

Hydrothermal Assessment of the Proposed Old Faithful Inn Sewer Line Route, Yellowstone National Park

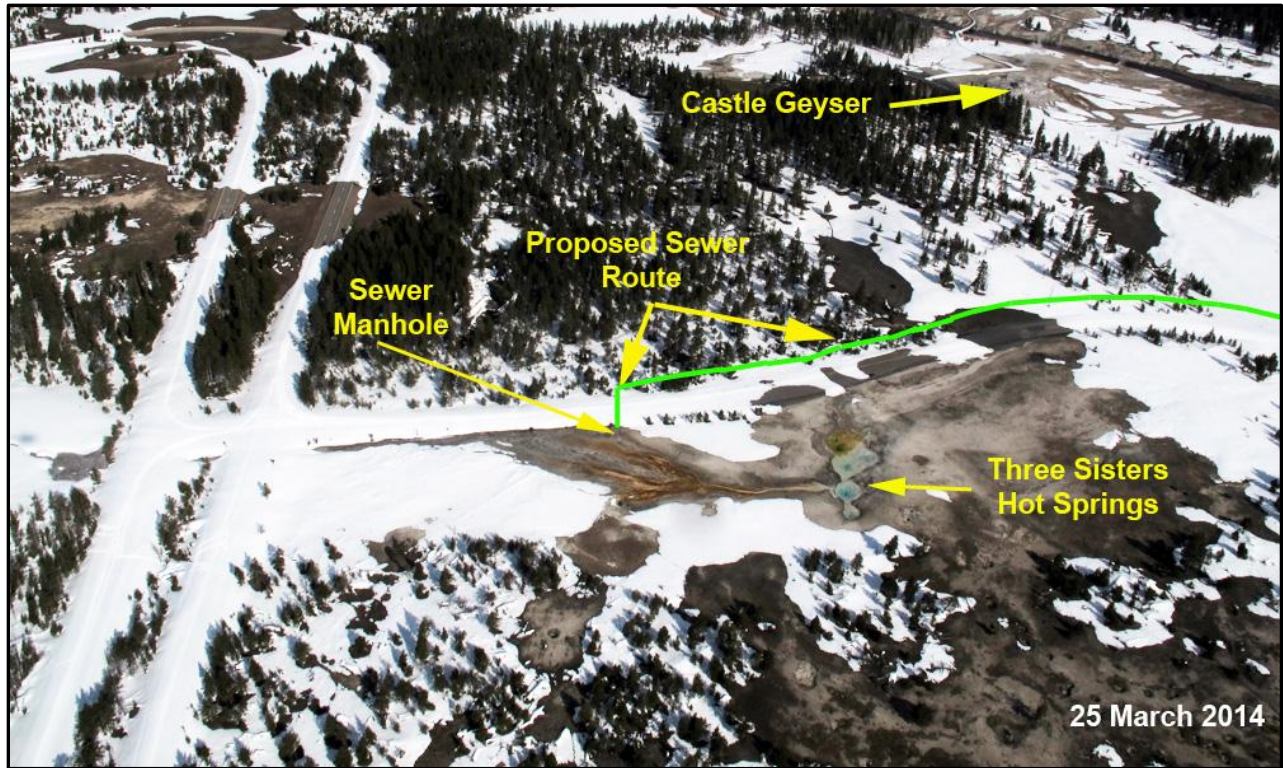


Figure 1. Oblique aerial photograph showing the proposed location of the Old Faithful sewer line (green solid line), the Three Sisters hot springs and the two-lane service road providing ingress and egress to the Old Faithful area. The lift station for the forced sewer line is to the right of this image. Notice the snow-free areas caused by significant heat flow. Helicopter- oblique view of the Old Faithful area acquired 25 March 2014. View to the north.

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EXECUTIVE SUMMARY

A hydrothermal area is a contiguous geologic unit that usually includes one or more hydrothermal features. Its boundary is the maximum spatial extent of hydrothermally altered ground, hydrothermal deposits, hydrothermal gas emissions, or heated ground. Thus, a hydrothermal area is more than individual hydrothermal features such as hot springs, geysers, steam vents, and mudpots.

Park management plans to replace the existing Old Faithful Inn forced sewer line between the lift station and the manhole in the Myriad Group (Figure 1). This report summarizes the hydrothermal and geologic conditions encountered along the proposed route for the sewer line.

All proposed sites are within an *active* hydrothermal area as defined by hydrothermally altered ground, hydrothermal deposits, and elevated ground temperatures. Thirty-one ground temperatures measured at 85 cm (33.5 in) depth ranged from 10.5 to 39.7 °C (50.9 to 103.5 °F). In addition, gas concentrations and wet hydrothermal muds at 11 sites indicate the presence of shallow (less than one meter or three feet depth) hydrothermal fluids.

INTRODUCTION

A new sewer line is proposed to replace the failing sewer line for the Old Faithful Inn. The proposed route begins at the lift station, follows the access road from the lower gas station to the four lane, and ends at a sewer manhole located in the Myriad Group. In early May 2014, YNP geologists conducted an assessment of hydrothermal conditions along a proposed route for the Old Faithful sewer line that had been marked by Mike Finken and Molly Nelson, Yellowstone National Park Maintenance Division. Yellowstone National Park geologists (Henry Heasler and Cheryl Jaworowski) drilled thirty-three holes to assess subsurface temperatures, hydrothermal gas concentrations, and near-surface stratigraphy.

Historic development in the Old Faithful area has affected the Old Faithful hydrothermal area (for examples see Heasler et. al, 2009a; Heasler et. al, 2009b; Heasler and Jaworowski, 2005). Improperly located infrastructure has the potential to affect both the hydrogeology and heat flow of the Old Faithful hydrothermal system (Old Faithful Science Review Panel, 2014). The normal geologic or *unaffected* movement of heat, water, and gases through a natural underground plumbing system is the key to protecting the world-unique concentration of active geysers found in this area.

LOCATION OF STUDY AREA

On the northern edge of the Old Faithful developed area, the Old Faithful sewer line exists in an active hydrothermal area. The proposed route follows an access road to the Lower Gas Station, the lower General Store and the Old Faithful Inn (Figure 2). The proposed sewer line is north of the Three Sisters hot springs. The Three Sisters hot springs are a part of a spatially extensive and chemically similar hydrothermal system, known as the Myriad Group.

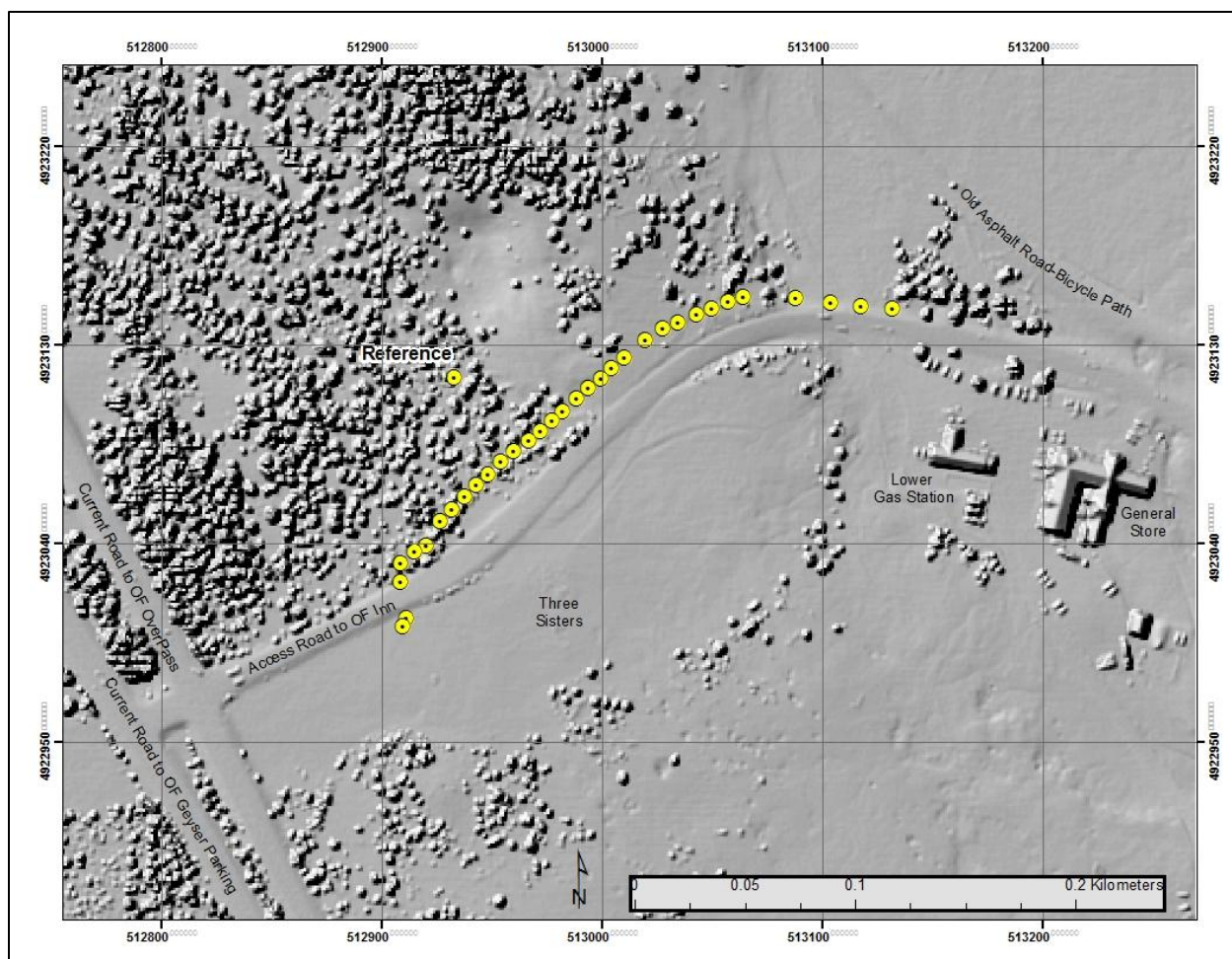


Figure 2. A LiDAR base map showing locations (yellow circles) assessed along proposed route of the Old Faithful sewer line. Notice the lower General Store, Gas Station, roads, and trees shown on this 2008 digital elevation model. The hydrothermal system known as the Myriad Group extends south from the access road towards the Old Faithful Inn, the General Store, and the bottom of the image. The NSF EarthScope project funded the acquisition of this geodetic-grade LiDAR imagery (available at www.opentopography.org) of the Upper Geyser Basin.

METHODOLOGY

Yellowstone National Park geologists conducted an aerial survey of the active hydrothermal area on 25 March 2014. A FLIR Systems ThermoCAM SC660 acquired helicopter-oblique, daytime visible (Figure 3) and thermal infrared (TIR) (Figure 4) images of the proposed sewer line. The daytime TIR image contains 307,200 surficial temperature estimates and displays hydrothermal ground radiating significant thermal infrared energy from the hydrothermal system.

On 15 May 2014, YNP geologists conducted a ground survey shortly after NPS personnel marked the proposed route for the OF sewer line (Figures 5 and 6). At this time, there still were small patches of snow among the trees. A FLUKE 574 thermal infrared sensor with an attached 0.5 cm (0.2 inch) diameter, 1.2 m (4-foot) long, type K thermocouple probe measured ground

temperatures generally at depths of 50 cm (19.7 inches) and 85 cm (33.5 inches). Geologists recorded temperatures and depth of measurements in a field notebook. Also, YNP geologists used a Drager X-am 7000 gas sensor to ensure safety and measure the amounts of hydrothermal gases in the 33 holes. Hydrothermal gases measured were carbon dioxide, hydrogen sulfide, and sulfur dioxide. Also measured were oxygen and methane. The Drager X-am meter was calibrated using fresh air before beginning gas measurements and calibrated three times during measurements. All temperature and hydrothermal gas data measured are presented in Appendix A.

Along the proposed route (Figures 5 and 6), YNP geologists used a Hilti TE 7-A rotary hammer drill to access 50 cm (19.7 inches) and 85 cm (33.5 inches) depths for all in-hole temperature and gas measurements. The 1.3 cm (½ inch) diameter drill was an 85 cm-long (33.5 inches) masonry drill bit. In the morning, geologists located a site for a reference hole and deployed temperature loggers with sensors at 3 depths (0 cm, 50 cm, and 85 cm; 0 inches, 19.7 inches, and 33.5 inches) and a sensor for recording air temperature. After installation of a temperature logger in the reference hole, geologists drilled all 33 holes to 50 cm (19.7 inches) and allowed the in-hole temperatures to equilibrate (approximately 45 minutes) before measuring gases and temperature. After taking measurements at 50 cm (19.7 inches), geologists similarly drilled all holes to 85 cm (33.5 inches) and let in-hole temperatures equilibrate (approximately 45 minutes). The ease of drill-bit penetration varied with depth and among the holes drilled. In the upper 50 cm (19.7 inches), drilling either easily penetrated unconsolidated deposits or penetrated layers using moderate down-hole pressure. The drilling to 85 cm (33.5 inches) depth also varied depending upon the layers encountered. For example, geologists terminated the drilling of hole 1 when the substrate was too hard to penetrate. At 25 cm (9.8 inches) depth, it was thought that hole 1 was penetrating concrete. Thus, hole 1 was terminated at 25 cm (9.8 inches) depth. Geologists terminated drilling between 60 to 65 cm (24-26 inches) depth when the substrate became too hard to penetrate within holes 3 and 21. In hole 32, geologist could not measure gas concentration because the hole filled with hydrothermal water (11.4 to 13.2 °C).

A mobile mapping unit recorded accurate digital locations of the temperature sites. The mobile mapping system consists of a Trimble ProXH global positioning system (GPS) receiver with a Zephyr antenna and Allegro MX handheld field computer. After collecting data, geologists corrected the field locations using Trimble's GPS Pathfinder Office software and the Slough Creek Plate Boundary Observatory (PBO 720) precision GPS station. The horizontal accuracy of the corrected points (100%) varied from ± 5 to 15 cm (±2 inches to 6 inches). Due to data acquisition difficulties, the locations for holes 11 and 29 were estimated.

In the office, geologists transferred the field notes (temperatures, gas, and stratigraphy) into an excel spreadsheet for analyses.



Figure 3. Helicopter-oblique photograph showing snow-free areas on 25 March 2014. Notice the colorful hydrothermal water associated with the Three Sisters and the snow-free areas within the Myriad Group near the center of the photograph. View to the southwest.

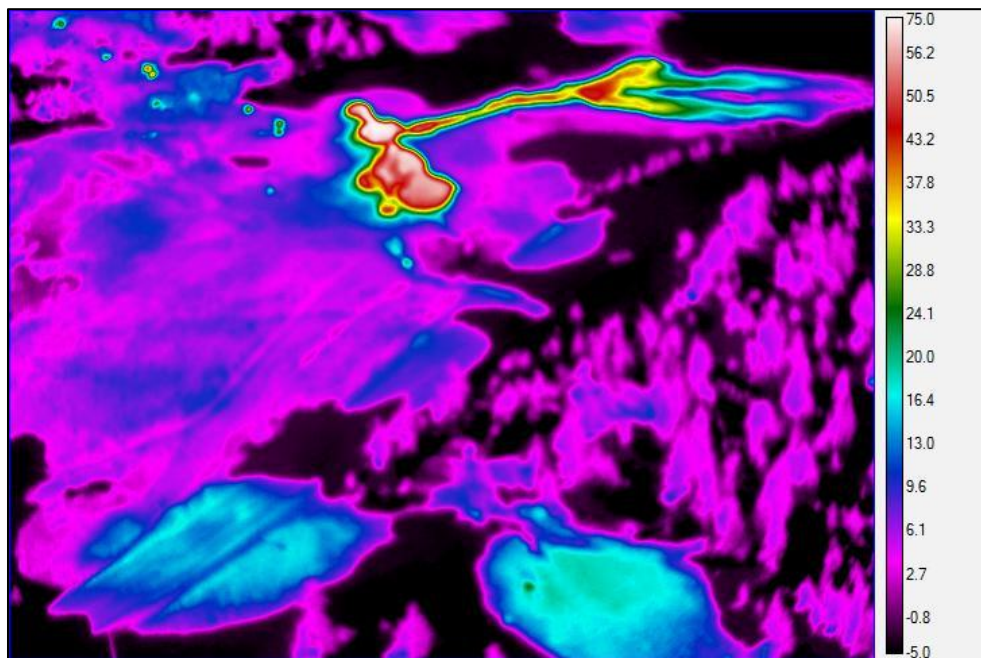


Figure 4. Helicopter-oblique, daytime, thermal infrared photograph showing warm areas that correlate with snow-free areas on 25 March 2014. Notice the Three Sisters within the Myriad Group (upper center of photograph). The temperature scale of the image ranges from -5.0°C (23°F) to 75°C (167°F). View to the southwest. Compare with visible photograph in Figure 3.

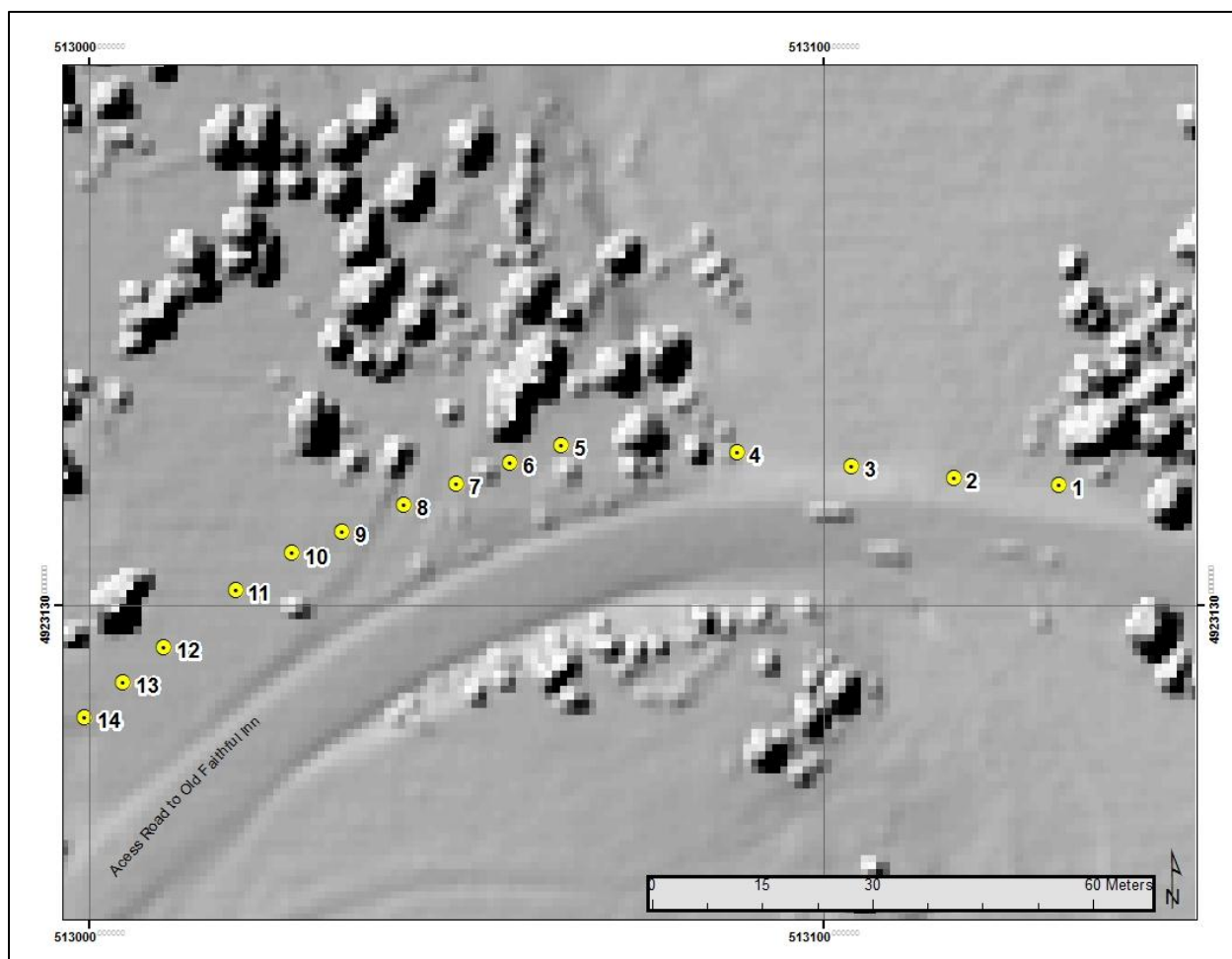


Figure 5. A LiDAR base map showing locations (1-14) assessed for subsurface temperatures, hydrothermal gases, and stratigraphy along proposed route of the Old Faithful sewer line. The NSF EarthScope project funded the acquisition of this geodetic-grade imagery (available at www.opentopography.org) of the Upper Geyser Basin.

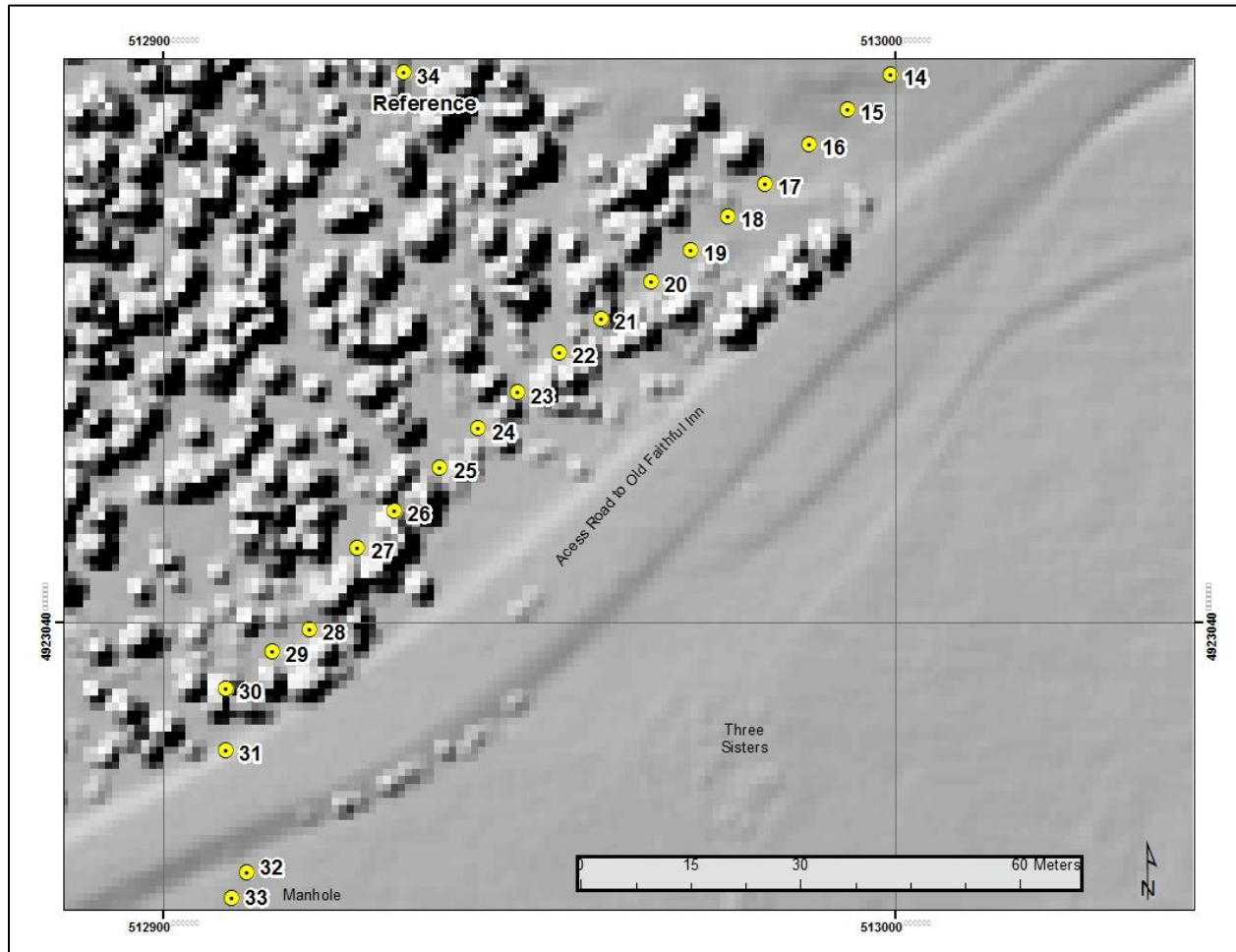


Figure 6. A LiDAR base map showing locations (14-32 and 34) assessed for subsurface temperatures, hydrothermal gases, and stratigraphy along proposed route of the Old Faithful sewer line. North-northwest of the Three Sisters, hole number 22 had the highest subsurface temperature. The NSF EarthScope project funded the acquisition of this geodetic-grade imagery (available at www.opentopography.org) of the Upper Geyser Basin.

RESULTS

Subsurface Temperatures

Before discussing temperature results, it is important to review the techniques used to acquire temperatures. Subsurface temperatures were measured at 33 locations at two depths, 50 and 85 cm (19.7 inches and 33.5 inches) (Figures 2, 5 and 6).

The one reference location provided hydrothermal context for analysis of temperature values along the proposed sewer line (Figure 7). The reference site was located approximately 40 meters (130 feet) to the northwest of the proposed sewer line (Figure 2). Located in a conifer forest, the reference site contained an Onset HOBO microstation with four thermistors. The four thermistors measured air temperature (black dashed curved line), the near-ground surface temperature (blue solid curved line), and temperatures at 50 and 85 cm depth (19.7 inches and 33.5 inches), every minute (Figure 7). The reference station documented daily variation in temperatures at 50 and 85 cm depth (19.7 inches and 33.5 inches) due to changing air temperatures. As can be seen from Figure 7, temperatures at those two depths did not vary due to changing air temperature. Thus, on 15 May 2014 the temperatures measured at the 33 locations were not significantly affected by air temperature.

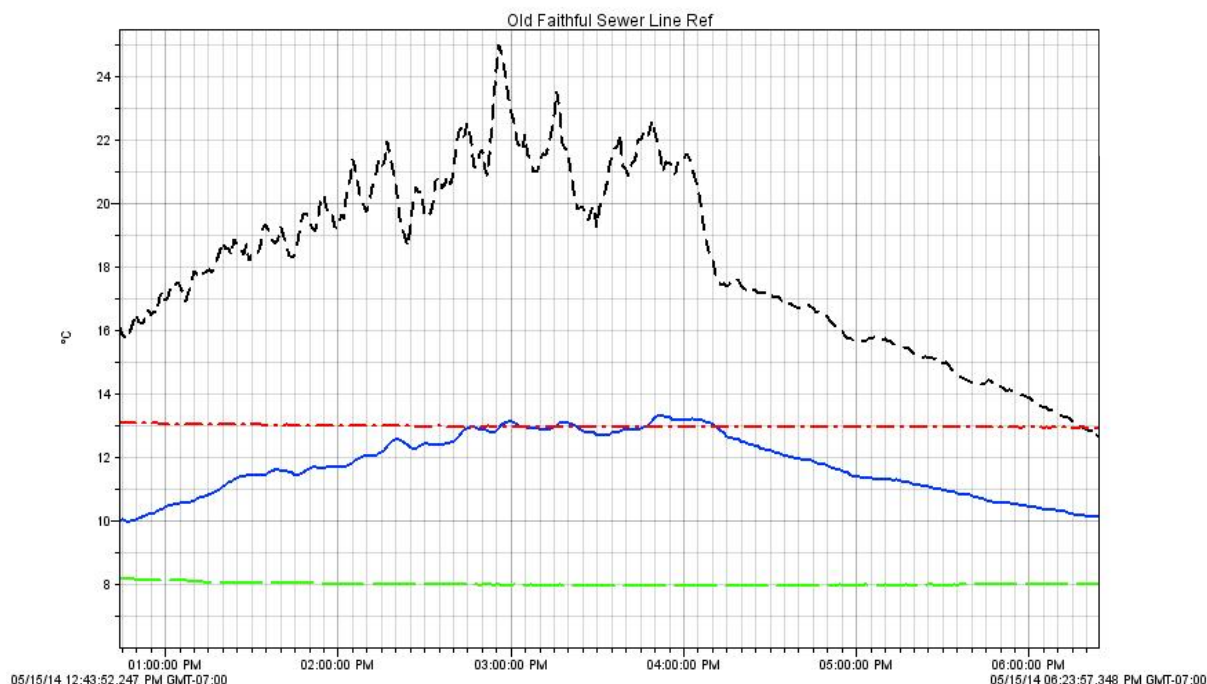


Figure 7. Temperatures measured on 15 May 2014 at a reference site approximately 40 m (130 feet) northwest of the proposed sewer line (Figure 6). The black line with short dashes represents the air temperatures, the solid blue line represent near-ground surface temperatures, the green line with long dashes represent temperatures at 50 cm (19.7 inches) depth and the red line with dashes and dots indicates temperatures at 85 cm (33.5 inches) depth. Note the constancy of the temperature at 50 cm (19.7 inches) depth (8 °C; 46.4 °F) and at 85 cm (33.5 inches) depth (13 °C; 55.4 °F).

This reference site confirms that the proposed route occurs in an area of high heat flow. One observation that supports this statement is the measured temperatures at 50 cm and 85 cm (19.7 inches and 33.5 inches) depth. On 15 May 2014, the temperature at 85 cm (33.5 inches) depth was greater than the temperature at 50 cm (19.7 inches) depth, thus defining an area of high heat flow. A finite difference numerical model of one-dimensional, time-dependent, conductive heat transfer clearly indicates that the temperature at 85 cm (33.5 inches) depth would normally be less than the temperature at 50 cm (19.7 inches) depth (Figure 8) given the following parameters: a normal heat flow of $67 \text{ } 10^{-3} \text{ Wm}^{-2}$, a mean annual air temperature of $1.1 \text{ } ^\circ\text{C}$ ($34 \text{ } ^\circ\text{F}$) and a thermal diffusivity of $1.0 \text{ } 10^{-6} \text{ m}^2 \text{ sec}^{-1}$. It is important to note that the annual air temperature at Old Faithful that varies $17 \text{ } ^\circ\text{C}$ ($31 \text{ } ^\circ\text{F}$) sinusoidally through the year and must be taken in account when interpreting temperature data. Thus, a high background heat flow in the area of the reference hole is one plausible explanation for the observed temperatures in the reference hole.

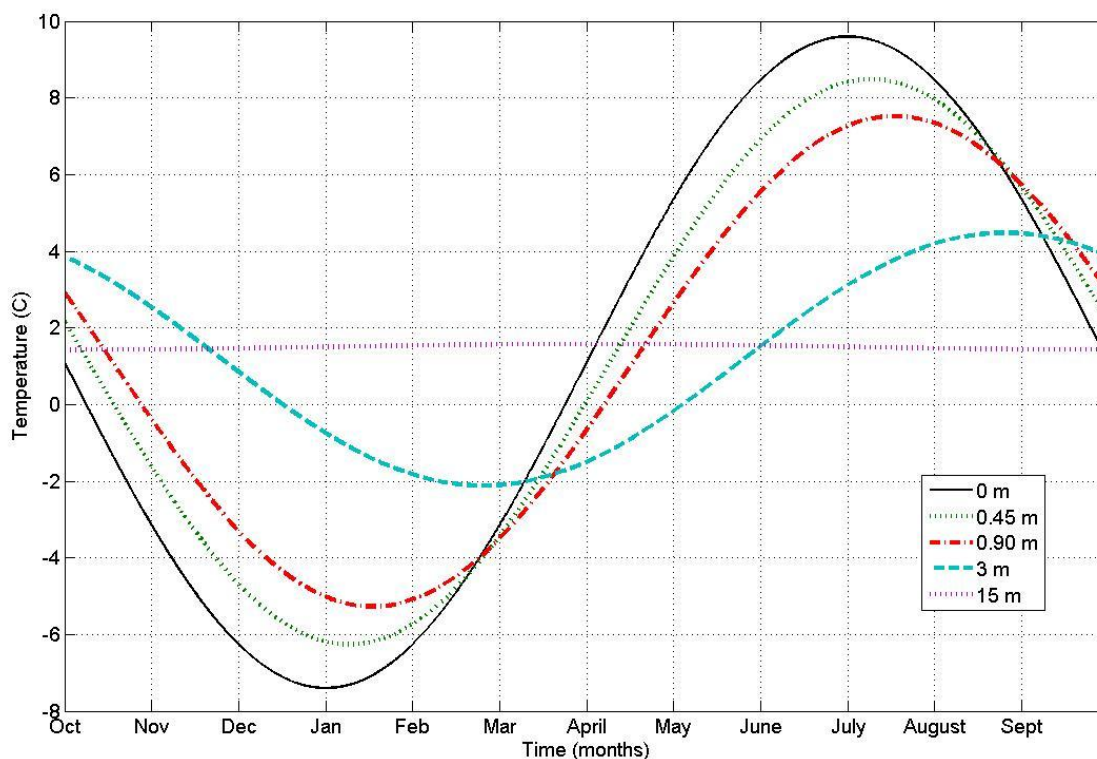


Figure 8. Temperatures through time at varying depths calculated using a one-dimensional, time-dependent heat conduction finite difference numerical model. The solid black line represents an approximation of the variation in air temperature through one year. The dotted green line represents temperature at 45 cm (17.7 inches) depth, the dash-dot red line represents temperatures at 90 cm (35.4 inches) depth, the dashed light blue line represents temperatures at 2 m (6.6 feet) depth, and the dotted purple line represents temperatures at 15 m (49.2 feet) depth. Notice that in mid-May, the ground temperature for a regional normal value of heat flow of $67 \text{ } 10^{-3} \text{ Wm}^{-2}$ at 90 cm (35.4 inches) depth is less than the temperature at 45 cm (17.7 inches) depth.

Figure 9 (50 cm (19.7 inches) depth) and Figure 10 (85 cm (33.5 inches)) depth) show temperatures measured along the route of the proposed sewer line. At 50 cm (19.7 inches) depth, the maximum temperature measured was 28.0 °C (82.4 °F) in hole 22. At 85 cm (33.5 inches) depth, the maximum temperature was 39.7 °C (103.5 °F) in hole 22.

All temperatures (Figures 9 and 10) are significantly warmer than temperatures in a non-hydrothermal area. The high temperature anomalies in holes 18 through 29 indicate the presence of shallow hydrothermal fluid movement.

For this study, all measured temperatures were below the boiling temperature for water at the Old Faithful area. At the elevation of Old Faithful (about 2,225 m or 7,300 feet), water boils at 92 °C (198 °F).

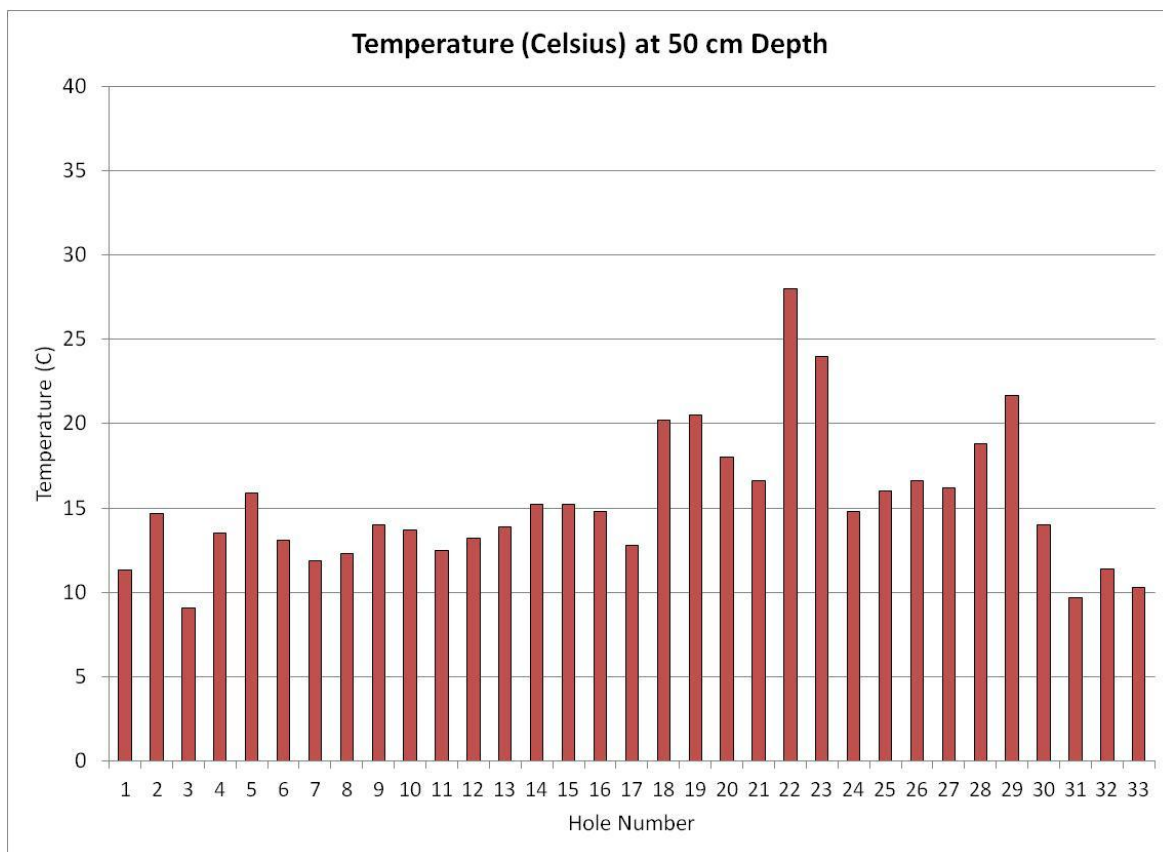


Figure 9. Graph showing temperatures for all holes along the proposed sewer line and the reference site (hole number 34) at 50 cm (19.7 inches) depth. Note the high temperature value 28.0 °C (82.4 °F) at hole 22. All measured temperatures at 50 cm (19.7 inches) depth are greater than temperatures in the reference site at 50 cm (19.7 inches) depth.

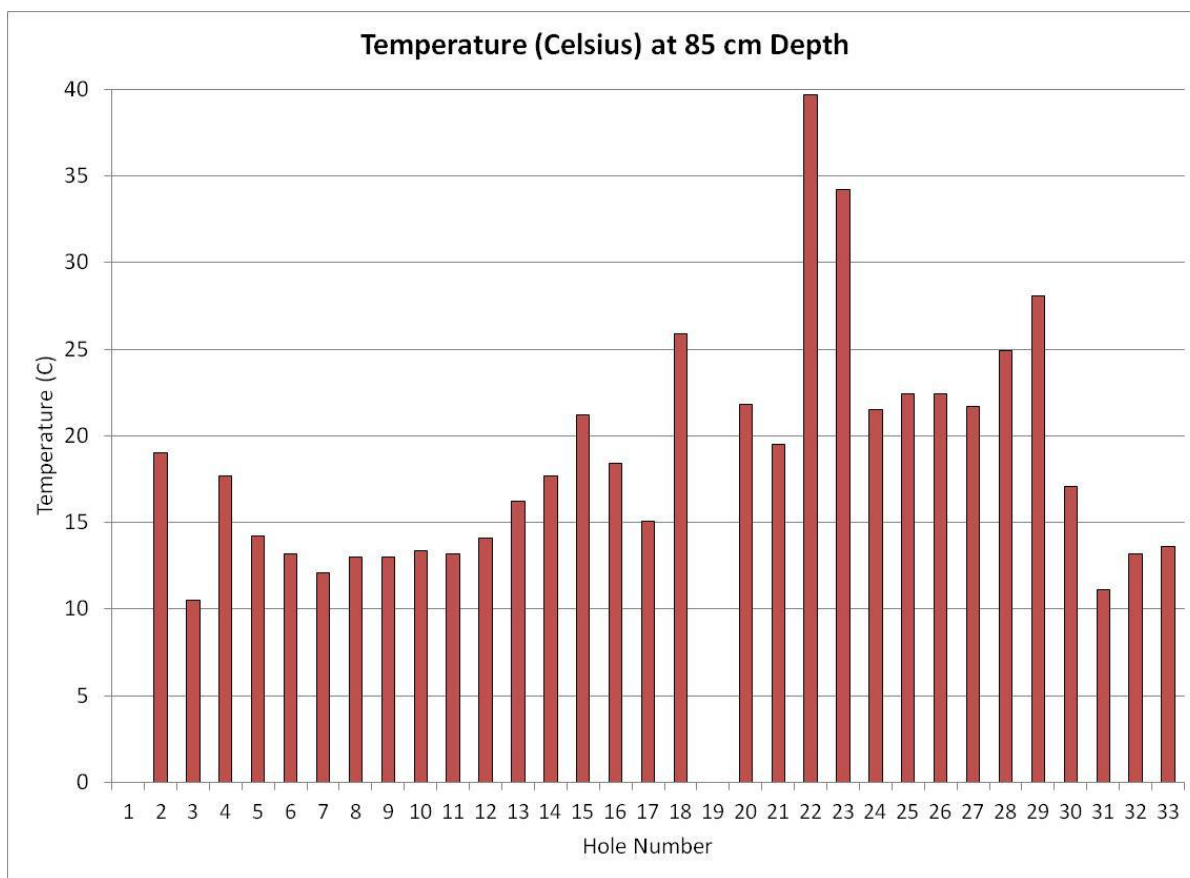


Figure 10. Graph showing temperatures for all holes along the proposed sewer line and the reference site (hole number 34) at 85 cm (33.5 inches) depth. . Due to a hard substrate, measurements could not be done in some holes because the holes could not be drilled beyond 50 cm (19.7 inches) depth. Note the high temperature value of 39.7 C (103.5 °F) in hole 22.

Hydrothermal Gas Measurements

Hydrothermal gas concentrations at 33 locations along the route of the proposed sewer line and at one reference location (Figure 2) provided another means of assessing the active hydrothermal system. Gases were measured at two depths, 50 and 85 cm (19.7 inches and 33.5 inches) with a sensor that could detect the following gases: carbon dioxide, sulfur dioxide, hydrogen sulfide, oxygen and methane. On 15 May 2014, carbon dioxide was the primary hydrothermal gas detected (Figures 11 and 12).

The concentration of CO₂ in fresh outdoor air is approximately 330 ppm (0.033%). Indoors, carbon dioxide can become slightly elevated where there is insufficient ventilation. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) currently recommends that indoor CO₂ levels not exceed the outdoor concentration by more than about 600 ppm (Western Area Power Administration, 2008). The Occupational Safety and Health Administration (OSHA) identifies 5000 ppm (0.5%) as the permissible exposure limit of carbon dioxide contaminant in air, over an 8-hour time-weighted average (OSHA, 2006). OSHA recommends immediate evacuation of an area containing 5% or more carbon dioxide.

The pattern of elevated carbon dioxide levels (Figures 11 and 12) matches the pattern of elevated temperatures (Figures 9 and 10). At 50 cm depth, the highest measured carbon dioxide level on 15 May 2014 was 2.65 % in hole 18. At 85 cm depth, the highest measured carbon dioxide level on 15 May 2014 was 3.5 % in hole 22.

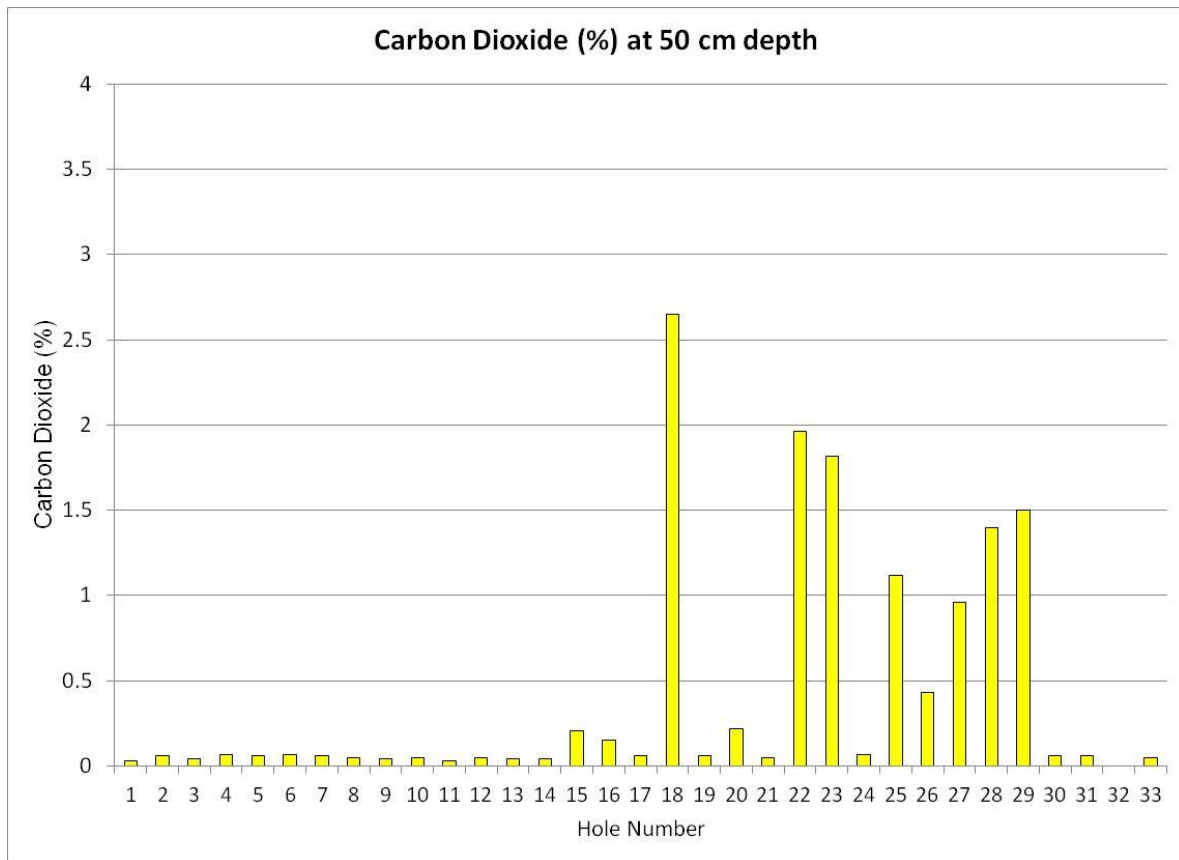


Figure 11. Graph showing carbon dioxide gas concentration for all holes along the proposed sewer line and the reference site (hole number 34) at 50 cm (19.7 inches) depth. Note the high carbon dioxide gas concentrations in holes 18, 22, 23, 25-29.

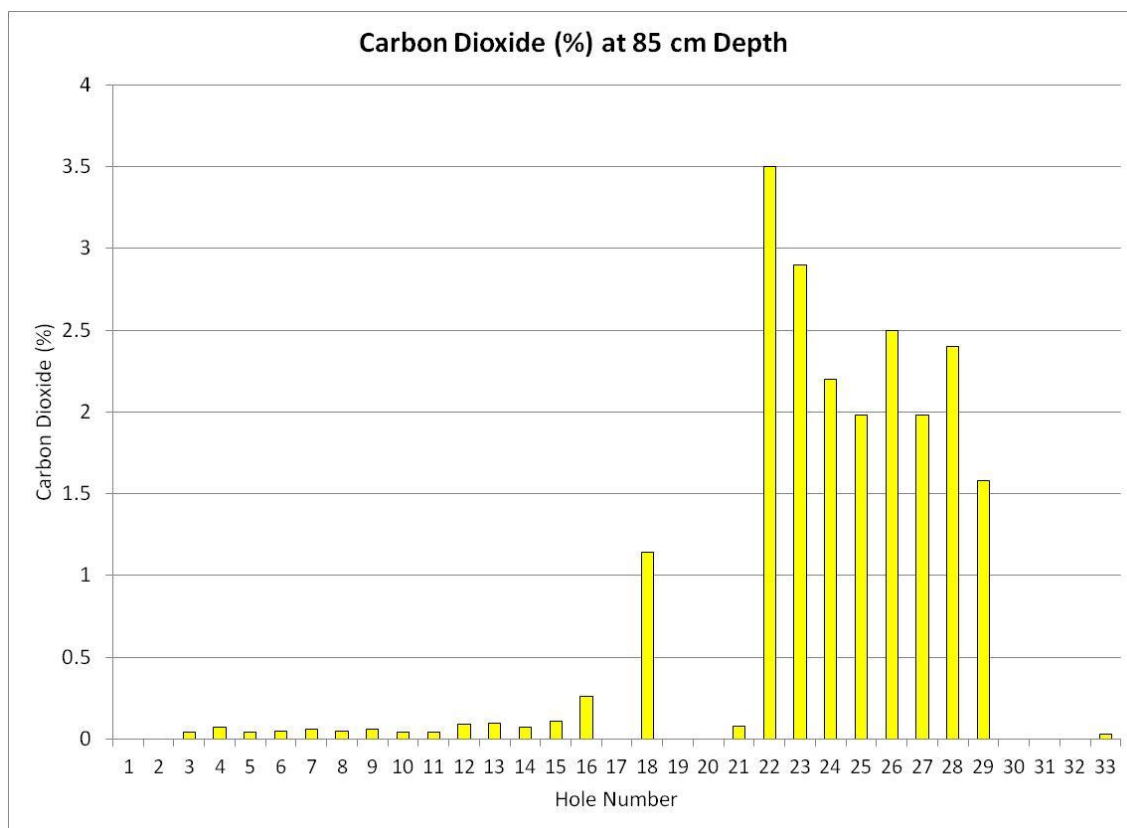


Figure 12. Graph showing carbon dioxide gas concentration for all holes along the proposed sewer line and the reference site (hole number 34) at 85 cm (33.5 inches) depth. Gas measurement was not possible in all holes either due to water in the hole, collapsing holes, or holes that could not be drilled beyond 50 cm (19.7 inches) depth due to hardness of the substrate. Note the high concentrations at hole 22 and the pattern of increased carbon dioxide levels in holes 18 and holes 22 – 29.

DISCUSSION

Relevant Geology

The world-unique concentration of active geysers in the Old Faithful area reflects the bedrock and surficial geology of the Upper Geyser Basin. For example, the Old Faithful and Geyser Hill groups are interconnected hydrothermal systems. An understanding of the geology is necessary for protecting the hydrothermal systems within the Upper Geyser Basin and balancing the demand for development.

Previous geologic mapping (Christiansen and Blank, 1974; Waldrop, 1975; and Muffler and others, 1982) shows the geologic setting of the Upper Geyser Basin hydrothermal system. Christiansen and Blank's (1974) bedrock map shows sediments and silica-rich sinter between the lava flows of the Mallard Lake Dome (Mallard Lake rhyolite flow) and the Madison Plateau (Summit Lake rhyolite flow). Mapping by Christiansen and Blank (1974) and Muffler and others (1982) shows the location of the historic development within the sinter plain (Figure 13). Waldrop's (1975) geologic mapping emphasizes the various types of sediments in the Upper Geyser Basin and Old Faithful area. He describes (1) the obsidian-rich sediments eroded from nearby lava flows, (2) the hydrothermally deposited silica-rich, white to light gray sinter, and (3) various glacial and late glacial sediments. Muffler and others (1982) provide a detailed geologic map of the Upper Geyser Basin. Recent studies (Watts and others 2012) identified that the previously mapped 516 ± 7 ka Biscuit Basin rhyolite flow consists of three units: the 781 ± 76 ka East Biscuit Basin flow, the 261 ± 17 ka South Biscuit Basin flow and the 155 ± 9 ka North Biscuit Basin flow. Regardless of this new information about the bedrock geology of the Upper Geyser Basin, the detailed map of the Upper Geyser Basin (Muffler and others, 1982) clearly shows the access road and the sewer line on sinter (yellow color on Figure 13).

In the Upper Geyser Basin, a red-clay layer or other hydrothermal clays (white or peach color) exist within the hydrothermal systems. Clay minerals form when hydrothermal waters interact with obsidian-rich sands and may form a barrier to boiling temperature steam and water flow. Excavation into clay layers can result in the sudden release of boiling-temperature fluids. Due to the importance of clay layers, Yellowstone Park personnel sited the new Old Faithful Visitor Center away from areas with a red-clay layer. Additionally, while assessing potential hydrocarbon plumes at the lower gas station, Wyoming Department of Environmental Quality personnel terminated drilling when they encountered a red-clay layer at the Lower Gas Station.

The geology encountered during the assessment of the proposed sewer line is consistent with the previous geologic mapping (sinter and unconsolidated ice-contact sediments). Along the eastern portion of the study area (holes 2 through 15) the rotary bit generally drilled easily through unconsolidated sediments. Between holes 15 and 21, the drill bit penetrated various layers including white powder and brown mud. Along the western edge of the study area, it is significant that holes 22 through 31 penetrated moist, white fine cuttings. Wet and warm mud coated the drill bit as it was pulled out of these holes.

Bedrock Geology of the Old Faithful Area

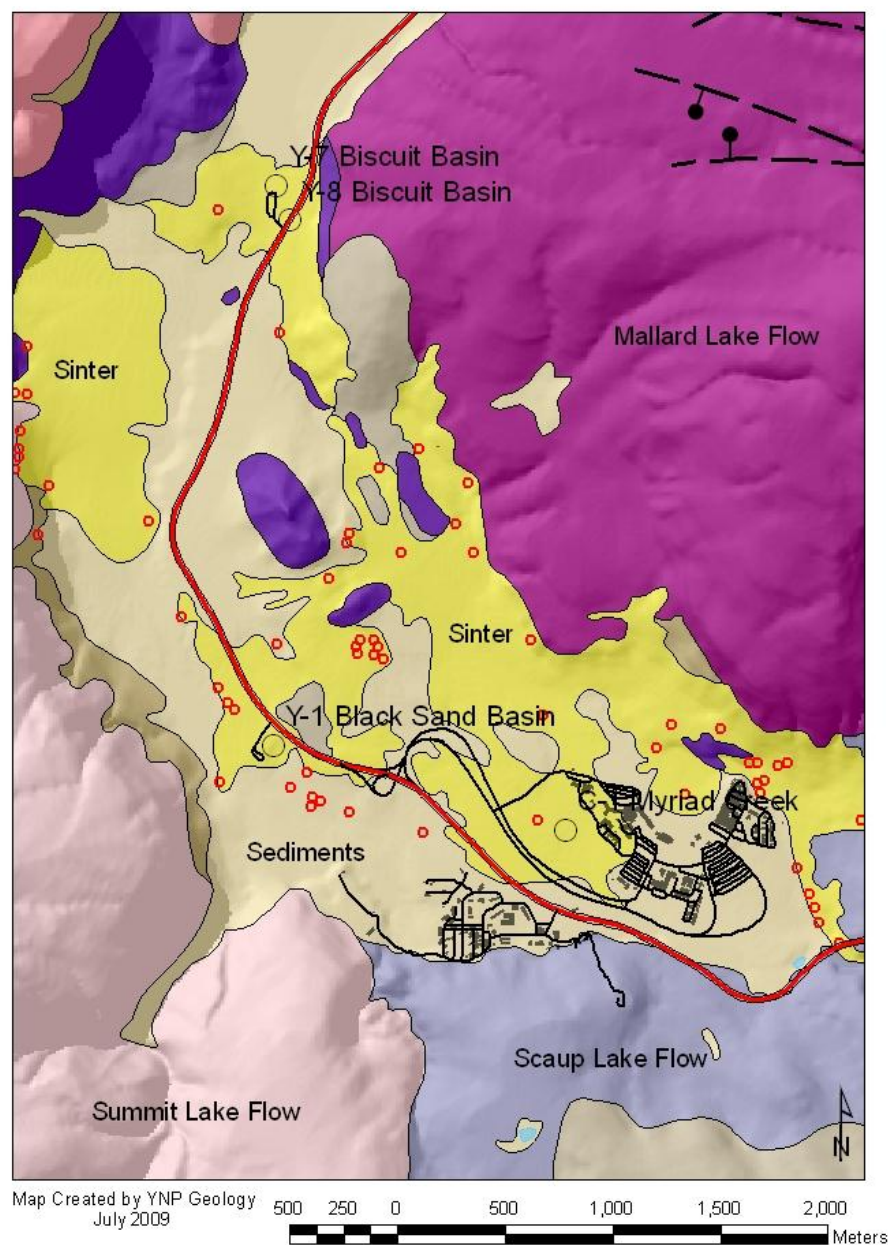


Figure 13. Map showing the bedrock geology of the Old Faithful area draped over topography (modified from Christiansen and Blank, 1974). Notice the lava flows (Mallard Lake (hot pink), Summit Lake (light pink) and Scaup Lake (lilac)) surrounding the Upper Geyser Basin. Obsidian-rich sediments (tan) and sinter (yellow) occur between the lava flows. The multi-age Biscuit Basin lava flow (purple) crops out in the Upper Geyser Basin. The thick red line is the main road and the black lines are other roads in the Old Faithful area. Red circles are hydrothermal features from Christiansen and Blank (1974).

In addition to the volcanic and late glacial stratigraphy of the Upper Geyser Basin, faults and fractures play an important role in the flow of hydrothermal fluids. The faulted Mallard Lake flow shows the following trends: east-west, north, northwest, north-northeast, and northeast. It is reasonable to expect similar structural trends of faults and/or fractures within the Upper Geyser Basin. For example, the Three Sisters hot springs trend north. And the highest measured subsurface temperatures (hole 22) occur north-northwest of the Three Sisters hot springs. Thus, the high temperatures measured in hole 22 may relate to north-trending fractures and/or the stratigraphy within the hydrothermal system.

SUMMARY

The proposed Old Faithful Inn sewer line replacement occurs within an active hydrothermal area. Evidence supporting this statement includes elevated ground temperatures, high concentrations of carbon dioxide gas, hydrothermally altered ground, and hydrothermal deposits. The proximity of the proposed sewer line to the Three Sisters hot springs and the Myriad Group increases the likelihood of adverse impacts to hydrothermal features and the hydrothermal system. Potential impacts to the hydrothermal resource and features due to the proposed sewer line cannot be determined with certainty.

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Appendix A

Locations and Data Values

Datum WGS84, all times are Mountain Daylight,

Point	Northing	Easting	Depth (cm)	Temp (°C)	CO2 (%)	O2 (%)	Time	Depth (cm)	Temp (oC)	CO2 (%)	O2 (%)	Time	Comment
1	4923146	513132	25	11.3	0.03	20.9	14:35						
2	4923147	513118	50	14.7	0.06	20.9	14:36	80	19.0			16:18	
3	4923149	513104	50	9.1	0.04	20.9	14:37	60	10.5	0.04	20.9	16:22	
4	4923151	513088	50	13.5	0.07	20.9	14:39	85	17.7	0.07	20.9	16:24	
5	4923152	513064	50	15.9	0.06	20.9		85	14.2	0.04	20.9		
6	4923149	513057	50	13.1	0.07	20.9		85	13.2	0.05	20.9		
7	4923146	513050	45	11.9	0.06	20.9		85	12.1	0.06	20.9	16:31	
8	4923144	513043	50	12.3	0.05	20.9	14:47	85	13.0	0.05	20.9	16:33	
9	4923140	513035	50	14.0	0.04	20.9	14:52	85	13.0	0.06	20.9	16:35	
10	4923137	513028	50	13.7	0.05	20.9	14:54	85	13.4	0.04	20.9	16:36	
11	4923132	513020	50	12.5	0.03	20.9	14:56	85	13.2	0.04	20.9	16:39	
12	4923124	513010	50	13.2	0.05	20.9	14:58	85	14.1	0.09	20.9	16:40	
13	4923119	513005	50	13.9	0.04	20.9	15:03	85	16.2	0.10	20.9	16:42	
14	4923115	512999	50	15.2	0.04	20.9	15:05	85	17.7	0.07	20.9	16:45	
15	4923110	512994	50	15.2	0.21	20.9	15:09	85	21.2	0.11	20.9	16:51	
16	4923105	512988	50	14.8	0.15	20.9	15:12	85	18.4	0.26	20.9	16:52	
17	4923100	512982	50	12.8	0.06	20.9	15:14	85	15.1			16:55	
18	4923095	512977	50	20.2	2.65	20.1	15:30	85	25.9	1.14	20.6	16:55	
19	4923091	512972	48	20.5	0.06	20.9		85					
20	4923087	512967	50	18.0	0.22	20.9	15:41	85	21.8			16:58	
21	4923081	512960	50	16.6	0.05	20.9	15:43	65	19.5	0.08	20.9	16:59	
22	4923077	512954	50	28.0	1.96	20.1	17:45	85	39.7	3.50	19.8	18:57	
23	4923071	512949	50	24.0	1.82	20.1	17:50	85	34.2	2.90	19.8	19:00	
24	4923066	512943	50	14.8	0.07	20.9	18:03	85	21.5	2.20	19.5	19:02	
25	4923061	512938	50	16.0	1.12	20.1	18:06	85	22.4	1.98	19.6	19:05	
26	4923055	512932	50	16.6	0.43	20.5	18:09	85	22.4	2.50	19.2	19:06	
27	4923050	512927	50	16.2	0.96	20.2	18:12	85	21.7	1.98	19.3	19:09	
28	4923039	512920	50	18.8	1.40	20.0	18:10	85	24.9	2.40	19.4	19:10	
29	4923036	512915	50	21.7	1.50	18.9	18:20	85	28.1	1.58	19.7	19:12	
30	4923031	512909	50	14.0	0.06	20.9	18:23	85	17.1			19:15	
31	4923023	512909	50	9.7	0.06	20.9		85	11.1				
32	4923006	512911	50	11.4			18:30	85	13.2			19:30	
33	4923002	512909											Manhole
34	4923115	512933	50	10.3	0.05	20.9	11:55	85	13.6	0.03	20.9	12:10	Ref. Site