



Potential Application of Radiogenic Isotopes and Geophysical Methods to Understand the Hydrothermal System of the Upper Geyser Basin, Yellowstone National Park

Natural Resource Report NPS/YELL/NRR—2015/1077





ON THIS PAGE

Photograph of Grand Geyser, Upper Geyser Basin, 1999.

Photograph courtesy of National Park Service, Jim Peaco, photographer

ON THE COVER

Photograph of Old Faithful Geyser in the winter, Upper Geyser Basin, 1964.

Photograph courtesy of the National Park Service, Photographer unknown;

Potential Application of Radiogenic Isotopes and Geophysical Methods to Understand the Hydrothermal System of the Upper Geyser Basin, Yellowstone National Park

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James B. Paces¹, Andrew J. Long², Karl Koth³

¹U.S. Geological Survey
Geosciences and Environmental Change Science Center
Denver Federal Center
Denver, Colorado 80225

² U.S. Geological Survey
Washington Water Science Center
934 Broadway, Suite 300
Tacoma, WA 98402

³ U.S. Geological Survey,
South Dakota Water Science Center
1608 Mountain View Road
Rapid City, South Dakota 57702

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Abstract

Numerous geochemical and geophysical studies have been conducted at Yellowstone National Park to better understand the hydrogeologic processes supporting the thermal features of the Park. This report provides the first $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{234}\text{U}/^{238}\text{U}$ data for thermal water from the Upper Geyser Basin (UGB) intended to evaluate whether heavy radiogenic isotopes might provide insight to sources of groundwater supply and how they interact over time and space. In addition, this report summarizes previous geophysical studies made at Yellowstone National Park and provides suggestions for applying non-invasive ground and airborne studies to better understand groundwater flow in the subsurface of the UGB.

Multiple samples from Old Faithful, Aurum, Grand, Oblong, and Daisy geysers characterized previously for major-ion concentrations and isotopes of water ($\delta^2\text{H}$, $\delta^{18}\text{O}$, and ^3H) were analyzed for Sr and U isotopes. Concentrations of dissolved Sr and U are low ($4.3\text{--}128\text{ ng g}^{-1}\text{ Sr}$ and $0.026\text{--}0.0008\text{ ng g}^{-1}\text{ U}$); consequently only $^{87}\text{Sr}/^{86}\text{Sr}$ data are reported for most samples. Values of $^{87}\text{Sr}/^{86}\text{Sr}$ for most geysers remained uniform between April and September 2007, but show large increases in all five geysers between late October 2007 and early April, 2008. By late summer of 2008, $^{87}\text{Sr}/^{86}\text{Sr}$ values returned to values similar to those observed a year earlier. Similar patterns are not present in major-ion data measured on the same samples. Furthermore, large geochemical differences documented between geysers are not observed in $^{87}\text{Sr}/^{86}\text{Sr}$ data, although smaller differences between sites may be present. Sr-isotope data are consistent with a stratified hydrologic system where water erupted in spring and summer of 2007 and summer of 2008 equilibrated with local intracaldera rhyolite flows at shallower depths. Water erupted between October 2007 and April 2008 includes greater amounts of groundwater that circulated deep enough to acquire a radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$, most likely from Archean basement rocks. Details of how the shallow and deep components interact and mechanisms causing these interactions remain unknown, but the data demonstrate the usefulness of obtaining Sr-isotope data from future sample campaigns.

Geophysical methods that would be useful for characterization of the UGB subsurface properties and geothermal system include electromagnetic (EM), gravity, and ambient seismic. A suite of ground-based EM methods could be used in a synergistic combination together with airborne EM surveys to provide data for a range of spatial scales and resolutions. Existing thermal data for the shallow subsurface could be used to relate ground and airborne EM survey data to locations of geothermal fluids near the surface. Gravity surveys would be useful for mapping subsurface density anomalies and possibly monitoring changes in degree of saturation with groundwater. Ambient seismic surveys would be useful for estimating the thickness of unconsolidated deposits that contain the shallow groundwater system.

A study that combines radiogenic isotope tracers with geophysical methods has the potential to better characterize the geothermal workings in the UGB. Insights gained could lead to a better understanding of the geothermal system and how Park infrastructure may cause perturbations. Measurements of radiogenic isotopes from multiple geysers and pools in localized areas within the UGB that are coupled with data from geophysical surveys would help refine conceptual models of mixing between deep- and shallow-derived subsurface fluids.

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Introduction

Yellowstone National Park was established as the world's first national park in 1872 in large part to preserve and protect the unique hydrothermal features present within the magmatically active volcanic caldera. Many of these features, including the iconic Old Faithful Geyser, are concentrated in the Upper Geyser Basin (UGB) located in the western half of the Yellowstone caldera (Figure 1). Since the mid-1960's, annual visitations to the Park have exceeded 2 million, growing steadily to over 3.5 million in the last several years (NPS Stats, 2015). The UGB in general and Old Faithful Geyser in particular are under threat from increased pressure from seasonal tourism and National Park Service (NPS) efforts to accommodate greater public demand for access. To minimize impacts on the natural hydrothermal features in the UGB, a greater understanding of the hydrodynamic system is required.

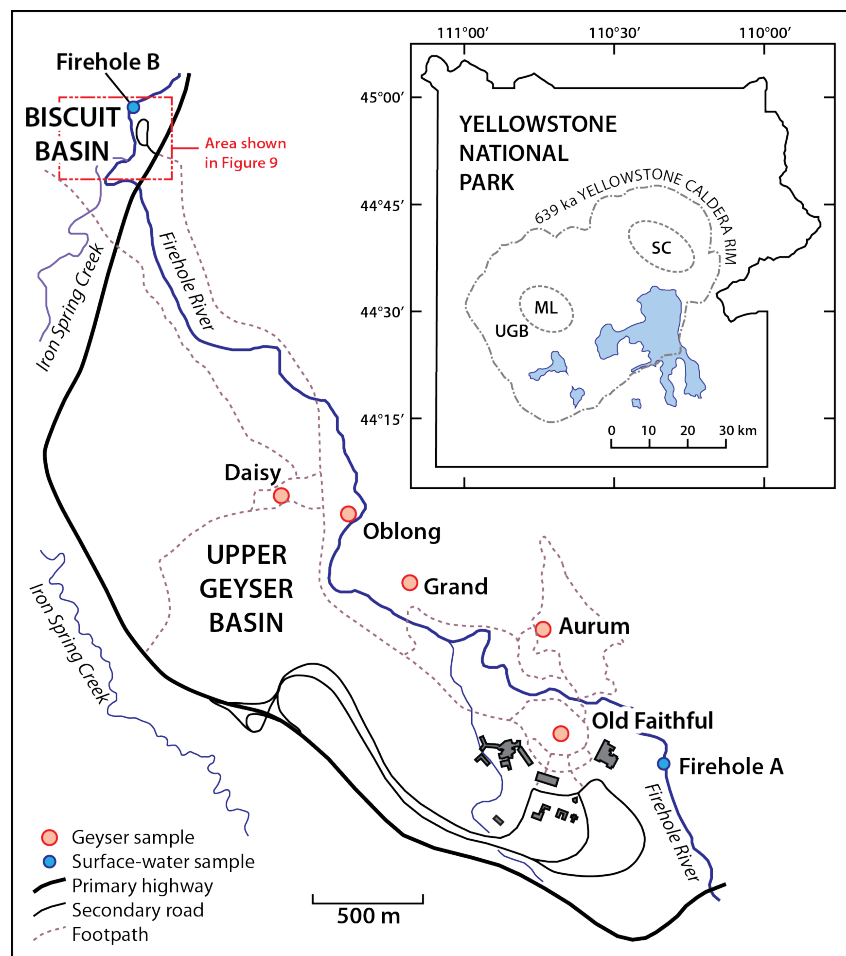


Figure 1: Sketch map of the Upper Geyser Basin showing locations of geysers (large red circles) and Firehole River sites (small blue circles above [A] and below [B] the Upper Geyser Basin) sampled for this study. Latitude and longitude coordinates for individual sampling sites are given in Table 1. Inset map showing the outline of Yellowstone National Park along with general location of the Upper Geyser Basin (UGB) inside the 639-ka-old Yellowstone caldera just west of the Mallard Lake resurgent dome (ML). The Sour Creek resurgent dome (SC) is also outlined. Modified from Hurwitz and others (2012).

Substantial work has been devoted to characterizing the geological, hydrological, hydrochemical, and physical nature of the UGB (Heasler and others, 2009c; Old Faithful Science Review Panel [OFSRP], 2014; Hurwitz and Lowenstern, 2014). Studies have demonstrated that the hydrothermal features depend on interactions between young, cool recharge to the shallow subsurface and upwelling plumes of older, deeper-circulating thermal water. Although several studies have demonstrated that different geysers in the UGB have distinct chemical compositions (Fournier, 1989; Hurwitz and others, 2007, 2008, 2012; McCleskey and others, 2012), it is not clear if those differences are caused by near-surface chemical processes, or by different degrees of mixing between deeper and shallower reservoirs including the possible involvement of multiple unique flow paths and/or deeper groundwater reservoirs.

The main objective of this report is to evaluate whether application of natural radiogenic isotope tracers and a combination of non-invasive geophysical measurements are likely to offer new insights into plumbing systems supplying the hydrothermal features in the UGB. Mixing between cooler meteoric water recharged locally with deeper thermal groundwater form the main components of the UGB hydrothermal system; however, the origins and nature of the deeper, hotter component and the degree to which geysers in the UGB are interconnected are not well understood. Natural tracers of groundwater flow and water/rock interaction involving radiogenic isotopes of Sr ($^{87}\text{Sr}/^{86}\text{Sr}$) and U ($^{234}\text{U}/^{238}\text{U}$) have the potential to help illuminate the origins and heterogeneities of the deep groundwater component but have not been systematically applied to water samples within the Park. Furthermore, combined non-invasive surface geophysical methods including electromagnetic, ground-penetrating radar (GPR), microgravity, and ambient seismic surveys have been underused in the UGB and may offer ways of examining subsurface plumbing. This report describes scoping studies that address the variability of Sr and U isotopic compositions in groundwater samples from several of the major geysers in the UGB. Results indicate that these tracers may offer a simple, non-invasive tool to better understand sources, flow paths, and connectivity of plumbing systems. In addition, a number of surface-based and airborne geophysical methods are evaluated for their potential to better understanding the UGB subsurface. The potential for combining both isotope and geophysical studies across the same localized areas may offer insights that have not been realized in the past.

Radiogenic Isotope Tracers

Natural tracers of groundwater flow capable of distinguishing between multiple sources are needed to better understand the interplay between shallow and deep hydrologic components. Unfortunately, concentrations of dissolved chemical constituents as well as light stable isotopes can be strongly affected by many near-surface processes such as dilution with meteoric water, evaporative concentration, liquid-vapor phase separation, mineral precipitation, sorption, and ion-exchange. Those processes may result in large compositional shifts that complicate interpretations of hydrologic source mixing. Therefore, natural tracers that remain unaffected by near-surface processes are desirable. Heavy radiogenic isotopes of Sr and U have been used successfully to characterize hydrologic sources and mixing relations in a variety of environments (Barbieri and Voltaggio, 1998; Drexler and others, 2014; Paces and Wurster, 2014; Dogramaci and Skrzypek, 2015). Because mass differences between isotopes of both Sr and U are small compared to their total atomic masses, $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{234}\text{U}/^{238}\text{U}$ compositions remain largely unmodified by many physical processes that can strongly affect other constituents. Furthermore, both trace metals are commonly present in groundwater at concentration levels that allow measurement at high levels of precision and accuracy. Therefore, $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{234}\text{U}/^{238}\text{U}$ in groundwater from hydrothermal eruptions may offer unique insights into UGB plumbing systems that have not been observed using other geochemical methods.

Isotope signatures of Sr and U in water from the UGB are largely uninvestigated. Sr isotopic compositions have been reported for a number of rhyolites and basalts throughout the caldera (Doe and others, 1982; Hildreth and others, 1991; Abedini, 2009). Those data were used to interpret the petrologic origins and magmatic processes of rocks in the Yellowstone Plateau volcanic field. Sr-isotope data are also available for early Tertiary volcanic rocks and Precambrian metamorphic rocks exposed in uplifted core complexes in the Absaroka and Beartooth ranges north and east of the caldera (Feeley and others, 2002; Feeley and Cosca, 2003; Lindsay and Feeley, 2003; Wooden and Mueller, 1988; Montgomery and Lytwyn, 1984). A small number of samples of travertine from the Mammoth Hot Springs area as well as travertine and sinter from the Lower Geyser Basin and UGB have been analysed for Sr and Pb isotopes (Leeman and others, 1977) or U-Th geochronology (Sturchio and others, 1994). Resulting $^{87}\text{Sr}/^{86}\text{Sr}$ and initial $^{234}\text{U}/^{238}\text{U}$ values of those deposits reflect the compositions inherent in groundwater discharge from which they formed. To date, no systematic study of Sr or U isotope compositions of groundwater within the Park have been made.

Water Samples

In order to evaluate variations in major-element chemistry and water isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$, and ^3H) in UGB geysers, Hurwitz and others (2012) collected samples of groundwater eruptions from five geysers (Old Faithful, Daisy, Grand, Oblong, and Aurum) between April 2007 and September 2008. In addition, surface flow from the Firehole River above and below the UGB was analyzed. Geothermometry results indicated that thermal reservoirs at temperatures of 190–210°C feed all the geysers in the UGB. Chemical and H- and O-isotope data showed only limited variations within and between the different geysers. Nevertheless, differences in patterns indicated that hydraulic conditions at shallower levels allow small geysers (Aurum) to be more affected by meteoric water recharge, whereas pool geysers (such as Oblong and Daisy) are more affected by evaporation. Very

small variations in water chemistry at Grand Geyser were interpreted as evidence of a subsurface reservoir that is larger than the other geysers. Concentrations of major dissolved species in samples of Old Faithful Geyser were shown to have remained nearly constant since 1884 despite large changes in eruption intervals. Those observations led the authors to conclude that no major changes have occurred in the UGB hydrothermal system for more than one hundred years.

Splits of groundwater samples remaining from the 2007–2008 study were obtained and used to determine radiogenic isotope compositions in this scoping study. A total of 45 of the 58 samples reported in Table 2 of Hurwitz and others (2012) were received mostly in 30 or 60 ml bottles. Samples had been filtered and acidified previously (Section 2 of Hurwitz and others, 2012), and all were clear and colorless with no observable precipitate. Water samples had been stored at room temperature since their collection. However, because of their small differences in relative mass, isotopes of Sr and U will not fractionate under these conditions, and ratios will remain unmodified during storage.

Water samples from the 2007–2008 collection were analyzed in this study to determine ranges of Sr and U concentration expected in UGB groundwater as well as whether $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{234}\text{U}/^{238}\text{U}$ compositions showed substantial seasonal or inter-site variation. The greatest advantage of using this set of samples is that they represent a comprehensive time-series suite that had been well characterized for major ions and water isotopes. The greatest disadvantage is that only small volumes were available, which presents analytical challenges if dissolved-ion concentrations are low.

Results

Analytical methods used to determine concentration and isotope data in this report are described in detail in the appendix A. Concentrations of Sr and U in samples of UGB water are low relative to groundwater from many other settings. The median concentration of Sr for 38 geyser-water samples is 10.5 ng/g ($\mu\text{g/L}$) and the median concentration of U for 11 geyser-water samples is 0.018 ng/g (Table 1). Low concentrations of Sr are not surprising due to cation exchange in zeolitically altered volcanic rocks that are likely present at depth. Ca concentrations are similarly low and Na concentrations enriched in the same geyser waters compared to surface flow (median Na/Ca of ~ 690 in geyser water compared to ~ 8.5 in Firehole River water; data from Hurwitz and others, 2012). Low concentrations of U are likely caused by reducing conditions at depth, where U forms low-solubility tetravalent species rather than readily soluble hexavalent species typical in oxidized systems.

Table 1. Sr and U concentrations and isotopic compositions for groundwater erupted from geysers in the Upper Geyser Basin and from two surface-water sample sites along the Firehole River near Old Faithful Lodge and Biscuit Basin parking areas, Yellowstone National Park, Wyoming.

Sample Identifier	Collection Date	Sr conc. (ng/g)	⁸⁷ Sr/ ⁸⁶ Sr atomic, ±2σ		U conc. (ng/g)	²³⁴ U/ ²³⁸ U activity ±2σ	
Aurum Geyser (44.464590° Lat., -110.829499° Long.)							
UGB041307-ARM	13-Apr-07	15.0	0.713475	0.000024			
UGB052907-ARM	29-May-07	8.97	0.713959	0.000014			
UGB071607-ARM	16-Jul-07	29.5	0.720001	0.000013			
UGB102407-ARM	24-Oct-07	5.68	0.726762	0.000016			
UGB011608-ARM	16-Jan-08	6.82	0.720316	0.000013			
UGB040908-ARM	9-Apr-08	4.47	0.721405	0.000017			
UGB092108-ARM	21-Sep-08	4.29	0.714082	0.000018			
Daisy Geyser (44.470203° Lat., -110.843591° Long.)							
UGB-041207-DZY	12-Apr-07	128.	0.718018	0.000026	0.018	1.05	0.01
UGB-102407-DZY	24-Oct-07	69.0	0.729881	0.000013	0.018	1.24	0.12
UGB011608-DZY	16-Jan-08	8.22	0.718559	0.000014			
UGB040908-DZY	9-Apr-08	14.7	0.722497	0.000021			
UGB-081408-DZG	14-Aug-08	40.9	0.718446	0.000016	0.016	1.16	0.03
UGB-082108-DZG	21-Aug-08	95.3	0.718357	0.000013	0.020	1.12	0.02
UGB082808-DZY	28-Aug-08	7.41					
UGB091208-DZY	12-Sep-08	6.82	0.718426	0.000074			
UGB092108-DZY	21-Sep-08	6.45	0.718518	0.000030			
Grand Geyser (44.466657° Lat., -110.836977° Long.)							
UGB071607-GRN	16-Jul-07	8.99	0.717167	0.000011			
UGB090707-GRN	7-Sep-07	10.5	0.716895	0.000014			
UGB102407-GRN	24-Oct-07	6.43	0.725589	0.000012			
UGB011608-GRN	16-Jan-08	11.6	0.733889	0.000027			
UGB040908-GRN	9-Apr-08	80.6	0.721512	0.000012			
Oblong Geyser (44.469368° Lat., -110.840247° Long.)							
UGB-041207-OBL	12-Apr-07	50.4	0.717801	0.000025	0.025	0.86	0.04
UGB-053007-OBL	30-May-07	44.7	0.717926	0.000013	0.026	1.05	0.02
UGB071607-OBL	16-Jul-07	5.07	0.717805	0.000012			
UGB-102407-OBL	24-Oct-07	23.0	0.737474	0.000011			
UGB011708-OBL	17-Jan-08	6.23	0.725068	0.000016			
UGB-040908-OBL	9-Apr-08	41.1	0.723285	0.000016	0.026	1.11	0.02
Old Faithful Geyser (44.460491° Lat., -110.828079° Long.)							
UGB-041207-OFG	12-Apr-07		0.718140	0.000009	0.0054	1.60	0.08
UGB052807-OFG	28-May-07	13.2	0.718224	0.000031	0.0008	2.11	0.09

Sample Identifier	Collection Date	Sr conc. (ng/g)	$^{87}\text{Sr}/^{86}\text{Sr}$ atomic, $\pm 2\sigma$		U conc. (ng/g)	$^{234}\text{U}/^{238}\text{U}$ activity $\pm 2\sigma$	
UGB-071607-OFG	16-Jul-07	14.3	0.718315	0.000047	0.0010		
UGB090707-OFG	7-Sep-07	17.9	0.718438	0.000013			
UGB-102407-OFG	24-Oct-07	66.5	0.730566	0.000035	0.0052	0.76	0.05
UGB011608-OFG	16-Jan-08	11.2	0.718592	0.000014			
UGB040908-OFG	9-Apr-08	10.0	0.721602	0.000017			
UGB081408-OFG	14-Aug-08	8.30	0.718395	0.000017			
UGB082108-OFG	21-Aug-08	9.08	0.717937	0.000014			
UGB082808-OFG	28-Aug-08	8.09	0.718026	0.000035			
UGB091208-OFG	12-Sep-08	7.62	0.718156	0.000019			
Firehole River Above Upper Geyser Basin (44.459808° Lat., -110.822131° Long.)							
39184041207-FHA	12-Apr-07	50.9	0.709799	0.000022			
39379102407-FHA	24-Oct-07	10.7	0.713069	0.000029			
39464011708-FHA	17-Jan-08	67.1	0.712248	0.000013			
39547040908-FHA	9-Apr-08	14.7	0.710662	0.000014			
Firehole River Below Upper Geyser Basin (44.486282° Lat., -110.852709° Long.)							
UGB052707-FHB	27-May-07	14.5	0.709949	0.000014			
UGB102407-FHB	24-Oct-07	11.9	0.714312	0.000019			
UGB011808-FHB	18-Jan-08	17.8	0.710488	0.000017			
UGB040908-FHB	9-Apr-08	16.3	0.712177	0.000012			

Samples from Hurwitz and others, 2012

Given the limited size of the samples (total of 12–52 g of water), only marginal Sr and U abundances were available for isotope characterization (median values of 380 ng for Sr and 0.54 ng for U). This was particularly problematic for measuring $^{234}\text{U}/^{238}\text{U}$, and resulted in activity ratios (AR) with large analytical errors. As a result, U isotope compositions were only determined on the first set of samples. Data for Sr isotopes are more robust, although 2-sigma uncertainties for $^{87}\text{Sr}/^{86}\text{Sr}$ determinations given in Table 1 are larger than those typically reported for samples where several μg of Sr are available.

UGB groundwater samples have a very large range of $^{87}\text{Sr}/^{86}\text{Sr}$ values from 0.71347 to 0.73747 (Table 1) that includes both intra-geyser as well as inter-geyser variations. In general, geyser-water samples have higher $^{87}\text{Sr}/^{86}\text{Sr}$ values than most volcanic rocks comprising the Yellowstone Plateau (Figure 2). Analyses of basalts reported by Hildreth and others (1991) and Abedini (2009) have a median $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.70599 and reflect the less-radiogenic Sr (that is, lower $^{87}\text{Sr}/^{86}\text{Sr}$) inherent in their mantle sources. Introduction of heat into the lithosphere resulted in melting of the lower crust, which produced rhyolites containing more-radiogenic Sr (higher $^{87}\text{Sr}/^{86}\text{Sr}$). The median present-day $^{87}\text{Sr}/^{86}\text{Sr}$ reported for 20 rhyolite analyses by Hildreth and others is 0.71267, although the distribution is skewed with a few rock units having values as high as 0.72702. Earlier analyses of

basalts and rhyolites from the Yellowstone Plateau volcanic field yielded similar results (Doe and others, 1982), but with greater scatter caused, in part, by the less precise methods used at the time. Early Tertiary mafic to felsic volcanic rocks of the Absaroka Range exposed north and northeast of the caldera have $^{87}\text{Sr}/^{86}\text{Sr}$ values that are similar to those obtained for Yellowstone basalts ranging from 0.70433 to 0.70826 with a median value of 0.70622 (34 analyses compiled from Feeley and others, 2002; Feeley and Cosca, 2003; Lindsay and Feeley, 2003).

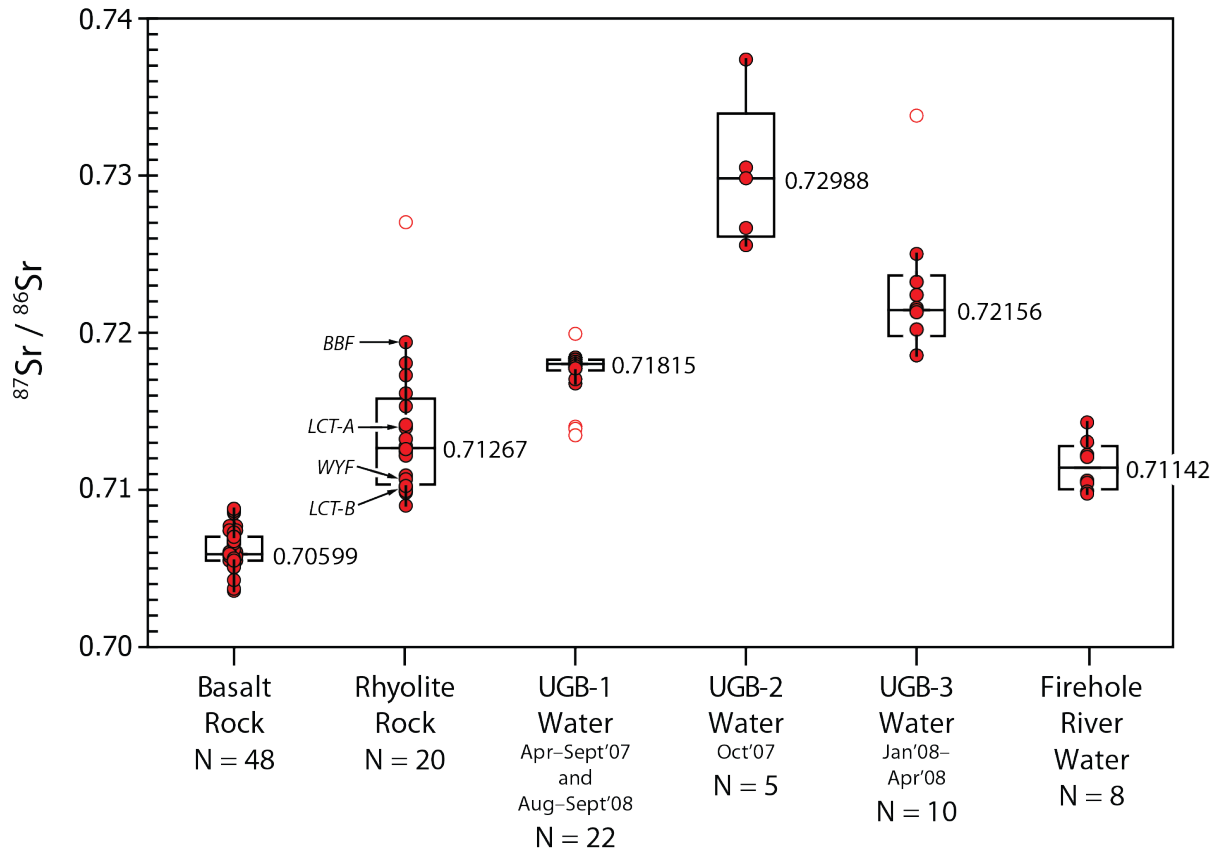


Figure 2: Box-and-whisker plot of $^{87}\text{Sr}/^{86}\text{Sr}$ data from Yellowstone basaltic and rhyolitic rocks, groundwater from the Upper Geyser Basin (UGB) and surface water from the Firehole River. Data for rocks are from Hildreth and others (1991) and Abedini (2009). Data for waters are from Table 1. Median values are given to the right of the line in each box. Boxes depict the upper and lower quartiles (25% of the data above and below the median), and whiskers extend to the upper and lower extremes, excluding outliers (open circles). Labeled circles for rhyolites include the Biscuit Basin Flow (BBF), the West Yellowstone Flow (WYF), and the Lava Creek Tuffs A and B (LCT-A and LCT-B).

Sr isotope data for UGB geyser water shown in Figure 2 are separated into three groups based on collection date. Most water sampled between April and September of 2007 and between August and September 2008 (group UGB-1) show a narrow range of $^{87}\text{Sr}/^{86}\text{Sr}$ values with a median of 0.71815. Statistical outliers within this group are all from Aurore Geyser. The second group (UGB-2) represents groundwater eruptions collected on October 24, 2007. All five geysers have $^{87}\text{Sr}/^{86}\text{Sr}$ values that are much higher than those observed earlier in the season. Although there is substantially more dispersion, the median $^{87}\text{Sr}/^{86}\text{Sr}$ for all five water samples is 0.72988. The third group consists

of samples collected in January and April of 2008 (UGB-3). Nine of those ten samples yield a median $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.72156, which is intermediate between the other two groups.

Surface-water samples collected from two sites on the Firehole River above and below the UGB have a median $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.71142, which is substantially lower than groundwater from UGB geysers. In particular, the sample collected on April 12, 2007, above UGB has the lowest value measured for water samples analyzed in this study (0.70980) and represents water least affected by geyser contributions. This value is well within the range of Yellowstone rhyolites (Figure 2) and is consistent with a source of Sr derived from water/rock interaction with local soils. In all but one set of samples, $^{87}\text{Sr}/^{86}\text{Sr}$ values for river water below UGB is higher than river water above UGB, consistent with the addition of groundwater with radiogenic Sr from geyser discharge in the UGB.

Only ten UGB samples were analyzed for U-isotopic compositions (Table 1). Because of the very low U concentrations and small sample sizes, measured $^{234}\text{U}/^{238}\text{U}$ AR have large analytical uncertainties and are susceptible to modification from spike addition and the blank from chemical processing. Therefore, analytical artifacts are likely and may explain at least some of the observed $^{234}\text{U}/^{238}\text{U}$ AR variations. Water from Old Faithful Geyser had the lowest U concentrations (0.0054 ng/g) and greatest scatter of measured $^{234}\text{U}/^{238}\text{U}$ AR values ranging from 0.76 ± 0.05 to 2.11 ± 0.09 . Water from the other geysers had slightly higher U concentrations (0.016 to 0.026 ng/g) and a more restricted range of $^{234}\text{U}/^{238}\text{U}$ AR values from 1.05 ± 0.02 to 1.24 ± 0.12 , with one anomalously low value of 0.86 ± 0.04 from Oblong Geyser. Sturchio and others (1994) reported a similar range of initial $^{234}\text{U}/^{238}\text{U}$ AR values (1.03–1.27) for 16–47 ka travertines from Gardiner, MT, but somewhat higher values (1.49–3.08) for travertines from the Mammoth Hot Spring and Sheepeater Canyon areas. No correlations are observed between Sr and U isotope data for UGB thermal waters. However, until larger sample volumes and better U-isotope results are obtained, it is unclear how diagnostic $^{234}\text{U}/^{238}\text{U}$ measurements may prove.

Temporal Variations in $^{87}\text{Sr}/^{86}\text{Sr}$

Groundwater from all five UGB geysers shows systematic variations in $^{87}\text{Sr}/^{86}\text{Sr}$ over the period of sampling from April 2007 to April or September 2008 (Figure 3A). Temporal patterns are typified by samples from Old Faithful Geyser, which had the largest number of samples collected over the 18-month study period. At Old Faithful, $^{87}\text{Sr}/^{86}\text{Sr}$ values remained more-or-less constant for groundwater erupted between April and early September, 2007 (0.71814–0.71844). The radiogenic Sr content increased dramatically in the subsequent sample collected on October 24, resulting in an $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.73057. Water sampled in January and April of 2008 had lost much of this radiogenic component, but $^{87}\text{Sr}/^{86}\text{Sr}$ values remained elevated (0.71859–0.72160) relative to groundwater collected in spring and summer of 2007. By late summer 2008, $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.71794–0.71839 had returned to within the range observed in the previous summer.

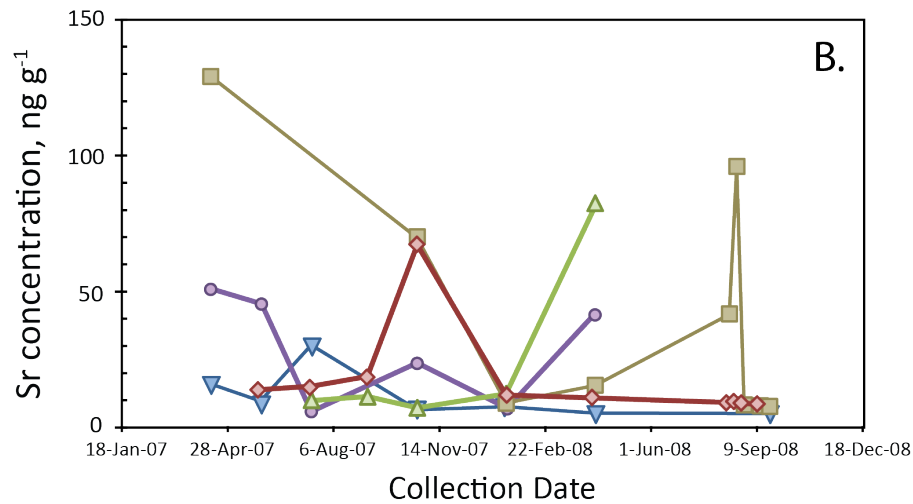
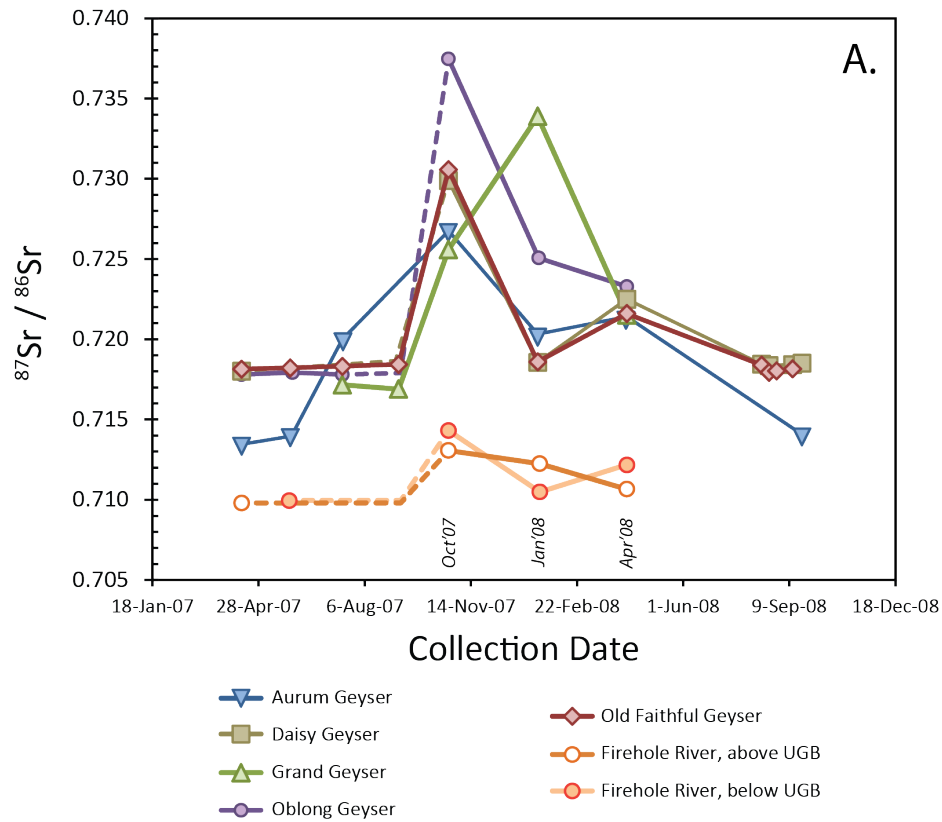


Figure 3: Time-series plots of $^{87}\text{Sr}/^{86}\text{Sr}$ (A) and Sr concentrations (B) for groundwater from eruptions of five geysers in the Upper Geyser Basin and surface-water from the Firehole River. Data are from Table 1. Dotted lines connecting sample dates are extrapolated for Daisy and Oblong geysers and for Firehole River data under the assumption that they would follow trends observed in Old Faithful samples.

Large increases in $^{87}\text{Sr}/^{86}\text{Sr}$ for October 2007 samples were observed at all sites, although the degree in radiogenic-Sr enrichment was different in other geysers. Groundwater from Daisy Geyser has $^{87}\text{Sr}/^{86}\text{Sr}$ variations that are nearly identical to samples from Old Faithful Geyser throughout the sample period (Figure 3A). Groundwater from Oblong Geyser showed the greatest increase in $^{87}\text{Sr}/^{86}\text{Sr}$ for the October sample (0.71781–0.73747), whereas Grand Geyser showed the smallest

increase (from 0.71690 to 0.72559, although a much higher value of 0.73389 was observed in January). The pattern of temporal changes at Aurum Geyser is distinct from other geysers, differing primarily by showing more noticeable increases in radiogenic Sr throughout late spring to summer compared to the lowest value observed in April 2007.

Isotopic compositions of surface flow in the Firehole River reflect patterns of $^{87}\text{Sr}/^{86}\text{Sr}$ variation seen in geyser water, albeit to much lower degrees and from far fewer samples analyzed. Samples collected from spring 2007 have the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ values for sites both above and below the UGB. Samples from summer or early Fall were not analyzed, but by October 2007, streamflow at both sites had significantly higher $^{87}\text{Sr}/^{86}\text{Sr}$. Values remain elevated in surface-flow samples collected in January and April 2008.

Similar patterns of systematic variation are not observed in other constituents. Sr concentrations can show large differences between time-series samples from the same geyser (Figure 3B), but the types of systematic change that are obvious in $^{87}\text{Sr}/^{86}\text{Sr}$ data are not observed in Sr concentrations. Consequently, correlations are not observed in plots of $^{87}\text{Sr}/^{86}\text{Sr}$ versus reciprocal Sr concentration (Figure 4), which are commonly used to evaluate mixing in suites of related samples (Faure and Mensing, 2005). Simple binary mixtures of shallow meteoric infiltration and deeper thermal groundwater within the UGB are expected to produce linear trends in Figure 4. The absence of such trends indicates that either more than two reservoirs contribute groundwater to geyser eruptions, or that groundwater experiences additional chemical or physical process that affect concentrations to greater degrees than $^{87}\text{Sr}/^{86}\text{Sr}$. Decoupling of trace-element concentrations dissolved in water from Sr- and U-isotope compositions was demonstrated elsewhere despite simple binary mixing of water sources (Paces and Wurster, 2014).

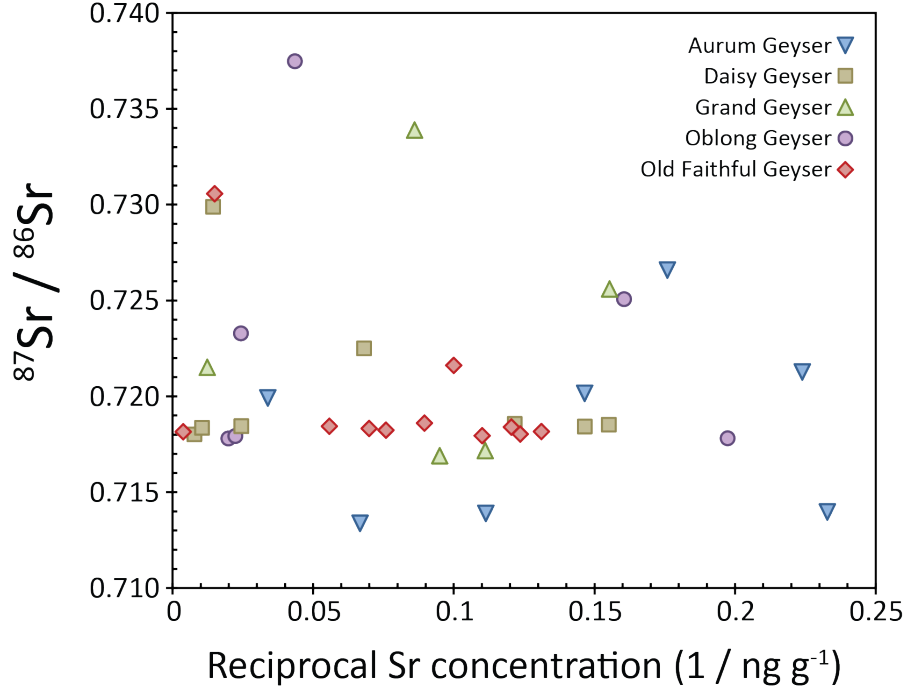


Figure 4: Strontium-isotope mixing plot for groundwater eruptions from five geysers in the Upper Geyser Basin. Data are from Table 1. Reciprocal concentration values are used because samples related by simple mixing of two endmembers will yield linear trends.

Hurwitz and others (2012) evaluated seasonal variation of major-ions and water isotopes from the same set of geyser water samples. They recognized temporal variations that exceeded analytical uncertainties in Old Faithful, Daisy, Oblong, and Aurum geyser waters, but not at Grand Geyser, which showed very uniform compositions (Figure 5). However, the scale of variation observed in those constituents is small compared to the very large differences observed in $^{87}\text{Sr}/^{86}\text{Sr}$ values. Furthermore, time-series plots of major ions and water isotopes from the same samples analyzed for $^{87}\text{Sr}/^{86}\text{Sr}$ do not exhibit systematic enrichments or depletions starting in fall of 2007. Consequently, $^{87}\text{Sr}/^{86}\text{Sr}$ values are not correlated with major-ion concentrations when samples having radiogenic Sr are considered (Figures 6).

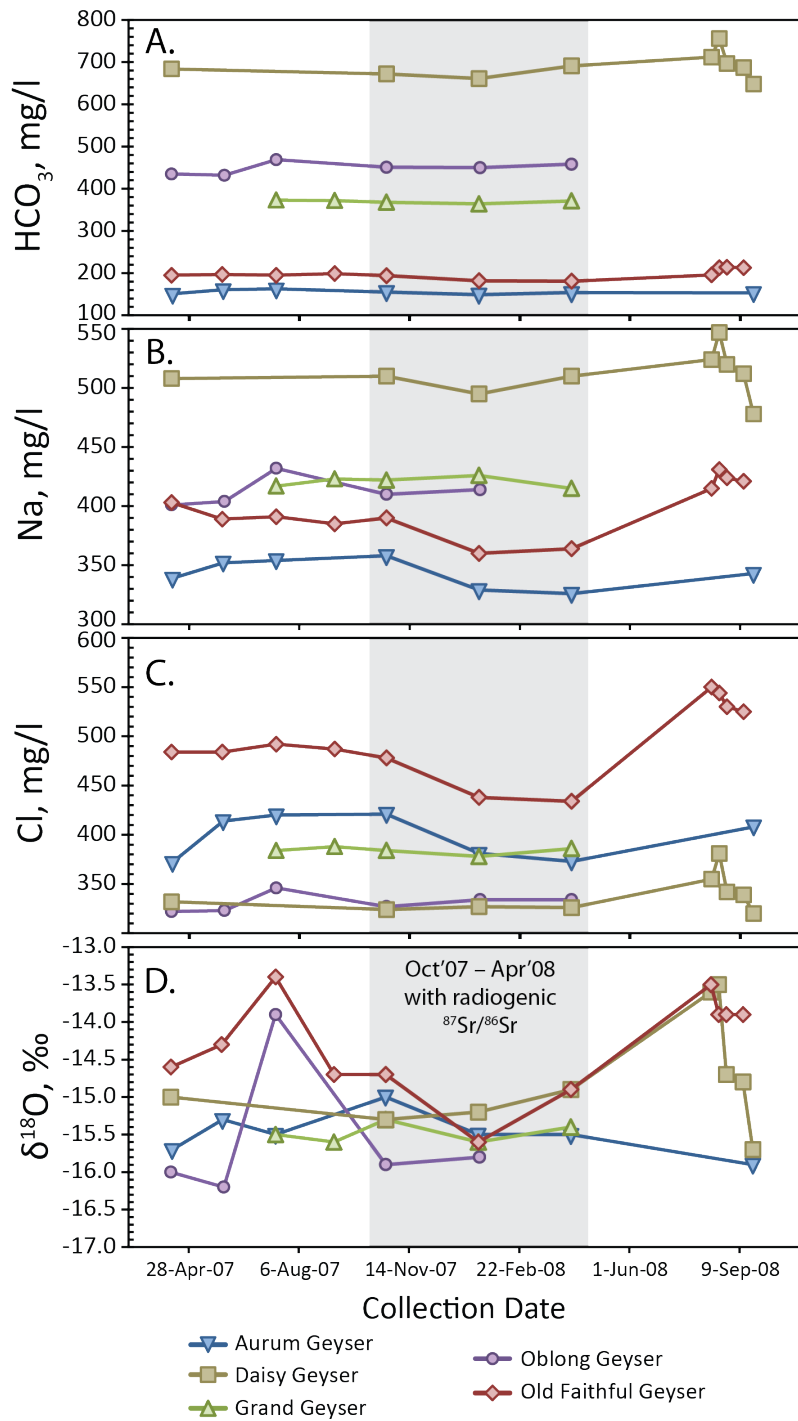


Figure 5: Time-series plots of major ion concentrations (bicarbonate, sodium, and chlorine) and oxygen isotope values ($\delta^{18}\text{O}$) for the same Upper Geyser Basin groundwater samples analyzed for $^{87}\text{Sr}/^{86}\text{Sr}$ and shown in Figure 3. Data are from Hurwitz and others (2012). The period of time that includes large increases in $^{87}\text{Sr}/^{86}\text{Sr}$ values (October 2007 to April 2008) are shown with gray shading.

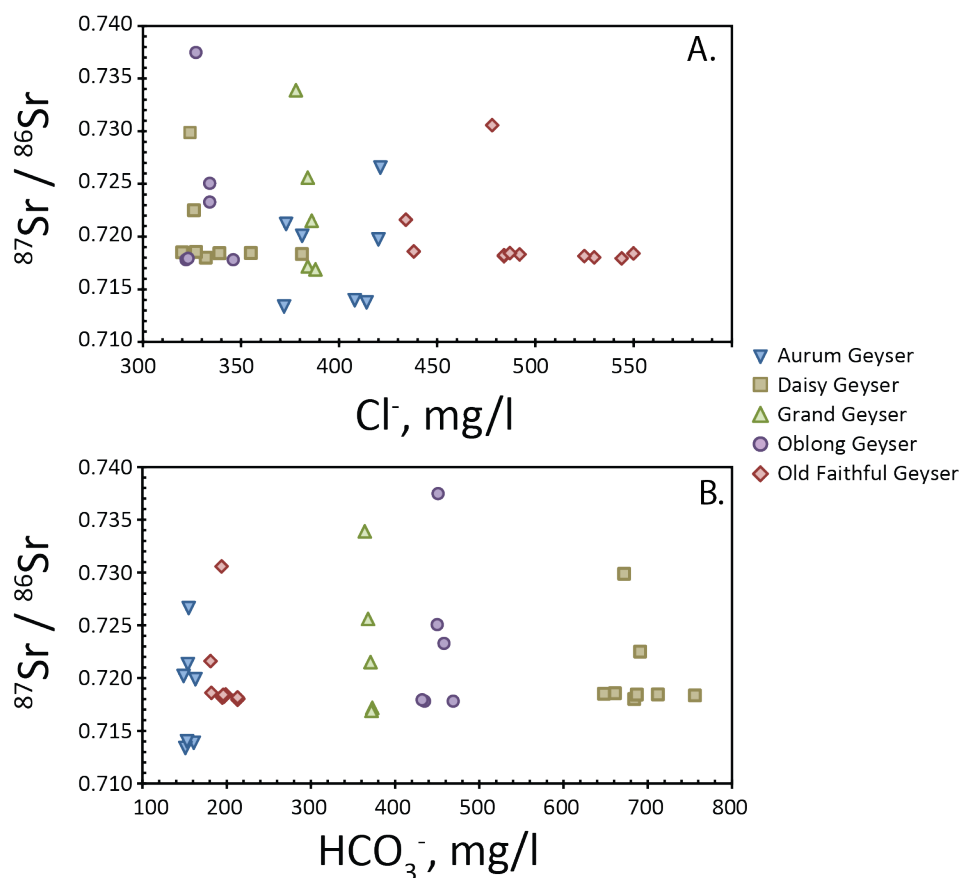


Figure 6: Variations between $^{87}\text{Sr}/^{86}\text{Sr}$ values and major-ion concentrations including chloride (A) and bicarbonate (B).

It is also notable that even though samples from Grand Geyser had uniform major-ion and water-isotope compositions throughout the sampling period (Hurwitz and others, 2012), the same samples showed very large deviations in $^{87}\text{Sr}/^{86}\text{Sr}$ values (Figures 6A and 6B). Like other major ions, Sr concentrations in Grand Geyser water remained relatively uniform (6.4 to 11.6 ng/g) from July 2007 through January 2008 despite large changes in $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 3), only increasing sharply in the April 2008 sample. The fact that $^{87}\text{Sr}/^{86}\text{Sr}$ compositions can change substantially at the same time chemical compositions remain constant provides insight on the mixing components that supply groundwater to geyser eruptions.

Variations in $^{87}\text{Sr}/^{86}\text{Sr}$ between Geysers

Geysers sampled from the UGB form an array of thermal features extending approximately 1700 m northwest of Old Faithful Geyser (Figure 1). Concentrations of major ions can show large differences between geysers along this trend (Figure 5). For instance, Old Faithful Geyser at the southeast end of the UGB has substantially lower Na and HCO_3^- and higher Cl^- concentrations compared to Daisy Geyser at the opposite end, whereas groundwater from Grand and Oblong geysers have intermediate concentrations. However, both Old Faithful and Daisy geysers have nearly identical $^{87}\text{Sr}/^{86}\text{Sr}$ compositions in all pairs of time-series samples (Figure 3A). This similarity implies that groundwater supplying eruptions at both geysers is derived from the same or very similar

reservoirs beneath the UGB despite their spatial separation. This reservoir shares the same inputs at the same times from both shallow and deep groundwater sources. The chemical differences observed between the two geysers by Hurwitz and others (2012) can be attributed to near-surface physical processes or chemical reactions that do not impact $^{87}\text{Sr}/^{86}\text{Sr}$ fractionation.

Samples from Oblong Geyser have very similar compositions to other UGB geysers during parts of the year when erupting water is dominated by the low $^{87}\text{Sr}/^{86}\text{Sr}$ component. However the Oblong subsurface reservoir is more susceptible to contributions from the radiogenic-Sr source that resulted in $^{87}\text{Sr}/^{86}\text{Sr}$ values higher than those at Old Faithful and Daisy geysers sampled in fall and winter (Figure 3A). Groundwater supplying Aukum Geyser shows larger deviations of $^{87}\text{Sr}/^{86}\text{Sr}$ values throughout the sampling period compared to other geysers. Despite its close proximity to Old Faithful Geyser, Aukum groundwater had a substantially lower $^{87}\text{Sr}/^{86}\text{Sr}$ composition in early 2007 and late 2008, and greater variability in the sample from late summer (Figure 3A).

Discussion of Sr-Isotope Results

Groundwater analyses in the current study represent an initial attempt to evaluate the range of variation in Sr and U isotope compositions in UGB geysers and how those results might provide insights into the plumbing system and processes within the local hydrothermal system. Data presented in the previous section demonstrates that significant Sr-isotope variability is present both between geysers in the UGB as well as over time at individual geysers. The following sections give a brief overview of how those variations may offer insights into hydrologic sources and how those sources may interact in subsurface reservoirs.

Origins of Sr-Isotope Signatures

The isotopic compositions of Sr dissolved in surface-water and groundwater samples are derived from water-rock (or soil) interaction plus mixing of separate water sources to yield the $^{87}\text{Sr}/^{86}\text{Sr}$ value in the final solution. Rock exposed at the surface and in the shallow subsurface in the UGB consists of caldera-filling rhyolitic tuffs, post-caldera rhyolite lava flows, and sediments derived from those volcanic rocks. Hildreth and others (1991) reported present-day $^{87}\text{Sr}/^{86}\text{Sr}$ values for Lava Creek Tuff and West Yellowstone Flow ranging from 0.71012 to 0.71393 (appendix B). Although these compositions are all lower than the median value observed in UGB group-1 thermal waters (Figure 2), they are generally consistent with the $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.70980 observed in Firehole River water sampled above UGB in the spring of 2007. Hildreth and others also reported a substantially higher value of 0.71939 for the Biscuit Basin lava flow. Although this lava flow does not have a large surface expression (Christiansen, 2001), it underlies the younger West Yellowstone lava flows and likely forms the main rock unit in the shallow UGB subsurface. Therefore, much of the Sr present in thermal waters constituting group UGB-1 on Figure 2 is likely derived from interactions between infiltration, heated meteoric groundwater, and volcanic rock in the shallow subsurface.

In contrast, thermal waters sampled on October 24, 2007 (group UGB-2 on Figure 2) have very high $^{87}\text{Sr}/^{86}\text{Sr}$ values that cannot be derived by water/rock interaction with any known intracaldera volcanic rocks. The only Yellowstone volcanic rock known to have a present-day $^{87}\text{Sr}/^{86}\text{Sr}$ value higher than the Biscuit Basin lava flow is Member C of the 2.1 Ma Huckleberry Ridge Tuff (outlier

with a value of 0.72702 in Figure 2). This unit is only exposed south of the Yellowstone Plateau, and is the smallest distinct ash-flow subsheet of the Huckleberry Ridge Tuff (Christiansen, 2001). It is not known to be present as coherent subsurface unit within the Yellowstone caldera. Even if it were, samples of thermal groundwater in group UGB-2 have $^{87}\text{Sr}/^{86}\text{Sr}$ values that are substantially higher than even that rhyolitic tuff. Therefore, the high $^{87}\text{Sr}/^{86}\text{Sr}$ values in the UGB-2 group thermal waters record interactions with rocks having a substantially more radiogenic Sr signature.

The most likely source of highly radiogenic Sr are rocks with elevated Rb/Sr ratios that have generated ^{87}Sr by decay of its radioactive parent, ^{87}Rb . Because of the long half-life of ^{87}Rb (4.92×10^{10} a; Steiger and Jäger, 1977), large amounts of time are required to evolve appreciable ^{87}Sr . Rocks that most readily meet these requirements are ancient felsic rocks forming the Precambrian crust underlying the Yellowstone Plateau volcanic field. The nature and distribution of Precambrian rocks buried within the Yellowstone caldera are not known, but uplifted late Archean gneisses and schists constitute basement rocks exposed in the cores of the Gallatin Range and Beartooth Massif in the northern part of the Park (Christiansen, 2001; Sims and others, 2001) and in nearby Teton and Wind River ranges (Love and Christiansen, 1985). Wooden and Mueller (1988) reported present-day Sr-isotopic compositions for Archean-aged andesitic amphibolites, granodiorites, and granites from the Beartooth Mountains that ranged from 0.70617 to 0.78304 (N=30; appendix B). The median $^{87}\text{Sr}/^{86}\text{Sr}$ value for granitic rocks (N=15) is 0.73558. Montgomery and Lytwyn (1984) report present-day $^{87}\text{Sr}/^{86}\text{Sr}$ values for schists, biotite granodiorites, and quartz monzonites from the southern Snowy Block of the Beartooth Mountains that exceed a value of 1.0 (median $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.8128 for 54 whole-rock analyses appendix B). These rocks are capable of supplying radiogenic Sr to groundwater that circulates deeply enough in or adjacent to the caldera to encounter them. None of the possible Paleozoic sedimentary rocks or early Tertiary rocks overlying the crystalline basement are likely to have $^{87}\text{Sr}/^{86}\text{Sr}$ values higher than the Yellowstone rhyolites (Leeman and others, 1977; Feeley and others, 2002; Feeley and Cosca, 2003; Lindsay and Feeley, 2003). Therefore, the data for UGB geyser water samples collected in late 2007 and early 2008 (UGB-2 and UGB-3 groups in Figure 2) require input from a deeply circulating component relative to groundwater that was present earlier in 2007 or later in 2008 (UGB-1 group in Figure 2). More than one end member may contribute to the wide range of elevated $^{87}\text{Sr}/^{86}\text{Sr}$ values observed in the October 2007 geyser samples; however, the maximum observed value from Oblong Geyser implies that at least one radiogenic source has $^{87}\text{Sr}/^{86}\text{Sr}$ substantially higher than 0.7375

Mixing of Shallow and Deep Sources

Sr-isotope data are consistent with conceptual models involving a stratified water column (White and others, 1975; Fournier, 1989; Hurwitz and Lowenstern, 2014). The shallower groundwater component derives its Sr by water/rock interactions with intracaldera rhyolite lavas (primarily the Biscuit Basin lava flow and equivalents) within the UGB subsurface. The groundwater component with elevated $^{87}\text{Sr}/^{86}\text{Sr}$ requires input of radiogenic Sr derived through interactions with Archean rocks, presumably through circulation to greater depth within the caldera. Uniformly low $^{87}\text{Sr}/^{86}\text{Sr}$ compositions present in Group-1 UGB groundwater throughout much of the year and in most of the geysers likely reflects the end member representing the shallow groundwater source. Estimating the end-member composition of the deeper source is more difficult because a similarly uniform range of

high- $^{87}\text{Sr}/^{86}\text{Sr}$ water has not been identified. The much more variable $^{87}\text{Sr}/^{86}\text{Sr}$ values in Group-2 and Group-3 UGB groundwater likely reflects small but variable additions of the deeper source into the geyser plumbing system.

Without better characterization of the radiogenic end-member, it is not possible to use the $^{87}\text{Sr}/^{86}\text{Sr}$ data to quantify mixing proportions of the two sources in any given sample. The fact that chemical concentrations of groundwater at each geyser show only minimal, if any, changes throughout the year (Hurwitz and others, 2012) while $^{87}\text{Sr}/^{86}\text{Sr}$ compositions show very large differences indicates that either the chemistry of shallow and deep water sources are very similar except for their Sr-isotopes, or that the deeper component has an extremely high $^{87}\text{Sr}/^{86}\text{Sr}$ such that only very small additions are needed to alter the $^{87}\text{Sr}/^{86}\text{Sr}$ of the resulting mixed water dramatically. Substantially higher Sr concentrations in the deeper source would also facilitate large changes in $^{87}\text{Sr}/^{86}\text{Sr}$ of the resulting mixture, especially given the low Sr concentrations in the Na-rich, Ca-poor shallow groundwater. Although correlations between $^{87}\text{Sr}/^{86}\text{Sr}$ and Sr concentrations are not observed (Figure 4), cation exchange with zeolitically altered rhyolite after mixing could result in decoupling of the two parameters.

Possible “Seasonal” Variability

Temporal variations in $^{87}\text{Sr}/^{86}\text{Sr}$ may or may not be related to seasonality. Only one 18-month cycle was examined, so it is not clear if the observed signal represents an annual feature in UGB systems or represents a unique hydrologic occurrence.

If the variations observed in this study are related to annual hydrologic cycles, mixing may reflect a response to infiltration and recharge at different times throughout the year. The hydrologic interface between the shallow and deep water sources may fluctuate vertically over time resulting in more or less of the deeper component entering the boiling zone where geyser initiation takes place. Early in the season when snowmelt and meteoric recharge are high, the hydrologic interface may extend well below the boiling depth. When less local recharge becomes available later in the season, the shallow zone may thin, allowing greater access of water from deeper groundwater circulation into geyser reservoirs. Consequently, heated groundwater that erupts under those conditions is likely to have higher $^{87}\text{Sr}/^{86}\text{Sr}$ compositions reflecting a component of water that interacted with Precambrian basement rocks.

If this mechanism is viable, higher radiogenic Sr compositions are more likely to be observed in drier years, whereas wetter years may show no influence from the deeper component. Furthermore, non-erupting pools may be less influenced by influxes from deeper zones compared to geysers that are able to tap deeper reservoirs.

The only samples in the current data set that allow year-to-year differences were those collected in April of 2007 and 2008. Values of $^{87}\text{Sr}/^{86}\text{Sr}$ in discharge from all five geysers were substantially higher in April 2008 compared to those from the previous year (Figure 3A). Snow depth data measured at Old Faithful (National Oceanic and Atmospheric Administration COOP weather station number 486845) for the winter of 2008 was substantially larger than the previous year and remained on the ground at least a month later into spring (solid blue line in Figure 7). Stream discharge

volumes measured in the Firehole River above the UGB were also lower in the winter of 2008 compared to 2007 (dashed red line in Figure 7). Those data imply that less recharge may have been available to replenish shallow groundwater in the UGB when the April 2008 samples were collected. Samples from Old Faithful and Daisy geysers collected in late summer and early fall of 2008 are consistent with ample recharge to the shallow UGB subsurface.

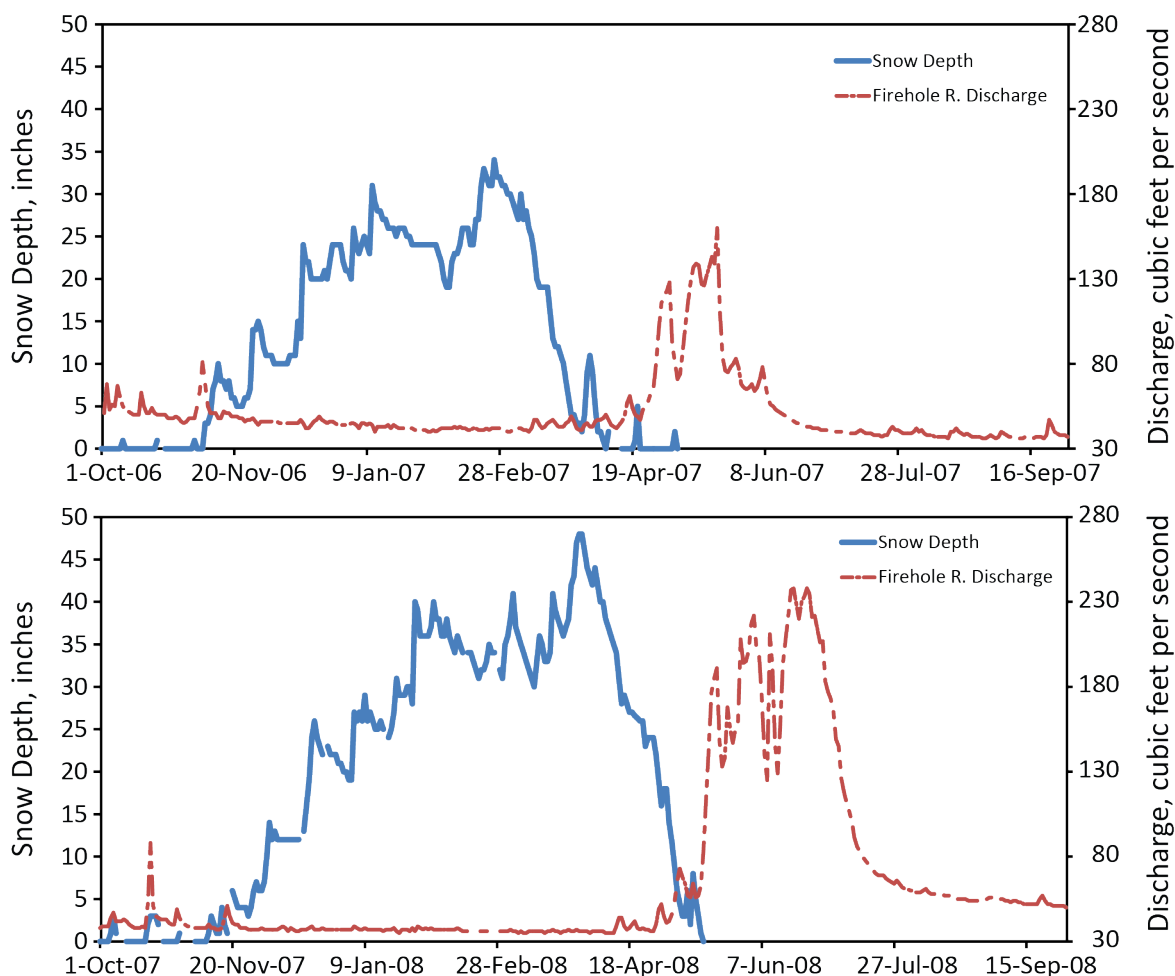


Figure 7: Daily record of snow depth measured at the Old Faithful COOP weather station (#486845) and stream discharge measured at the USGS Firehole River at Old Faithful gage station (#06036805), located at Firehole A sample site, between October 1, 2006 and September 30, 2008. Discharge data available at http://waterdata.usgs.gov/nwis/nwisman/?site_no=06036805&agency_cd=USGS. Snow-depth data available at <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wyoldf>

Alternatively, groundwater with radiogenic signatures identified in October 2007 geyser samples may have been released as a pulse from deeper parts of the hydrothermal system. Hurwitz and Lowenstern (2014) describe a process hypothesized in earlier studies (Fournier, 1999; 2007) where the low-permeability boundary between ductile and brittle rock behavior can be episodically breached in response to local areas of high strain. As a consequence, pore fluids originating in the deep lithostatic-pressure zone may be injected into the shallow hydrostatic-pressure zone where the

associated heat and magmatically derived fluids are dissipated within the advecting hydrothermal system (Dzurisin and others, 1990; Fournier, 1999). Several earthquake swarms have been documented between 2004 and 2010; however, Yellowstone seismic activity in 2007 and 2008 was particularly quiescent (https://volcanoes.usgs.gov/volcanoes/yellowstone/yellowstone_monitoring_48.html). Furthermore, intervals between eruptions measured at all five geysers show no obvious changes that might correspond to the shifts in Sr-isotope compositions identified between September and October 2007 samples (Figure 8). Those data are consistent with constant inputs of heat over this time period despite the Sr evidence that water from deeper sources were tapped in eruptions during the fall of 2007.

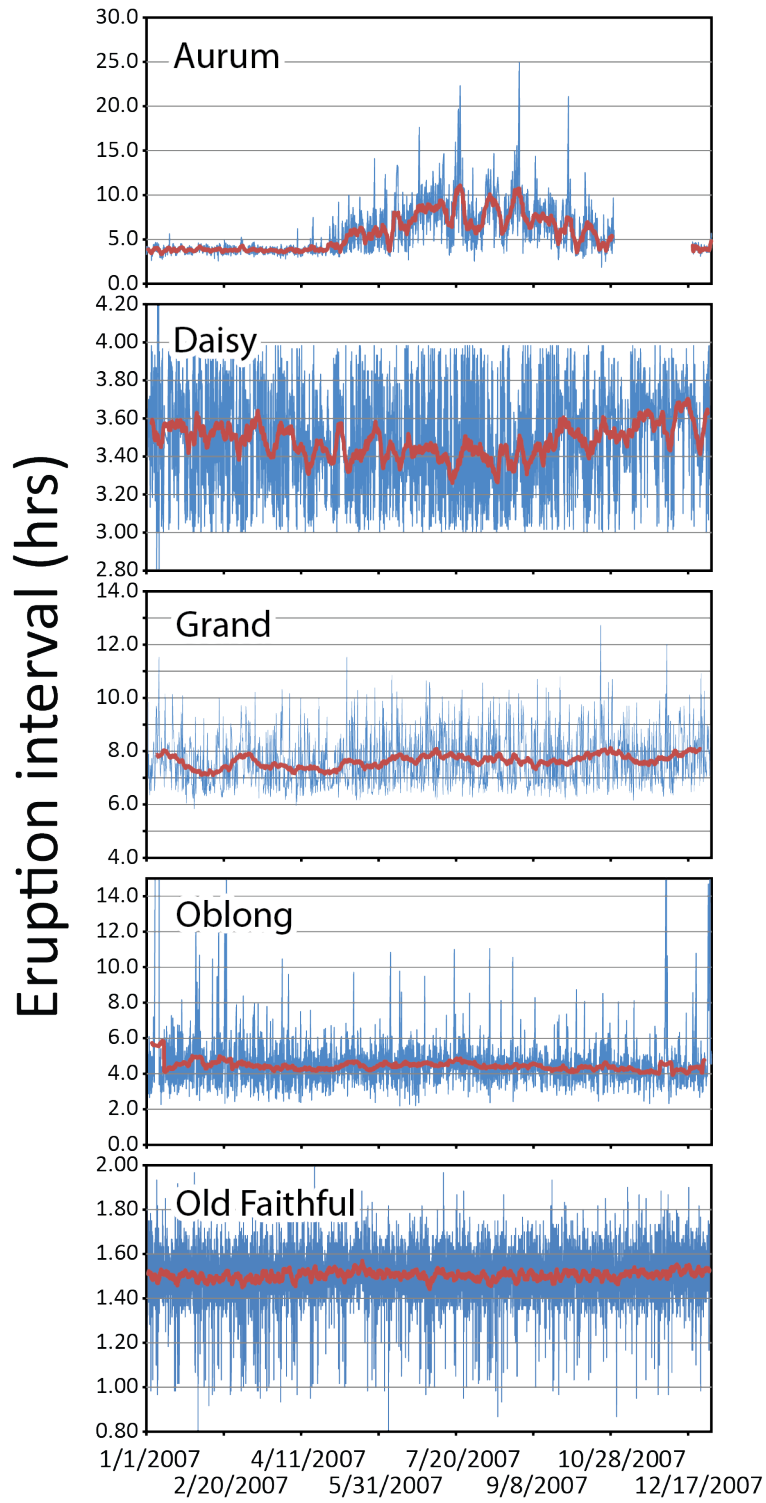


Figure 8: Record of geyser eruption intervals for the five geysers sampled for $^{87}\text{Sr}/^{86}\text{Sr}$ over a one year period in 2007. Blue lines represent individual eruption intervals; red lines represent 40-point running average (24-point for Aurum Geyser). Data are from the Geyser Observation and Study Association (http://www.geyserstudy.org/maps_ugb_submap.aspx).

Geophysics and Imagery

Previous Work in the Park

The Old Faithful Science Review Panel (2014) for Yellowstone National Park summarized the current geological and hydrological understanding of the Upper Geyser Basin (UGB) relevant to managing park resources and defined key knowledge gaps in understanding anthropogenic effects on park resources. Hurwitz and Lowenstern (2014) provide an excellent review of numerous publications that describe a wide range of geophysical methods applied to Yellowstone National Park. Numerous studies have helped elucidate the functioning of Old Faithful Geyser. For example, Rinehart (1969) noted changes in the eruption cycle of Old Faithful Geyser that resulted from the Hebgen Lake Earthquake of 1959. More recently, the mechanics and subsurface properties of Old Faithful Geyser were characterized by seismic methods (Kedar and others, 1996; Vandemeulebrouck and others, 2013), by pressure and temperature measurements (Hutchinson and others, 1997; Kedar and others, 1998), and by analysis of supercritical and supersonic flow (Kieffer, 1989). The following is a brief review of selected publications relevant to subsurface characterization of geothermal areas.

Gibson and Hinman (2013) applied electromagnetic terrain (EMT) conductivity in Sentinel Meadows and Octopus Spring areas in the Lower Geyser Basin (LGB) and concluded that hot springs are fed by conduits largely isolated from shallow groundwater, and that groundwater mixing occurs after hot springs discharge at the surface followed by infiltration of conductive water into the shallow aquifer rather than by upward leakage of deeper groundwater in the shallow subsurface. Karlstrom and others (2013) measured water discharge, acoustic emissions, infrared intensity, and visible and infrared video to quantify the energetics and dynamics of eruptions from the Lone Star Geyser (about 5 km from UGB). These investigators detected oscillations in the conduit water level immediately before and after eruptions and found that water in outflow channels included base flow (i.e., shallow groundwater) as well as thermal water ejected from the geyser cone. In a related study, Vandemeulebrouck and others (2014) examined seismic, tilt, Lidar, thermal, and gravity data from eruption cycles of the Lone Star geyser to identify key subsurface processes throughout the geyser's eruption cycle. Hurwitz and others (2014) studied changes in the intervals between eruptions in UGB and concluded that Daisy Geyser intervals lengthen by evaporation and heat loss in response to large wind storms and cold air. A ground-penetrating-radar survey was conducted in April 2015 in the Old Faithful Geyser area; however, results are not available at the time this report was written (Shaul Hurwitz, pers. comm., May 2015).

Livo and others (2007) used airborne visible and infrared imaging spectrometer (AVIRIS) data to map mineralogy of the land surface and identified hydrothermally altered rock, including a detailed image of UGB. On the basis of alteration minerals identified, these investigators concluded that fluid-channel locations change with time, blocking and unblocking passageways through fluid-leaching action and earthquakes. Overprinting of these alteration minerals suggest that chemical-compositional changes are active. Vaughan and others (2012a; 2012b) used satellite thermal infrared (TIR) data to measure, map, and monitor geothermal activity and, thereby, estimate the radiant geothermal heat flux. A decade-long time-series of TIR data indicated that seasonal cycles dominate

temporal changes. Vaughan and others (2014) provided geospatial data for geothermally heated ground in Yellowstone National Park.

Other regional studies include Kelbert and others (2012), who examined electromagnetic data for the deep crust and mantle of the Yellowstone hot spot and inferred that there is little or no melt in the lower crust and upper mantle directly beneath the Yellowstone caldera. Those conclusions are contrary to earlier regional seismic-refraction studies of the deep crust and mantle in the eastern Snake River Plain that interpreted data to indicate the presence of a low-velocity zone in the lower crust beneath Yellowstone between depths of 20 and 40 km (Priestly and Orcutt, 1982; Peng and Humphreys, 1998). Seismic tomography imaging has been particularly useful for interpreting the presence and extent of crustal magma chambers (Husen and others, 2004; Farrell and others 2014).

Methods Complimentary to Isotope Studies

Several geophysical methods have the potential to provide data capable of better characterizing subsurface material and shallow groundwater flow in UGB. These methods may be particularly effective when coordinated with radiogenic-isotope studies to provide new insights into the functioning of the UGB hydrothermal system.

Electromagnetic Surveys

The Old Faithful Science Review Panel (2014) proposed that airborne electromagnetic (EM) surveys could help characterize flow paths of hydrothermal fluids on a park-wide scale. Alternatively, ground-based EM survey methods are more labor intensive and require physical access to the land surface but have the potential to yield higher resolution data than airborne EM for selected areas of interest. Herein, we describe four ground-based EM survey methods that could provide insights and characterization of the movement of subterranean fluids, which can be related to available airborne EM data. Applying multiple ground-based EM survey methods together in the same location would provide a complimentary dataset that possibly could result in a three-dimensional hydrogeologic framework for an area covering as much as 600 m in length and width. Comparison of ground and airborne EM data would help to interpret airborne EM data in areas not surveyed by ground methods and airborne EM data would help place any detailed ground-based survey data within a regional context. Furthermore, EM methods provide the most benefit if borehole geological data are available to assist in data interpretation. Fortunately, four research boreholes have been drilled in UGB and provide data related to lithology, hydrology, and thermal profiles for the basin (White and others, 1975; Old Faithful Science Review Panel, 2014).

The first EM method is natural potential (also known as self potential, spontaneous potential, or streaming potential), and involves placing two copper-sulfate electrodes connected by a wire into the ground or water source at two locations (Schiaivone and Quarto, 1984; Wanfang and others, 1999; Stevanovic and Dragisic, 1998). The natural, or ambient, electrical potential (i.e., voltage) of the earth between the two electrodes is measured. Natural potential is generated by charged particles, or ions, moving in groundwater. In the absence of molecular diffusion, resulting data provide a measure of the groundwater velocity along the line between the two electrodes, where high potential indicates high velocity. Natural potential has been used in karst aquifers to characterize fast-flowing water in fractures and conduits (Wanfang and others, 1999; Stevanovic and Dragisic, 1998; Jardani

and others, 2006). Schiavone and Quarto (1984) used natural potential to relate upward groundwater flow to basement-rock discontinuities or lithologic boundaries. Wilkinson and others (2005) used natural potential to locate an air filled mine shaft and a back-filled mine shaft.

Natural potential surveys conducted in the UGB could help characterize groundwater movement and define areas of focused flow. Electrode pairs placed at different locations within a study area would map zones of higher or lower EM potential that could be interpreted as zones of greater or lesser flow in the subsurface. Electrodes placed in separate pools and in the ground surrounding the pools might establish patterns that reflect subsurface connectivity (fig. 9).

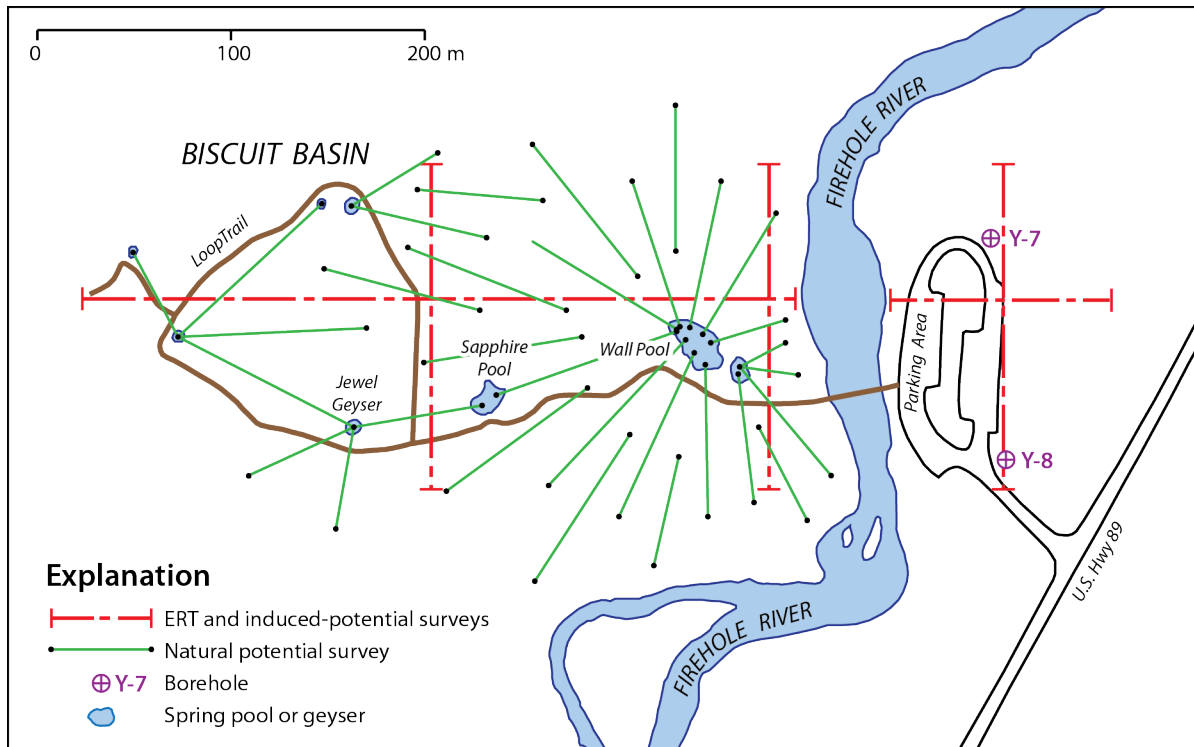


Figure 9: Example plan of a geophysical ground-based survey for Biscuit Basin that consists of three electromagnetic (EM) methods: electrical-resistivity tomography (ERT), induced potential, and natural potential. Borehole data would be used to calibrate and interpret the EM data.

A second EM method is electrical-resistivity tomography (ERT), which consists of an array of electrodes placed in the ground along the length of a connecting wire (Ushijima and Mizunaga, 1989; Telford and others, 1990; Loke and Barker, 1996; Sirieix and others, 2014). A current is injected into a dipole pair of electrodes at one end of the array, and a receiving dipole pair of electrodes measures the resistivity of the earth between the two pairs. The current is injected as a series of quick pulses. Different pairs within a stationary array (Figure 9) can be used to measure different areas and depths along the array. Characteristics of the hydrogeologic material are then inferred from different resistivity measurements. Interpretation of ERT is enhanced when applied in combination with the natural potential method (Wilkinson and others, 2005; Jardani and others, 2006). As such, it is desirable to deploy ERT arrays over the same area surveyed for natural potential.

The third EM method is called induced potential, or induced polarization, which enhances the resolution of the ERT profile (Telford and others, 1990). The same array used for ERT can also be used for induced potential by introducing an electrical potential into the earth between two dipole pairs. Unlike the ERT survey, current is injected for a period of time long enough to electrically polarize the earth. Relaxation of this polarization following the current-injection period is measured. Characteristics of the hydrogeologic material are then inferred from the different rates of relaxation at different locations and depths.

The fourth EM method involves deploying transmitting and receiving coils that are carried by two individuals while measuring the resulting EM signal at different distances of coil separation. Non-invasive ground-EM meters capable of making these measurements have been developed by Geonics Limited (<http://www.geonics.com/html/conductivitymeters.html>) and are marketed as EM34TM meters. This method induces an EM field, and data resolution is dependent on the coil separation distance, with a maximum measurement depth of 60 m. Resulting data measured from ground EM34 surveys would provide subsurface electrical resistivity similar to airborne EM measurements, but at spatial resolutions intermediate between those of airborne EM and the other ground-survey methods previously described. EM34 surveys would be useful to complement, and possibly calibrate, airborne EM data.

Finally, existing data related to shallow ground temperatures could be used to relate ground and airborne EM-survey data to locations of geothermal fluids near the surface. TIR ASTER data show thermal anomalies for the entire park at a 90-m pixel resolution (Vaughan and others, 2014). A number of unpublished reports describe the use of ground-surface temperatures and airborne TIR data to assess the relation and possible effects of park infrastructure on the UGB geothermal system (Heasler and Jaworowski, 2011a, 2011b, 2014a, 2014b; Heasler and others, 2009a, 2009b, 2009c, 2014). Heasler and others (2004) describe a geothermal monitoring plan for the park that includes water levels, temperature, and water-quality for groundwater wells; chloride-flux monitoring in streamflow; thermal-feature inventory; and mapping of thermal areas by remote-sensing.

Gravity Surveys

Gravity-anomaly and microgravity surveys with a portable relative-gravity meter could be helpful in combination with EM-survey data. Relative gravity measurements would be effective for mapping subsurface density anomalies resulting from different geological media and groundwater storage. Those data could enhance subsurface characterization determined using EM-survey data. Data collection for this method would involve measuring relative gravity at numerous locations within a ground-based EM-survey area. Density differences are then derived from relative differences in gravity measurements.

If complications related to ground movement could be overcome, a series of microgravity surveys conducted over time could be used to monitor changes in spatial density anomalies, which could be interpreted as changes in groundwater flow patterns. Microgravity methods also have been used elsewhere to assess temporal changes in density at single locations and, thereby, determine groundwater storage changes and rock porosity (e.g., Koth and Long, 2012).

Ambient-Seismic Surveys

An ambient-seismic survey measures seismic waves in the earth's crust that can be generated by global and local crustal movement, local anthropogenic activity such as vehicles in transit, and wind that causes motion of trees and buildings. An ambient seismic survey can be useful for estimating a bedrock surface overlain by unconsolidated geological material such as glacial deposits. Therefore, this method could potentially provide an estimate of the glacial-deposit thickness in an area such as the UGB. This information could be important for characterizing the framework for fluid movement in the shallow subsurface. The seismic spectrum of the ratio of the horizontal-to-vertical seismic signal indicates the depth to bedrock if this spectrum can be correlated to borehole data for several locations (Delgado and others, 2000). If the bedrock surface is fragmented by weathering or by the effects of hydrothermal fluids, then the ambient-seismic method might not be effective; however, the effectiveness of this method could be easily tested.

Example of a Geophysical Ground Survey

An example of a ground-based geophysical survey involving multiple methods is shown in Figure 9 for illustrative purposes. In this case, multiple water pools in the Biscuit Basin geothermal area are depicted along with potential placements of geophysical measurements. Areas such as this are particularly attractive for initial geophysical studies because access to existing drill core and downhole measurements from nearby boreholes (in this case, Y-7 and Y-8) could provide vertical control for calibration of geophysical measurements. Several natural-potential arrays could be deployed with one electrode in a pool and the other in the ground surrounding the pool to assess movement of shallow groundwater in relation to the pool. Additional deployments with both electrodes in the ground would assess groundwater farther from the pool. Samples of water collected from the pools at the same time that surveys are conducted could be analyzed for radiogenic isotopes to evaluate hydrologic connectivity from a geochemical viewpoint. ERT arrays, initially deployed along perpendicular transects, would provide a general hydrogeological characterization of the surveyed area. Induced-potential data could be collected by using the same array deployment as for ERT. These perpendicular transects would provide two-dimensional datasets for ERT profiles. Microgravity and ambient seismic measurements could be made at locations arranged in a uniform grid with 100-m spacing, for example, across the whole surveyed area. After initial geological characterizations are completed using data from the initial surveys, additional ERT arrays could be deployed along several parallel transects that would provide a three-dimensional hydrogeological framework.

Summary and Conclusions

An initial set of groundwater samples collected from geysers in the UGB exhibit intriguing patterns of Sr-isotope variation over an 18-month period from April 2007 to September 2008. Results can be summarized as follows:

- Sr and U concentrations in thermal waters are low, and only Sr-isotopic compositions could be reliably determined from the available archived samples.
- Water from Old Faithful, Grand, Oblong, and Daisy geysers had a narrow range of $^{87}\text{Sr}/^{86}\text{Sr}$ values during spring and summer of 2007 which are consistent with Sr derived from water/rock interaction with rhyolite flows in the shallow subsurface (specifically, with rocks that have present-day $^{87}\text{Sr}/^{86}\text{Sr}$ values similar to analyses reported for the Biscuit Basin lava flow by Hildreth and others, 1991).
- Groundwater from all of the five geysers showed very large increases in $^{87}\text{Sr}/^{86}\text{Sr}$ values for samples collected in late October 2007. Elevated $^{87}\text{Sr}/^{86}\text{Sr}$ values persisted in most samples from January and early April of 2008, but by summer of 2008, $^{87}\text{Sr}/^{86}\text{Sr}$ returned to the same, lower values observed a year earlier.
- $^{87}\text{Sr}/^{86}\text{Sr}$ compositions are nearly identical in groundwater erupted from Old Faithful and Daisy geysers, despite the fact they had the greatest spatial separation between sites. $^{87}\text{Sr}/^{86}\text{Sr}$ values in groundwater from the intervening geysers show greater deviations.
- Despite the very large shifts in $^{87}\text{Sr}/^{86}\text{Sr}$, similar changes are not reflected in major-ion concentrations or isotopic compositions of water ($\delta^2\text{H}$, $\delta^{18}\text{O}$, ^3H). Conversely, the large geochemical differences observed between different geysers are commonly not apparent in $^{87}\text{Sr}/^{86}\text{Sr}$ data, which are less sensitive to near-surface physical and chemical processes that can dramatically affect concentration data.
- Sr-isotope data are consistent with a stratified hydrothermal system: shallow groundwater acquires its lower $^{87}\text{Sr}/^{86}\text{Sr}$ signature from volcanic rocks in the local subsurface whereas deeper groundwater incorporates substantially more-radiogenic Sr — most likely from felsic Archean rocks underlying the caldera.

Sr-isotope data determined in this study demonstrate their use as a sensitive indicator of groundwater sources and mixing between various hydrothermal reservoirs beneath the UGB. Their potential may be even more effective if combined with geophysical studies designed to determine the hydrodynamic framework of the subsurface in the same area.

Geophysical methods that would be useful for characterization of the UGB subsurface properties and geothermal system include electromagnetic (EM), gravity, and ambient seismic surveys. A suite of ground-based EM methods that could be used in a synergistic combination are natural potential, electrical-resistivity tomography (ERT), induced potential, and a method that uses the Geonics Limited ® EM34 meter. In addition, airborne EM surveys would provide data similar to the EM34

meter, except over larger areas but with lower spatial resolution. Existing thermal data for the shallow subsurface could be used to relate ground and airborne EM survey data to locations of geothermal fluids near the surface. Gravity surveys would be useful for mapping subsurface density anomalies that result from different geological media and groundwater content and, therefore, would enhance subsurface characterization from EM-survey data. Temporal surveys of microgravity, if found to be applicable in this setting, could be used to monitor changes in groundwater storage volumes, which would be helpful in characterizing seasonal or annual groundwater flow patterns. Ambient seismic surveys would be useful for estimating depths to the bedrock surface underlying unconsolidated deposits, which contain shallow groundwater that may be distinct from groundwater flowing through fractured bedrock.

A study that combines radiogenic isotope tracers with geophysical methods has the potential to provide a more detailed characterization of the geothermal workings in the UGB than currently exists. $^{87}\text{Sr}/^{86}\text{Sr}$ data from this scoping study offer a promising means of identifying groundwater sources, quantifying mixing relations between subsurface reservoirs, and evaluating the degree of connectivity between geysers and pools in the UGB without the complications of near-surface chemical processes. Those types of data, combined with information about the geologic framework and focused groundwater flow in the shallow groundwater system gained through a combination of geophysical methods, might help explain mechanisms of flow and mixing, including the dynamics of plumbing systems feeding geysers and pools in the UGB. The effects of seasonal hydrologic change in geyser discharge are also likely to provide a greater understanding of recharge and mixing in the subsurface. New insights gained by such a combined study involving natural isotope tracers and geophysical data would be useful for scientific and public interest and could lead to a better understanding of how park infrastructure may be affecting the geothermal system.

Literature Cited

- Abedini, A.A., 2009. Basalt petrogenesis and evolution in the Yellowstone Plateau Volcanic Field. Thesis, California State University, East Bay, Hayward, CA.
- Barbieri, M., and M., Voltaggio. 1998. Applications of Sr isotopes and U-series radionuclides to the hydrogeology of Sangemini area (Terni, central Italy). *Mineralogica et Petrographica Acta* 41:119–126.
- Cheng, H., R. L. Edwards, C. –C. Shen, V. J. Polyak, Y. Asmerom, J. Woodhead, J. Hellstrom, Y. Wang, X. Kong, C. Spötl, X. Wang, E. C. Alexander Jr. 2013. Improvements in ^{230}Th dating, ^{230}Th and ^{234}U half-life values, and U–Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry. *Earth and Planetary Science Letters* 371–372:82–91.
- Christiansen, R.L. 2001. The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana. U.S. Geological Survey Professional Paper 729–G.
- Delgado, J., C.L. Casado, J. Giner, A. Estevez, A. Cuenca, and S. Molina. 2000. Microtremors as a geophysical exploration tool: Applications and limitations. *Pure Applied Geophysics* 157:1445–1462.
- Doe, B.R., W. P. Leeman, R. L. Christensen, and C. E. Hedge. 1982. Lead and strontium isotopes and related trace elements as genetic tracers in the upper Cenozoic rhyolite-basalt association of the Yellowstone volcanic field. *Journal of Geophysical Research* 87:4785–4806.
- Dogramaci, S., and G. Skrzypek. 2015. Unravelling sources of solutes in groundwater of an ancient landscape in NW Australia using stable Sr, H and O isotopes. *Chemical Geology* 393–394:67–78.
- Drexler, J.Z., J. B. Paces, C. N. Alpers, L. Windham-Myers, L. A. Neymark, T. D. Bullen, and H. E. Taylor. 2014. $^{234}\text{U}/^{238}\text{U}$ and $\delta^{87}\text{Sr}$ in peat as tracers of paleosalinity in the Sacramento-San Joaquin Delta of California, USA. *Applied Geochemistry* 40:164–179.
- Dzurisin, D., J. C. Savage, and R. O. Fournier. 1990. Recent crustal subsidence at Yellowstone Caldera, Wyoming. *Bulletin of Volcanology* 52:247–270.
- Farrell, J., R. B. Smith, S. Husen, and T. Diehl. 2014. Tomography from twenty-six years of seismicity reveals the spatial extent of the Yellowstone crustal magma reservoir extends well beyond the Yellowstone Caldera. *Geophysical Research Letters* 41:3068–3073.
- Faure, G., and T. M. Mensing. 2005. *Isotopes – Principles and Applications*, third edition. John Wiley & Sons, New York.
- Feeley, T.C., and M. A. Cosca. 2003. Time vs. composition trends of magmatism at Sunlight volcano, Absaroka volcanic province, Wyoming. *Geological Society of America Bulletin* 115:714–728.

- Feeley, T.C., M. A. Cosca, and C. R. Lindsay. 2002. Petrogenesis and implications of calc-alkaline cryptic hybrid magmas from Washburn volcano, Absaroka volcanic province, USA. *Journal of Petrology* 43:663–703.
- Fournier, R.O. 1989. Geochemistry and dynamics of the Yellowstone National Park hydrothermal system. *Annual Review of Earth and Planetary Sciences* 17:13–53.
- Fournier, R. O. 1999. Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment. *Economic Geology* 94:1193–1211.
- Fournier, R.O. 2007. Hydrothermal systems and volcano geochemistry. Pages 323–342 in Dzurisin, D., *Volcano Deformation, New Geodetic Monitoring Techniques*. Springer-Praxis Books in Geophysical Sciences, Praxis Publishing Ltd., Chichester, UK.
- Gibson, M. L., and N. W. Hinman. 2013. Mixing of hydrothermal water and groundwater near hot springs, Yellowstone National Park (USA): Hydrology and geochemistry. *Hydrogeology Journal* 21:919–933.
- Heasler H.P., and C. Jaworowski, 2011a. Analyses of Ground Temperatures and Geothermal Gases in the Laurel Dormitory Area at Old Faithful, Yellowstone National Park. Internal report available through Yellowstone National Park archives, 19 p. Accessed October 2015 at <https://irma.nps.gov/App/Reference/Profile/2224397>
- Heasler H.P., and C. Jaworowski, 2011b. Anthropogenic Impacts to the Hydrothermal System within the Old Faithful Area, Yellowstone National Park. Internal report available through Yellowstone National Park archives, 14 p. Accessed October 2015 at <https://irma.nps.gov/App/Reference/Profile/2224398>
- Heasler H.P., and C. Jaworowski, 2014a. Hydrothermal Assessment of the Proposed Old Faithful Inn Sewer Line Route, Yellowstone National Park. Internal report available through Yellowstone National Park archives, 20 p. Accessed October 2015 at <https://irma.nps.gov/App/Reference/Profile/2224399>
- Heasler H.P., and C. Jaworowski. 2014b. July 14 hydrothermal assessment of the proposed Old Faithful Inn sewer line route, Yellowstone National Park. Internal report available through Yellowstone National Park archives, 13 p. Accessed October 2015 at <https://irma.nps.gov/App/Reference/Profile/2224400>
- Heasler H.P., C. Jaworowski, C. Feeney, B. Carr, and D. Foley. 2009a. Preliminary Geothermal Analyses of the Area at the Historic Old Faithful Pub, Yellowstone National Park. Internal report available through Yellowstone National Park archives, 19 p. Accessed October 2015 at <https://irma.nps.gov/App/Reference/Profile/2224396>
- Heasler H.P., C. Jaworowski, C. Feeney, and D. Foley. 2009b. Temperature Measurements at the Historic Old Faithful Pub, Yellowstone National Park. Internal report available through

- Yellowstone National Park archives, 8 p. Accessed October 2015 at <https://irma.nps.gov/App/Reference/Profile/2224395>
- Heasler, H. P., C. Jaworowski, and D. Foley. 2009c. Geothermal systems and monitoring hydrothermal features. Pages 105–140 *in* R. Young and L. Norby, editors, *Geological Monitoring*. Geological Society of America, Boulder, Colorado.
- Heasler HP., C. Jaworowski, and D. Mahony, 2014. Hydrothermal Assessment of Proposed Old Faithful Inn Sewer Line Routes, Yellowstone National Park. Internal report available through Yellowstone National Park archives, 34 p. Accessed October 2015 at <https://irma.nps.gov/App/Reference/Profile/2224401>
- Heasler, H., C. Jaworowski, and D. Susong. 2004. A geothermal monitoring plan for Yellowstone National Park. Internal report available through Yellowstone National Park archives, 22 p. Accessed October 2015 at: <https://irma.nps.gov/App/Reference/Profile/2224394>
- Hildreth, W., A. N. Halliday, and R. L. Christiansen. 1991. Isotopic and chemical evidence concerning the genesis and contamination of basaltic and rhyolitic magma beneath the Yellowstone Plateau Volcanic Field. *Journal of Petrology* 32:63–138.
- Hurwitz, S., A. G. Hunt, and W.C. Evans. 2012. Temporal variations of geyser water chemistry in the Upper Geyser Basin, Yellowstone National Park, USA. *Geochemistry, Geophysics, Geosystems* 13:Q12005.
- Hurwitz, S., A. Kumar, R. Taylor, and H. Heasler. 2008. Climate-induced variations of geyser periodicity in Yellowstone National Park, USA. *Geology* 36:451–454.
- Hurwitz, S., and J. B. Lowenstern. 2014. Dynamics of the Yellowstone hydrothermal system. *Reviews of Geophysics* 51:375–411.
- Hurwitz, S., J. B. Lowenstern, and H. Heasler. 2007. Spatial and temporal geochemical trends in the hydrothermal system of Yellowstone National Park—Inferences from river solute fluxes. *Journal of Volcanology and Geothermal Research* 162:149–171.
- Hurwitz, S., R.A. Sohn, K. Luttrell, and M. Manga. 2014. Triggering and modulation of geyser eruptions in Yellowstone National Park by earthquakes, earth tides, and weather: *Journal of Geophysical Research: Solid Earth* 119(3):1718–1737.
- Husen, S., R. B. Smith, and G. P. Waite. 2004. Evidence for gas and magmatic sources beneath the Yellowstone volcanic field from seismic tomographic imaging. *Journal of Volcanology and Geothermal Resources* 131:397–410.
- Hutchinson, R. A., J. A. Westphal, and S. W. Kieffer. 1997. In situ observations of Old Faithful Geyser. *Geology* 25:875–878.

- Jaffey, A.H., K.F. Flynn, L.E. Glendenin, W.C. Bentley, and A.M. Essling. 1971. Precision measurements of half-lives and specific activities of ^{235}U and ^{238}U . *Physical Review C* 4:1889–1906.
- Jardani, A., J. P. Dupont, and A. Revil. 2006. Self-potential signals associated with preferential groundwater flow pathways in sinkholes. *Journal of Geophysical Research* 111:B09204.
- Karlstrom, L., S. Hurwitz, R. A. Sohn, J. Vandemeulebrouck, F. Murphy, M. L. Rudolph, M. J. S. Johnston, M. Manga, and R. B. McCleskey. 2013. Eruptions at Lone Star Geyser, Yellowstone National Park, USA, Part 1: Energetics and eruption dynamics. *Journal of Geophysical Research, Solid Earth* 118:1–15.
- Kedar, S., B. Sturtevant, and H. Kanamori. 1996. The origin of harmonic tremor at Old Faithful Geyser. *Nature* 379:708–711.
- Kedar, S., H. Kanamori, and B. Sturtevant. 1998. Bubble collapse as the source of tremor at Old Faithful Geyser. *Journal of Geophysical Research* 103:24,283–224,299.
- Kelbert, A., G. D. Egbert, and C. deGroot-Hedlin. 2012. Crust and upper mantle electrical conductivity beneath the Yellowstone hotspot track. *Geology* 40:447–450.
- Kieffer, S. W. 1989. Geologic nozzles. *Reviews of Geophysics* 27:3–38.
- Koth, K.R., and A.J. Long. 2012. Microgravity methods for characterization of groundwater storage changes and aquifer properties in the karstic Madison Aquifer in the Black Hills of South Dakota. U.S. Geological Survey Scientific Investigations Report 2012-5158.
- Leeman, W.P., B. R. Doe, and J. F. Whelan. 1977. Radiogenic and stable isotope studies of hot-spring deposits in Yellowstone National Park and their genetic implications. *Geochemical Journal* 11:65–74.
- Lindsay, C. R., and T. C. Feeley. 2003. Magmagenesis at the Eocene Electric Peak–Sepulcher Mountain complex, Absaroka Volcanic Province, USA. *Lithos* 67:53–76.
- Livo, K. E., F. A. Kruse, R. N. Clark, R. F. Kokaly, and W. C. P. Shanks, III. 2007. Hydrothermally altered rock and hot-spring deposits at Yellowstone National Park—Characterized using airborne visible- and infrared-spectroscopy data. Pages 491–507 in L. A. Morgan, editor. *Integrated Geoscience Studies in the Greater Yellowstone Area: Volcanic, Hydrothermal and Tectonic Processes in the Yellowstone Geocosystem*, U. S. Geological Survey Professional Paper 1717.
- Loke, M. H., and R. D. Barker. 1996. Practical techniques for 3D resistivity surveys and data inversion. *Geophysical Prospecting* 44:499–523.
- Love, J. D., and A. C. Christiansen. 1985. Geologic map of Wyoming. U.S. Geological Survey. http://ngmdb.usgs.gov/Prodesc/proddesc_16366.htm

- Ludwig, K.R., A. R. Wallace, and K. R. Simmons. 1985. The Schwartzwalder uranium deposit, II: age of uranium mineralization and Pb-isotope constraints on genesis. *Economic Geology* 80:1858–1871.
- McArthur, J.M, R. J. Howarth, and R. R. Bailey. 2001. Strontium isotope stratigraphy: LOWESS version 3: Best fit to the marine Sr-isotope curve for 0–509 Ma and accompanying look-up table for deriving numerical age. *Journal of Geology* 109:155–170.
- McArthur, J. M., D. Rio, F. Massari, D. Castradori, T. R. Bailey, M. Thirlwall, and S. Houghton. 2006. A revised Pleocene record for marine- $^{87}\text{Sr}/^{86}\text{Sr}$ used to date an interglacial event recorded in the Cockburn Island Formation, Antarctic Peninsula. *Palaeogeography, Palaeoclimatology, Palaeoecology* 242:126–136.
- McCleskey, R. B., L. E. Clor, J. B. Lowenstern, W. C. Evans, and D. K. Nordstrom. 2012. Solute and geothermal flux monitoring using electrical conductivity in the Madison, Firehole and Gibbon Rivers, Yellowstone National Park. *Applied Geochemistry* 27:2,370–2,381.
- Montgomery, C. W., and J. N. Lytwyn. 1984. Rb-Sr systematics and ages of principal Precambrian lithologies in the South Snowy Block, Beartooth Mountains. *Journal of Geology* 92:103–112.
- NPS Stats, 2015. Annual Park Recreation Visitation (1904 – Last Calendar Year). URL accessed April 2015 at [https://irma.nps.gov/Stats/SSRSReports/Park%20Specific%20Reports/Annual%20Park%20Recreation%20Visitation%20\(1904%20-%20Last%20Calendar%20Year\)?Park=YELL](https://irma.nps.gov/Stats/SSRSReports/Park%20Specific%20Reports/Annual%20Park%20Recreation%20Visitation%20(1904%20-%20Last%20Calendar%20Year)?Park=YELL)
- Old Faithful Science Review Panel (OFSRP). 2014. Hydrogeology of the Old Faithful area, Yellowstone National Park, Wyoming, and its relevance to natural resources and infrastructure. U.S. Geological Survey Open-File Report 2014–1058.
- Paces, J.B., and F. C. Wurster. 2014. Natural uranium and strontium isotope tracers of water sources and surface water–groundwater interactions in arid wetlands — Pahrnagat Valley, Nevada, USA. *Journal of Hydrology* 517:213–225.
- Peng, X., and E. D. Humphreys. 1998. Crustal velocity structure across the eastern Snake River plain and the Yellowstone Swell. *Journal of Geophysical Research, Solid Earth and Planets* 103:7171–7186.
- Priestley, K., and J. Orcutt. 1982. Extremal travel time inversion of explosion seismology data from the Eastern Snake River Plain, Idaho. *Journal of Geophysical Research* 87:2634–2642.
- Rinehart, J. S. 1969. Old Faithful geyser performance 1870 to 1966. *Bulletin of Volcanology* 33:153–163.
- Schiavone, D., and R. Quarto. 1984. Self-potential prospecting in the study of water movements. *Geoexploration* 22:47–58.

- Sims, P.K., C. A. Finn, and V. L. Rystrom. 2001. Preliminary Precambrian basement map showing geologic—geophysical domains, Wyoming. U.S. Geological Survey Open-File Report 2001-199.
- Sirieix, C., J. Riss, F. Rey, F. Prétou, and R. Lastennet. 2014. Electrical resistivity tomography to characterize a karstic Vauclisian spring: Fontaine d'Orbe (Pyrénées, France). *Hydrogeology Journal* 22:911-924.
- Steiger, R.H., and E. Jäger, 1977. Subcommittee on geochronology: convention on the use of decay constants in geo- and cosmochemistry. *Earth and Planetary Science Letters* 36:359–362.
- Stevanovic, Z., and V. Dragisic. 1998. An example of identifying karst groundwater flow. *Environmental Geology* 35:241–244.
- Sturchio, N. C., K. L. Pierce, M. T. Murrell, and M. L. Sorey. 1994. Uranium-series ages of travertines and timing of the last glaciation in the northern Yellowstone area, Wyoming—Montana. *Quaternary Research* 41:265–277.
- Telford, W. M., L. P. Geldart, and R. E. Sheriff. 1990. *Applied Geophysics* (Second edition). Cambridge University Press, Cambridge, UK.
- Ushijima, K., and H. Mizunaga. 1989. Detection of cavities by the mise-a-la-masse and Pole-dipole resistivity surveys. Conference on Today's Technology for the Mining and Metallurgical Industries / Papers Presented at the MMIJ/IMM Joint Symposium. Kyoto, Japan, October 2–4, 1989.
- Vandemeulebrouck, J., P. Roux, and E. Cros. 2013. The plumbing of Old Faithful Geyser revealed by hydrothermal tremor. *Geophysical Research Letters* 40:1989–1993.
- Vandemeulebrouck, J., R. A. Sohn, M. L. Rudolph, S. Hurwitz, M. Manga, M. J. S. Johnston, S. A. Soule, D. McPhee, J. M. G. Glen, L. Karlstrom, and F. Murphy. 2014. Eruptions at Lone Star Geyser, Yellowstone National Park, USA, Part 2: Constraints on Subsurface Dynamics. *Journal of Geophysical Research, Solid Earth* 119:1–20.
- Vaughan, R. G., J. B. Lowenstern, L. P. Keszthelyi, C. Jaworowski, and H. Heasler. 2012a. Mapping Temperature and Radiant Geothermal Heat Flux Anomalies in the Yellowstone Geothermal System Using ASTER Thermal Infrared Data. *Geothermal Resources Council Transactions* 36:1403–1410.
- Vaughan, R. G., L. P. Keszthelyi, J. B. Lowenstern, C. Jaworowski, and H. Heasler. 2012b. Use of ASTER and MODIS thermal infrared data to quantify heat flow and hydrothermal change at Yellowstone National Park. *Journal of Volcanology and Geothermal Research* 233–234:72–89.
- Vaughan, R. G., H. Heasler, C. Jaworowski, J. B. Lowenstern, and L. P. Keszthelyi. 2014. Provisional maps of thermal areas in Yellowstone National Park, based on satellite thermal infrared imaging and field observations. U.S. Geological Survey Scientific Investigations Report 2014–5137.

- Wanfang, Z., B. F. Beck, and J. B. Stephenson. 1999. Investigation of groundwater flow in karst areas using component separation of natural potential measurements. *Environmental Geology* 37:19–25.
- Wilkinson, P. B., J. E. Chambers, P. I. Meldrum, R. D. Ogilvy, C. J. Mellor, and S. Caunt. 2005. A comparison of self-potential tomography with electrical resistivity tomography for the detection of abandoned mineshafts. *Journal of Environmental and Engineering Geophysics* 10:381–389.
- White, D. E., R. O. Fournier, J. P. Muffler, and A. H. Truesdell. 1975. Physical results of research drilling in the thermal areas of Yellowstone National Park, Wyoming. U.S. Geological Survey Professional Paper 892.
- Wooden, J. L. and P. A. Mueller. 1988. Pb, Sr, and Nd isotopic compositions of a suite of late Archean, igneous rocks, eastern Beartooth Mountains: Implications for crust-mantle evolution. *Earth and Planetary Science Letters* 87:59–72.

Appendix A: Analytical Methods

All data including strontium and uranium concentrations determined by isotope dilution and $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{234}\text{U}/^{238}\text{U}$ compositions were determined by thermal ionization mass spectrometry at USGS laboratories in Denver, CO. Water was transferred from the original high-density polyethylene bottles to 15-ml Teflon[®] PFA vials, where it was evaporated, in several stages if necessary, and taken to dryness. Small amounts of a double-spike (highly enriched ^{236}U and ^{233}U) tracer solution were added to a limited number of samples that were analyzed for U prior to evaporation. Separate aliquots between 0.03 and 0.30 g from the original water samples were separately weighed and spiked with known amounts of tracer solution enriched in ^{84}Sr and were processed separately to determine Sr concentrations by isotope dilution.

Both Sr and U isotopic compositions were determined from the same starting solution using two separate, but piggy-backed, ion-exchange columns. Ion chromatography relied on AG1 $\times$ 8 (200-400 mesh) in columns used for U and Sr-Spec[™] (50-100 μm) in columns used for Sr. Evaporated salts were dissolved in 7M nitric acid and loaded onto U columns, which dripped directly into Sr columns. After washing with $\sim$ 4 resin volumes of 7M nitric acid, columns were separated and processed independently (an additional $\sim$ 6 resin volumes of 6M hydrochloric acid for U and a total of $\sim$ 35 resin volumes of 7M nitric acid for Sr). U and Sr were eluted into separate vials using 0.05M nitric acid. The same columns and resin used to purify Sr for isotope compositions were used to process the spiked-Sr aliquots for isotope dilution analyses.

Purified Sr salts were loaded onto single rhenium filaments on top of an initial load of tantalum oxide used as an activator. Both Sr and U were run on a Thermo Finnigan Triton[™] multi-collector, thermal ionization, isotope ratio mass spectrometer. Sr isotope ratios were determined in multi-dynamic, triple-jump analytical mode, and the resulting $^{87}\text{Sr}/^{86}\text{Sr}$ atomic ratios were corrected for mass fractionation using $^{88}\text{Sr}/^{86}\text{Sr}$ measured during the same run. Fractionation-corrected $^{87}\text{Sr}/^{86}\text{Sr}$ values determined on replicate analyses of the National Institute of Standards and Technology Sr-isotope standard, NIST 987, yielded a mean value of 0.7102487 ± 0.0000065 ($\pm 2 \times$ standard deviation [SD] for 160 values) which is statistically identical to the accepted value of 0.710248 (McArthur and others, 2001). Given this agreement, values of $^{87}\text{Sr}/^{86}\text{Sr}$ reported for unknowns require little correction for inter-laboratory bias. Nevertheless, measured $^{87}\text{Sr}/^{86}\text{Sr}$ values were corrected by adjusting the unknown value by the same amount required to force the mean value obtained for NIST 987 analyzed along with the samples to the accepted value. Replicate analyses of Sr in the modern-marine carbonate standard, EN-1, run during this same time gave a mean value of 0.709174 ± 0.000009 ($\pm 2 \times$ SD for 73 analyses) which is identical to the accepted value of 0.7091741 ± 0.0000024 for modern seawater (McArthur and others, 2006). Analytical errors for $^{87}\text{Sr}/^{86}\text{Sr}$ values used in this report represent 95% confidence levels ($\sim 2\sigma$) and include within-run uncertainties and external error based on replicate analyses of standards. Sr concentrations determined by isotope-dilution were calculated from measured $^{84}\text{Sr}/^{86}\text{Sr}$ and the known amounts of ^{84}Sr added as spike. Uncertainties for concentration are limited by calibration of the spike concentration and are estimated to be better than 0.5 percent.

Purified U salts were loaded onto rhenium filaments that formed the evaporation side of double filament assemblies. U isotope ratios were determined in multi-dynamic peak-hopping mode using a single secondary electron multiplier. Ratios were corrected for mass fractionation using the known $^{236}\text{U}/^{233}\text{U}$ isotope ratio in an added double spike. Replicate analyses of U-isotope standard (NIST 4321B run between April 2014 and March 2015) yielded a mean $^{234}\text{U}/^{235}\text{U}$ atomic ratio of 0.0072767 ± 0.0000064 ($\pm 0.088\%$ based on $2 \times \text{SD}$ for 54 analyses), which is slightly lower than the accepted value (0.007294 ± 0.000028). Corrections for instrument bias were made by normalizing $^{234}\text{U}/^{235}\text{U}$ values measured for unknowns by the same factor needed to adjust measured $^{234}\text{U}/^{235}\text{U}$ ratios for the SRM 4321B standard run in the same magazine to the accepted value. Measured $^{234}\text{U}/^{235}\text{U}$ atomic ratios were converted to $^{234}\text{U}/^{238}\text{U}$ activity ratios (AR) using decay constants published by Cheng and others (2013) ($\lambda_{234} = 2.82206 \times 10^{-6} \text{ yr}^{-1}$) and Jaffey and others (1971) ($\lambda_{238} = 1.55125 \times 10^{-10} \text{ yr}^{-1}$), assuming that all U has an atomic $^{238}\text{U}/^{235}\text{U}$ composition of 137.88 (Steiger and Jäger, 1977). Replicate analyses of solutions of 69 million year old U ore (Ludwig and others, 1985) in radioactive secular equilibrium analyzed in this manner yielded a $^{234}\text{U}/^{238}\text{U}$ AR value of 1.0003 ± 0.0040 ($2 \times \text{SD}$ for 24 analyses). Analytical errors for measured $^{234}\text{U}/^{238}\text{U}$ AR values are given at the 95% confidence level ($2 \times \text{SD}$) and include contributions from within-run uncertainties (counting statistics) plus uncertainties propagated from blank, spike, and mass fractionation corrections, as well as external error derived from multiple analyses of the U isotope standard.

Appendix B: Compilation of Sr-isotope Data for Rocks

Published Sr-isotope data (present day) for rocks that may be present in the Yellowstone caldera subsurface

Sample ID	Unit name or geographic area	Rock type	Rb (ppm)	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr, present day	±2σ	Ref. No.*
Quaternary rhyolite/basalt association, Yellowstone Plateau Volcanic Field							
78YH-13	Snake River Butte flow	Rhyolite	166.4	53.65	0.71023	0.00004	1
65YR-3A	Huckleberry Ridge Tuff A	Rhyolite	186.0	21.42	0.71242	0.00003	1
74IP-149B	Huckleberry Ridge Tuff B	Rhyolite	112.9	87.59	0.70991	0.00005	1
7YC-194	Huckleberry Ridge Tuff C	Rhyolite	142.5	67.74	0.72702	0.00002	1
78YH-10A	Blue Creek flow	Rhyolite	186.6	16.00	0.71804	0.00004	1
8YC-460A	Mesa Falls Tuff	Rhyolite	178.0	32.54	0.70897	0.00003	1
OYC-563	Lewis Canyon Rhyolite	Rhyolite	163.9	51.19	0.71413	0.00002	1
8YC-413	Lava Creek Tuff A	Rhyolite	272.2	2.24	0.71393	0.00008	1
9YC-520A	Lava Creek Tuff B	Rhyolite	140.0	30.19	0.71012	0.00003	1
9YC-496A	Canyon flow	Rhyolite	178.9	83.95	0.71612	0.00003	1
78YH-54	Biscuit Basin flow	Rhyolite	190.9	48.28	0.71939	0.00003	1
6YC-43B	Cougar Creek flow	Rhyolite	211.2	16.01	0.71218	0.00002	1
74Y-176	Riverside flow	Rhyolite	195.9	2.88	0.71276	0.00014	1
6YC-137	Obsidian Cliff flow	Rhyolite	238.8	2.41	0.71531	0.00005	1
78YH-43	Landmark dome	Rhyolite	250.2	1.75	0.71322	0.00033	1
Oye-608	Willow Park dome	Rhyolite	155.7	34.03	0.71258	0.00006	1
81Y-219	Gibbon River flow	Rhyolite	348.9	0.49	0.7173	0.00033	1
78YH-67	Dry Creek flow	Rhyolite	185.1	13.36	0.7098	0.00018	1
6YC-169	West Yellowstone flow	Rhyolite	183.6	6.12	0.71065	0.00004	1
OYC-567	Pitchstone Plateau flow	Rhyolite	191.4	3.02	0.71087	0.00012	1
OYC-635	Junction Butte Basalt Overhanging Cliff flow	Basalt	25.3	364.4	0.70707	0.00002	1
74IP-77	Basalt of Teton River at Teton River	Basalt	5.00	211.0	0.70553	0.00001	1
8YC-475	Basalt of The Narrows lowest flow	Basalt	28.20	407.9	0.70424	0.00005	1

Sample ID	Unit name or geographic area	Rock type	Rb (ppm)	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr, present day	±2σ	Ref. No.*
OYC-638	Basalt of The Narrows topmost flow	Basalt	24.60	625.0	0.70377	0.00002	1
6YC-144	Warm River Basalt at Warm River	Basalt	1.39	281.9	0.70565	0.00002	1
OYC-640A	Undine Falls Basalt at Undine Falls	Basalt	6.77	410.6	0.70513	0.00004	1
6YC-14	Falls River Basalt at Gibson Mdw	Basalt	6.22	251.1	0.70886	0.00003	1
81YH-89	Falls River Basalt at Gibson Mdw	Basalt	5.45	253.9	0.70885	0.00002	1
78YH-31	Falls River Basalt SE of Marysville	Basalt	10.90	292.1	0.70681	0.00007	1
6YC-133	Swan Lake Flat Basalt Sheepeater flow	Basalt	8.46	385.0	0.70597	0.00004	1
6YC-139	Madison River Basalt at Cougar Creek	Basalt	27.30	293.9	0.70659	0.00002	1
6YC-142	Gerrit Basalt hwy above U. Mesa Falls	Basalt	4.89	189.1	0.70601	0.00002	1
74IP-45	Gerrit Basalt Ripley Butte flow	Basalt	3.16	219.1	0.70675	0.00003	1
74IP-86	Gerrit Basalt Hatchery Butte flow	Basalt	13.71	305.2	0.70711	0.00002	1
78YH-38	Gerrit Basalt Box Canyon flow	Basalt	5.00	247.1	0.70873	0.00002	1
74IP-44	Gerrit Basalt Eccles Butte flow	Basalt	4.00	189.0	0.70698	0.00002	1
74IP-88	Gerrit Basalt SE of Pole Bridge Camp	Basalt	1.00	220.0	0.70628	0.00002	1
8YC-471C	Osprey Basalt at Undine Falls	Basalt	8.854	391.2	0.70578	0.00002	1
AIP-01-05	Gerrit Basalt	Basalt	4.15	249.1	0.70874	0.00010	2
AIP-02-05	Gerrit Basalt	Basalt	1.93	342.9	0.70515	0.00010	2
AIP-03-05	Gerrit Basalt	Basalt	10.75	271.9	0.70736	0.00010	2
AIP-04-05	Gerrit Basalt	Basalt	1.03	173.8	0.70683	0.00010	2
AYS-05-05	Osprey Basalt	Basalt	14.60	342.3	0.70756	0.00010	2
AYS-06-05	Osprey Basalt	Basalt	3.19	325.6	0.70552	0.00010	2
AYS-07-05	Madison River Basalt	Basalt	25.05	285.8	0.70678	0.00010	2
AYS-08-05	Madison River Basalt	Basalt	5.61	273.9	0.70751	0.00010	2
AIP-09-05	Falls River	Basalt	8.64	280.2	0.70868	0.00010	2
AYS-10-05	Swan Lake Flat	Basalt	5.51	372.0	0.70597	0.00010	2
AYS-11-05	Swan Lake Flat	Basalt	4.46	335.2	0.70525	0.00010	2
AYS-12-05	Swan Lake Flat	Basalt	2.59	237.3	0.70560	0.00010	2
AYS-13-05	Swan Lake Flat	Basalt	7.91	406.0	0.70584	0.00010	2

Sample ID	Unit name or geographic area	Rock type	Rb (ppm)	Sr (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$, present day	$\pm 2\sigma$	Ref. No.*
AYS-14-05	Swan Lake Flat	Basalt	7.46	408.8	0.70595	0.00010	2
AYS-15-05	Swan Lake Flat	Basalt	4.50	361.0	0.70559	0.00010	2
AYS-16-05	Undline Falls Basalt	Basalt	4.22	446.3	0.70544	0.00010	2
AYS-18-05	Undline Falls Basalt	Basalt	8.31	410.8	0.70553	0.00010	2
AYS-19-05	Undline Falls Basalt	Basalt	5.72	425.6	0.70526	0.00010	2
AIP-20-05	Warm River Basalt	Basalt	2.79	169.1	0.70600	0.00010	2
AIP-21-05	Warm River Basalt	Basalt	3.06	247.2	0.70612	0.00010	2
AYS-22-05	Basalt of the Narrows	Basalt	17.74	618.7	0.70369	0.00010	2
AYS-23-05	Basalt of the Narrows	Basalt	39.19	398.1	0.70791	0.00010	2
AYS-24-05	Junction Butte Basalt	Basalt	41.36	392.3	0.70792	0.00010	2
AYS-25-05	Junction Butte Basalt	Basalt	4.59	368.8	0.70559	0.00010	2
AIP-26-05	Snake River Basalt	Basalt	3.56	288.8	0.70571	0.00010	2
AIP-27-05	Snake River Basalt	Basalt	11.77	309.9	0.70570	0.00010	2
AIP-28-05	Snake River Basalt	Basalt	7.51	269.8	0.70683	0.00010	2
Early Tertiary Volcanic Rocks, Absaroka volcanic province							
SM9712	Sepulcher Mountain	Basaltic andesite	36	647	0.70665	0.00001	3
SM9709	Sepulcher Mountain	Andesite	45	1016	0.707283	0.00001	3
SM9716	Sepulcher Mountain	Andesite	37	718	0.707131	0.00001	3
SM9725	Sepulcher Mountain	Andesite	35	837	0.707017	0.00001	3
SM9704	Sepulcher Mountain	Andesite	42	1410	0.707217	0.00001	3
SM9814	Sepulcher Mountain	Dacite	46	768	0.707568	0.00001	3
SM9706	Sepulcher Mountain	Rhyolite	48	631	0.707673	0.00001	3
EP9847	Electric Peak	Basalt	16	388	0.707405	0.00001	3
EP9716	Electric Peak	Andesite	38	805	0.706915	0.00001	3
EP9715	Electric Peak	Andesite	41	764	0.707177	0.00001	3
EP9718	Electric Peak	Rhyolite	49	763	0.707574	0.00001	3
EP9832	Electric Peak	Rhyolite	70	333	0.70771	0.00001	3

Sample ID	Unit name or geographic area	Rock type	Rb (ppm)	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr, present day	±2σ	Ref. No.*
MW9713	SW Washburn Range	Basaltic andesite	22	463	0.70585	0.00002	4
MW9714	SW Washburn Range	Basaltic andesite	23	1008	0.70573	0.00002	4
MW9710	SW Washburn Range	Dacite	45	782	0.70632	0.00002	4
MW974	SW Washburn Range	Dacite	81	510	0.70826	0.00002	4
MW9730	Mt. Washburn	Basaltic andesite	33	841	0.70596	0.00002	4
MW9731	Mt. Washburn	Andesite	38	953	0.70631	0.00002	4
MW929	Mt. Washburn	Andesite	38	694	0.70711	0.00002	4
MW9743	Mt. Washburn	Andesite	46	1025	0.70614	0.00002	4
MW9746	Sulphur Creek Stock	Andesite	38	799	0.70636	0.00002	4
SV97-25	Sunlight volcano	Trachyandesite	39	1114	0.70441	0.00002	5
SV97-6	Sunlight volcano	Latite	113	1194	0.70447	0.00002	5
SV98-9	Sunlight volcano	Trachyandesite	115	1678	0.70494	0.00002	5
SV98-3	Sunlight volcano	Trachyandesite	74	979	0.70523	0.00002	5
SV98-5	Sunlight volcano	Trachyandesite	153	961	0.70529	0.00002	5
SV98-2	Sunlight volcano	Trachyandesite	134	1410	0.70516	0.00002	5
SV97-39	Sunlight volcano	Trachyandesite	89	2107	0.70529	0.00002	5
SV97-38	Sunlight volcano	Trachyte	125	2167	0.70433	0.00002	5
SV98-11	Sunlight volcano	Trachyandesite	174	1236	0.70542	0.00002	5
SV98-17	Sunlight volcano	Latite	98	1319	0.70469	0.00002	5
SV98-12	Sunlight volcano	Latite	140	1244	0.70496	0.00002	5
SV97-33	Sunlight volcano	Trachyte	121	2115	0.70438	0.00002	5
Late Archean rocks, Beartooth Uplift, Montana/Wyoming							
BTR-3	Eastern Beartooth Plateau Block	Andesitic amphibolites			0.70708	0.0001	6
BTR-12	Eastern Beartooth Plateau Block	Andesitic amphibolites			0.72323	0.0001	6
BTR-25	Eastern Beartooth Plateau Block	Andesitic amphibolites			0.71496	0.0001	6
BTR-26	Eastern Beartooth Plateau Block	Andesitic amphibolites			0.71108	0.0001	6
BTR-34	Eastern Beartooth Plateau Block	Andesitic amphibolites			0.7246	0.0001	6

Sample ID	Unit name or geographic area	Rock type	Rb (ppm)	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr, present day	±2σ	Ref. No.*
BTR-40	Eastern Beartooth Plateau Block	Andesitic amphibolites			0.71077	0.0001	6
BTR-36	Eastern Beartooth Plateau Block	Andesitic amphibolites			0.74611	0.0001	6
BTR-43	Eastern Beartooth Plateau Block	Andesitic amphibolites			0.70915	0.0001	6
BTR-56	Eastern Beartooth Plateau Block	Andesitic amphibolites			0.71144	0.0001	6
BTR-58	Eastern Beartooth Plateau Block	Andesitic amphibolites			0.71976	0.0001	6
BTR-7	Eastern Beartooth Plateau Block	Granodiorite			0.77351	0.0001	6
BTR-15	Eastern Beartooth Plateau Block	Granodiorite			0.72741	0.0001	6
BTR-28	Eastern Beartooth Plateau Block	Granodiorite			0.74181	0.0001	6
BTR-35	Eastern Beartooth Plateau Block	Granodiorite			0.7275	0.0001	6
BTR-47	Eastern Beartooth Plateau Block	Granodiorite			0.73202	0.0001	6
BTR-2	Eastern Beartooth Plateau Block	Granite			0.70617	0.0001	6
BTR-6	Eastern Beartooth Plateau Block	Granite			0.71246	0.0001	6
BTR-8	Eastern Beartooth Plateau Block	Granite			0.78304	0.0001	6
BTR-9	Eastern Beartooth Plateau Block	Granite			0.7802	0.0001	6
BTR-11	Eastern Beartooth Plateau Block	Granite			0.74417	0.0001	6
BTR-16	Eastern Beartooth Plateau Block	Granite			0.74513	0.0001	6
BTR-17	Eastern Beartooth Plateau Block	Granite			0.75517	0.0001	6
BTR-20	Eastern Beartooth Plateau Block	Granite			0.73986	0.0001	6
BTR-22	Eastern Beartooth Plateau Block	Granite			0.76234	0.0001	6
BTR-33	Eastern Beartooth Plateau Block	Granite			0.73558	0.0001	6
BTR-42	Eastern Beartooth Plateau Block	Granite			0.72139	0.0001	6
BTR-45	Eastern Beartooth Plateau Block	Granite			0.72988	0.0001	6
QC-33	Eastern Beartooth Plateau Block	Granite			0.72695	0.0001	6
QC-34	Eastern Beartooth Plateau Block	Granite			0.72933	0.0001	6
QC-40	Eastern Beartooth Plateau Block	Granite			0.72489	0.0001	6
79-11	South Snowy Block, Blacktail Deer Creek	Schist	104	160	0.7886	0.00031	7
79-12	South Snowy Block, Blacktail Deer Creek	Schist	65.1	110	0.7728	0.00031	7
79-13	South Snowy Block, Blacktail Deer Creek	Schist	87.5	144	0.7737	0.00031	7

Sample ID	Unit name or geographic area	Rock type	Rb (ppm)	Sr (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$, present day	$\pm 2\sigma$	Ref. No.*
80-16	South Snowy Block, Blacktail Deer Creek	Schist	92.4	183	0.7650	0.00031	7
80-17	South Snowy Block, Blacktail Deer Creek	Schist	144	98	0.8664	0.00031	7
80-18	South Snowy Block, Blacktail Deer Creek	Schist	48.5	159	0.7476	0.00031	7
80-19	South Snowy Block, Blacktail Deer Creek	Schist	115	132	0.8193	0.00031	7
80-20	South Snowy Block, Blacktail Deer Creek	Schist	194	151	0.8550	0.00031	7
79-5	South Snowy Block, Bear Creek	Schist	45.4	191	0.7401	0.00031	7
79-6A	South Snowy Block, Bear Creek	Schist	80.4	134	0.7700	0.00031	7
79-6B	South Snowy Block, Bear Creek	Schist	0.75	90	0.7084	0.00031	7
79-6C	South Snowy Block, Bear Creek	Schist	57.2	191	0.7378	0.00031	7
79-60	South Snowy Block, Bear Creek	Schist	124	87.3	0.8697	0.00031	7
79-6E	South Snowy Block, Bear Creek	Schist	87.2	282	0.7490	0.00031	7
79-7	South Snowy Block, Garnet Hill	Schist	13	126	0.7140	0.00031	7
79-9	South Snowy Block, Garnet Hill	Schist	97.2	144	0.7748	0.00031	7
79-10	South Snowy Block, Garnet Hill	Schist	100	166	0.7659	0.00031	7
79-14	South Snowy Block, Garnet Hill	Schist	113	134	0.8063	0.00031	7
79-15	South Snowy Block, Garnet Hill	Schist	136	93.1	0.8764	0.00031	7
79-1	South Snowy Block; Gardiner-Jardine road	Schist	113	132	0.7963	0.00031	7
79-2	South Snowy Block; Gardiner-Jardine road	Schist	47.6	140	0.7410	0.00031	7
79-3	South Snowy Block; Gardiner-Jardine road	Schist	138	167	0.7896	0.00031	7
80-10	South Snowy Block; Gardiner-Jardine road	Schist	91.5	122	0.7808	0.00031	7
80-11	South Snowy Block; Gardiner-Jardine road	Schist	90.2	59.1	0.8501	0.00031	7
80-13	South Snowy Block; Gardiner-Jardine road	Schist	76.7	53.6	0.8420	0.00031	7
79-4A	South Snowy Block; Jardine/Mineral Hill	Schist	8.1	128	0.7122	0.00031	7
79-4B	South Snowy Block; Jardine/Mineral Hill	Schist	273	4.19	10.7000	0.00031	7
79-4C	South Snowy Block; Jardine/Mineral Hill	Schist	58.4	3.35	2.2850	0.00031	7
79-40	South Snowy Block; Jardine/Mineral Hill	Schist	303	4.45	10.6600	0.00031	7
79-4E	South Snowy Block; Jardine/Mineral Hill	Schist	238	7.63	3.4420	0.00031	7
79-4F	South Snowy Block; Jardine/Mineral Hill	Schist	7.92	138	0.7073	0.00031	7

Sample ID	Unit name or geographic area	Rock type	Rb (ppm)	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr, present day	±2σ	Ref. No.*
80-5	South Snowy Block	Biotite granodiorite	79.1	277	0.7300	0.00031	7
80-6	South Snowy Block	Biotite granodiorite	94.8	279	0.7417	0.00031	7
80-7	South Snowy Block	Biotite granodiorite	110	272	0.7518	0.00031	7
80-8	South Snowy Block	Biotite granodiorite	59.4	498	0.7170	0.00031	7
80-9	South Snowy Block	Biotite granodiorite	68.2	449	0.7216	0.00031	7
80-24	South Snowy Block	Biotite granodiorite	172	146	0.8378	0.00031	7
80-25	South Snowy Block	Biotite granodiorite	160	142	0.8297	0.00031	7
80-26	South Snowy Block	Biotite granodiorite	202	149	0.8557	0.00031	7
80-31	South Snowy Block	Biotite granodiorite	96.8	297	0.7386	0.00031	7
80-32	South Snowy Block	Biotite granodiorite	106	204	0.7612	0.00031	7
80C-2	South Snowy Block; Crevice Mtn Stock	Qtz monzonite	239	117	0.9310	0.00031	7
80C-4	South Snowy Block; Crevice Mtn Stock	Qtz monzonite	241	120	0.9297	0.00031	7
80C-7	South Snowy Block; Crevice Mtn Stock	Qtz monzonite	237	119	0.9272	0.00031	7
80C-21	South Snowy Block; Crevice Mtn Stock	Qtz monzonite	241	126	0.9235	0.00031	7
80C-23	South Snowy Block; Crevice Mtn Stock	Qtz monzonite	239	127	0.9234	0.00031	7
80C-24	South Snowy Block; Crevice Mtn Stock	Qtz monzonite	244	128	0.9220	0.00031	7
80C-50	South Snowy Block; Hellroaring Stock	Qtz monzonite	233	93.6	0.9954	0.00031	7
80C-51	South Snowy Block; Hellroaring Stock	Qtz monzonite	252	92.3	1.0210	0.00031	7
80C-52	South Snowy Block; Hellroaring Stock	Qtz monzonite	249	102	0.9974	0.00031	7
80C-53	South Snowy Block; Hellroaring Stock	Qtz monzonite	254	95	1.0110	0.00031	7
80C-54	South Snowy Block; Hellroaring Stock	Qtz monzonite	239	93	0.9950	0.00031	7
80C-55	South Snowy Block; Hellroaring Stock	Qtz monzonite	251	91.2	1.0270	0.00031	7
80C-56	South Snowy Block; Hellroaring Stock	Qtz monzonite	251	94.8	1.0190	0.00031	7

*References: (1) Hildreth and others, 1991; (2) Abendini, 2009; (3) Lindsay and Feeley, 2003; (4) Feeley and others, 2002; (5) Feeley and Cosca, 2003; (6) Wooden and Mueller, 1988; (7) Montgomery and Lytwyn, 1984

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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National Park Service
U.S. Department of the Interior



Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

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