by the same ratio in air.

HeNe_Air: The He/Ne ratio in the sample divided by the same ratio in air.

$^4He/^{40}Ar^*$: Counts of ^4He divided by the calculated radiogenic ^{40}Ar (that is, subtracting that ^{40}Ar calculated as derived from air). This value approximates the decay ratio of U, Th, and other elements that produce He daughter products compared with those that produce Ar (that is, K).

$\delta^{13}C$-CO_2: The $^{13}C/^{12}C$ ratio in CO_2, as normalized by the same ratio in the standard Vienna PeeDee Belemnite (VPDB). Units in per mil. $\delta^{13}C_{sample} = \{(^{13}C/^{12}C$ sample) / ($^{13}C/^{12}C$ standard) $- 1\} \times 1000$. Two-sigma uncertainty is 0.2 per mil.

$\delta^{13}C$-CH_4: The $^{13}C/^{12}C$ ratio in CH_4, as normalized by the same ratio in the standard Vienna PeeDee Belemnite (VPDB). Units in per mil. $\delta^{13}C_{sample} = \{(^{13}C/^{12}C$ sample) / ($^{13}C/^{12}C$ standard) $- 1\} \times 1000$. Two-sigma uncertainty is 0.2 per mil.

$\delta^{34}S$-H_2S: The $^{34}S/^{32}S$ ratio in H_2S, as normalized by the $^{34}S/^{32}S$ ratio in the standard Canyon Diablo Troilite (CDT). Units in per mil. $\delta^{34}S_{sample} = \{(^{34}S/^{32}S$ sample) / ($^{34}S/^{32}S$ standard) $- 1\} \times 1000$. One sigma uncertainty is 0.1 per mil.

$CO_2\_^3He$: The molar ratio of CO_2 to ^3He in the gas sample. The propagated one-sigma uncertainty is 5 percent relative.

δD_s: The ratio of D/H in steam condensed from the gas sample. Steam was condensed to liquid water in select fumarole and frying pan samples. The value is normalized to the D/H ratio in the standard Vienna Standard Mean Ocean Water (VSMOW). Units are reported in per mil (‰). $\delta D_{sample} = \{(D/H$ sample) / (D/H standard) $- 1\} \times 1000$. Analytical uncertainty of 1.0 per mil (2003-8) and 0.3 permil (2009), respectively.

$\delta^{18}O_s$: The ratio of $^{18}O/^{16}O$ in steam condensed from the gas sample. Steam was condensed to liquid water in select fumarole and frying pan samples. The value is normalized to the $^{18}O/^{16}O$ ratio in the standard Vienna Standard Mean Ocean Water (VSMOW). Units are reported in per mil (‰). $\delta^{18}O_{sample} = \{(^{18}O/^{16}O \text{ sample}) / (^{18}O/^{16}O \text{ standard}) – 1\} \times 1{,}000$. Analytical uncertainty is 0.1 per mil.

N_2/Ar: The N_2/Ar ratio in the sample. For comparison, the air ratio is 83.6. The ratio in air-equilibrated meteoric water at 10°C is 37.7 (Wilhelm and others, 1977). Propagated one-sigma uncertainty is 1.4 percent relative.

YNP Thermal Features Database: The name of our sampled feature in the Yellowstone National Park Thermal Features Database (http://www.rcn.montana.edu/Features/Search.aspx). We only provide the name if our thermal feature is believed to be precisely the same as that shown in the thermal features database.

Data Formats and Uncertainties: Table 3 Water Analyses

Below we outline the data columns in table 3 and information relevant for interpretation of values and their related uncertainties.

Sample: Alpha-numeric codes begin with YL and are followed by a two-digit year code (03 for 2003, for example), a hyphen, and a sample number for that year, finishing with a W (for water).

Location: Informal name for the sampled feature. The name could be a defined thermal feature or could indicate simply that it was sampled in the same general location. When we sampled an actual thermal feature denoted in the Yellowstone Thermal Features database (http://www.rcn.montana.edu/Features/Search.aspx), we list the name of that feature in the "YNP Thermal Features Database" column.

Identical Feature: If the water sample comes from the same feature that was sampled for gas (with the same sample name excepting the "W"), then the answer is YES. If the water sample comes from a nearby feature, the answer is NO. For example, the fumarole sampled as YL07-04 is from a steaming area near Inkpot Spring, whereas YL07-04W came from Inkpot Spring itself. In addition, two water samples were collected from areas where gas was not sampled.

Date: In month/day/year format (mm/dd/yyyy).

Temp: Temperature in degrees Celsius. Temperature can be reproducibly measured to within 0.1°C, but accuracy may be limited to ~0.5°C because of temperature variability within the feature and instrumental variations.

Easting: East-west location in Universal Transverse Mercator (UTM) coordinate system, Zone 12. Datum is NAD83 (nearly identical to WGS84). Units are in meters. Uncertainties are generally ~3 m.

Northing: North-south location in Universal Transverse Mercator (UTM) coordinates, Zone 12. Datum is NAD83 (nearly identical to WGS84). Units are in meters. Uncertainties are generally ~3 m.

δD_w: The ratio of D/H in the sampled thermal water. The value is normalized to the D/H ratio in the standard Vienna Standard Mean Ocean Water (VSMOW). Units are reported in per mil (‰). $\delta D_{sample} = \{(D/H \text{ sample}) / (D/H \text{ standard}) – 1\} \times 1{,}000$. Analytical uncertainty of 1.0 per mil (2003-8) and 0.3 per mil (2009), respectively.

$\delta^{18}O_w$: The ratio of $^{18}O/^{16}O$ in the sampled thermal water. The value is normalized to the $^{18}O/^{16}O$ ratio in the standard Vienna Standard Mean Ocean Water (VSMOW). Units in per mil (‰). $\delta^{18}O_{sample} = \{(^{18}O/^{16}O \text{ sample}) / (^{18}O/^{16}O \text{ standard}) – 1\} \times 1{,}000$. Analytical uncertainty of 0.1 per mil.

pH (F): pH as measured in the field. For hot spring waters, we used paper indicator strips with an uncertainty of about 0.5. For cold spring waters pH was measured using a calibrated meter with an uncertainty of about 0.1.

pH (L): pH as measured in the laboratory using a calibrated meter with an uncertainty of about 0.1.

Cond. μS/cm: Specific conductance as measured in the laboratory using a calibrated meter.

Cations: Al, B, Br, Ca, Fe, K, Mg, Na, NH4$^+$, and SiO$_2$ in mg/l. As, Ba, Cd, Co, Cr, Cs, Cu, Li, Mn, Mo, Ni, Sr, Ti, U, and Zn in μg/l.

Anions: Br, Cl$^-$, CO$_3^{2-}$, F, HCO$_3^-$, PO$_4^{3-}$, and SO$_4^{2-}$ in mg/l.

TDS: Total dissolved solids in mg/l.

Cation: Cation totals in meq/l.

Anion: Anion totals in meq/l.

Balance: percentage mismatch between anions and cations.

Results

Bulk Gas Chemistry

Nearly all samples were dominated by CO_2 (table 2), most with more than 90 mol percent on a dry-gas basis (excluding water from steam). Exceptions were a few samples high in atmospheric gases either from air contamination during sampling or from boiling of meteoric water (usually samples with low Xg). The next most abundant gas was N_2, averaging 3.1 mol percent and with a median of 1.0 percent, followed by H_2S (average of 1.3 mol percent, median of 0.9 percent) (table 4). Gas from a slow-bubbling pool near the Snake River, south of the park (fig. 1) had a very anomalous N_2 content in excess of 44 mol percent.

Table 3. Water chemistry, stable isotope values, and sample collection parameters for waters collected within and around Yellowstone Park, Wyoming during 2003 through 2012 (part 1).

[Analyte concentrations are reported in mg/l or mg/l. Stable isotope values of water are reported in per mil relative to SMOW (δD and $\delta^{18}O$). A blank cell indicates that an analysis was not attempted. Field pH values (pH F) in bold were determined using a meter, and others were determined using indicator paper. Laboratory pH values (pH L) were determined using a meter.]

Sample number	Location	Feature	Identical Feature	Date	Temp °C	Easting meters	Northing meters	δD_w per mil	$\delta^{18}O_w$ per mil	pH (F)	pH (L)	Cond. µS/cm	Al mg/l	As µg/l	B mg/l	Ba µg/l	Br mg/l	Ca mg/l	Cd µg/l	Cl mg/l	Co µg/l	CO3 mg/l	Cr µg/l
YL03-01W	Lone_Star	hot spring pool	No	09/04/2003	94.0	515429	4918413	-145	-15.7	8.0			0.50	1460	4.9	5.09	1.32	1.6		434			
YL03-08W	Dishwater	pool with gas	Yes	09/06/2003	89.4	523384	4952086	-132	-9.1	3.1			1.58	2400	9.3	32.5	1.96	6.1		655			
YL03-09W	Beryl_Spring	hot spring pool	No	09/07/2003	93.6	520077	4947298	-145	-14.6	6.6			0.35	2700	7.2	1.68	1.58	4.0		559			
YL03-11W	Black_Pit	pool with gas	Yes	09/07/2003	93.9	523595	4952211	-119	-9.6	6.6			0.18	16	1.7	20.9	0.07	2.2		41.8			
YL03-13W	Nymph_Lake_new_feature	fry	Yes	09/08/2003	93.6	521471	4955495	-144	-15.2	8.1			0.38	3620	6.4	12.5	1.37	3.7		443			
YL03-14W	Terrace_Springs	pool with gas	Yes	09/08/2003	63.3	512184	4944102	-156	-18.6	6.5			0.03	190	1.4	5.27	0.16	20		65.4			
YL03-15W	W._Nymph_Lake_Thermal_Area1	hot spring pool	Yes	09/09/2003	82.0	520335	4954609	-118	-6.7	(1)			6.8	3.1	0.58	107	<0.01	9.6		1.3			
YL03-21W	Smokejumper4	pool with gas	Yes	09/12/2003	92.1	503559	4918096	-137	-15.6	5.3			0.72	<0.26	<0.04	6.24	<0.01	0.4		1.1			
YL04-06W	Bison_Kill	fry	No	09/14/2004	8.5	523471	4954042	-102	-12.4	6.6			0.03		7.3	90.9	0.50	28		370			
YL04-09W	Back_Basin2	pool with gas	Yes	09/15/2004	67.4	522963	4952193	-128	-10.7	[2]3.1			1.30		8.6	29.1	1.90	5.8		605			
YL04-13W	Hundred_Springs_Plain	pool with gas	Yes	09/15/2004	89.1	523113	4953330	-147	-15.6	6.4			0.12		8.3	81.4	1.90	2.1		617			
YL04-16W	Y. River Spring near Tower	hot spring flowing	No	09/16/2004	31.6	548920	4971425	-152	-17.4	5.5			0.10		13.0	59.3	0.32	120		104			
YL04-AW	Nymph_Lake_new_feature	fry	No	05/24/2004	61.0	521471	4955495	-136	-14.3	5.5			0.14		6.4	20.3	1.30	4.1		448			
[6]YL05-11W	Chocolate_Pots	hot spring flowing	Yes	09/16/2005	52.5	520496	4950780	-148	-19.1	5.0	8.47	686	0.16	37	0.5	53.1	0.07	20	0.030	32.5	<0.1		<0.3
YL05-02W	Terrace_Springs	pool with gas	Yes	09/13/2005	62.3	512184	4944102	-150	-18.9	6.5	8.40	1402	0.04	176	1.0	12.2	0.13	19	0.350	64.8	<0.1		0.5
YL05-03W	Frying_Pan_Spring	fry	Yes	09/15/2005	91.8	521979	4955476	-113	-8.9	[3]1.5	2.02	4810	26	9.0	0.09	75.6	1.0	7.9	2.65	0.30	3.4		8.8
YL05-10W	Nymph_Lake_new_feature	fry	Yes	09/16/2005	93.5	521456	4955507	-135	-15.0	7.0	8.06	1823	0.08	3090	6.5	29.0	1.50	4.2	0.090	478	<0.1		<0.3
YL05-15W	Narrow_Gauge	hot spring flowing	Yes	09/19/2005	74.8	522880	4979593	-149	-18.3	7.0	7.51	2580	0.03	501	3.4	77.6	0.40	330	<0.02	162	<0.1		<0.3
YL05-17W	Quagmire	hot spring flowing	Yes	09/21/2005	93.4	515413	4934994	-142	-16.4	8.5	9.34	1563	0.20	1340	4.3	7.22	1.00	1.5	0.360	343	<0.1		<0.3
YL07-04W	Behind_Inkpot	hot spring flowing	No	09/14/2007	92.0	545104	4956992	-120	-8.1	5.0		3800	0.25	0.2	22.0	52.8	<0.01	44		0.20			
YL07-10W	Steamvalve	pool with gas	Yes	09/15/2007	68.8	523494	4952561			3.5			2.20	0.6	5.0	26.3	0.80	2.4	<3	249	<0.4		<3
YL07-16W	Beryl_Spring	hot spring pool	No	09/17/2007	88.9	520077	4947298			6.6			0.25	2.4	8.9	19.4	1.70	5.3	<3	575	<0.4		<3
YL08-03W	Potts_Basin1	pool with gas	Yes	09/17/2008	68.8	533421	4919761	-124	-8.9	6.0			0.02	947	1.7	1.59	0.34	0.29	4.52	140	4.5		2.9
YL08-07W	Snake_River_HS	hot spring flowing	Yes	09/18/2008	81.4	527133	4887672	-140	-18.4	6.0			<0.01	525	1.7	349	0.40	56	2.34	150	<0.001		1.0
YL08-12W	Poison_Spring	pool with gas	Yes	09/20/2008	39.3	522453	4979039	-146	-18.0	6.0			0.01	560	3.6	62.7	0.38	315	2.31	160	<0.001		4.3
YL08-15W	Obsidian_Pool	hot spring pool	Yes	09/21/2008	89.2	544530	4939794	-132	-13.9	5.0			0.77	349	6.2	38.8	0.68	8.8	1.33	250	0.45		0.9
YL08-18W	Brimstone1	pool with gas	Yes	09/25/2008	6.6	562143	4915346	-146	-23.9	[4]3.0			130	24.6	0.02	7.95	0.0005	169	0.45	0.56	0.56		135
YL08-19W	Brimstone2	pool with gas	Yes	09/25/2008	16.3	562447	4914975	-139	-21.7	2.0			23	6.2	<0.02	8.72	0.01	53	<0.001	0.29	0.77		44
YL08-20W	Brimstone3	pool with gas	Yes	09/25/2008	~13	562134	4915341	-140	-22.3	[5]1.5			69	8.6	0.01	12.4	0.0005	96	<0.001	2.00	0.65		140
YL09-05W	Heart_Middle	pool with gas	Yes	09/11/2009	85.8	538455	4905116			7.7	8.02	1822	0.34	1230	3.9	<5	0.88	0.9	5.80	300	<5	2.1	<25
YL09-18W	Pelican_Creek_Trail	pool with gas	Yes	09/16/2009	6.7	557027	4935598	-135	-17.5	5.0	4.83	418	8.0	2.9	<0.02	51.0	0.06	30	<2	0.68	<2		<10
YL11-08W	Shoshone_02	fry	No	09/12/2011	83.2	516451	4911476	-129	-14.7	1.6		3800	15.0	2	0.08	72	<0.08	0.96	<2	0.24	<2		<10
YL11-09W	Shoshone_13	hot spring pool	No	09/12/2011	93.0	516361	4911273	-139	-16.6	2.3		1468	5.96	241	1.1	76		2.69	<5	72	<5	0	<25
YL11-10W	Shoshone_14	hot spring pool	No	09/12/2011	86.5	516430	4911320	-136	-15.9	2.2		1638	5.10	203	0.9	72	0.16	3.75	<5	56	<5	0	<25
YL11-11W	Shoshone_03	hot spring pool	Yes	09/12/2011	86.5	516447	4911596	-141	-16.4	6.9		825	0.27	61	1.3	6	0.26	0.62	<2	90	<2	0.1	<10
YL11-12W	Shoshone_19	hot spring flowing	No	09/13/2011	91.0	516019	4910663	-147	-17.9	7.9		1791	0.14	1212	2.7	<5	0.56	0.48	7	200	<5	4.6	<25
YL11-13W	Shoshone_04 (nr)	fry	No	09/13/2011	86.5	516142	4911145	-117	-9.9	1.7		2900	9.84	<5	0.52	83	<0.1	0.47	<5	0.16	<5	0	<25
YL11-15W	Shoshone_11 (nr)	pool	No	09/13/2011	86.2	516196	4911471	-140	-15.7	7.0		1760	0.37	1225	4.4	<5	0.92	0.09	7	330	<5	0.3	<25
YL11-18W	Shoshone_09	pool with gas	Yes	09/14/2011	76.5	515954	4910960	-142	-16.5	7.2		1815	0.12	1149	3.1	<5	0.64	0.53	6	240	<5	0.5	<25
YL11-19W	Shoshone_10	pool with gas	Yes	09/14/2011	85.2	516121	4911400	-141	-16.4	7.0		1492	0.35	621	2.2	<5	0.44	0.60	<5	160	<5	0.3	<25
YL11-20W	Taurus_Spring	hot spring pool	No	09/13/2011	94.4	516029	4911098	-145	-17.7	8.1		1831	0.23	897	2.6	<5	0.52	0.16	<5	190	<5	11.2	<25
YL11-21W	Gourd_Spring	hot spring pool	No	09/13/2011	92.8	516070	4911320	-145	-18.1	7.9		1625	0.23	616	2.1	<5	0.4	0.58	<5	160	<5	6	<25
YL11-22W	Shoshone_15	hot spring pool	No	09/13/2011	93.3	516113	4911366	-145	-18.2	7.8		1636	0.14	597	2.1	<5	0.4	0.61	<5	150	<5	8.4	<25
YL11-23W	Shoshone_20	lake	No	09/13/2011	17.0	520051	4912754	-131	-16.8	7.7		88.4	0.02	25	0.10	2	0.02	2.84	<1	7.6	<1	0	<5
YL11-28W	Coral_Spring	hot spring pool	No	09/15/2011	80.7	515779	4911112	-144	-17.1	8.3		1517	0.27	773	2.5	<5	0.52	0.50	<5	190	<5	19.1	<25
YL11-29W	Shoshone_08	hot spring pool	No	09/15/2011	88.0	515863	4911232	-144	-17.3	7.4		1560	4.21	769	2.3	<6	0.44	3.15	8	170	<6	1	<6
YL11-30W	Shoshone_18	creek	No	09/14/2011	13.3	516000	4912504	-143	-18.9	7.2		21.5	<0.01	1	<0.01	9	<0.01	1.10	<1	0.34	<1	0	<5
YL11-SCD	Shoshone_16	creek	No	09/14/2011	20.0	516066	4910752	-143	-18.7	7.9		240	0.04	80	0.34	2	0.07	2.19	<1	26	<1	0	<5
YL11-SCU	Shoshone_17	creek	No	09/14/2011	13.6	515831	4912474	-144	-19.0	7.0		101.7	0.03	15	0.12	2	0.03	2.65	<1	9.7	<1	0	<5
YL12-06 W	Helen's Cool Pool	pool with gas	Yes	07/25/2012	23.2	545673	4941001	-150	-19.5	5.6		611	0.1	45	0.31	96	<0.01	44.1	<2	16	<2	0	8
YL12-08 W	Monument Frying Pan	fry	No	09/06/2012	90.7	519507	4947902	-122	-12.4	1.7		3230	69.3	39	0.35	67	<0.2	3.1	<5	0.4	<5	0	9
YL12-12 W	Pool Highland Basin	hot spring pool	No	09/09/2012	77.7	530483	4939260	-127	-11.5	1.6		3410	2.23	369	<0.03	76	0.2	0.3	5	0.2	<3	0	<3
YL12-13 W	Muddy Pool Highland Basin	hot spring pool	No	09/09/2012	89.1	530491	4939253	-120	-9.2	1.8		2790	72.5	871	<0.05	93	<0.2	1.8	11	0.0	<5	0	96
YL12-16 W	Nez Perce Creek	creek	No	09/11/2012	13.7	523264	4937794	-146	-18.7	8.1		509	0.02	10	0.84	6	0.16	8.2	<2	60.0	<2	0.0	<2
YL12-17 W	Spruce Creek	creek	No	09/11/2012	21.5	523240	4937756	-146	-19.3	7.8		287	0.23	15	0.31	2	0.05	7.8	<1	20	<1	0	<1
YL12-19 W	Nymph_Lake_new_feature	fry	Yes	09/13/2012	85.8	521452	4955523	-129	-10.7	1.7		5040	114	81	0.41	42	<0.5	6.7	<5	0.5	<5	0	51
YL12-21W	Obsidian Creek Pool water	pool with gas	Yes	09/13/2012	68.8	520644	4959557	-139	-14.4	6.1		1180	114	1672	4.8	35	0.76	11.4	17	260	<3.5	0	<3.5
YL12-23 W	Ebro Hot Spring	hot spring flowing	No	09/14/2012	57.9	552358	4937398	-140	-14.6	2.6		932	14.4	260	1.4	28	<0.04	4.3	4	14.0	<3	0	10
YL12-25 W	Sulfur Hills Fumarole #2 water	fry	Yes	09/14/2012	83.2	554027	4938193	-111	-8.8	1.9		3300	65.8	61	14.0	56	<0.2	1.5	<5	25.0	<5	0	51

[1] pH for YL03-15 not measured and charge balance optimized by assuming a pH = 2.0.

[2] YL04-09 charge balance optimized by assuming a pH of 2.5.

[3] YL05-03 charge balance optimized by assuming a pH of 1.82.

[4] YL08-18 charge balance optimized by assuming a pH of 2.1.

[5] YL08-20 charge balance optimized by assuming a pH of 1.75.

[6] YL05-11 likely lost CO2 to degassing.

Table 3. Water chemistry, stable isotope values, and sample collection parameters for waters collected within and around Yellowstone Park, Wyoming during 2003 through 2012 (part 2).—Continued

[Analyte concentrations are reported in mg/l or mg/l. Stable isotope values of water are reported in per mil relative to SMOW (δD and δ¹⁸O). A blank cell indicates that an analysis was not attempted. Field pH values (pH F) in bold were determined using a meter, and others were determined using indicator paper. Laboratory pH values (pH L) were determined using a meter.]

Sample number	Cs µg/l	Cu µg/l	F mg/l	Fe mg/l	HCO_3 mg/l	K mg/l	Li µg/l	Mg mg/l	Mn µg/l	Mo µg/l	Na mg/l	Ni µg/l	NH_4 mg/l	PO_4 mg/l	Rb µg/l	SiO_2 mg/l	SO_4 mg/l	Sr µg/l	Ti µg/l	U µg/l	Zn µg/l	TDS mg/l	Anion meq/l	Cation meq/l	Balance
YL03-01W			16.2	<0.05	165	16	2600	0.014	6.1	13	350			<0.01	163	250	25	21		0.042	4.1	1100	16.4	15.9	-3%
YL03-08W			4.7	0.057	0	54	5700	0.109	198	63	370			<0.01	559	430	132	25		0.057	9.2	1680	21.5	19.7	-9%
YL03-09W			18.7	<0.05	108	19	5800	0.020	23	134	400			<0.01	363	250	72	8.3		<0.05	20	1340	20.1	18.8	-7%
YL03-11W			2.2	<0.05	27	15	680	0.183	60	8.1	100			<0.01	111	170	186	10		0.012	6.4	520	5.6	5.0	-11%
YL03-13W			11.8	<0.05	126	41	3300	0.035	33	270	290			<0.01	364	490	30	14		0.340	5.2	1320	15.9	14.5	-9%
YL03-14W			7.35	<0.05	788	29	660	0.862	235	41	280			<0.01	183	140	12	40		8.800	6.9	554	15.4	14.1	-9%
YL03-15W			0.39	1.54	0	26	55	2.75	538	0.76	33			<0.01	150	300	663	32		1.300	54	1050	13.8	13.7	-1%
YL03-21W			3.59	<0.05	45	11	50	0.026	7.0	0.16	40			<0.01	67	230	54	1.4		<0.05	3.9	341	2.1	2.2	4%
YL04-06W			4.40	0.259	343	75	2700	3.78	323		370			<0.01	373	35	161	449		1.500		1060	19.6	20.0	2%
YL04-09W			5.40	0.071	0	33	5000	0.074	26		290			<0.01	339	310	117	16		0.024		1390	19.8	17.9	-10%
YL04-13W			5.30	<0.05	18	64	5600	0.017	6.2		280			<0.01	547	410	43	12		<0.05		1430	18.9	14.7	-25%
YL04-16W			2.38	0.211	352	43	910	23.0	130		91			<0.01	130	80	272	963				752	14.5	13.1	-10%
YL04-AW			7.20	0.193	52	43	3500	0.267	146		250			<0.01	333	380	71	14		7.200		1220	15.3	12.6	-20%
[6] YL05-11W	65.7	1.2	4.39	5.57	270	22	800	2.02	1480	8.7	120	<30		<0.01	128	100	25	70	14	0.73	6.1	333	6.1	7.2	17%
YL05-02W	30.9	2.9	7.36	0.440	787	32	710	0.906	238	40	280	<30		<0.01	174	140	11	41	22	8.5	27	558	15.4	14.2	-8%
YL05-03W	10.1	1.9	0.30	22.7	0	12	37	3.69	310	0.20	12	<30		<0.01	65.4	140	957	62	74	0.15	68	1190	19.9	20.8	4%
YL05-10W	293	3.0	7.60	0.390	75	39	3800	0.222	109	30	280	<30		<0.01	321	400	41	16	66	0.05	6.8	1260	16.1	13.9	-14%
YL05-15W	209	1.2	3.10	1.40	902	52	1600	67.2	9.0	<0.2	120	<30		<0.01	293	49	556	1930	7.0	<0.006	6.1	1350	31.1	28.8	-8%
YL05-17W	513	3.0	31.4	0.330	167	9	4000	0.012	<1	140	250	<30		<0.01	135	200	17	4.2	31	<0.006	7.3	861	14.5	11.9	-20%
YL07-04W	2.87		0.40	0.950	23	15	2.3	16.1	329		32		730	0.4	51	150	1830	342				2850	38.4	45.7	17%
YL07-10W	37.0	<20	3.40	0.700	0	16	1900	<0.3	26.9	50	210	<0.7		<0.01	81	760	133	21	25	<0.7	66.0	1390	10.0	10.3	3%
YL07-16W	621	<20	18.8	<0.2	104	23	6800	<0.3	21	111	390	2.0		<0.01	270	320	69	23	19	<0.7	9.0	1420	20.4	18.8	-9%
YL08-03W		0.33	12.0	0.021	366	20	2800	0.024	27	30.8	330	<0.001		0.04		270	140	0.6			17	921	13.5	15.2	12%
YL08-07W		<0.001	5.50	0.006	292	22	1100	8.58	2.8	<0.001	160	<0.001		<0.01		63	44	371			14	512	10.2	11.1	8%
YL08-12W		<0.001	2.80	0.096	655	54	1700	71.0	6.8	<0.001	140	<0.001		<0.01		54	650	2040			<0.001	1450	28.9	29.2	1%
YL08-15W		0.11	15.0	0.541	34	35	1700	1.61	77	166	300	0.33		0.02		320	230	57			16	1170	13.2	14.8	12%
YL08-18W		<0.001	2.00	8.39	0	44	40	99.3	1830	<0.001	78	1.00		0.3		100	2200	2350			<0.001	2830	45.8	43.4	-5%
YL08-19W		<0.001	0.16	2.57	0	14	<0.01	73.0	1320	<0.001	19	0.22		<0.01		74	1100	441			12	1360	22.9	22.5	-2%
YL08-20W		0.11	16.7		0	34	<0.01	105	1820	<0.001	43	17		0.5		89	2000	1100			36	2460	41.6	42.5	2%
YL09-05W		<5	25.4	<0.005	316	17	6000	<0.005	<5	93	410	<5		<0.01	226	300	153	13				1220	18.3	19.3	6%
YL09-18W		<2	0.53	2.74	70	5	21	20.9	500	<2	14	<2		<0.01	<20	90	172	425			<2	344	4.8	5.0	5%
YL11-08W		<2	0.32	3.1	0	12	<2	0.163	64	<2	2.6	<2		<0.01	42	200	1200	6			59	1435	25.0	25.0	0.3%
YL11-09W		<5	4	4.3	0	30	272	0.331	149	<5	75	<5		<0.01	162	390	370	8			58	961	9.7	9.9	-2.7%
YL11-10W		<5	2.9	7.04	0	32	213	0.486	215	<5	63	<5		<0.01	207	460	450	10			78	1086	11.7	11.1	5.6%
YL11-11W		<2	9.8	0.02	194	15	306	0.020	12	2	160	<2		<0.01	114	290	42	<2			<2	803	7.3	7.1	3.1%
YL11-12W		<5	28	0.01	453	14	716	<0.005	12	91	340	<5		0.08	128	320	39	<5			6	1411	15.4	15.5	-0.7%
YL11-13W		<5	0.16	1.22	0	6.4	<50	0.089	27	<5	2.7	<5		0.08	<50	130	910	<5			47	1065	19.8	18.9	4.7%
YL11-15W		<5	25	0.02	211	14	1672	<0.005	<5	48	330	<5		0.08	105	320	59	<5			<5	1304	15.2	15.4	-1.0%
YL11-18W		<5	28	0.01	390	13	1074	<0.005	92		350			0.08	135	320	49	<5			8	1403	15.9	15.7	1.0%
YL11-19W		<5	19	0.04	388	12	1704	0.018	6	20	300	<5		0.04	131	260	74	<5			<5	1226	13.9	13.4	3.1%
YL11-20W		<5	22	0.01	447	14	1411	<0.005	<5	52	330	<5		0.04	134	280	42	<5			5	1346	14.9	15.1	-1.7%
YL11-21W		<5	19	<0.005	464	13	1637	<0.005	<5	24	300	<5		<0.01	121	250	39	<5			<5	1256	13.7	14.2	-2.9%
YL11-22W		<5	18	<0.005	443	12	1638	0.013	<5	24	300	<5		<0.01	114	250	39	<5			<5	1225	13.7	13.5	0.8%
YL11-23W		<1	2.4	0.015	23	3.1	53	0.375	1	3	14.0	<1		0.01	13	37	2.9	4			<5	93	0.9	0.8	9.7%
YL11-28W		<5	22	0.013	423	13	1642	0.011	<5	56	330	<5		0.04	125	290	41	<5			7	1331	14.9	15.0	-0.6%
YL11-29W		<6	20	0.003	460	16	1606	<0.6	87	<6	300	<6		0.04	125	240	44	<6			32	1280	14.9	14.4	4.0%
YL11-30W		<1	0.08	0.013	8	3.0	<10	0.240	<1	<1	1.3	<1		<0.01	11	60	1.5	5			<1	75	0.2	0.2	19.0%
YL11-SCD		<1	3.9	0.049	69	4.9	196	0.218	8	6	46	<1		<0.01	30	75	6.1	4			<1	235	2.3	2.2	3.8%
YL11-SCU		<1	2	0.039	32	3.7	33	0.279	9	2	16	<1		<0.01	17	54	1.7	5			<1	122	1.0	0.9	2.3%
YL12-06 W		<6	2.8	7.20	389	17	162	21.6	768	4	65	<4		0.02	<40	190	2.6	323			63	760	7.7	7.0	8.8%
YL12-08 W		<15	0.4	6.37	0	32	31	0.332	41	<5	24	<10		<0.01	121	350	1200	25			108	1700	30.0	25.0	16.8%
YL12-12 W		<9	0.2	0.64	0	1.2	<3	0.108	10	<3	0.6	<6		<0.01	<60	210	1000	4			<30	1200	28.0	20.8	29.0%
YL12-13 W		<15	0.4	42.80	0	8.3	18	3.4	174	<5	2.6	32		0.60	<100	320	1400	48			93	1900	28.0	29.1	-2.6%
YL12-16 W		<6	7.3	0.02	85	14	314	1.000	3	10	87	<4		<0.01	94	120	58	14			<20	440	4.7	4.7	0.4%
YL12-17 W		<1	7.2	0.06	79	6.6	188	0.891	7	13	47	<1		<0.01	49	96	25	11			<2	290	2.7	2.8	-1.4%
YL12-19 W		<15	1.0	39.70	0	45	64	4.78	459	<5	50	16		<0.01	<60	370	2200	40			338	2800	37.0	45.7	-21.1%
YL12-21W		<3.5	2.6	0.01	55	53	2555	0.153	56	4	190	<3.5		<0.01	491	250	110	57			8	949	10.7	10.7	-0.7%
YL12-23 W		<9	0.4	9.56	0	15	112	1.850	60	<3	16	<6		<0.01	<100	190	260	24			31	530	6.1	5.8	4.9%
YL12-25 W		<15	0.4	8.68	0	7.4	5	1.060	21	<5	1.6	12		0.20	<100	340	1400	135			67	1900	21.0	29.8	-33.0%

[1] pH for YL03-15 not measured and charge balance optimized by assuming a pH of 2.0.

[2] YL04-09 charge balance optimized by assuming a pH of 2.5.

[3] YL05-03 charge balance optimized by assuming a pH of 1.82.

[4] YL08-18 charge balance optimized by assuming a pH of 2.1.

[5] YL08-20 charge balance optimized by assuming a pH of 1.75.

[6] YL05-11 likely lost CO2 to degassing.

Table 4.   Statistical synthesis of individual gas species, and radiogenic and stable isotope data for Yellowstone gas samples.

[Summary data include one result per sample location; for sites with replicate analyses the data were averaged]

	Units	Minimum	Maximum	Average	1 sigma	Median	No. Samples
Xg (%)		0.050	150	25	38	2.1	116
CO_2	mol %	50.1	99.8	92.1	9.5	95.0	117
H_2S	mol %	0.0020	30.18	2.51	4.33	1.1	117
NH_3	mol %	0.0002	1.17	0.10	0.26	0.0	114
He	mol %	0.00003	0.0547	0.0059	0.0073	0.0040	117
H_2	mol %	0.00003	8.67	0.80	1.65	0.18	117
Ar	mol %	0.0010	1.02	0.08	0.13	0.0	117
O_2	mol %	0.0002	6.68	0.26	0.97	0.0	117
N_2	mol %	0.10	44.7	3.7	6.8	1.6	117
CH_4	mol %	0.0003	8.18	0.58	0.97	0.3	117
C_2H_6	mol %	0.00002	0.0477	0.0046	0.0083	0.0016	117
CO	mol %	0.00002	0.0049	0.0011	0.0013	0.0004	24
C_3H_8	mol %	0.00002	0.0051	0.0010	0.0012	0.0004	38
C_4H_{10}	mol %	0.00003	0.0015	0.0004	0.0004	0.0003	36
C_5H_{12}	mol %	0.0001	0.0006	0.0003	0.0002	0.0001	32
HCl	mol %	0.0010	1.50	0.07	0.21	0.0	116
R/Ra		0.76	16.43	6.62	3.66	6.73	85
Rc/Ra		0.76	16.43	6.80	3.63	6.86	84
Ar40/36		281	736	344	93	308	83
$\delta^{13}C$-CO_2	per mil	-13.3	0.4	-3.4	1.5	-3.2	94
$\delta^{13}C$-CH_4	per mil	-46.4	-21	-33	7.7	-32.3	42
N_2/Ar		25.1	202	43.7	18.6	39.3	117

Within individual thermal basins, H_2S tended to have higher values in samples with low Xg. Hydrogen averaged 0.5 percent but ranged as high as 6.9 percent and was particularly high at Smokejumper Hot Springs, Washburn Hot Springs, and Hot Spring Basin. Similarly, CH_4 averaged 0.5 percent but reached 8.2 percent at Washburn Hot Springs. NH_3 was notable in samples from Washburn Hot Springs, where concentrations exceeded 1 mol percent, and was > 0.5 percent in a few samples from the Eastern Yellowstone group. Ar values ranged from 0.001 to 1.0 percent, and N_2/Ar ratios were consistent with derivation of these gases primarily from air-saturated meteoric water. All but 12 samples had ratios within the range of 30 to 50; the N_2/Ar of air-saturated water at 10°C should be 37.7, compared with a value of 83.6 in air (Wilhelm and others, 1977). Samples with the highest N_2 and Ar generally were those with the most entrained air. However, O_2 was found in far less abundance than would be appropriate for air-saturated meteoric water (N_2/O_2 = 1.84), probably reflecting reaction of O_2 in groundwater or hydrothermal fluid before mixing/boiling and return to the surface in geothermal gas.

Gas to Steam Ratio (Xg)

The range of gas contents of frying pans (Xg <11 percent) and high-temperature fumaroles (≤14 percent) (table 2) are similar, reflecting boiling and addition of some steam from surface waters. The highest Xg values in high-temperature fumaroles were found consistently at Mud Volcano (fig. 1) and ranged from 10 to 14 percent. The lowest Xg value of any Yellowstone fumarole was 0.05 percent (equivalent to a steam/gas molar ratio of 2,000) in the Norris Back Basin (fig. 1).

Because steam may be lost from gas as it bubbles up through thermal springs, the Xg values of samples from pools are more variable than Xg contents of samples collected at fumaroles or frying pans (table 2). The gas/steam ratios are controlled by temperature, depth of water, and the flux of gas through the feature. Xg ratios for pool samples are generally high (table 2), and most pools with low Xg values are those with temperatures at or close to boiling. The organic-rich gas vents along the Yellowstone River near Tower Junction (Devils Den) (fig. 1) are very unusual in this dataset but are classified in table 2 as fumaroles for simplicity. The Xg contents of the three samples range from 74 to 89 percent (table 2)—these lukewarm (<30°C) gassy emanations lack the steam that is typically a significant component of true fumarole emissions.

Isotopes

Condensed fumarolic steam had δD_s values varying from ~ −180 up to −140 per mil, compared with δD_w values from −160 to −110 per mil for nearby hot spring waters (tables 2, 3; fig. 3). Hot spring waters in this study have δD_w values similar to published values of Yellowstone cold waters (ellipse in fig. 3; Balistrieri and others, 2007; Gemery-Hill and others, 2007; Kharaka and others, 2002; Rye and Truesdell, 1993, 2007) but have slightly higher $\delta^{18}O$ values and plot to the right of the Global Meteoric Water Line. Five cold waters from this study have δD_w and $\delta^{18}O_w$ values ranging from −146 to −102 and −24 to −12 per mil, respectively (table 3).

The $\delta^{13}C$ values of CO_2 ranged from −13.3 to 0.4 per mil, but the great majority of samples varied only from −5 to –2 (table 2, fig. 4). In fact, 104 of 110 samples fit within that relatively narrow range. The lowest value (by far) of
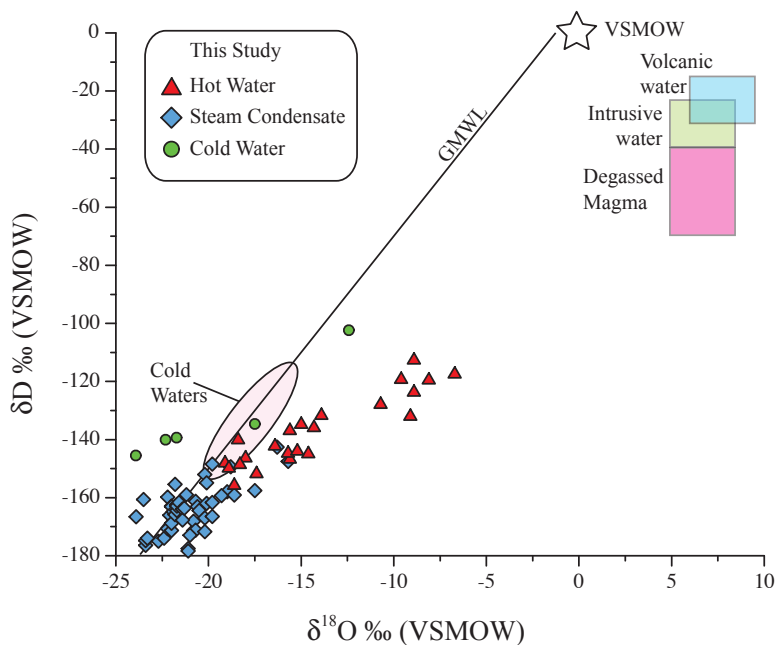
Figure 3. Plot of δD vs. δ^{18}O relative to Vienna Standard Mean Ocean Water (VSMOW) for condensed steam from selected Yellowstone fumaroles and for hot and cold spring waters from this study. The cold water field (pink ellipse) is from Kharaka and others (2002). Boxes showing the fields for volcanic water, intrusive water, and degassed magma are from Hedenquist and Lowenstern (1994). GMWL = global meteoric water line.

–13.3 per mil was for gas emerging from the Snake River hot spring, our southernmost sample located well outside the Yellowstone Caldera. Such values are more similar to those associated with low-temperature geothermal systems such as those found to the east near Cody, Wyoming (Lorenson and Kvenvolden, 1993; Lorenson and others, 1991). The highest $\delta^{13}C\text{-}CO_2$ values were ≥0 per mil from two bubbling pools at Potts Basin.

The spread in helium isotope Rc/Ra (fig. 5) ranged from values below 1.0 at Steamboat Point, Devils Den (R/Ra only), and the Snake River hot spring (table 2) to the highest values

at Mud Volcano (14.98–16.49), which are similar to those found by Craig and others (1978), Kennedy and others (1985), and Werner and Brantley (2003). The locations within the park with the highest values are in the northeastern part of the caldera (Mud Volcano, Forest Springs, and Crater Hills) and the Gibbon River Basins along the northern margin of the caldera. High values around 10 are also known from Shoshone Hot Springs (Hearn and others, 1990), but those springs were not sampled as part of this study. Outside the Yellowstone Caldera, Rc/Ra values >7.0 were found only at sites north of the caldera in the Gibbon River Basins, Norris
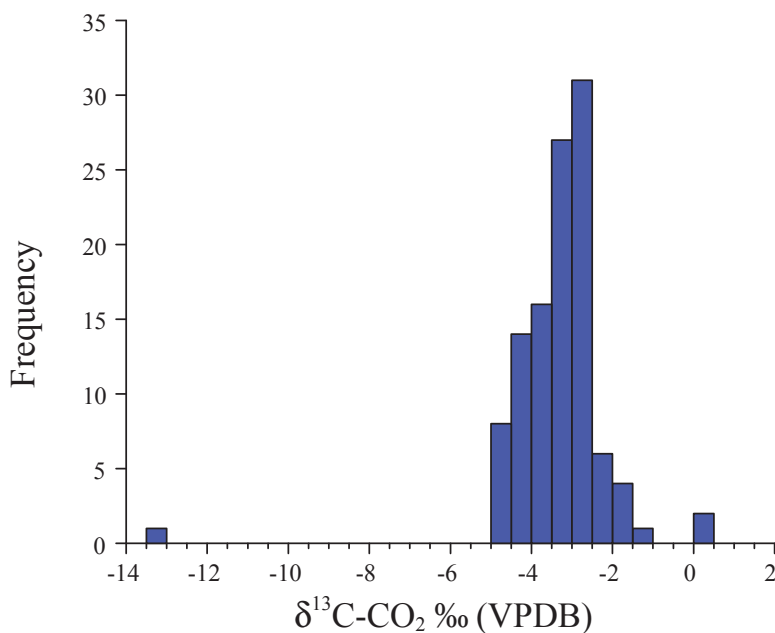
Figure 4. Histogram showing δ^{13}C values relative to the standard Vienna PeeDee Belemnite (VPDB) for CO_2 in Yellowstone gas: δ^{13}C values of 104 of the 110 samples are between -2 and -5 per mil. Roughly half of the samples have $\delta^{13}C\text{-}CO_2$ values between -3 and -4 per mil. One sample with an anomalously low $\delta^{13}C\text{-}CO_2$ value of -13.3 per mil is from a hot spring near the Snake River, south of the park boundary.

Geyser Basin, and Mammoth Hot Springs. Not all samples in the Norris Mammoth Corridor, though, yielded high values, as the sample from Roaring Mountain was notably low (see also Kennedy and others, 1985).

Discussion

Water and Steam Isotopes (δ^{18}O and δD)

All water and steam samples are very depleted in D and ^{18}O relative to volcanic gas and magma-derived water (Giggenbach, 1992a), consistent with a meteoric origin for the water with relatively minimal (< a few percent) influence of magmatic water (Craig and others, 1956). The hot spring waters have likely exchanged oxygen during water-rock reaction (Craig and others, 1956), which typically produces a positive shift in $\delta^{18}O_w$ with little or no change in δD_w. The difference in δ^{18}O and δD values between seven steam condensates and co-sampled thermal waters (tables 2 and 3) are consistent with fractionation factors expected for boiling at temperatures between 90°C and 110°C (Friedman and O'Neil, 1977; Horita and Wesolowski, 1994). For example, using the equations from Horita and Wesolowski (1994), spring water near Lone Star Geyser, sample YL03-01W ($\delta 18O_w = -15.7$ and $\delta D_w = -145$), would be in equilibrium at 100°C with steam having an isotopic composition of $\delta 18O_w = -20.6$ and $\delta D_w = -173$, almost precisely the values observed in fumarolic steam condensate from YL03-01A (table 2).

Gas Chemistry

Different regions had unique gas chemistries (fig. 6). For example, parts of the Norris Geyser Basin were characterized by abundant air-derived gas (N_2, Ar, O_2), whereas reduced gases (CH_4, H_2S, H_2) were high at Hot Spring Basin and high H_2S was found at Roaring Mountain. Relative amounts of He, N_2, and Ar in fumaroles and frying pans are such that virtually all samples plot on a single trend, oriented between air-saturated meteoric water and a He-rich end member (fig. 7). With the exception of slightly elevated N_2 at Washburn Hot Springs, presumably due to breakdown of organic-rich sediments in the mid to shallow crust, there is little evidence for N_2-rich sources as are common in subduction-zone volcanoes (Giggenbach, 1992b).

Systematics of CH_4-Ar-He (fig. 8) illustrate that individual thermal areas have a unique character, ranging from Ar-rich (groundwater-derived) to those with diverse CH_4/He ratios. In helium-rich samples the helium is usually attributed either to deep crustal sources (low Rc/Ra) or mantle sources (high Rc/Ra) (Giggenbach and others, 1993), both of which are present at Yellowstone. Methane, in contrast, is typically attributed to crustal sources (Giggenbach and others, 1993; Lowenstern and Janik, 2003) and when plotted with helium provides a simple method to help discriminate crustal and magmatic endmembers (Chiodini, 2009).

Some geographic areas—for example, Norris (group 8), the Upper Geyser Basin (group 15), and the Gibbon River Basins (group 18)—have narrowly defined CH_4/He and form
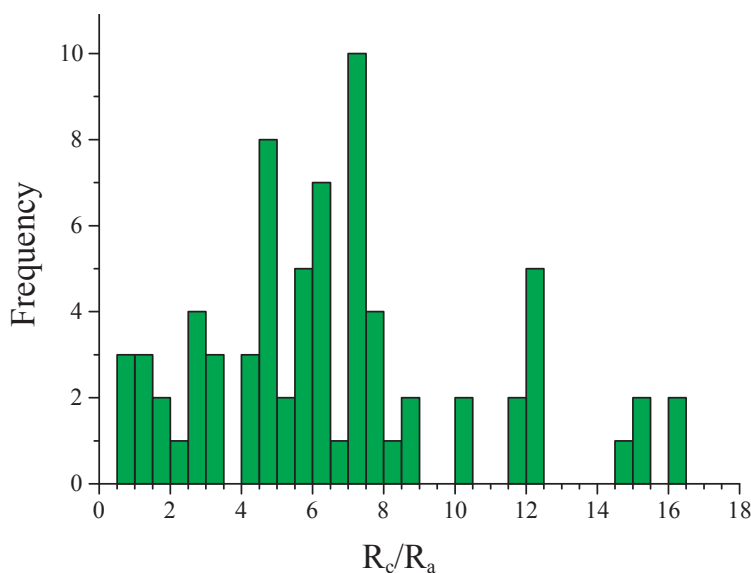
Figure 5. Histogram showing ^{3}He/^{4}He R$_c$/R$_a$ values for 73 gas samples collected from Yellowstone. Values range from about 0.8 to 16.5. The highest values are from the Mud Volcano area (group 14).
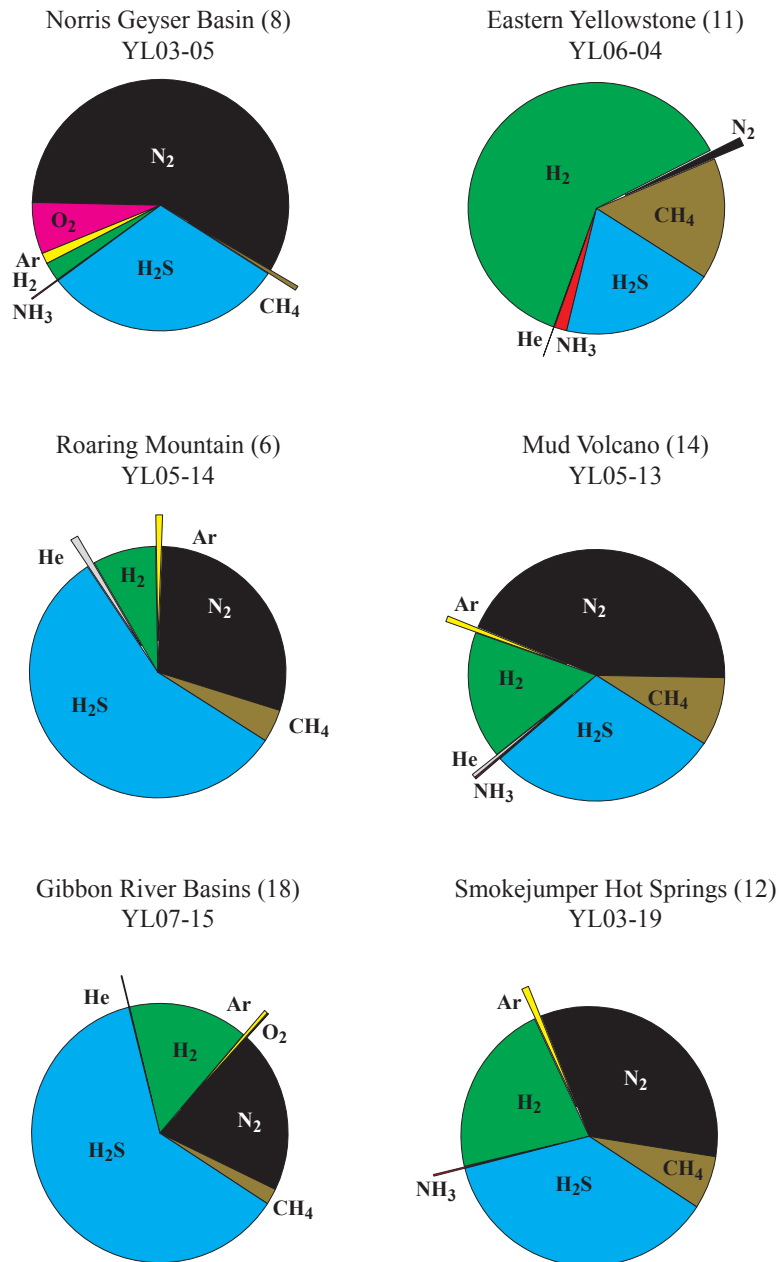
Figure 6. Pie charts demonstrate the differences among gas discharges at Yellowstone. Each section represents that part of the gas fraction after omitting H_2O and CO_2. Very narrow sections are extended for visibility. The Norris Geyser Basin is N_2-rich, consistent with low Xg from steam produced by boiling of meteoric water. Hot Spring Basin (Eastern Yellowstone group) is comparatively rich in reduced gas species such as H_2 and CH_4. Beryl Spring (Gibbon River Basins group) and Roaring Mountain contain a greater proportion of H_2S relative to the other gases. Numbers in parentheses above each chart correspond to the sample groups as defined in table 1.
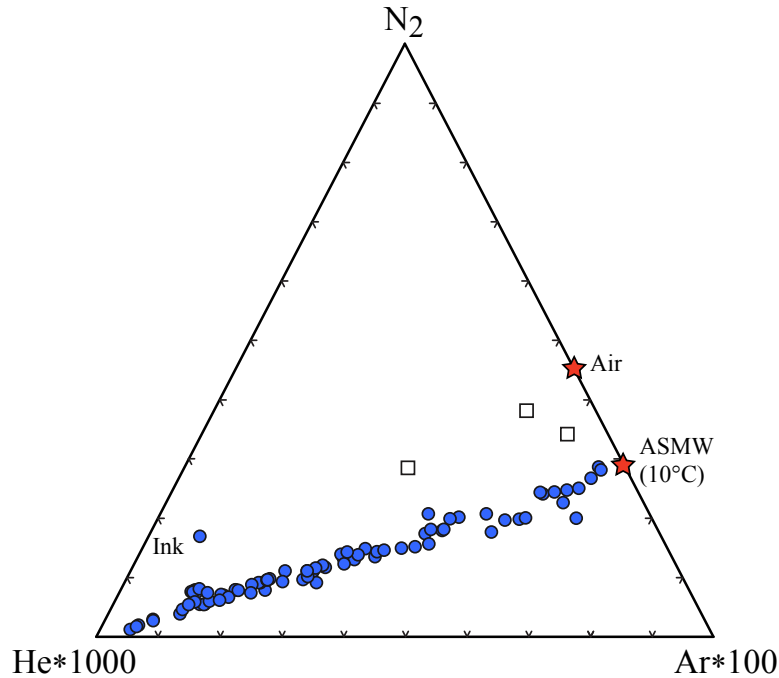
Figure 7. Ternary diagram showing He, N_2, and Ar relations for gas collected from fumaroles and frying pans, which demonstrates that nearly all represent mixtures derived from air-saturated meteoric water with He-rich endmember(s). Squares show three samples that contain some air. Ink is a N_2-rich sample from the Washburn Hot Springs group. ASMW = Air-saturated meteoric water.
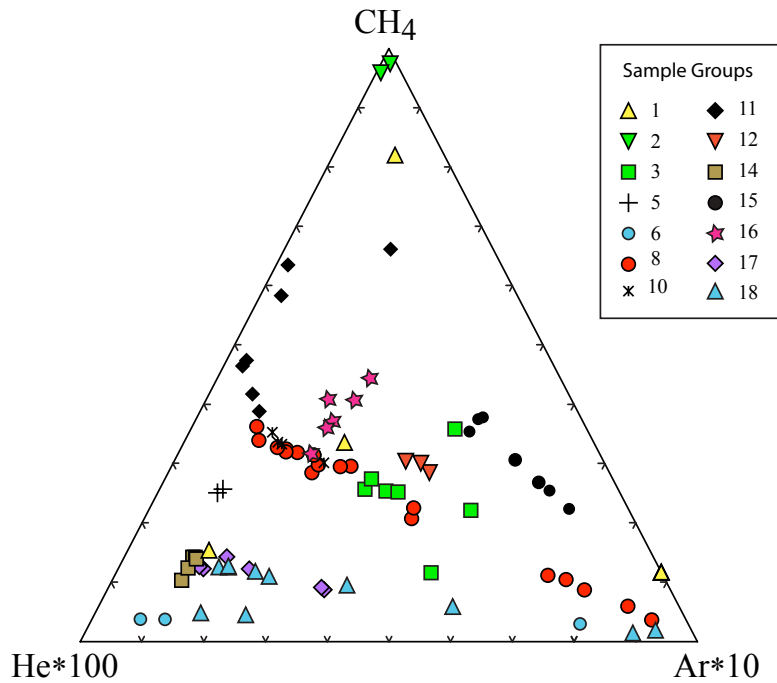
Figure 8. Ternary diagram showing He, CH_4, and Ar relations for gas collected from fumaroles and frying pans, which demonstrates that Yellowstone gases can be discriminated by their CH_4/He ratios, that discrete geographic areas have unique CH_4/He ratios and that most groups form an array of mixtures of magmatic and crustal gases with those derived from boiling of meteoric waters (Ar-endmember). Numbers listed in the legend correspond to the sample groups as defined in table 1.

linear trends from the Ar apex (fig. 8). Interestingly, $CH_4/$He ratios in some areas that are distant from one another are similar and fall along the same trends. The North of Norris samples (for example, Frying Pan Springs, Nymph Lake, and the West Nymph Lake Thermal Area, group 17) are collinear with gases from the Gibbon River Basins (group 18), ~5 km to the south, and with Mud Volcano (group 14), 25 km to the southeast. Conversely, spatial proximity does not ensure similarity in $CH_4/$He ratios, as nearby areas have geochemically unique characteristics. $CH_4/$He ratios for the North of Norris Geyser Basin group are distinct from Norris Geyser Basin itself (fig. 9). Of all the groups, only the Heart Lake, Lower Geyser Basin, and Eastern Yellowstone groups show substantial internal diversity in $CH_4/$He (fig. 8).

The geochemical distinctions that we observed clearly are not related to the type of thermal feature. Fumaroles, pools, and frying pans from the same thermal basin (for example, Norris Geyser Basin) demonstrate similar gas ratios, such as $CH_4/$He or CO_2/H_2. Moreover, water chemistry is not a key factor. At the Norris Geyser Basin, gases that issue from neutral waters at Hundred Springs Plain have the same $CH_4/$He ratio as gases from acid, steam-heated waters nearby at "Bison Flat," along the Gibbon River. Yet neutral waters of the Upper Geyser Basin are distinct from those at Heart Lake or Crater Hills. Gas from acid, steam-heated terrains at Mud Volcano, Smokejumper Hot Springs, and Forest Springs display remarkable internal consistency within groups (fig. 8) but are different from each other and are each readily identifiable by their distinct gas ratios. Only the gases from the carbonate-forming waters at Mammoth Hot Springs and Terrace Springs share some similarity in having high CO_2 and very low He and CH_4 (table 2).

Some authors use methane-to-ethane ratios (CH_4/C_2H_6) as the basis for gas geothermometry (Darling, 1998; Tassi and others, 2007), but the strong thermogenic character in some Yellowstone gases (Des Marais and others, 1981) can produce suspicious results. For example, subsurface temperatures calculated for Brimstone Basin (average $CH_4/C_2H_6 = 100$), an area without any discernible geothermal heat flow, would exceed those of Hot Spring Basin (average $CH_4/C_2H_6 = 42$),
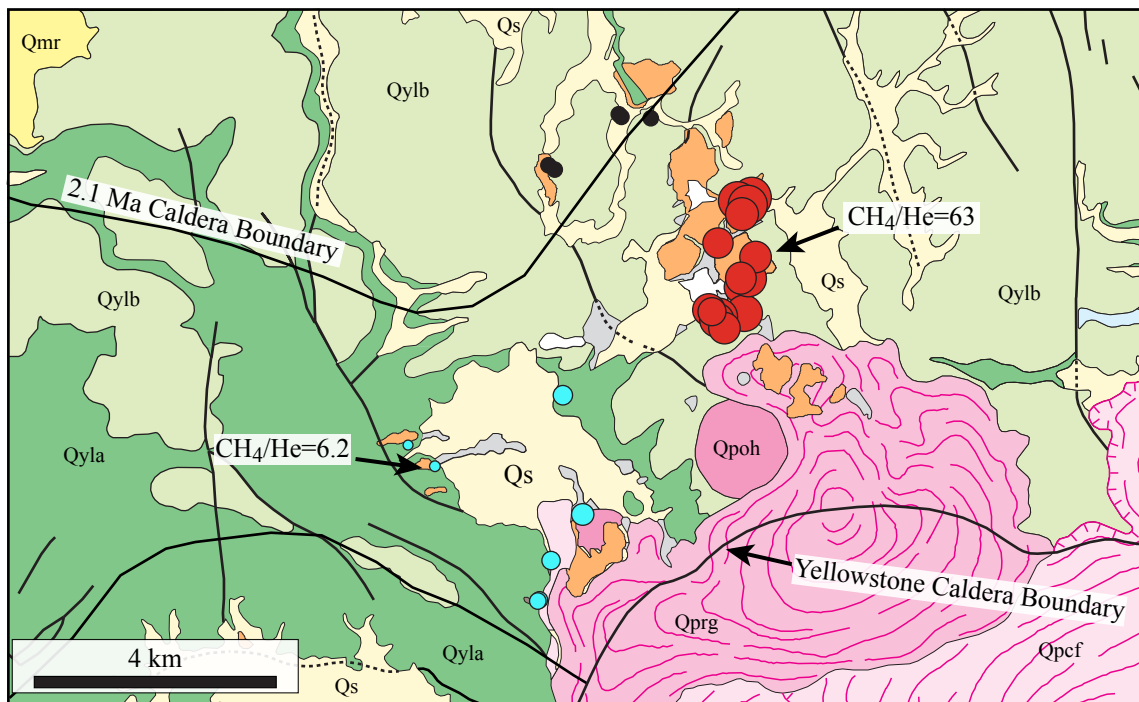
Figure 9. Map (from Christiansen, 2001) of the area around Norris Geyser Basin, showing some of the gas-sample localities plotted as colored dots sized in proportion to the $CH_4/$He ratio. Norris Geyser Basin samples are red, Gibbon River Basin are blue, and North of Norris Geyser Basin are black. The $CH_4/$He ratios for two samples, Sylvan_Springs2 and Porcelain_Terrace1 are shown as examples. Ratios in the Norris Geyser Basin are significantly higher than in the two other areas to the north and south. Geological units are Lava Creek Tuff Unit A (Qyla), Lava Creek Tuff Unit B (Qylb), alluvium (Qs), Gibbon River rhyolite flow (Qprg), Gibbon Hill Dome (Qpoh), Solfatara Plateau flow (Qpcf), and Madison River basalt (Qmr). Orange indicates areas of hydrothermal alteration, gray indicates hot spring deposits, white indicates cemented ice-contact deposits, blue is a lake.

seemingly one of the hottest basins at Yellowstone on the basis of other gas geothermometers and geophysical data (Werner and others, 2008). Our findings show that, while CH_4/C_2H_6 ratios vary considerably across Yellowstone (table 2, fig. 10), they are generally constrained within individual thermal groups. These discrete trends in figure 10 show that near-surface biological activity or temperature variations exert limited control and instead imply that lithologies and redox conditions in the source region strongly control the CH_4/C_2H_6 ratio. Although our $\delta^{13}C$-CH_4 analyses only begin in 2008, a plot of those values against C_2H_6/CH_4 (fig. 11) indicates that the CH_4 is mainly a mixture of abiotic and thermogenic end members, with the thermogenic signature strongest in features associated with exposures of the Eocene Absaroka Volcanic Supergroup rocks. Apparent trends toward the biogenic box (at Brimstone Basin, Heart Lake, and Potts Basin) may indicate either minor addition or minor removal of isotopically light CH_4 due to near-surface microbial processes.

We note that H_2 concentrations (also used as a geothermometer when normalized to Ar; Giggenbach and Goguel, 1989) and H_2/CO_2 ratios correlate with geography rather than inferred and known subsurface temperatures (White and others, 1975; Fournier, 1989), implying that different areas may have unique oxidation states rather than varying temperatures. For example, figure 7 of Fournier

(1989) shows that chloride-enthalpy relations indicate that Norris and Crater Hills waters rise from the highest temperature geothermal reservoirs. In contrast, hydrogen-argon ratios at Norris (average ratio of 17) and Crater Hills (3.4) are much lower than the hydrogen-rich (seemingly reduced) gases from Eastern Yellowstone (414), Washburn Hot Springs (1,200) and Smokejumper Hot Springs (29).

The distinct gas signatures are most likely related to the lithologies with which subsurface hydrothermal fluids have interacted. Our samples from the Eastern Yellowstone and Washburn Hot Springs groups are enriched in CH_4 and have consistently high CH_4/He (table 2, fig. 8). The Eastern Yellowstone samples from Hot Spring Basin and areas at the eastern edge of Yellowstone Lake emerge where Eocene Absaroka Volcanic Supergroup rocks are found. Units within these rocks are known for their abundant organic carbon and are associated with petroleum seeps such as those found at Rainbow Hot Springs (Love and Good, 1970; Clifton and others, 1990). Terrace Springs, by contrast, emerges from the north wall of the caldera, closer to sedimentary rocks of the Mesozoic/Paleozoic Gallatin Mountains than any other thermal area within the caldera. Gas from Terrace Springs has little CH_4 or H_2S, and instead has high concentrations of CO_2. In addition, samples from Mud Volcano have low concentrations of CH_4, and have very high Xg and Rc/Ra values. Lowenstern and Hurwitz
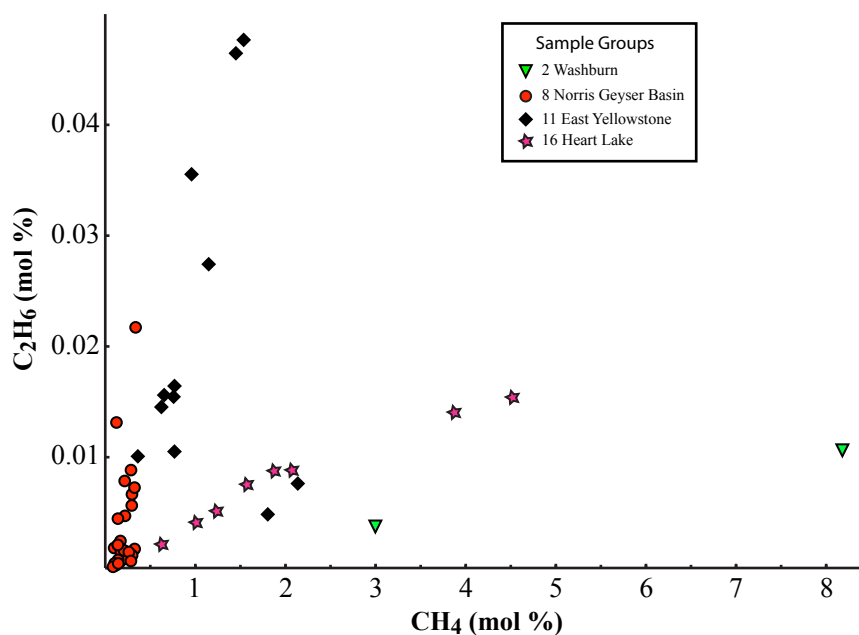
Figure 10. Plot showing mol percent CH_4 versus mol percent C_2H_6 for samples from Eastern Yellowstone, Washburn Hot Springs, Norris Geyser Basin, and Heart Lake (groups 11, 2, 8, and 16, respectively). The discrete linear trends require constant but differing CH_4/C_2H_6 ratios in each of these geographic areas.

(2008) concluded that parts of the Yellowstone hydrothermal systems, especially those in acid sulfate terrains such as Mud Volcano, are gas-saturated down to several kilometers depths. The low CH_4 and lack of radiogenic He imply that crustal inputs have less influence on gases in this particular part of the park, potentially because magma is either shallower (Husen and others, 2004), more recently emplaced, or has a more direct connection to the surface.

Summary

We present a dataset containing 167 gas analyses and 59 water analyses collected from thermal areas at Yellowstone from 2003 through 2012. Data are organized into 17 sampling groups plus a group containing miscellaneous samples. Our gas samples show minimal effects by mixing with air and most have N_2/Ar consistent with derivation from air-saturated water. Stable isotope values ($\delta^{18}O$ and δD) of waters agree with previous detailed studies that the thermal waters are predominantly derived from meteoric waters. $\delta^{18}O$ and δD values of condensed steam are 20 to 30 per mil lower than associated thermal waters, consistent with boiling at temperatures between 90°C and 110°C. Isotope values of carbon and helium indicate gases are derived from mixtures of a variety of crustal and magmatic sources. Individual thermal areas have distinct gas signatures that differentiate them from other thermal areas at Yellowstone. We interpret these characteristic gas signatures as indicative of mixing of diverse magmatic, crustal, and meteoric gas sources within the subsurface. Wallrocks influence gas chemistry in some areas, defining local oxidation states, gas concentrations, and gas ratios. Organic species such as CH_4 and C_2H_6 are derived primarily from breakdown of organic-rich sediment, combined with abiogenic reaction of CO_2 and H_2O under geothermal conditions. Trends toward biogenic CH_4 indicate that biological activity may produce a small proportion of the gas flowing from Yellowstone hot springs and fumaroles.
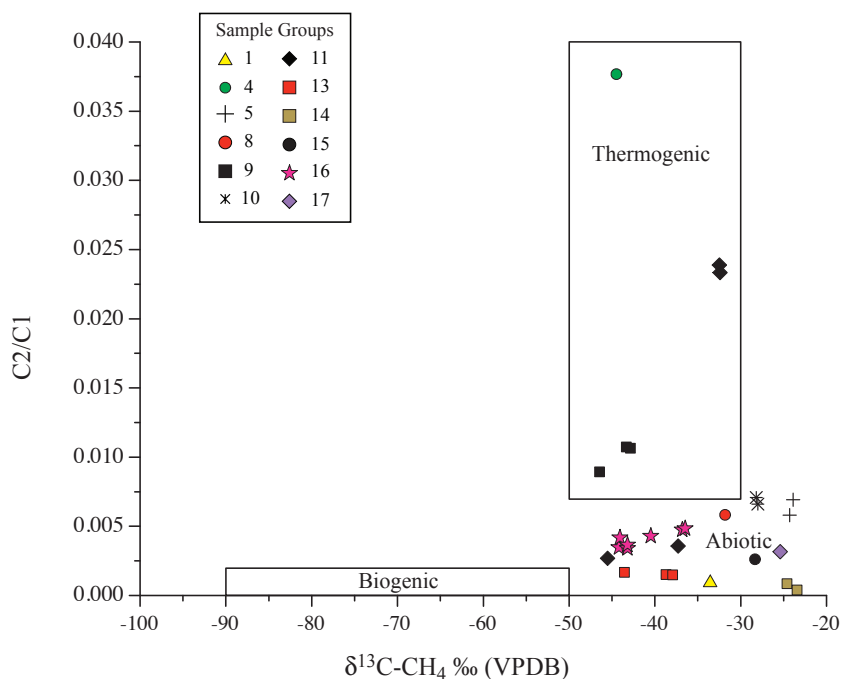
Figure 11. Plot showing the ethane to methane ratio (C2/C1) versus the $\delta^{13}C$ value of methane (C1), as normalized by the same ratio in the standard Vienna PeeDee Belemnite (VPDB), for gas collected from fumaroles, frying pans, and pools at Yellowstone. Fields for thermogenic and biogenic after Pohlman and others (2009). Numbers listed in the legend correspond to the sample groups as defined in table 1.

Acknowledgments

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