

# **Water-Chemistry and On-Site Sulfur-Speciation Data for Selected Springs in Yellowstone National Park, Wyoming, 1996-1998**

**Open-File Report 01-49**



**U.S. Department of the Interior  
U.S. Geological Survey**

# Water-Chemistry and On-Site Sulfur-Speciation Data for Selected Springs in Yellowstone National Park, Wyoming, 1996-1998

By James W. Ball<sup>1</sup>, D. Kirk Nordstrom<sup>1</sup>, R. Blaine McCleskey<sup>1</sup>, Martin A. A. Schoonen<sup>2</sup>, and Yong Xu<sup>2</sup>

<sup>1</sup>U.S. Geological Survey

<sup>2</sup>Department of Earth and Space Sciences, State University of New York at Stony Brook

Open-File Report 01-49

**Cover Photography:** View of Cinder Pool, Norris Geyser Basin, Yellowstone National Park looking to the north. The main pool overflow is to the lower left (southwest). One Hundred Spring Plain is to the upper right (northeast).

Boulder, Colorado  
2001



U.S. DEPARTMENT OF THE INTERIOR  
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY  
Charles G. Groat Director

The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

---

For additional information write to:

Chief, Branch of Regional Research  
U.S. Geological Survey  
Denver Federal Center  
Box 25046, MS-418  
Denver, Colorado 80225

Copies of this report can be purchased from:

U.S. Geological Survey  
Branch of Information Services  
Denver Federal Center,  
Box 25286  
Denver, Colorado 80225-0286

## CONTENTS

Abstract.....	1
Introduction.....	1
Purpose and Scope.....	2
Acknowledgments.....	2
Sample Locations.....	4
Methods Of Sample Collection, Stabilization, And Analysis.....	4
Sample Collection.....	4
Analytical Methods.....	11
Sample Treatment for Thiosulfate and Sulfate Determinations.....	11
Acidity Titrations.....	12
Revised pH.....	13
Water-Chemistry Data.....	14
References Cited.....	29
Appendix.....	33

## FIGURES

1. Map showing location of sampling areas in Yellowstone National Park, Wyo. ....	3
2. Sampling locations for hot springs at Norris Geyser Basin and Frying Pan Spring, Yellowstone National Park, Wyo.....	5
3. Sampling locations in the Artists Paintpots and Geyser Springs Group of the Gibbon Geyser Basin, Yellowstone National Park, Wyo.....	6
4. Sampling locations for the Sylvan Springs area of Gibbon Geyser Basin, Yellowstone National Park, Wyo.....	7
5. Sampling locations for Heart Lake Geyser Basin, Yellowstone National Park, Wyo.....	8
6. Sampling sites for Alluvium and Columbine Creeks and their tributaries, Yellowstone National Park, Wyo.....	9

## TABLES

1. Storage and stabilization methods for filtered samples.....	10
2. Detailed sample site descriptions.....	15
3. Site data and water analyses for Brimstone Basin.....	17
4. Site data and water analyses for Norris Geyser Basin.....	21
5. Site data and water analyses for Gibbon Geyser Basin.....	23
6. Site data and water analyses for Heart Lake Geyser Basin.....	25
7. Site data and water analyses for S <sub>2</sub> O <sub>3</sub> and H <sub>2</sub> S for Upper, Lower, and Norris Geyser Basins.....	26
8. <sup>2</sup> H, <sup>18</sup> O, and <sup>34</sup> S isotope analyses.....	27
9. Results for field blanks.....	28
10. Methods of analysis.....	34
11. Explanation of methods of analysis.....	35
12. Measurements of Standard Reference Waters.....	38



# **Water-Chemistry and On-Site Sulfur-Speciation Data for Selected Springs in Yellowstone National Park, Wyoming, 1996-1998**

*By James W. Ball, D. Kirk Nordstrom, R. Blaine McCleskey, Martin A. A. Schoonen, and Yong Xu*

## **ABSTRACT**

Fifty-eight water analyses are reported for samples collected from 19 hot springs and their overflow drainages and one ambient-temperature acid stream in Yellowstone National Park (YNP) during 1996-98. These water samples were collected and analyzed as part of research investigations on microbially mediated sulfur oxidation in stream waters and sulfur redox speciation in hot springs in YNP and chemical changes in overflow drainages that affect major ions, redox species, and trace elements. The research on sulfur redox speciation in hot springs is a collaboration with the State University of New York at Stony Brook, Northern Arizona University, and the U.S. Geological Survey (USGS). One ambient-temperature acidic stream system, Alluvium Creek and its tributaries in Brimstone Basin, was studied in detail. Analyses were performed adjacent to the sampling site, in an on-site mobile laboratory truck, or later in a USGS laboratory, depending on stability and preservability of the constituent.

Water temperature, specific conductance, pH, Eh, dissolved oxygen (D.O.), and dissolved H<sub>2</sub>S were determined on-site at the time of sampling. Alkalinity and F were determined within a few days of sample collection by titration and by ion-selective electrode, respectively. Concentrations of S<sub>2</sub>O<sub>3</sub> and S<sub>x</sub>O<sub>6</sub> were determined as soon as possible (minutes to hours later) by ion chromatography (IC). Concentrations of Cl, SO<sub>4</sub>, and Br were determined by IC within a few days of sample collection. Concentrations of Fe(II) and Fe(total) were determined by ultraviolet/visible spectrophotometry within a few days of sample collection. Densities were determined later in the USGS laboratory. Concentrations of Li, Na, and K were determined by flame atomic absorption (Li) and emission (Na, K) spectrometry. Concentrations of Al, As(total), B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe(total), Mg, Mn, Ni, Pb, Si, Sr, V, and Zn were determined by inductively-coupled plasma optical emission spectrometry. Trace concentrations of Cd, Se, As(total), Ni, and Pb were determined by Zeeman-corrected graphite-furnace atomic-absorption spectrometry. Trace concentrations of As(total) and As(III) were determined by hydride generation using a flow-injection analysis system.

## **INTRODUCTION**

Spectacular hot spring and geyser activity led to the designation of Yellowstone National Park (YNP) as the first national park in the world and inspired numerous scientific investigations. Investigations into the water chemistry of hot springs, geysers, streams, and rivers in YNP have been conducted primarily by the USGS, dating back to the study by Gooch and Whitfield (1888) and the comprehensive study by Allen and Day (1935). More recent water-chemistry data are available for six samples reported by White and others (1963), 166 samples reported by Rowe and others (1973), 541 samples reported by Thompson and others (1975), 422 samples reported by Thompson and Yadav (1979), 45 samples reported by Stauffer and others (1980), 38 samples reported by Thompson

and Hutchinson (1981), 17 samples reported by Kharaka and others (1991), and over 450 samples reported by Thompson and DeMonge (1996). White and others (1988), Fournier (1989), Fournier and others (1994), and Ball and others (1998a; 1998b) have reported additional data.

Waters at YNP have pH values ranging from 1 to 10, temperatures from ambient to boiling, and high concentrations of As, H<sub>2</sub>S, SO<sub>4</sub>, and HCO<sub>3</sub> relative to most natural waters. Numerous redox reactions and mineral-precipitation reactions occur. As well as being valuable natural resources, active geothermal areas such as YNP provide enormous insight into formation of mineral deposits, microbiological processes in extreme environments, and water-rock interactions.

## **Purpose and Scope**

The present study is the second phase of a collaborative research project between the USGS, the State University of New York (SUNY) at Stony Brook, and Northern Arizona University. The purpose of this investigation is to study the occurrence, origin, rates of formation and disappearance, and hydrogeochemical significance of unstable redox species of sulfur in mineral springs and geothermal waters. Several papers have been published that report results of the first phase of this project and of other collaborative research efforts (Ball and others, 1998b; Xu and Schoonen, 1995; Xu and others, 1996; 1998; 2000).

During 1996-98, 58 water samples were collected and analyzed for major and trace constituents from six areas of YNP (fig. 1): Norris Geyser Basin, Gibbon Geyser Basin (Geyser Springs and Sylvan Springs Groups), Heart Lake Geyser Basin, Lower Geyser Basin (reduced sulfur species only), Upper Geyser Basin (reduced sulfur species only), and Brimstone Basin. Water in Alluvium Creek and its tributaries and discharging from springs in Brimstone Basin provided a range of pH values and dissolved constituent concentrations that allowed study of low-temperature sulfur oxidation processes. The analyses for the hot-spring areas are some of the most complete available, containing major ions, trace elements, and redox species such as Fe(II)/Fe(total), As(III)/As(total), H<sub>2</sub>S, S<sub>2</sub>O<sub>3</sub>, and SO<sub>4</sub>.

## **Acknowledgments**

We extend our appreciation to the staff of Yellowstone National Park for permission to collect water samples and for their generous assistance on numerous occasions. We are especially thankful to the late Rick Hutchinson for his advice and his interest in our work since 1974.

The authors thank T. B. Coplen (USGS, Reston, VA) for H and O isotope determinations and R. O. Rye (USGS, Denver, CO) for S isotope determinations. The participation of SUNY at Stony Brook in this project is sponsored by the National Science Foundation-Earth Sciences.



Figure 1. Location of sampling areas in Yellowstone National Park, Wyo.

## **SAMPLE LOCATIONS**

Eight samples for complete analysis were taken from Norris Geyser Basin and Frying Pan Spring (fig. 2). Nine samples were collected at Gibbon Geyser Basin; six samples were collected from the Geyser Springs Group, east of the Gibbon River near Artists Paintpots (fig. 3), and three samples were collected from the Sylvan Springs Group, west of the Gibbon River (fig. 4). Two samples were collected from Heart Lake Geyser Basin (fig. 5). Nineteen samples were collected at Brimstone Basin. Fourteen samples were taken from Alluvium Creek and its tributaries, with the remaining five samples taken from Columbine Creek and its tributaries (fig. 6). Twenty samples were collected for  $S_2O_3$  and  $H_2S$  determinations, 10 samples from Norris Geyser Basin, (fig. 2), and 10 samples from Upper and Lower Geyser Basins (locations not shown).

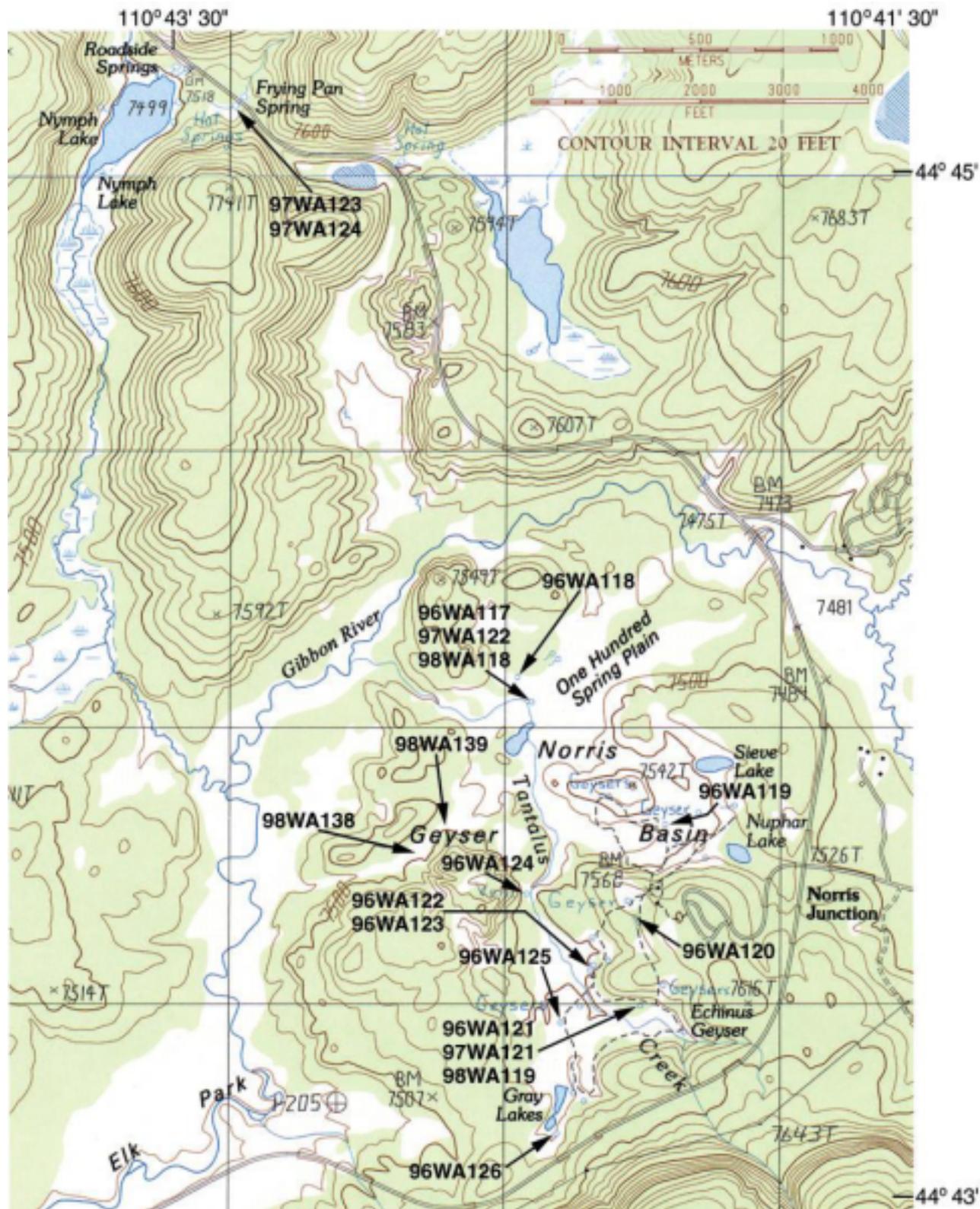
## **METHODS OF SAMPLE COLLECTION, STABILIZATION, AND ANALYSIS**

Methods of sample collection, stabilization, and analysis used in this study are discussed in the following sections.

### **Sample Collection**

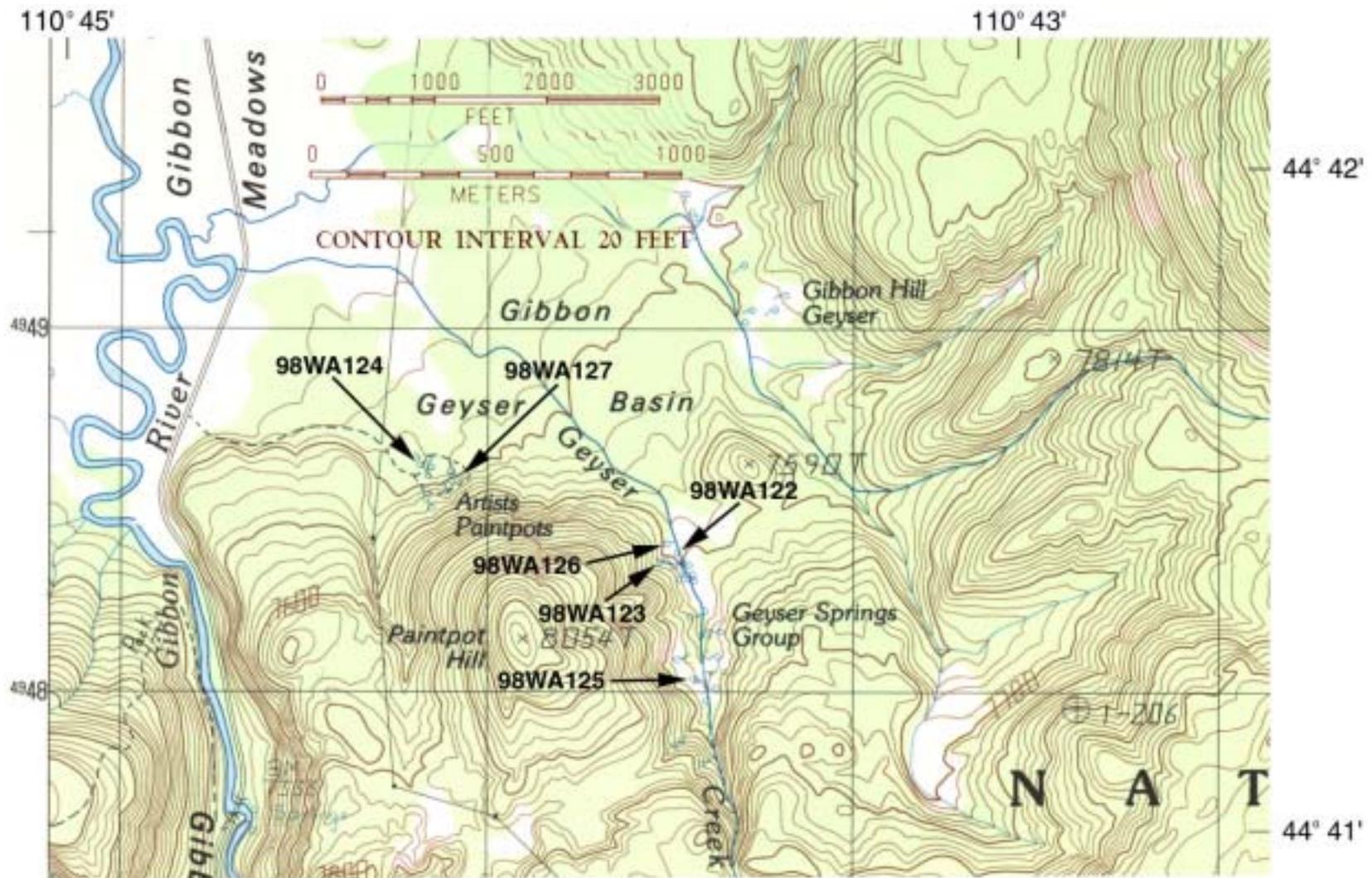
Samples were collected as close to the source of each spring as possible and at various locations along Alluvium Creek and its tributaries. To protect fragile hot spring mineral formations and to minimize changes in temperature, pH, and water chemistry during sampling, samples from the middle of pools were collected using an insulated stainless steel container attached to the end of an extendable aluminum pole. The container was rinsed several times with sample water to minimize sample contamination and assure thermal equilibration. At more easily accessible sites, spring water was withdrawn directly from the source or channel through silicone tubing using a peristaltic pump.

A mobile laboratory truck containing an ion chromatograph, UV-visible spectrophotometer, autotitrator, and reagent-grade water system was set up as close to each sampling site as feasible so that unstable species such as redox species of Fe and intermediate sulfur oxyanions could be determined quickly after collection.



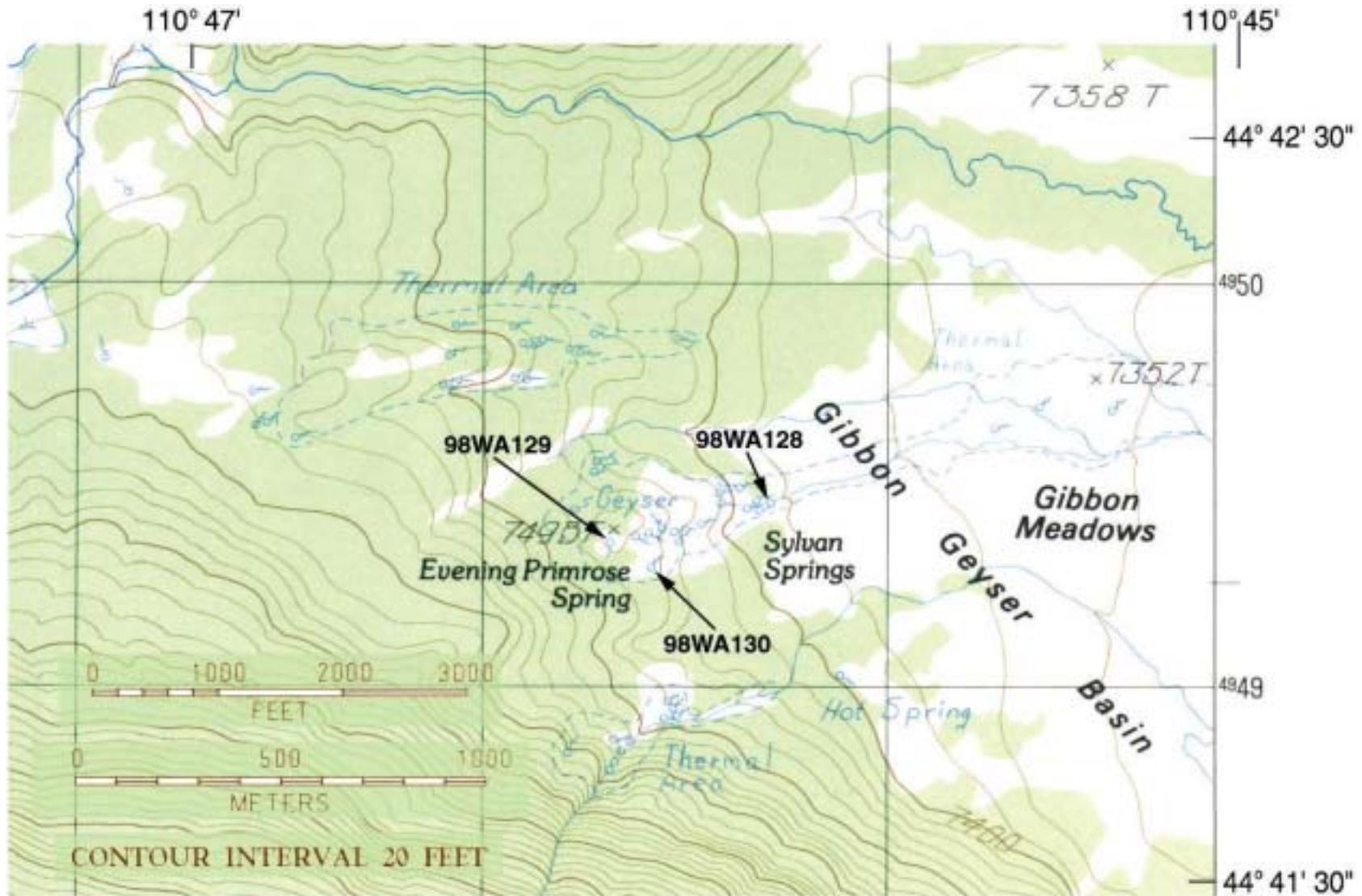
Base from composite of U.S. Geological Survey Norris Junction and Obsidian Cliff quadrangles, 1:24,000 (1986)

Figure 2. Sampling locations for hot springs at Norris Geyser Basin and Frying Pan Spring, Yellowstone National Park, Wyo.



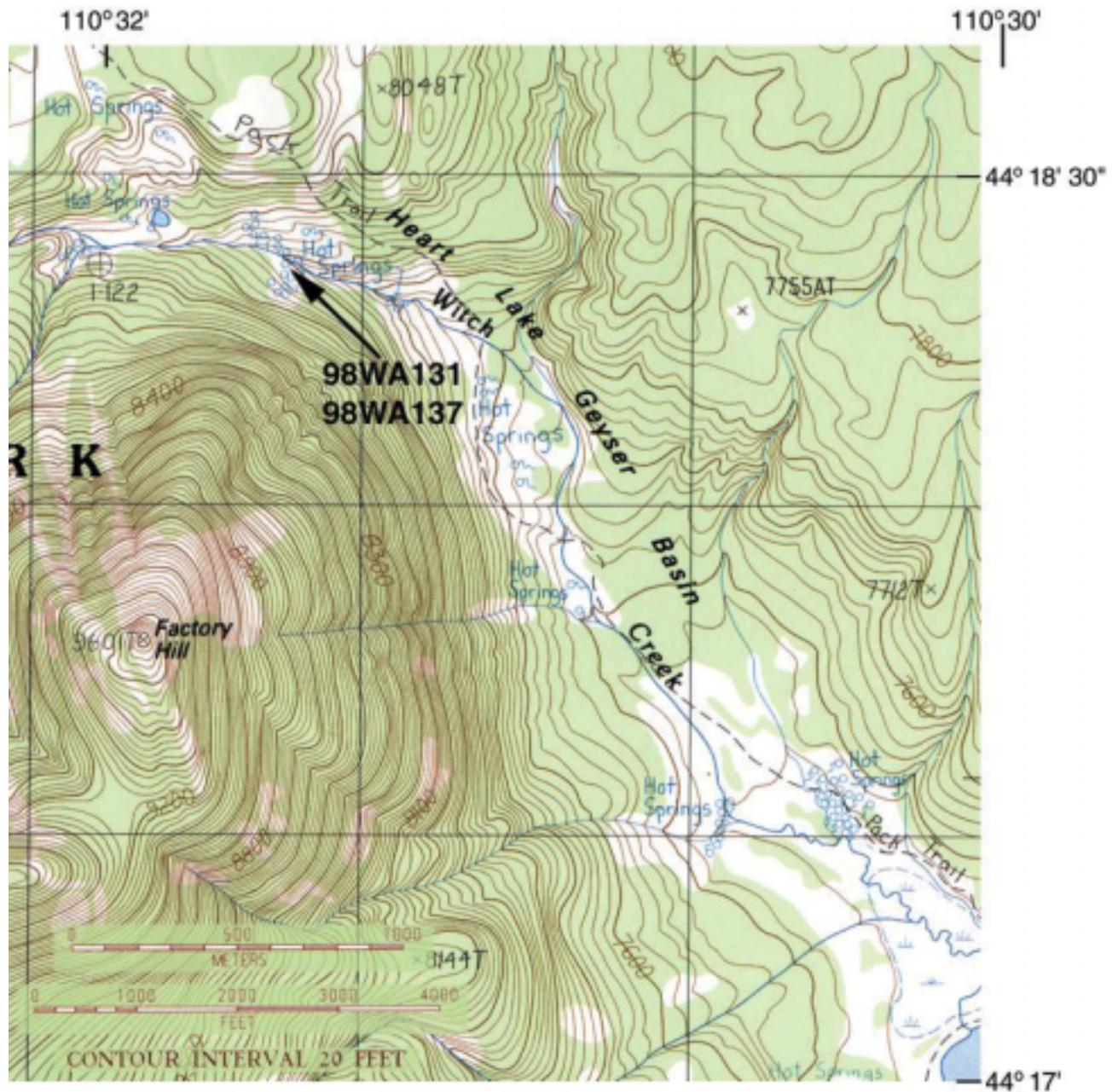
Base from U.S. Geological Survey Norris Junction quadrangle, 1:24,000 (1986)

Figure 3. Sampling locations in the Artists Paintpots and Geysers Springs Group of the Gibbon Geyser Basin, Yellowstone National Park, Wyo.



Base from U.S. Geological Survey Madison Junction quadrangle, 1:24,000 (1986)

Figure 4. Sampling locations for the Sylvan Springs area of Gibbon Geyser Basin, Yellowstone National Park, Wyo.



Base from U.S. Geological Survey Mount Sheridan quadrangle, 1:24,000 (1986)

Figure 5. Sampling locations for Heart Lake Geyser Basin, Yellowstone National Park, Wyo.



Samples for the determination of major cations, trace metals, Fe(II) and Fe(total), major anions, alkalinity, density, NH<sub>4</sub>, and dissolved SiO<sub>2</sub>, were filtered by pumping from the source with a portable peristaltic pump fitted with medical-grade silicone tubing through a 142-mm diameter all-plastic filter holder (Kennedy and others, 1976) containing a 0.1- $\mu$ m Millipore filter membrane. Samples for determination of H<sub>2</sub>S, SO<sub>4</sub>, and S<sub>2</sub>O<sub>3</sub> were suctioned by hand into a plastic syringe to avoid the inclusion of atmospheric air, then forced through a syringe-mounted 0.45- $\mu$ m membrane filter. Dissolved H<sub>2</sub>S was determined onsite at the time of sample collection. Stabilizing reagents for intermediate sulfur species were put into the syringe before sample was collected. Unfiltered samples for the determination of isotopes of H and O were either pumped or dipped from the source and stored in amber glass bottles. Storage and stabilization of filtered samples are summarized in table 1.

Temperature, specific conductance, and D.O. measurements were made by immersing probes directly into the source or into an unfiltered sample collected in an insulated container. Measurements for Eh and pH were made on unfiltered sample water pumped from the source through an acrylic plastic flow-through cell containing a thermometer, Eh and pH electrodes, and test tubes containing calibrating solutions.

Table 1. Storage and stabilization methods for filtered samples

Sample type(s)	Storage container	Stabilization treatment in addition to refrigeration
Major and trace metals, Fe(II), and Fe(total)	Polyethylene bottles, soaked in 5% HCl and rinsed with double-distilled water	1% (v/v) concentrated HNO <sub>3</sub> (metal samples) or redistilled 6 N HCl (Fe(II/III) added)
Major anions, alkalinity, and density	Polyethylene bottles soaked by filling with double-distilled water for >48 hours	None
NH <sub>4</sub>	Same as major and trace metals, Fe(II), and Fe(total)	1% (v/v) 1:10 redistilled H <sub>2</sub> SO <sub>4</sub> added
SiO <sub>2</sub>	Same as major anions, alkalinity, and density	Immediately diluted 1:9 with distilled H <sub>2</sub> O
SO <sub>4</sub> , S <sub>2</sub> O <sub>3</sub>	60-mL plastic syringe	1.6% (v/v) 1 M Cd-(OOC-CH <sub>3</sub> ) <sub>2</sub> , CdCl <sub>2</sub> , or ZnCl <sub>2</sub> plus 0.2% (v/v) 5 M NaOH added to precipitate S(-II)

## **Analytical Methods**

Analytical methods are summarized in tables 10 and 11 in the Appendix. Because most constituents were determined using established procedures, the analytical methods are described only briefly in table 11. In the following section, only general conditions or variants of standard procedures are discussed.

All reagents were of purity at least equal to the reagent-grade standards of the American Chemical Society. Double-distilled deionized water and re-distilled acids were used in all preparations. For ICP, FAAS, and ZGFAAS analyses, external standards, blanks, sample dilutions, and spiking solutions usually were made with commercial ICP elemental standard solutions. In some cases, standard solutions were prepared from elements or their compounds of the highest commercially available purity. USGS standard reference water samples (SRWS) were used as independent standards. Additional information about the USGS SRWS program can be obtained at <http://bqs.usgs.gov/srs>.

Samples were diluted as necessary to bring analyte concentrations within the optimal range of the analytical method. For major and trace cation analyses done by ICP, several dilutions of each sample, with the extremes of the range differing by dilution factors from 2 to 100, were analyzed to check for concentration effects on the analytical method.

Calibration curves were determined by using standards within each set of analyses. If matrix effects were evident, spike-recovery and/or standard-addition measurements were performed. USGS SRWS 67, 69, 71, 73, T117, T133, T143, and T153 were used to check the analytical methods for major and trace metals, and SRWS M102 and M140 were used to check the analytical methods for major anions. The SRWS data are presented in table 12 in the Appendix. Estimates of ICP detection limits are reported in table 11 in the Appendix and were assumed equal to  $3\sigma_{\text{blank}}$ , where  $\sigma_{\text{blank}}$  is the standard deviation of several dozen measurements of the constituent in a blank solution treated as a sample. Also listed in table 11 are typical values of analytical reproducibility for each method of analysis in samples containing the analyte at concentrations at least ten times the detection limit. These parameters were estimated for FAAS and ZGFAAS in a similar manner, using about a dozen measurements of blanks.

## **Sample Treatment for Thiosulfate and Sulfate Determinations**

Determination of dissolved sulfur species presents particularly difficult analytical challenges, making competent sampling and analytical procedures critical to the success of the research. For example, dissolved  $\text{H}_2\text{S}$  can volatilize rapidly or oxidize to S,  $\text{S}_2\text{O}_3$ , other S species of intermediate oxidation state, and  $\text{SO}_4$ . Without proper precautions, all these species can be considered unstable and thus their concentrations subject to change. Because on-site determinations or special preservation techniques are crucial for reliable determination of unstable species concentrations, the USGS mobile laboratory truck described earlier was used to determine unstable species concentrations within minutes to hours of sample collection.

The distribution of sulfur species during oxidation of H<sub>2</sub>S will change with storage time according to the rates of several competing reactions (Ball and others, 1998b). In the hot springs, high temperature and the presence of oxidation-catalyzing bacteria cause these reactions to proceed at a much faster rate than in cooled and filtered samples stored for later analysis. For example, S<sub>2</sub>O<sub>3</sub> is oxidized rapidly to SO<sub>4</sub> at high temperatures, but this reaction proceeds at a negligible rate (Rolla and Chakrabarti, 1982) under typical sample-storage conditions. Major oxidation products are expected to be SO<sub>4</sub> and S<sub>2</sub>O<sub>3</sub>, with elemental S, polythionates (S<sub>n</sub>O<sub>6</sub><sup>2-</sup>), and polysulfides (S<sub>n</sub><sup>2-</sup>) as minor products.

To prevent over-estimation of the *in-situ* concentration of SO<sub>4</sub> and S<sub>2</sub>O<sub>3</sub>, S(-II) oxidation was minimized by drawing unfiltered sample into a 60 mL syringe containing 1 mL of 1 M ZnCl<sub>2</sub> plus 0.5 mL 5 M NaOH. This technique caused the oxidation-resistant ZnS species to precipitate. Sulfate and S<sub>2</sub>O<sub>3</sub> were determined by syringe-filtering the sample directly into the ion chromatograph on-site in the mobile laboratory or storing it on ice and analyzing it a few days to weeks later at the USGS laboratory in Boulder, Colorado, or SUNY at Stony Brook. Results for duplicate determinations by both techniques were similar.

### Acidity Titrations

Acidity is the base-neutralizing capacity of a solution and is defined as the equivalent sum of all the acids that are titratable with a strong base (Stumm and Morgan, 1981). From 1 to 48 hours after collection, filtered, unacidified samples with field pH less than 3.5 were titrated to a pH greater than 7 using an autotitrator and standardized NaOH. The NaOH titrant (0.01 - 0.05 M) was standardized daily by titrating a known quantity of potassium hydrogen phthalate (KHC<sub>8</sub>H<sub>4</sub>O<sub>4</sub>). The titrator was programmed for 50- to 100- $\mu$ L constant-volume additions or constant change in mV, typically 10 mV per addition. Equivalence points were determined using a modified Gran's function:

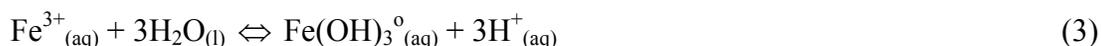
$$F_{\text{acid}} = (V_0 + V_{\text{NaOH}}) \times 10^{-\text{pOH}}, \quad (1)$$

where  $F_{\text{acid}}$  = the Gran function,  $V_0$  = sample volume,  $V_{\text{NaOH}}$  = volume of NaOH titrant added, and  $\text{pOH} = 14$  minus the pH.

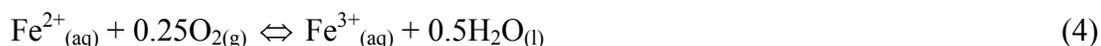
The portion of the titration curve generated for total acidity will lie in the basic region where  $[\text{H}^+]$  is negligible compared with  $[\text{OH}^-]$ . Therefore,  $\text{OH}^-$  substitutes for  $\text{H}^+$ , or  $10^{-\text{pOH}}$  for  $10^{-\text{pH}}$  in equation (1) (Barringer and Johnsson, 1996). The most important reactions contributing to total acidity are SO<sub>4</sub> hydrolysis:



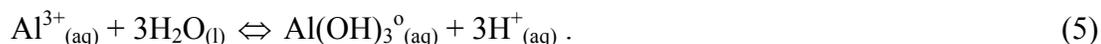
Fe hydrolysis:



where the  $\text{Fe}^{3+}$  comes mostly from the oxidation of  $\text{Fe}^{2+}$ :



and the hydrolysis of Al:



Free  $\text{H}^+$  was derived by subtracting the hydrogen produced by hydrolysis of  $\text{SO}_4^{2-}$ , Fe, and Al from the total acidity. The  $\text{HSO}_4^-$  concentration was estimated using an interactive version (PHREEQCI version 2.2 alpha) of the geochemical modeling code PHREEQC (Parkhurst and Appelo, 1999) in conjunction with the WATEQ4F (Ball and Nordstrom, 1991) database. Sample pH was calculated by combining the activity coefficient determined by PHREEQCI with  $\text{H}^+$  molality and computing the common logarithm of the resulting activity.

### Revised pH

Most geochemical reactions are strongly influenced by pH. Therefore, accurate and precise pH determinations are important in determining the fate of many chemical constituents. For samples with low pH,  $\text{H}^+$  is frequently the dominant cation in acid waters of YNP. Thus, inaccurate pH measurements can cause poor speciation and charge balance calculations. Alternatively, charge imbalance could be used to estimate pH at low pH values. Together with pH estimated from charge imbalance, measurements of field pH, laboratory pH, and pH determined from free  $\text{H}^+$  obtained by total acidity titration provide four methods for constraining the sample pH. Each measurement has biases that can affect the accuracy of the determination.

For both field and laboratory pH measurements, extreme care was taken to ensure that two bracketing calibration buffers placed in the flow-through cell were equilibrated to the sample temperature, and calibration was rechecked until repeat measurements were within 0.05 pH unit. Despite these precautions, temperature effects, malfunctioning reference junctions, and extended equilibration times may result in poor readings. In the field, the sample water may not be at chemical equilibrium and meters are powered by batteries and exposed to the elements; any one of these conditions may affect the accuracy of the measurement. Oxidation and hydrolysis of Fe and hydrolysis of Al can cause the pH to change during storage so that the laboratory pH is different from the field pH. The analytical uncertainty of  $\text{SO}_4$ , Fe, and Al determinations, the rate of Fe and Al hydrolysis during the titration, uncertainties in the thermodynamic database, and the analytical uncertainty of the titration all affect pH determined from free  $\text{H}^+$  in the total acidity titration.

All of these factors were considered when evaluating and selecting revised pH values. Typically, the field pH was considered to be the most accurate and precise unless the sample had a speciated charge imbalance greater than 10%, in which case laboratory pH and free  $\text{H}^+$  pH from the acidity titration were considered as substitutes. If laboratory pH gave the best charge balance, then it was used for revised pH; if acidity pH gave the best charge balance, it was used. Laboratory pH was selected as the revised pH in 10 instances and acidity pH was selected as the revised pH in 7 instances. Field pH was selected for the remaining 41 samples.

## WATER-CHEMISTRY DATA

Table 2 contains detailed descriptions of all sample locations. Feature names enclosed in quotation marks are unofficial names from Bryan (1995). Site data and water analyses for YNP springs sampled in 1996, 1997, and 1998 are presented in tables 3-6. Site data and reduced sulfur species analyses to document the occurrence of  $S_2O_3$  in YNP (see Ball and others, 1998b; Xu and others, 1998; 2000) are presented in table 7. The results of  $^2H$ ,  $^{18}O$ , and  $^{34}S$  isotope analyses are listed in table 8. Results for determinations on two field blanks are presented in table 9. Samples are sorted by spring, then by date of sample collection, and then by sampling site along the downstream overflow channel (if present). In the tables, “source” samples were collected at the origin of the spring, and “overflow channel” samples were collected at various distances downstream from the source. For data sets that contained concentrations of major anions and major cations, the WATEQ4F program (Ball and Nordstrom, 1991) was used to calculate ion sums and charge imbalance (C.I.), using the following calculation:

$$\text{C.I. (percent)} = \frac{100 \times (\text{meq/L cations} - \text{meq/L anions})}{(\text{meq/L cations} + \text{meq/L anions}) \div 2} \quad (6)$$

Note that the result of this calculation is twice the value that typically would be reported by an analytical laboratory, because equation (5) relates the cation-anion difference to the average of the two rather than to the sum of the ions comprising them. In tables 3-6, meq/L cations and meq/L anions values are rounded to 3 significant figures, and percent difference values are rounded to 0.1 percent. This rounding may cause differences between the percent difference values shown and those calculated using equation (6) and the meq/L cations and meq/L anions values listed in tables 3-6.

Table 2. Detailed sample site descriptions

Sample Code Number	Site Description	Latitude, Longitude ( $\pm 1''$ )
96WA101	Alluvium Creek, ~10 m from Yellowstone Lake shore	44°23'07"N, 110°14'29"W
96WA102	Alluvium Creek, ~300 m from Yellowstone Lake shore	44°23'09"N, 110°14'17"W
96WA103	Alluvium Creek, edge of Brimstone Basin below confluence of 96WA104 and 96WA105	44°23'05"N, 110°12'58"W
96WA104	Alluvium Creek, main drainage above confluence	44°23'05"N, 110°12'58"W
96WA105	Alluvium Creek, east flowing tributary above confluence	44°23'05"N, 110°12'58"W
96WA106	Punch Bowl Spring, Upper Geyser Basin	44°28'10"N, 110°50'52"W
96WA107	Octopus Spring, near Great Fountain Geyser	44°32'02"N, 110°47'44"W
96WA108	Giantess Geyser, Upper Geyser Basin	44°27'49"N, 110°49'41"W
96WA109	Ear Spring, Upper Geyser Basin	44°27'52"N, 110°49'46"W
96WA110	Sulphide Spring, Upper Geyser Basin	44°27'54"N, 110°49'49"W
96WA111	Sapphire Pool, Upper Geyser Basin	44°29'06"N, 110°51'16"W
96WA112	Field blank	---
96WA113	Unnamed spring, south of Azure Spring along Firehole River	44°33'40"N, 110°49'59"W
96WA114	Unnamed spring, south of Bath Spring	44°33'39"N, 110°50'00"W
96WA115	Bath Spring, Lower Geyser Basin	44°33'40"N, 110°50'01"W
96WA116	Cavern Spring, Lower Geyser Basin	44°33'41"N, 110°50'01"W
96WA117	Cinder Pool, Norris Geyser Basin	44°43'57"N, 110°42'36"W
96WA118	Horseshoe Spring, Norris Geyser Basin	44°43'58"N, 110°42'37"W
96WA119	Constant Geyser, Norris Geyser Basin	44°43'44"N, 110°42'08"W
96WA120	Emerald Spring, Norris Geyser Basin	44°43'36"N, 110°42'11"W
96WA121	Cistern Spring, Norris Geyser Basin	44°43'23"N, 110°42'16"W
96WA122	Palpitator Spring, Norris Geyser Basin	44°43'27"N, 110°42'21"W
96WA123	Fearless Geyser, Norris Geyser Basin	44°43'28"N, 110°42'20"W
96WA124	Perpetual Spouter, Norris Geyser Basin	44°43'13"N, 110°42'28"W
96WA125	Porkchop Spring, Norris Geyser Basin	44°43'21"N, 110°42'25"W
96WA126	Big Alcove Spring, Norris Geyser Basin	44°43'08"N, 110°42'25"W
97WA121	Cistern Spring, Norris Geyser Basin	44°43'35"N, 110°42'21"W
97WA122	Cinder Pool, Norris Geyser Basin	44°43'57"N, 110°42'36"W
97WA123	Frying Pan Spring	44°45'08"N, 110°43'18"W
97WA124	Overflow channel, ~61m downstream from Frying Pan Spring	44°45'08"N, 110°43'20"W
97WA125	Alluvium Creek, ~12m from lake shore, Brimstone Basin	44°23'07"N, 110°14'29"W
97WA126	Alluvium Creek, ~305 m upstream from Thoroughfare Trail, Brimstone Basin	44°23'22"N, 110°13'54"W
97WA127	Alluvium Creek, ~1070 m upstream from Thoroughfare Trail, Brimstone Basin	44°23'34"N, 110°13'23"W

Table 2. Detailed sample site descriptions—Continued

Sample Code Number	Site Description	Latitude, Longitude ( $\pm 1''$ )
97WA128	Alluvium Creek, ~1700 m upstream from Thoroughfare Trail, Brimstone Basin	44°23'23"N, 110°13'15"W
97WA129	Small tributary to Alluvium Creek, ~1700 m upstream from Thoroughfare Trail, Brimstone Basin	44°23'22"N, 110°12'16"W
97WA130	Alluvium Creek, ~2300 m upstream from Thoroughfare Trail, Brimstone Basin	44°22'58"N, 110°12'56"W
97WA131	South tributary to Columbine Creek, Brimstone Basin	44°23'27"N, 110°12'45"W
98WA118	Cinder Pool, Norris Geyser Basin	44°44'07"N, 110°42'30"W
98WA119	Cistern Spring, Norris Geyser Basin	44°43'42"N, 110°42'15"W
98WA120	South fork of south tributary to Columbine Creek, Brimstone Basin	44°23'16"N, 110°12'31"W
98WA121	Alluvium Creek at mouth, Brimstone Basin	44°23'07"N, 110°14'29"W
98WA122	Unnamed spring, Geyser Springs Group, Gibbon Geyser Basin	44°41'25"N, 110°43'42"W
98WA123	"Bone Pool," Geyser Springs Group, Gibbon Geyser Basin	44°41'25"N, 110°43'45"W
98WA124	Unnamed spring, Artists Paintpots, Gibbon Geyser Basin	44°44'30"N, 110°44'20"W
98WA125	"Bat Pool," Geyser Springs Group, Gibbon Geyser Basin	44°41'13"N, 110°43'43"W
98WA126	"Bull's Eye Spring," Geyser Springs Group, Gibbon Geyser Basin	44°41'26"N, 110°43'46"W
98WA127	Unnamed spring, Artists Paintpots, Gibbon Geyser Basin	44°44'30"N, 110°44'15"W
98WA128	Unnamed spring Sylvan Springs Group, Gibbon Geyser Basin	44°42'00"N, 110°45'54"W
98WA129	Unnamed spring, Sylvan Springs Group, Gibbon Geyser Basin	44°41'45"N, 110°46'22"W
98WA130	Evening Primrose Spring, Sylvan Springs Group, Gibbon Geyser Basin	44°41'30"N, 110°46'36"W
98WA131	Unnamed spring - Fissure Group, Heart Lake	44°18'19"N, 110°31'39"W
98WA132	Alluvium Creek, ~760 m upstream from lake shore, Brimstone Basin	44°23'34"N, 110°13'41"W
98WA133	Small tributary to Alluvium Creek, ~1700 m upstream from Thoroughfare Trail, Brimstone Basin	44°23'22"N, 110°12'16"W
98WA134	North fork of south tributary to Columbine Creek, Brimstone Basin	44°23'22"N, 110°12'16"W
98WA135	Field Blank	---
98WA136	South tributary to Columbine Creek, Brimstone Basin	44°23'28"N, 110°12'48"W
98WA137	~2 m from 98WA131, Fissure Group- Heart Lake	44°18'19"N, 110°31'39"W
98WA138	Main drainage, Ragged Hills area, Norris Geyser Basin	44°43'40"N, 110°42'51"W
98WA139	Main drainage, ~80 m down drainage of Ragged Hills, Norris Geyser Basin	44°43'41"N, 110°42'48"W
98WA140	South tributary to Columbine Creek, Brimstone Basin	44°23'29"N, 110°13'09"W

Table 3. Site data and water analyses for Brimstone Basin

Description	Alluvium Creek				
Sample Code Number	96WA101	96WA102	96WA103	96WA104	96WA105
Date Collected	8/16/1996	8/16/1996	8/17/1996	8/17/1996	8/17/1996
Temperature (°C)	9.5	16	9	17	11.5
Density (g/mL) at 20°C	0.99899	0.99922	0.99977	0.99968	0.99997
pH, field / lab / acidity	2.91 / 2.98 / 2.97	2.88 / 2.86 / 2.87	2.17 / 2.10 / 2.10	2.98 / 2.95 / 3.02	1.87 / 1.79 / 1.77
pH, revised	2.91	2.86	2.10	2.95	1.77
Spec Cond (µS/cm) field / lab	1220 / 1240	--- / 1630	5000 / 4530	1880 / 2080	6500 / 8020
Eh (V)	---	---	---	---	---
D.O. (mg/L)	9.2	---	---	---	---
<u>Constituent (mg/L)</u>					
Ca	38	48	66	94	32
Mg	29	40	85	120	35
Sr	0.47	0.62	0.57	0.78	0.37
Ba	0.013	0.012	0.040	0.014	0.010
Na	19	24	19	23	15
K	9.0	12	17	19	17
Li	0.010	0.010	0.030	0.040	0.009
SO <sub>4</sub>	560	770	1400	1100	1700
S <sub>2</sub> O <sub>3</sub>	---	---	---	---	---
H <sub>2</sub> S	---	---	0.38	0.041	1.2
Alkalinity (as HCO <sub>3</sub> )	---	---	---	---	---
Acidity (mM) total / free H <sup>+</sup>	5.8 / 1.2	8.0 / 1.5	17 / 9.0	6.7 / 1.1	31 / 20
F	0.17	0.18	0.22	0.27	0.14
Cl	<1	13	<3	57	25
Br	<3	<3	<6	<6	<8
NH <sub>4</sub>	---	---	---	---	---
SiO <sub>2</sub>	95	110	79	77	79
B	0.2	0.022	<0.2	0.035	0.024
Al	38	53	40	44	37
Fe (total)	2.09	4.53	5.24	6.31	4.61
Fe (II)	0.420	0.790	3.65	2.71	4.40
Mn	0.60	0.88	1.6	2.3	0.83
Cu	0.009	0.013	<0.001	0.001	<0.001
Zn	0.038	0.040	0.027	0.026	0.026
Cd	<0.001	0.001	<0.001	<0.001	<0.001
Cr	0.065	0.098	0.11	0.15	0.055
Co	0.017	0.018	0.008	0.008	0.008
Ni	0.03	0.03	<0.02	<0.02	<0.02
Pb	0.004	0.005	0.005	<0.001	<0.001
Be	0.0007	0.0003	0.0004	0.0007	<0.0001
V	0.005	0.012	0.040	0.049	0.031
Se (total)	<0.0003	<0.0003	0.0003	0.0003	0.003
As (total)	<0.02	<0.02	<0.02	<0.02	<0.02
As (III)	---	---	---	---	---
Sum cations (meq/L)	8.03	10.1	20.0	15.6	26.3
Sum anions (meq/L)	8.39	11.3	20.7	17.1	25.7
Charge imbalance (percent)	-4.4	-11.9	-3.7	-9.1	2.6

Table 3. Site data and water analyses for Brimstone Basin -- Continued

Description	Alluvium Creek	Alluvium Creek	Alluvium Creek	Alluvium Creek	Alluv. Cr. trib.
Sample Code Number	97WA125	97WA126	97WA127	97WA128	97WA129
Date Collected	8/12/1997	8/12/1997	8/12/1997	8/12/1997	8/12/1997
Temperature (°C)	7.2	13.1	22.0	23.9	18.0
Density (g/mL) at 20°C	0.99896	1.00010	1.00050	1.02550	1.00134
pH, field / lab / acidity	2.62 / 2.70 / 2.38	2.05 / 2.17 / 1.81	2.00 / 2.09 / 1.86	1.98 / 2.07 / 1.87	1.46 / 1.53 / 1.06
pH, revised	2.62	2.05	2.00	1.98	1.46
Spec Cond (µS/cm) field / lab	2110 / 1910	5380 / 5030	5790 / 5730	5690 / 5870	18400 / 18000
Eh (V)	0.763	0.831	0.743	0.678	0.603
D.O. (mg/L)	9.0	6.8	6.2	5.4	4.0
<u>Constituent (mg/L)</u>					
Ca	40	59	64	70	20
Mg	36	59	66	76	12
Sr	0.58	0.77	0.81	0.90	0.38
Ba	<0.01	0.01	0.01	0.02	0.02
Na	19	26	27	30	35
K	13	25	28	31	45
Li	0.02	0.03	0.03	0.03	0.02
SO <sub>4</sub>	710	1500	1700	1800	4300
S <sub>2</sub> O <sub>3</sub>	---	---	---	---	---
H <sub>2</sub> S	---	---	---	---	---
Alkalinity (as HCO <sub>3</sub> )	---	---	---	---	---
Acidity (mM) total / free H <sup>+</sup>	11 / 4.7	31 / 18	30 / 16	31 / 16	150 / 100
F	<0.1	<0.1	<0.1	0.42	0.35
Cl	2.4	4.1	3.4	5.0	11
Br	<0.2	<0.2	<0.2	<0.4	<0.4
NH <sub>4</sub>	---	---	---	---	---
SiO <sub>2</sub>	86	88	84	85	97
B	0.026	0.027	0.026	0.029	0.023
Al	47	66	68	73	88
Fe (total)	6.16	15.8	17.4	17.9	14.5
Fe (II)	0.288	1.54	1.34	4.89	12.9
Mn	0.79	1.1	1.2	1.3	0.37
Cu	0.010	<0.001	<0.001	<0.001	<0.00005
Zn	0.046	0.053	0.054	0.057	0.060
Cd	<0.00002	<0.00002	<0.00002	<0.00002	<0.00002
Cr	0.085	0.13	0.14	0.15	0.12
Co	0.017	0.019	0.018	0.021	0.022
Ni	0.029	0.021	0.020	0.022	0.18
Pb	0.0010	0.0030	<0.0003	<0.0003	0.0030
Be	<0.0001	0.0010	0.0010	0.0010	0.0040
V	0.022	0.069	0.078	0.082	0.048
Se (total)	0.0004	0.0007	0.0008	0.0009	0.0020
As (total)	0.004	0.008	0.010	0.009	0.014
As (III)	---	---	---	---	---
Sum cations (meq/L)	10.5	21.2	22.9	24.4	49.6
Sum anions (meq/L)	10.4	21.0	23.0	23.4	58.5
Charge imbalance (percent)	0.6	1.0	-0.2	4.2	-16.5

Table 3. Site data and water analyses for Brimstone Basin -- Continued

Description	Alluvium Creek	Columb. Cr. trib	Columb. Cr. trib	Alluvium Creek	Alluvium Creek
Sample Code Number	97WA130	97WA131	98WA120	98WA121	98WA132
Date Collected	8/13/1997	8/13/1997	9/19/1998	9/18/1998	9/18/1998
Temperature (°C)	9.8	11.2	5.1	7.0	10.4
Density (g/mL) at 20°C	1.00061	0.99873	---	---	---
pH, field / lab / acidity	1.81 / 1.92 / 1.68	--- / 2.69 / ---	2.02 / 2.31 / 2.24	2.71 / --- / ---	1.84 / --- / ---
pH, revised	1.81	2.69	2.31	2.71	1.84
Spec Cond (µS/cm) field / lab	8740 / 7780	1280 / 1350	4760 / 2940	--- / 2170	8250 / ---
Eh (V)	0.649	---	0.505	---	---
D.O. (mg/L)	9.0	7.0	7.7	---	---
<u>Constituent (mg/L)</u>					
Ca	67	15	29	---	---
Mg	48	8.7	20	---	---
Sr	1.2	0.17	0.41	---	---
Ba	0.012	0.028	0.014	---	---
Na	36	7.0	19	---	---
K	43	5.2	11	---	---
Li	0.030	0.008	0.010	---	---
SO <sub>4</sub>	2400	320	730	2800	2000
S <sub>2</sub> O <sub>3</sub>	---	---	---	---	---
H <sub>2</sub> S	---	---	---	---	---
Alkalinity (as HCO <sub>3</sub> )	---	---	---	---	---
Acidity (mM) total / free H <sup>+</sup>	47 / 24	---	12 / 6.5	---	---
F	<0.2	<0.2	0.23	<0.2	---
Cl	6.9	8.4	2.5	1.2	2.7
Br	<0.4	<0.4	<0.1	<0.1	<0.1
NH <sub>4</sub>	---	---	---	---	---
SiO <sub>2</sub>	91	48	80	---	---
B	0.027	0.016	0.11	---	---
Al	110	12	35	---	---
Fe (total)	28.6	2.65	5.47	---	---
Fe (II)	21.2	2.64	5.02	---	---
Mn	0.88	0.28	0.47	---	---
Cu	0.0004	0.0005	0.007	---	---
Zn	0.089	0.013	0.015	---	---
Cd	0.0001	<0.00002	<0.001	---	---
Cr	0.20	0.013	0.039	---	---
Co	0.028	0.003	0.005	---	---
Ni	0.037	<0.0005	<0.02	---	---
Pb	<0.0001	<0.0003	<0.0001	---	---
Be	0.003	<0.0001	0.0002	---	---
V	0.13	0.014	0.030	---	---
Se (total)	0.002	<0.0003	<0.0003	---	---
As (total)	0.018	0.001	<0.0003	---	<0.0003
As (III)	---	---	<0.0005	---	<0.0005
Sum cations (meq/L)	31.8	4.67	11.1	---	---
Sum anions (meq/L)	32.8	5.75	11.5	---	---
Charge imbalance (percent)	-3.1	-20.7	-3.3	---	---

Table 3. Site data and water analyses for Brimstone Basin -- Continued

Description	Alluv. Cr. trib.	Columb. Cr. trib	Columb. Cr. trib	Columb. Cr. trib
Sample Code Number	98WA133	98WA134	98WA136	98WA140
Date Collected	9/18/1998	9/19/1998	9/19/1998	9/19/1998
Temperature (°C)	13.5	6.0	6.0	8.9
Density (g/mL) at 20°C	1.00336	---	0.99874	0.99883
pH, field / lab / acidity	1.37 / 1.26 / 1.23	3.35 / --- / ---	2.13 / 2.64 / 2.56	2.01 / 2.56 / 2.52
pH, revised	1.23	3.35	2.56	2.52
Spec Cond (µS/cm) field / lab	38100 / 26800	450 / ---	2420 / 1490	2610 / 2190
Eh (V)	---	---	0.506	0.481
D.O. (mg/L)	---	---	8.2	6.6
<u>Constituent (mg/L)</u>				
Ca	35	---	23	24
Mg	20	---	13	15
Sr	0.68	---	0.25	0.28
Ba	0.016	---	0.023	0.021
Na	48	---	10	12
K	57	---	6.1	7.4
Li	0.030	---	0.012	0.010
SO <sub>4</sub>	6500	93	380	460
S <sub>2</sub> O <sub>3</sub>	---	---	---	---
H <sub>2</sub> S	---	---	---	---
Alkalinity (as HCO <sub>3</sub> )	---	---	---	---
Acidity (mM) total / free H <sup>+</sup>	130 / 71	---	5.3 / 3.0	6.3 / 3.3
F	3.0	0.18	0.23	0.25
Cl	21	0.1	1.1	1.0
Br	<0.1	<0.1	<0.1	<0.3
NH <sub>4</sub>	---	---	---	---
SiO <sub>2</sub>	110	---	63	68
B	0.066	---	0.016	0.11
Al	100	---	16	20
Fe (total)	25.2	---	2.96	4.65
Fe (II)	23.2	---	2.57	2.01
Mn	0.67	---	0.49	0.54
Cu	0.002	---	0.002	<0.001
Zn	0.091	---	0.012	0.015
Cd	0.002	---	<0.001	<0.001
Cr	0.21	---	0.019	0.023
Co	0.031	---	0.001	0.003
Ni	<0.02	---	<0.02	<0.02
Pb	<0.0001	---	<0.0001	<0.0001
Be	0.006	---	0.001	0.001
V	0.093	---	0.014	0.016
Se (total)	0.006	---	0.0007	0.0009
As (total)	0.004	0.001	<0.0003	<0.0003
As (III)	<0.0005	<0.0005	<0.0005	<0.0005
Sum cations (meq/L)	82.7	---	6.52	7.29
Sum anions (meq/L)	85.2	---	6.34	7.46
Charge imbalance (percent)	-3.0	---	2.8	-2.2

Table 4. Site data and water analyses for Norris Geyser Basin

Description	Cistern Spring	Cinder Pool	Frying Pan Spring	Frying Pan drainage
YNP Code	NBB201	NHSP103		
Sample Code Number	97WA121	97WA122	97WA123	97WA124
Date Collected	8/11/1997	8/12/1997	8/13/1997	8/13/1997
Temperature (°C)	80	<sup>1</sup> 82.2	<sup>1</sup> 60.6	<sup>1</sup> 43.8
Density (g/mL) at 20°C	---	0.99908	0.99879	0.99914
pH, field / lab / acidity	6.00 / 6.18 / ---	3.64 / 3.74 / 3.22	2.22 / 2.58 / 2.11	2.57 / 2.54 / 2.31
pH, revised	6.00	3.64	2.58	2.54
Spec Cond (µS/cm) field / lab	2020 / ---	2600 / 2580	1450 / 1850	1750 / 1980
Eh (V)	0.082	0.260	0.369	0.440
D.O. (mg/L)	0.14	1.5	0.5	2.5
<u>Constituent (mg/L)</u>				
Ca	3.7	8.0	2.3	2.4
Mg	0.079	0.046	0.38	0.46
Sr	0.015	0.027	0.015	0.015
Ba	0.032	0.066	0.061	0.062
Na	380	450	61	62
K	64	67	15	15
Li	5.1	5.3	0.42	0.42
SO <sub>4</sub>	59	77	360	380
S <sub>2</sub> O <sub>3</sub>	---	---	---	---
H <sub>2</sub> S	---	0.021	0.020	---
Alkalinity (as HCO <sub>3</sub> )	29.3	---	---	---
Acidity (mM) total / free H <sup>+</sup>	---	1.0 / 0.69	11 / 8.6	7.3 / 5.4
F	6.4	5.7	3.4	3.4
Cl	630	780	12	12
Br	2	2	<0.1	<0.1
NH <sub>4</sub>	0.97	5.8	2.3	1.9
SiO <sub>2</sub>	450	250	180	180
B	10	11	0.83	0.78
Al	0.16	2.1	4.1	4.6
Fe (total)	0.010	0.054	1.43	1.53
Fe (II)	0.008	0.052	1.41	1.41
Mn	0.053	0.007	0.033	0.035
Cu	<0.00005	<0.00005	0.001	<0.001
Zn	0.011	0.001	0.004	0.006
Cd	0.0002	0.0002	0.0001	<0.00002
Cr	<0.001	<0.001	<0.001	0.002
Co	0.001	0.002	<0.001	0.003
Ni	<0.0005	<0.0005	0.006	0.003
Pb	0.0007	<0.0001	0.0020	0.0020
Be	<0.0001	<0.0001	<0.0001	<0.0001
V	<0.001	<0.001	0.002	0.002
Se (total)	<0.0003	<0.0003	<0.0003	<0.0003
As (total)	2.1	3.1	0.29	0.31
As (III)	---	---	---	---
Sum cations (meq/L)	19.1	23.2	6.34	6.71
Sum anions (meq/L)	19.8	23.6	6.58	7.17
Charge imbalance (percent)	-3.9	-1.7	-3.6	-6.6

<sup>1</sup>Flow cell temperature

Table 4. Site data and water analyses for Norris Geyser Basin --- Continued

Description	Cinder Pool	Cistern Spring	Ragged Hills drainage	Ragged Hills drainage
YNP Code	NHSP103	NBB201		
Sample Code Number	98WA118	98WA119	98WA138	98WA139
Date Collected	9/15/1998	09/16/1998	9/20/1998	9/20/1998
Temperature (°C)	84	76	40	36.1
Density (g/mL) at 20°C	0.99915	0.99927	0.99913	---
pH, field / lab / acidity	4.32 / 4.31 / ---	5.88 / 7.02 / ---	3.23 / 3.20 / ---	2.91 / 3.13 / 3.16
pH, revised	4.32	5.88	3.23	3.16
Spec Cond (µS/cm) field / lab	2230 / 2280	1620 / 2010	1960 / 2190	1940 / ---
Eh (V)	-0.003	0.047	0.264	0.309
D.O. (mg/L)	2.6	---	---	---
<u>Constituent (mg/L)</u>				
Ca	6.3	2.8	5.2	4.7
Mg	0.017	0.13	0.24	0.24
Sr	0.021	0.011	0.017	0.017
Ba	0.019	0.029	0.14	0.080
Na	430	380	380	370
K	65	68	50	50
Li	5.6	5.2	4.7	4.6
SO <sub>4</sub>	43	70	85	85
S <sub>2</sub> O <sub>3</sub>	23	5.4	---	---
H <sub>2</sub> S	0.34	0.26	---	---
Alkalinity (as HCO <sub>3</sub> )	---	21.2	---	---
Acidity (mM) total / free H <sup>+</sup>	---	---	---	1.2 / 0.81
F	6.4	6.0	4.4	3.9
Cl	670	580	550	550
Br	2.2	1.9	7.3	1.7
NH <sub>4</sub>	1.8	1.8	---	0.84
SiO <sub>2</sub>	370	550	260	330
B	12	9.4	8.4	8.4
Al	0.71	0.12	1.8	2.1
Fe (total)	0.043	0.009	2.92	2.87
Fe (II)	0.043	0.007	2.64	2.43
Mn	<0.001	0.057	0.048	0.049
Cu	0.004	0.005	0.004	0.007
Zn	<0.001	<0.001	0.015	0.019
Cd	<0.001	<0.001	<0.001	<0.001
Cr	<0.002	<0.002	<0.002	<0.002
Co	<0.001	<0.001	<0.001	<0.001
Ni	<0.02	<0.02	<0.02	<0.02
Pb	<0.0001	<0.0001	<0.0001	<0.0001
Be	<0.0001	<0.0001	0.003	0.003
V	<0.001	<0.001	<0.001	<0.001
Se (total)	<0.0003	<0.0003	0.0004	0.0003
As (total)	2.6	1.8	2.3	2.0
As (III)	2.6	1.8	0.60	0.45
Sum cations (meq/L)	21.6	19.2	19.6	19.2
Sum anions (meq/L)	20.0	18.5	17.4	17.3
Charge imbalance (percent)	7.3	3.6	11.6	10.7

Table 5. Site data and water analyses for Gibbon Geyser Basin

Description	Unnamed, Geyser Springs	“Bone Pool,” Geyser Springs	Unnamed, Artists Paintpots	“Bat Pool,” Geyser Springs	“Bull’s Eye,” Geyser Springs
Sample Code Number	98WA122	98WA123	98WA124	98WA125	98WA126
Date Collected	9/17/1998	9/17/1998	9/17/1998	9/16/1998	9/16/1998
Temperature (°C)	89	93	78	93.8	75
Density (g/mL) at 20°C	0.99907	0.99851	0.99841	0.99929	0.99895
pH, field / lab / acidity	6.09 / 7.28 / ---	5.56 / 6.03 / ---	3.06 / 3.06 / 3.08	8.16 / 9.02 / ---	2.44 / 2.45 / 2.52
pH, revised	7.28	5.56	3.06	8.16	2.52
Spec Cond (µS/cm) field / lab	--- / 1920	--- / 1170	--- / 603	2180 / 2270	--- / 2480
Eh (V)	0.063	0.195	0.572	-0.231	---
D.O. (mg/L)	---	---	---	---	---
<u>Constituent (mg/L)</u>					
Ca	5.1	1.9	0.84	0.45	2.3
Mg	0.050	0.061	0.24	<0.0001	0.13
Sr	0.005	0.001	0.002	<0.001	0.003
Ba	0.012	0.001	0.010	0.001	0.0005
Na	390	230	14	510	160
K	31	12	18	25	15
Li	5.9	2.6	0.04	3.1	1.7
SO <sub>4</sub>	140	250	110	130	470
S <sub>2</sub> O <sub>3</sub>	13	2.3	<0.1	0.8	<0.1
H <sub>2</sub> S	0.042	0.25	0.009	0.66	0.05
Alkalinity (as HCO <sub>3</sub> )	17.9	5.0	---	337	---
Acidity (mM) total / free H <sup>+</sup>	---	---	1.2 / 0.9	---	5.9 / 3.4
F	11	4.8	0.20	22	2.5
Cl	460	180	0.4	420	100
Br	<0.1	0.6	<0.1	1.4	0.4
NH <sub>4</sub>	2.1	9.7	1.2	---	2.4
SiO <sub>2</sub>	250	200	200	240	230
B	5.6	2.7	0.041	5.1	1.6
Al	0.46	0.85	0.43	0.60	4.5
Fe (total)	0.120	0.691	0.343	0.065	0.498
Fe (II)	0.119	0.691	0.124	0.057	0.140
Mn	0.012	0.014	0.049	<0.001	0.025
Cu	0.009	<0.001	<0.001	<0.001	<0.001
Zn	<0.001	<0.001	0.020	<0.001	0.006
Cd	<0.001	<0.001	<0.001	<0.001	<0.001
Cr	<0.002	<0.002	<0.002	<0.002	<0.002
Co	<0.001	<0.001	<0.001	<0.001	<0.001
Ni	<0.02	<0.02	<0.02	<0.02	<0.02
Pb	<0.0001	0.0020	<0.0001	<0.0001	<0.0001
Be	<0.0001	<0.0001	0.0009	<0.0001	<0.0001
V	<0.001	<0.001	<0.001	<0.001	0.001
Se (total)	0.0004	<0.0003	<0.0003	<0.0003	<0.0003
As (total)	2.4	0.79	0.007	1.9	0.18
As (III)	2.4	0.79	<0.0005	1.5	0.079
Sum cations (meq/L)	18.8	10.7	2.04	22.9	11.3
Sum anions (meq/L)	16.7	10.4	2.04	20.9	10.4
Charge imbalance (percent)	11.9	2.5	-0.1	9.1	7.8

Table 5. Site data and water analyses for Gibbon Geyser Basin --- Continued

Description	Unnamed, Artists Paintpots	Unnamed, Sylvan Springs	Unnamed, Sylvan Springs	Evening Primrose Spring
Sample Code Number	98WA127	98WA128	98WA129	98WA130
Date Collected	9/16/1998	9/17/1998	9/17/1998	9/17/1998
Temperature (°C)	92	78.7	82	68
Density (g/mL) at 20°C	0.99903	0.99879	0.99947	1.00000
pH, field / lab / acidity	8.35 / 8.77 / ---	4.41 / 4.57 / ---	5.68 / 7.16 / ---	1.75 / 1.77 / 1.84
pH, revised	8.77	4.41	7.16	1.84
Spec Cond (µS/cm) field / lab	--- / 1840	1000 / 1400	1880 / 2200	5450 / 9270
Eh (V)	-0.091	0.085	-0.063	0.281
D.O. (mg/L)	---	---	---	---
<u>Constituent (mg/L)</u>				
Ca	3.8	3.7	4.1	10
Mg	0.003	<0.1	<0.1	0.43
Sr	0.004	0.006	0.013	0.029
Ba	<0.0005	0.070	0.007	0.076
Na	380	270	460	330
K	16	15	51	36
Li	5.4	2.6	6.5	1.1
SO <sub>4</sub>	140	160	160	1700
S <sub>2</sub> O <sub>3</sub>	<0.1	---	---	---
H <sub>2</sub> S	0.03	0.30	0.18	0.41
Alkalinity (as HCO <sub>3</sub> )	109	---	63.4	---
Acidity (mM) total / free H <sup>+</sup>	---	---	---	30 / 17
F	13	8.7	18	3.1
Cl	380	320	520	390
Br	1.3	1.0	1.6	1.1
NH <sub>4</sub>	---	4.2	0.72	8.5
SiO <sub>2</sub>	200	320	580	240
B	6.0	4.2	56	7.8
Al	0.31	2.9	0.36	10
Fe (total)	0.021	0.239	0.043	4.56
Fe (II)	0.010	0.239	0.043	2.55
Mn	<0.001	0.010	0.022	0.20
Cu	<0.001	<0.001	0.002	<0.001
Zn	<0.001	0.010	0.001	0.012
Cd	<0.001	<0.001	<0.001	<0.001
Cr	<0.002	<0.002	<0.002	<0.002
Co	<0.001	<0.001	<0.001	<0.001
Ni	<0.02	<0.02	<0.02	<0.02
Pb	<0.0001	<0.0001	<0.0001	0.016
Be	<0.0001	<0.0001	0.002	0.001
V	<0.001	<0.001	<0.001	0.001
Se (total)	<0.0003	0.0004	<0.0003	<0.0003
As (total)	2.2	1.7	3.2	1.7
As (III)	1.4	1.5	2.6	0.63
Sum cations (meq/L)	17.8	12.7	22.3	33.3
Sum anions (meq/L)	16.0	12.4	19.9	33.6
Charge imbalance (percent)	10.4	2.2	11.6	-1.1

**Table 6. Site data and water analyses for Heart Lake Geyser Basin**

Description	Unnamed spring, Near HLFNN92,	
	Fissure Group	Fissure Group
YNP Code	HLFNN92	
Sample Code Number	98WA131	98WA137
Date Collected	9/18/1998	9/19/1998
Temperature (°C)	92	93.0
Density (g/mL) at 20°C	1.00015	0.99885
pH, field / lab / acidity	4.53 / 4.25 / ---	3.56 / 3.35 / ---
pH, revised	4.53	3.56
Spec Cond (µS/cm) field / lab	800 / 1120	550 / 1180
Eh (V)	0.387	0.070
D.O. (mg/L)	---	---
<u>Constituent (mg/L)</u>		
Ca	0.32	0.68
Mg	<0.0001	0.004
Sr	0.005	0.014
Ba	0.002	0.007
Na	190	190
K	16	23
Li	2.1	2.0
SO <sub>4</sub>	330	400
S <sub>2</sub> O <sub>3</sub>	<0.1	<0.1
H <sub>2</sub> S	0.002	0.004
Alkalinity (as HCO <sub>3</sub> )	---	---
Acidity (mM) total / free H <sup>+</sup>	---	---
F	3.3	1.2
Cl	38	21
Br	0.2	<0.1
NH <sub>4</sub>	1.9	5.2
SiO <sub>2</sub>	300	350
B	0.85	0.54
Al	0.20	0.45
Fe (total)	0.040	0.108
Fe (II)	0.040	0.108
Mn	<0.001	0.003
Cu	<0.001	0.002
Zn	<0.001	0.002
Cd	<0.001	<0.001
Cr	<0.002	<0.002
Co	<0.001	<0.001
Ni	<0.02	<0.02
Pb	<0.0001	<0.0001
Be	0.011	0.008
V	<0.001	<0.001
Se (total)	<0.0003	0.0004
As (total)	0.018	0.048
As (III)	---	0.025
Sum cations (meq/L)	8.90	9.36
Sum anions (meq/L)	7.94	8.39
Charge imbalance (percent)	11.4	10.9

Table 7. Site data and water analyses for S<sub>2</sub>O<sub>3</sub> and H<sub>2</sub>S for Upper, Lower, and Norris Geyser Basins

Sample Code		Date	Temperature	pH	Spec cond	D.O.	S <sub>2</sub> O <sub>3</sub>	H <sub>2</sub> S
Number	Name	Collected	(°C)	field	(μS/cm) field		(mg/L)	
96WA106	Punch Bowl Spring	8/16/96	91.8	7.72	1390	0.7	0.07	0.10
96WA107	Octopus Spring	8/16/96	92.1	8.35	1080	<0.1	<0.01	0.059
96WA108	Giantess Geyser	8/17/96	93.0	8.84	1330	0.9	0.08	1.0
96WA109	Ear Spring	8/17/96	92.6	8.76	1270	1.1	<0.01	0.84
96WA110	Sulphide Spring	8/17/96	92.7	7.13	595	0.4	0.07	0.57
96WA111	Sapphire Pool	8/17/96	86.2	8.45	1490	0.8	0.11	0.001
96WA113	Unnamed spring south of Azure Spring	8/19/96	60.4	6.90	1570	1.8	0.07	0.030
96WA114	Unnamed spring south of Bath Spring	8/19/96	89.0	8.80	1090	<0.1	0.92	1.3
96WA115	Bath Spring	8/19/96	---	---	---	<0.1	1.1	2.0
96WA116	Cavern Spring	8/19/96	---	---	---	1.5	0.14	0.013
96WA117	Cinder Pool	8/20/96	91.3	3.50	1640	4.3	4.1	0.64
96WA118	Horseshoe Spring	8/20/96	91.3	2.77	1000	5.0	0.22	0.60
96WA119	Constant Geyser	8/20/96	---	3.57	1440	4.7	<0.01	0.016
96WA120	Emerald Spring	8/20/96	78.7	3.37	1890	1.9	<0.01	0.068
96WA121	Cistern Spring	8/20/96	---	6.03	1230	0.9	7.9	0.23
96WA122	Palpitator Spring	8/21/96	84.2	6.55	1350	8.0	0.12	0.034
96WA123	Fearless Geyser	8/21/96	91.3	5.57	1530	6.1	0.9	0.39
96WA124	Perpetual Spouter	8/21/96	87.3	4.80	1430	6.3	<0.01	0.039
96WA125	Porkchop Spring	8/21/96	47.3	6.78	2350	4.9	<0.01	0.003
96WA126	Big Alcove Spring	8/21/96	92.4	5.38	745	3.6	0.62	0.073

Table 8.  $^2\text{H}$ ,  $^{18}\text{O}$ , and  $^{34}\text{S}$  isotope analyses [ $^2\text{H}$ ,  $^{18}\text{O}$  in permil relative to VSMOW;  $^{34}\text{S}$  in permil relative to CDT]

Name	Sample Code No.	$\delta^2\text{H}$	$\delta^{18}\text{O}$	$\delta^{34}\text{S}$
Alluvium Creek at Yellowstone Lake shore	96WA101	-143	-19.3	---
Alluvium Creek	96WA102	-142	-19.5	---
Alluvium Creek, below confluence	96WA103	-141	-22.7	---
Alluvium Creek, main drainage above confluence	96WA104	-138	-22.5	---
Alluvium Creek, east flowing tributary above confluence	96WA105	-141	-22.5	---
Cinder Pool	96WA117	-117	-15.9	---
Horseshoe Spring	96WA118	-115	-16.1	---
Constant Geyser	96WA119	-114	-16.1	---
Emerald Spring	96WA120	-118	-16.0	---
Cistern Spring	97WA121	-132	-13.5	---
Cinder Pool	97WA122	-124	-9.3	---
Frying Pan Spring	97WA123	-119	-10.8	---
Frying Pan Spring, 61m downstream	97WA124	-117	-10.3	---
Alluvium Creek at mouth	97WA125	-139	-19.1	0.1
Alluvium Creek	97WA126	-129	-19.2	0.0
Alluvium Creek	97WA127	-136	-20.3	0.3
Alluvium Creek	97WA128	-135	-20.6	-0.1
Small tributary to Alluvium Creek	97WA129	-134	-20.1	0.1 / -0.1
Alluvium Creek	97WA130	-141	-19.2	-0.1
South tributary to Columbine Creek	97WA131	---	---	0.1
Cinder Pool	98WA118	-133	-12.3	7.2
Cistern Spring	98WA119	-133	-13.4	---
South fork of south tributary to Columbine Creek	98WA120	-137	-19.0	0.2
Alluvium Creek at Yellowstone Lake shore	98WA121	---	---	0.1 / -0.1
Unnamed Spring, Geyser Springs Group	98WA122	-133	-12.5	---
“Bone Pool,” Geyser Springs Group	98WA123	-127	-12.3	---
Unnamed Spring, Geyser Springs Group	98WA124	-137	-14.4	---
“Bat Pool,” Geyser Springs Group	98WA125	-141	-15.6	---
“Bull’s Eye,” Geyser Springs Group	98WA126	-129	-12.7	---
Unnamed Spring, Artists Paintpots	98WA127	-142	-15.6	---
Unnamed Spring, Sylvan Springs Group	98WA128	-122	-10.5	---
Unnamed Spring, Sylvan Springs Group	98WA129	-124	-10.1	---
Evening Primrose Spring, Sylvan Springs Group	98WA130	-117	-6.6	---
HLF 92, Fissure Group, Heart Lake	98WA131	-131	-14.3	---
Small tributary to Alluvium Creek	98WA133	-125	-20.3	-0.5
South tributary to Columbine Creek	98WA136	-135	-18.8	0.4
Fissure Group, Heart Lake, 2 m from 98WA131	98WA137	-129	-13.2	---
Main drainage, Ragged Hills area, Norris Geyser Basin	98WA138	-137	-14.6	---
South tributary to Columbine Creek	98WA140	-137	-18.7	0.2

Table 9. Results for field blanks

Sample Code Number	96WA112	98WA135
Date Collected	8/18/1996	9/19/1998
Temperature (°C) (*flow cell)	---	---
Density (g/mL) at 20°C	---	---
pH, field / lab	---	---
pH, revised	---	---
Spec Cond (µS/cm) field / lab	---	---
Eh (V)	---	---
D.O. (mg/L)	---	---
<u>Constituent (mg/L)</u>	(by ICP-MS)	
Ca	---	<0.05
Mg	---	0.008
Sr	0.00008	<0.001
Ba	0.00032	<0.0005
Na	---	0.014
K	---	0.005
Li	<0.004	<0.003
SO <sub>4</sub>	---	<0.5
S <sub>2</sub> O <sub>3</sub>	---	---
H <sub>2</sub> S	---	---
Alkalinity (as HCO <sub>3</sub> )	---	---
Acidity (mM) total / free H <sup>+</sup>	---	---
F	---	<0.1
Cl	---	<0.5
Br	---	<0.1
NH <sub>4</sub>	---	---
SiO <sub>2</sub>	---	<0.3
B	<0.1	<0.2
Al	0.021	<0.09
Fe (total)	---	<0.007
Fe (II)	---	<0.002
Mn	0.0004	<0.001
Cu	0.00055	0.002
Zn	0.0098	<0.001
Cd	0.0001	<0.001
Cr	<0.002	<0.002
Co	0.000009	<0.001
Ni	0.00034	<0.02
Pb	0.000063	<0.0001
Be	<0.00004	<0.0001
V	<0.001	<0.001
Se (total)	<0.0003	<0.0003
As (total)	0.0006	<0.0003
As (III)	---	<0.0005

## REFERENCES CITED

- Allen, E. T., and Day, A. L., 1935, Hot springs of the Yellowstone National Park: Carnegie Institution of Washington Publication Number 466, 525 p.
- American Public Health Association (APHA), 1985, Method 428C. Methylene blue method for sulfide, *in* Standard methods for the examination of water and wastewater (14th ed.): American Public Health Association, p. 403-405.
- Ball, J. W., Nordstrom, D. K., Jenne, E. A., and Vivit, D. V., 1998a, Chemical analyses of hot springs, pools, geysers, and surface waters from Yellowstone National Park, Wyoming, and vicinity, 1974-1975: U.S. Geological Survey Open-File Report 98-182, 45 p.
- Ball, J. W., Nordstrom, D. K., Cunningham, K. M., Schoonen, M. A. A., Xu, Y., and DeMonge, J. M., 1998b, Water-chemistry and on-site sulfur-speciation data for selected springs in Yellowstone National Park, Wyoming, 1994-1995: U.S. Geological Survey Open-File Report 98-574, 35 p.
- Ball, J. W., and Nordstrom, D. K., 1991, User's manual for WATEQ4F, with revised thermodynamic data base and test cases for calculating speciation of major, trace, and redox elements in natural waters: U.S. Geological Survey Open-File Report 91-183, 189 p.
- Barringer, J. L., and Johnsson, P. A., 1996, Theoretical considerations and a simple method for measuring alkalinity and acidity in low-pH waters by Gran titration: U.S. Geological Survey Water-Resources Investigations Report 89-4029.
- Barnard, W. R., and Nordstrom, D. K., 1980, Fluoride in precipitation-I. Methodology with the fluoride-selective electrode: *Atmospheric Environment*, v. 16, p. 99-103.
- Bryan, T. S., 1995, *The geysers of Yellowstone* (third edition): University Press of Colorado, 463 p.
- Coplen, T. B., Wildman, J. D., and Chen, J., 1991, Improvements in the gaseous hydrogen-water equilibrium technique for hydrogen isotope ratio analysis: *Analytical Chemistry*, v. 63, p. 910-912.
- Epstein, S. and Mayeda, T., 1953, Variation of  $^{18}\text{O}$  content of water from natural sources: *Geochimica et Cosmochimica Acta*, v. 4, p. 213-224.
- Fishman, M. J., and Friedman, L. C., eds., 1989, Methods for determination of inorganic substances in water and fluvial sediments: *Techniques of water-resources investigations of the U.S. Geological Survey*, Book 5, Chapter A1, p. 55-56.
- Fournier, R. O., 1989, Geochemistry and dynamics of the Yellowstone National Park hydrothermal system: *Annual Review of Earth and Planetary Sciences*, v. 17, p. 13-53.

- Fournier, R. O., Thompson, J. M., and Hutchinson, R. A., 1994, The geochemistry of hot spring waters at Norris Geyser Basin, Yellowstone National Park: Geothermal Resources Council Transactions, v. 18, p. 177-179.
- Gooch, F. A., and Whitfield, J. E., 1888, Analyses of waters of the Yellowstone National Park with an account of the methods of analysis employed: U.S. Geological Survey Bulletin 47, 84 p.
- Kharaka, Y. K., Mariner, R. H., Bullen, T. D., Kennedy, B. M., and Sturchio, N. C., 1991, Geochemical investigations of hydraulic connections between the Corwin Springs Known Geothermal Resources Area and adjacent parts of Yellowstone National Park, *in* Sorey, M. L., ed., Effects of potential geothermal development in the Corwin Springs Known Geothermal Resources Area: U.S. Geological Survey Water-Resources Investigations Report 91-4052, p. F-1 - F-38.
- Kennedy, V. C., Jenne, E. A., and Burchard, J. M., 1976, Back-flushing filters for field processing of water samples prior to trace-element analyses: U.S. Geological Survey Open-File Report 76-126, 12 p.
- Nordstrom, D. K., 1977, Thermochemical redox equilibria of ZoBell's solution: *Geochimica et Cosmochimica Acta*, v. 41, p. 1835-41.
- Parkhurst, D. L., and Appelo, C. A. J., 1999, User's guide to PHREEQC (version 2)—a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 99-4259, 312 p.
- Rolla, E. and Chakrabarti, C. L., 1982, Kinetics of decomposition of tetrathionate, trithionate, and thiosulfate in alkaline media: *Environmental Science and Technology*, v. 16, p. 852-857.
- Rowe, J. J., Fournier, R. O., and Morey, G. W., 1973, Chemical analysis of thermal waters in Yellowstone National Park, Wyoming, 1960-65: U.S. Geological Survey Bulletin 1303, 31 p.
- Solorzano, L., 1969, Determination of ammonia in natural waters by the phenolhypochlorite method: *Limnology and Oceanography*, v. 5, p. 799-801.
- Stauffer, R. E., Jenne, E. A., and Ball, J. W., 1980, Chemical studies of selected trace elements in hot-spring drainages of Yellowstone National Park: U.S. Geological Survey Professional Paper 1044-F, 20 p.
- Stookey, L. L., 1970, Ferrozine - a new spectrophotometric reagent for iron: *Analytical Chemistry*, v. 42, p. 779-781.
- Stumm, W., and Morgan, J. J., 1981 *Aquatic chemistry*, 3<sup>rd</sup> edition: New York, Wiley-Interscience, John Wiley and Sons, 1022 p.

- Thompson, J. M., and DeMonge, J. M., 1996, Chemical analyses of hot springs, pools, and geysers from Yellowstone National Park, Wyoming, and vicinity, 1980-1993: U.S. Geological Survey Open-File Report 96-68, 66 p.
- Thompson, J. M., and Hutchinson, R. A., 1981, Chemical analyses of waters from the Boundary Creek Thermal Area, Yellowstone National Park, Wyoming: U.S. Geological Survey Open-File Report 81-1310, 15 p.
- Thompson, J. M., Presser, T. S., Barnes, R. B., and Bird, D. B., 1975, Chemical analysis of the waters of Yellowstone National Park, Wyoming from 1965 to 1973: U.S. Geological Survey Open-File Report 75-25, 58 p.
- Thompson, J. M., and Yadav, S., 1979, Chemical analysis of waters from geysers, hot springs and pools in Yellowstone National Park, Wyoming from 1974 to 1978: U.S. Geological Survey Open-File Report 79-704, 48 p.
- White, D. E., Hem, J. D., and Waring, G. A., 1963, Chemical composition of subsurface waters, *in* Fleischer, M., ed., Data of Geochemistry, 6th edition: U.S. Geological Survey Professional Paper 440-F, 67 p.
- White, D. E., Hutchinson, R. A., and Keith, T. E. C., 1988, The geology and remarkable thermal activity of Norris Geyser Basin, Yellowstone National Park: U.S. Geological Survey Professional Paper 1456, 84 p.
- Xu, Y., and Schoonen, M. A. A., 1995, The stability of thiosulfate in the presence of pyrite in low-temperature aqueous solutions: *Geochimica et Cosmochimica Acta*, v. 59, p. 4605-4622.
- Xu, Y., Schoonen, M. A. A., and Strongin, D. R., 1996, Thiosulfate oxidation: catalysis of synthetic sphalerite doped with transition metals: *Geochimica et Cosmochimica Acta*, v. 60, p. 4701-4710.
- Xu, Y., Schoonen, M. A. A., Nordstrom, D. K., Cunningham, K. M., and Ball, J. W., 1998, Sulfur geochemistry of hydrothermal waters in Yellowstone National Park: I. The origin of thiosulfate in hot spring waters: *Geochimica et Cosmochimica Acta*, v. 62, p. 3729-3743.
- Xu, Y., Schoonen, M. A. A., Nordstrom, D. K., Cunningham, K. M., and Ball, J. W., 2000, Sulfur geochemistry of hydrothermal waters in Yellowstone National Park: II. Formation and decomposition of thiosulfate and polythionate in Cinder Pool: *Journal of Volcanology and Geothermal Research*, v. 97, p. 407-423.
- ZoBell, C. E., 1946, Studies on redox potential of marine sediments: 8. Other methods: *Bulletin of the American Association of Petroleum Geologists*, v. 30, p. 477-509.



---

## **APPENDIX**

---

Table 10. Methods of analysis

Parameter or Element	Descriptor	Typical <b>rsd</b> , <i>detection limit (mg/L)</i>
pH	PH	<b>0.02 pH units</b>
Spec Cond	COND	<b>~0.5%</b>
Eh	EC1	<b>~10%</b>
D.O.	EC2	<b>1%</b>
Ca	ICP	<b>~2%, 0.05</b>
Mg	ICP	<b>~2%, 0.09</b>
Sr	ICP	<b>~2%, 0.0005</b>
Ba	ICP	<b>~2%, 0.001</b>
Na	ICP; FAAS	<b>~2%, 0.4; ~2%, 0.005<sup>1</sup> (0.040)</b>
K	ICP; FAAS	<b>~2%, 0.05; ~2%, 0.025<sup>1</sup> (0.007)</b>
Li	FAAS	<b>~2%, 0.003</b>
SO <sub>4</sub>	IC1	<b>2-3%, 0.2</b>
S <sub>2</sub> O <sub>3</sub>	IC2	<b>2-3%, 0.09</b>
H <sub>2</sub> S	COLOR1	<b>0.005</b>
Alkalinity (as HCO <sub>3</sub> )	TITR1	<b>2%, 0.4</b>
Acidity (mM) total / free H <sup>+</sup>	TITR2	<b>2%, 0.4</b>
F	IC1; EC3	<b>2-3%, 0.03; ~3%</b>
Cl	IC1	<b>2-3%, 0.05</b>
Br	IC1	<b>2-3%, 0.1</b>
NO <sub>3</sub>	IC1	<b>2-3%, 0.09</b>
NH <sub>4</sub>	COLOR2; IC3	<b>3%, 0.01; ~2%</b>
SiO <sub>2</sub>	ICP	<b>~2%, 0.2</b>
B	ICP	<b>~2%, 0.09</b>
Al	ICP	<b>~2%, 0.09</b>
Fe (total)	ICP; COLOR3	<b>~2%, 0.02; 3%, 0.0005</b>
Fe (II)	COLOR3	<b>3%, 0.0005</b>
Mn	ICP	<b>~2%, 0.001</b>
Cu	ICP	<b>~2%, 0.07</b>
Zn	ICP	<b>~2%, 0.0005</b>
Cd	ICP; ZGFAAS	<b>~2%, 0.001; ~5%, 0.0001</b>
Cr	ICP	<b>~2%, 0.002</b>
Co	ICP	<b>~2%, 0.001</b>
Ni	ICP; ZGFAAS	<b>~2%, 0.02; ~5%, 0.0005</b>
Pb	ICP; ZGFAAS	<b>~2%, 0.007; ~5%, 0.0001</b>
Be	ICP	<b>~2%, 0.001</b>
V	ICP	<b>~2%, 0.001</b>
Se (total)	ZGFAAS	<b>~5%, 0.0003</b>
As (total)	ICP; FIAS; ZGFAAS	<b>~2%, 0.02; ~10%, 0.001; ~5%, 0.003</b>
As (III)	FIAS	<b>~10%, 0.001</b>
δ <sup>2</sup> H	ISOT1	<b>1.5 per mil</b>
δ <sup>18</sup> O	ISOT2	<b>0.1 per mil</b>

<sup>1</sup>Detection limit in flame emission mode

Table 11. Explanation of methods of analysis

Descriptor	Species Determined	Equipment Used	Reference(s) or comments
COLOR1	H <sub>2</sub> S	Hach model DR-2000 UV-Vis absorption spectrometer and Hach method # 8131 reagents	Method based on APHA (1985)
COLOR2	NH <sub>4</sub>	Alpkem model RFA-300 flow injection analyzer	Method based on Solorzano (1969)
COLOR3	Fe(II) and Fe(total)	Hewlett-Packard model 8452A diode array spectrometer with 1 and 5 cm cells	Ferrozine method (Stookey, 1970)
COND	Spec Cond	Orion Research model 126 meter	Automatic temperature correction, conductance check with 0.0100 N KCl
EC1	Eh	Orion Research model 96-78-00 Pt electrode	Electrode checked using ZoBell's solution (ZoBell, 1946; Nordstrom, 1977), at the sample temperature
EC2	D.O.	Orion Research model 840 DO meter and probe	Automatic sample temperature and barometric pressure correction
EC3	F <sup>-</sup>	Orion Research model 96-09 combination F <sup>-</sup> electrode	Barnard and Nordstrom (1980)
FAAS	Na, K, and Li	Perkin-Elmer model 5000 or AAnalyst 300 flame atomic absorption spectrometer with air/acetylene flame, single-slot burner head, and continuum background correction, in absorption (Li, Na, K) or emission (Na*, K*) mode	1000 mg/L Cs ionization buffer.
FIAS	As(total) and As(III)	Perkin-Elmer model 5000 or AAnalyst 300 atomic absorption spectrometer in absorption mode with a FIAS-100 flow injection analysis system hydride generator, quartz cell, and furnace	Pre-reduction of As(V) using KI +Ascorbic Acid + HCl
IC1	F <sup>-</sup> , Cl <sup>-</sup> , SO <sub>4</sub> <sup>2-</sup> and Br <sup>-</sup>	Dionex model 2000i/2010i ion chromatograph with AG4A guard and AS4A separator columns and an Anion Micromembrane Suppressor-II column	0.028 M NaHCO <sub>3</sub> + 0.022 M Na <sub>2</sub> CO <sub>3</sub> eluent
IC2	S <sub>2</sub> O <sub>3</sub> <sup>2-</sup>	Dionex model 2000i or 2010i ion chromatograph with two AG4A guard columns and AS4A separator column and an Anion Micromembrane Suppressor-II column	0.028 M NaHCO <sub>3</sub> + 0.022 M Na <sub>2</sub> CO <sub>3</sub> eluent
IC3	NH <sub>4</sub>	Dionex model DX-300 ion chromatograph with CS12A IonPac column and 22 mN H <sub>2</sub> SO <sub>4</sub> eluent	Analysis performed on year-old samples preserved in 1% HCl

Table 11. Explanation of methods of analysis--Continued

Descriptor	Species Determined	Equipment Used	Reference(s) or comments
ICP	Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe(total), K, Mg, Mn, Na, Ni, Pb, Si, Sr, V, Zn	Leeman Labs Plasma-Spec III, simultaneous, multi-element, inductively coupled plasma spectrometer. Hildebrand grid nebulizer and polyethylene spray chamber. RF frequency -27.5 MHZ at 1 kw. Ar coolant and nebulizer gas. Inter-element interferences were corrected with MEGACRUNCH software (J.W. Ball, unpub. data) or Leeman Labs Direct Reading Echelle, dual view, sequential, multi-element, inductively coupled plasma spectrometer. Hildebrand grid nebulizer and glass Scott spray chamber.	Analytical wavelengths - nanometers: Al: 308.25 As: 188.98 B: 249.68 Ba: 455.40 Be: 313.04 Ca: 315.90 Cd: 214.44 Co: 228.62 Cr: 206.142 Cu: 324.75 Fe: 238.20 K: 766.46 Mg: 279.08 Mn: 257.61 Na: 589.59 Ni: 231.60 Pb: 220.35 Si: 251.60 Sr: 421.60 V: 292.40 Zn: 206.20
ISOT1	$\delta^2\text{H}$	V.G. Micromass model 602 mass spectrometer	Coplen and others (1991). Standardization against VSMOW ( $\delta^2\text{H} = 0$ per mil) and SLAP ( $\delta^2\text{H} = -428$ per mil)
ISOT2	$\delta^{18}\text{O}$	DuPont model 21-491 mass spectrometer	Epstein and Mayeda (1953). Standardization against VSMOW ( $\delta^{18}\text{O} = 0$ per mil) and SLAP ( $\delta^{18}\text{O} = -55.5$ per mil)
pH	$[\text{H}^+]$	Orion Research model SA 250 meter, Orion Ross combination electrode	Two buffer calibration at sample temp. using 9.18, 7.00, 4.01, and 1.68 pH buffers
TITR1, TITR2	Alkalinity (as mg/L $\text{HCO}_3^-$ ) and acidity (total)	Orion Research model 960/940 autotitrator, potentiometric detection	Fishman and Friedman (1989)

Table 11. Explanation of methods of analysis--Continued

Descriptor	Species Determined	Equipment Used	Reference(s) or comments
ZGFAAS	Cd, As, Ni, Pb, Se	Perkin-Elmer model Zeeman 5000 or 4110ZL graphite furnace atomic absorption spectrometer, with pyrolytically coated graphite platform cell and Ar purge gas	Analytical wavelength, nm: Cd: 228.8 As: 193.7 Ni: 232.0 Pb: 283.3 Se: 196.0 Atomization temp., °C: Cd: 1400 As: 2000 Ni: 2300 Pb: 1500 Se: 1900 Matrix modifier: Cd: $\text{NH}_4\text{H}_2\text{PO}_4 / \text{Mg}(\text{NO}_3)_2$ As: Pd / $\text{Mg}(\text{NO}_3)_2$ Ni: None Pb: $\text{NH}_4\text{H}_2\text{PO}_4 / \text{Mg}(\text{NO}_3)_2$ Se: Pd / $\text{Mg}(\text{NO}_3)_2$

Table 12. Measurements of Standard Reference Waters [s, sample standard deviation]

Analyte	Analytical method	USGS SRWS	1996 Data				
			Observed concentration			Most probable value	
			n	mg/L	s	mg/L	s
Ca	ICP	T117	3	20.9	0.6	21.6	0.5
Mg	ICP	T117	3	10.1	0.3	10.05	0.44
Sr	ICP	T117	3	0.26	0.01	0.265	0.011
Sr	ICP	T153	3	0.323	0.006	0.311	0.013
Ba	ICP	T117	3	0.094	0.007	0.0985	0.0063
Ba	ICP	T153	3	0.197	0.006	0.184	0.009
Na	FAAS	T117	2	19.3	0.1	20	1.26
K	FAAS	T117	2	2.12	0.01	2.11	0.19
SO <sub>4</sub>	IC	M102	3	410	10	420	16
F	IC	M102	3	0.92	0.1	1.1	0.1
Cl	IC	M102	3	43.2	0.6	44	2
SiO <sub>2</sub>	ICP	T117	3	11.8	0.7	11.85	0.64
B	ICP	T117	3	0.162	0.004	0.151	0.021
B	ICP	T153	3	0.110	0.000	0.0994	0.0074
Al	ICP	T117	3	<0.2	---	0.079	0.0194
Al	ICP	T153	3	<0.09	---	0.035	0.005
Fe	ICP	T117	3	0.47	0.02	0.474	0.0182
Mn	ICP	T117	3	0.22	0.01	0.22	0.015
Mn	ICP	T153	3	0.079	0.001	0.075	0.003
Cu	ICP	T117	3	<0.2	---	0.006	0.0018
Cu	ICP	T153	3	0.022	0.003	0.024	0.002
Zn	ICP	T117	3	0.178	0.005	0.176	0.0093
Zn	ICP	T153	3	0.074	0.003	0.0726	0.0051
Cd	ICP	T117	3	<0.009	---	0.0022	0.0004
Cd	ICP	T153	3	0.017	0.000	0.016	0.0011
Cr	ICP	T117	3	<0.09	---	0.0103	0.0016
Cr	ICP	T153	3	0.016	0.001	0.015	0.0011
Co	ICP	T117	3	<0.01	---	0.0043	0.0007
Ni	ICP	T117	3	<0.02	---	0.01	0.0025
Ni	ICP	T153	3	0.035	0.002	0.0324	0.0021
Pb	ICP	T117	3	<0.1	---	0.005	0.0013
Pb	ICP	T153	3	0.054	0.006	0.0462	0.003
Be	ICP	T117	3	0.0040	0.0001	0.0048	0.0004
V	ICP	T117	3	<0.1	---	0.0047	0.0018
V	ICP	T153	3	0.018	0.001	0.019	0.001
Se	ZGFAAS	T133	4	0.020	0.001	0.021	0.003
Se	ZGFAAS	T143	4	0.0084	0.0004	0.0096	0.002
As	FIAS	T 117	15	0.008	0.001	0.0069	0.0014

Table 12. Measurements of Standard Reference Waters – Continued

Analyte	Analytical method	USGS SRWS	1997 Data				
			Observed concentration			Most probable value	
			n	mg/L	s	mg/L	s
Ca	ICP	M102	4	87	2	82	4
Mg	ICP	M102	4	61	2	58	2
Sr	ICP	69	4	0.62	0.02	0.612	0.052
Sr	ICP	73	4	0.61	0.02	0.617	0.047
Sr	ICP	M102	4	1.40	0.04	1.34	0.093
Sr	ICP	T153	3	0.323	0.006	0.311	0.013
Ba	ICP	69	4	0.033	0.004	0.043	0.022
Ba	ICP	73	4	0.170	0.006	0.203	0.084
Ba	ICP	T153	3	0.197	0.006	0.184	0.008
Na	ICP	M102	4	120	4	108	5
Na	FAAS	70	3	4.89	0.01	4.78	0.36
K	FAAS	M140	2	2.46	0.01	2.58	0.14
K	FAAS	70	2	2.75	0.01	2.82	0.26
K	FAAS	T143	2	2.36	0.01	2.5	0.21
Li	FAAS	69	2	0.421	0.001	0.397	0.03
SO <sub>4</sub>	IC	M102	4	450	4	420	16
F	IC	M102	1	1	---	1.1	0.1
Cl	IC	M102	4	44	1	44	2
Br	IC	M102	1	0.2	---	0.10	0.02
NO <sub>3</sub>	IC	M102	4	15	1	---	---
SiO <sub>2</sub>	ICP	M102	4	7.0	0.2	6.9	0.5
B	ICP	M102	4	0.39	0.06	0.31	0.038
B	ICP	T153	3	0.110	0.000	0.0994	0.0074
Al	ICP	69	4	0.58	0.03	0.620	0.137
Al	ICP	T153	3	<0.09	---	0.035	0.005
Fe (total)	Color	69	2	0.244	0.008	0.223	0.033
Fe (total)	Color	67	2	0.766	0.004	0.76	0.045
Mn	ICP	69	4	0.23	0.01	0.224	0.012
Mn	ICP	73	4	0.37	0.01	0.341	0.022
Mn	ICP	T153	3	0.079	0.001	0.075	0.0033
Cu	ICP	69	4	0.32	0.01	0.297	0.018
Cu	ICP	T153	3	0.022	0.003	0.024	0.0015
Zn	ICP	69	4	0.023	0.005	0.028	0.0079
Zn	ICP	73	4	0.270	0.005	0.252	0.019
Zn1	ICP	T153	3	0.074	0.003	0.0726	0.0051
Cd	ICP	73	4	0.014	0.002	0.016	0.0032
Cd	ZGFAAS	67	5	0.0091	0.0003	0.0095	0.0023
Cd	ICP	T153	3	0.017	0.000	0.016	0.0011

Table 12. Measurements of Standard Reference Waters – Continued

Analyte	Analytical method	USGS SRWS	1997 Data				
			Observed concentration			Most probable value	
			n	mg/L	s	mg/L	s
Cr	ICP	69	4	<0.05	---	0.005	0.0031
Cr	ICP	73	4	<0.02	---	0.0076	0.002
Cr	ICP	T153	3	0.016	0.001	0.015	0.0011
Co	ICP	73	4	0.016	0.002	0.0156	0.0026
Co	ICP	69	4	0.012	0.001	0.0141	0.0041
Ni	ICP	73	4	0.0120	0.0005	0.0129	0.0059
Ni	ZGFAAS	69	4	0.024	0.001	0.0184	0.0074
Ni	ICP	T153	3	0.035	0.002	0.0324	0.0021
Pb	ZGFAAS	69	7	0.024	0.002	0.023	0.016
Pb	ICP	T153	3	0.054	0.006	0.0462	0.003
Be	ICP	69	4	0.032	0.002	0.0318	0.0038
Be	ICP	73	4	0.021	0.001	0.0202	0.0021
V	ICP	M102	4	0.014	0.002	0.023	0.014
V	ICP	T153	3	0.018	0.001	0.019	0.001
Se	ZGFAAS	T133	4	0.020	0.001	0.021	---
Se	ZGFAAS	T143	4	0.0080	0.0004	0.0096	0.002
As	ZGFAAS	67	3	0.021	0.001	0.018	0.4

Table 12. Measurements of Standard Reference Waters – Continued

Analyte	Analytical method	USGS SRWS	1998 Data				
			Observed concentration			Most probable value	
			n	mg/L	s	mg/L	s
Ca	ICP	71	7	14	1	---	---
Ca	ICP	T143	7	56	2	54	2.2
Mg	ICP	71	7	2.0	0.2	---	---
Mg	ICP	T143	7	11.0	0.5	10	0.5
Sr	ICP	71	7	0.076	0.004	0.077	0.007
Sr	ICP	T143	7	0.29	0.02	0.31	0.015
Sr	ICP	T153	5	0.326	0.005	0.311	0.013
Ba	ICP	71	7	0.083	0.009	---	---
Ba	ICP	T143	7	0.078	0.008	0.082	0.005
Ba	ICP	T153	5	0.2	0.0	0.184	0.008
Na	ICP	T143	7	35	2	34	1.6
Na	FAAS	T143	10	33.8	0.4	34	1.6
K	FAAS	T143	14	2.47	0.05	2.5	0.21
K	ICP	T143	7	3.1	0.6	2.5	0.21
Li	FAAS	73	12	0.246	0.008	0.246	0.019
SO <sub>4</sub>	IC	M140	8	153	5	150	---
F	IC	M140	8	0.59	0.09	0.53	---
Cl	IC	M140	8	26	1	25.8	---
NO <sub>3</sub>	IC	M140	8	3.60	0.02	---	---
SiO <sub>2</sub>	ICP	71	7	4.4	0.3	---	---
SiO <sub>2</sub>	ICP	T143	7	23	1	23	1.7
B	ICP	71	7	<0.04	---	---	---
B	ICP	T143	7	<0.04	---	0.035	0.005
B	ICP	T153	7	0.13	0.02	0.10	0.0074
Al	ICP	71	7	0.5	0.1	0.49	0.11
Al	ICP	T143	7	<0.02	---	0.022	0.008
Al	ICP	T153	5	<0.09	---	0.035	0.0051
Fe (total)	ICP	T143	7	0.22	0.02	0.222	0.014
Fe (total)	Color	T143	3	0.228	0.002	0.222	0.014
Mn	ICP	71	7	0.03	0.02	0.035	0.005
Mn	ICP	T143	7	<0.01	---	0.018	0.002
Mn	ICP	T153	5	0.074	0.001	0.075	0.0033
Cu	ICP	71	7	<0.08	---	0.019	0.003
Cu	ICP	T143	7	<0.06	---	0.022	0.002
Cu	ICP	T153	5	0.025	0.004	0.024	0.0015
Zn	ICP	71	7	0.022	0.009	0.023	0.005
Zn	ICP	T143	7	0.017	0.008	0.020	0.002
Zn	ICP	T153	5	0.075	0.002	0.0726	0.0051

Table 12. Measurements of Standard Reference Waters – Continued

Analyte	Analytical method	USGS SRWS	1998 Data				
			Observed concentration			Most probable value	
			n	mg/L	s	mg/L	s
Cd	ICP	71	7	0.002	0.006	0.004	0.0007
Cd	ICP	T143	7	0.020	0.007	0.019	0.002
Cd	ICP	T153	5	0.017	0.000	0.016	0.0011
Cr	ICP	71	7	<0.05	---	0.011	0.003
Cr	ICP	T143	7	<0.03	---	0.037	0.003
Cr	ICP	T153	5	0.016	0.001	0.015	0.0011
Co	ICP	71	7	0.001	0.001	0.008	0.002
Co	ICP	T143	7	0.021	0.001	0.017	0.001
Ni	ICP	71	7	<0.007	---	0.009	0.004
Ni	ICP	T143	7	0.077	0.009	0.071	0.005
Ni	ICP	T153	5	0.035	0.002	0.0324	0.0021
Pb	ICP	71	7	<0.04	---	0.011	0.005
Pb	ICP	T143	7	0.10	0.03	0.083	0.007
Pb	ICP	T153	5	0.046	0.003	0.0462	0.003
Be	ICP	71	7	0.005	0.005	0.007	0.002
Be	ICP	T143	7	0.007	0.005	0.009	0.0007
V	ICP	71	7	<0.006	---	---	---
V	ICP	T143	7	0.024	0.004	0.03	0.003
V	ICP	T153	5	0.017	0.001	0.019	0.001
Se	ZGFAAS	T133	14	0.020	0.001	0.021	---
Se	ZGFAAS	T143	10	0.0084	0.0004	0.0096	0.002
As	ICP	T143	7	<0.2	---	0.015	0.001
As	FIAS	T143	7	0.015	0.001	0.015	0.001