

## Hydrothermal Assessment of Proposed Old Faithful Inn Sewer Line Routes, Yellowstone National Park

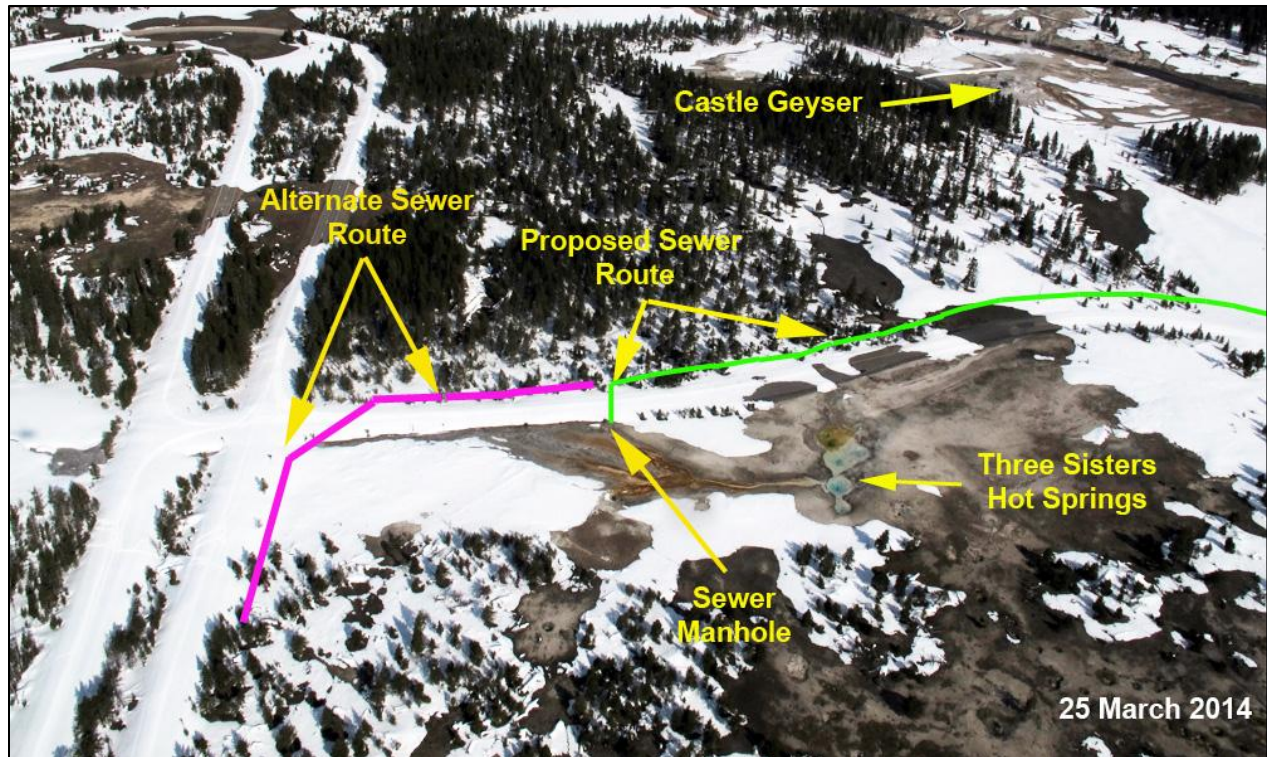


**Figure 1.** Oblique aerial photograph showing the proposed Old Faithful sewer line (green solid line), an alternate route for the sewer line (purple solid line), the Three Sisters hot springs and the two-lane service road providing ingress and egress to the Old Faithful area. The lift station for the 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.

By  
Henry Heasler, Cheryl Jaworowski, and Dan Mahony  
Geology Program, Yellowstone Center for Resources  
Yellowstone National Park



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## EXECUTIVE SUMMARY

Park management plans to replace the existing Old Faithful Inn forced sewer line between the lift station and the existing gravity portion of the sewer line in the Myriad Group.

Proposed routes for the sewer line are within an *active* hydrothermal system as defined by hydrothermally altered ground, hydrothermal deposits, and elevated subsurface temperatures. Fifty subsurface temperatures measured at 85 cm (33.5 in) depth ranged from 10.5 to 72.5 °C (50.9 to 162.5 °F). Hydrothermal gas concentrations (carbon dioxide) and wet hydrothermal muds at 15 sites also indicate an active hydrothermal system.

At this time, potential anthropogenic impacts to the hydrothermal resource and individual features cannot be determined with certainty.

## INTRODUCTION

A new sewer line is proposed to replace the failing sewer line for the Old Faithful Inn. The proposed routes begin at the lift station and follow the access road from the lower gas station towards the four-lane road. One route connects with the existing manhole in the Myriad Group while an alternate route continues along the service road, crosses the access road, and parallels the four-lane road thus connecting with the gravity portion of the existing sewer line (Figures 1 and 2). 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. On 15 May 2014, Yellowstone National Park geologists (Henry Heasler and Cheryl Jaworowski) drilled thirty-three holes to assess subsurface temperatures, hydrothermal gas concentrations, and near-surface stratigraphy. On 24 June 2014, Yellowstone National Park Geology Program staff (Henry Heasler, Cheryl Jaworowski and Dan Mahony) drilled an additional twenty holes to further assess subsurface temperatures, hydrothermal gas concentrations, and near-surface stratigraphy. On 1 July, Molly Nelson marked an alternate route for the proposed sewer line. Geologists, Cheryl Jaworowski and Henry Heasler, investigated the alternate route on 2 July 2014 (See Appendix A).

Historic development in the Old Faithful area has affected the Old Faithful hydrothermal system (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.

A hydrothermal area (2-dimensions) 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. A hydrothermal system (3-dimensions) integrates the subsurface geology (sediments, rock, layers, fractures, porosity, permeability, etc.) and geologic processes (i.e. fluid flow, hydrothermal alteration). The geology of the area and its relationship to hydrothermal resources of the Upper Geyser Basin hydrothermal system is discussed in Heasler and Jaworowski, 2014.

## LOCATION OF STUDY AREA

On the northwestern edge of the Old Faithful developed area, the existing Old Faithful sewer line is trenched into an active hydrothermal system. The proposed two routes follow an access road to the lower gas station, the 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 part of a spatially extensive, hydrothermal system and geochemically similar to other hydrothermal features within the Myriad Group.

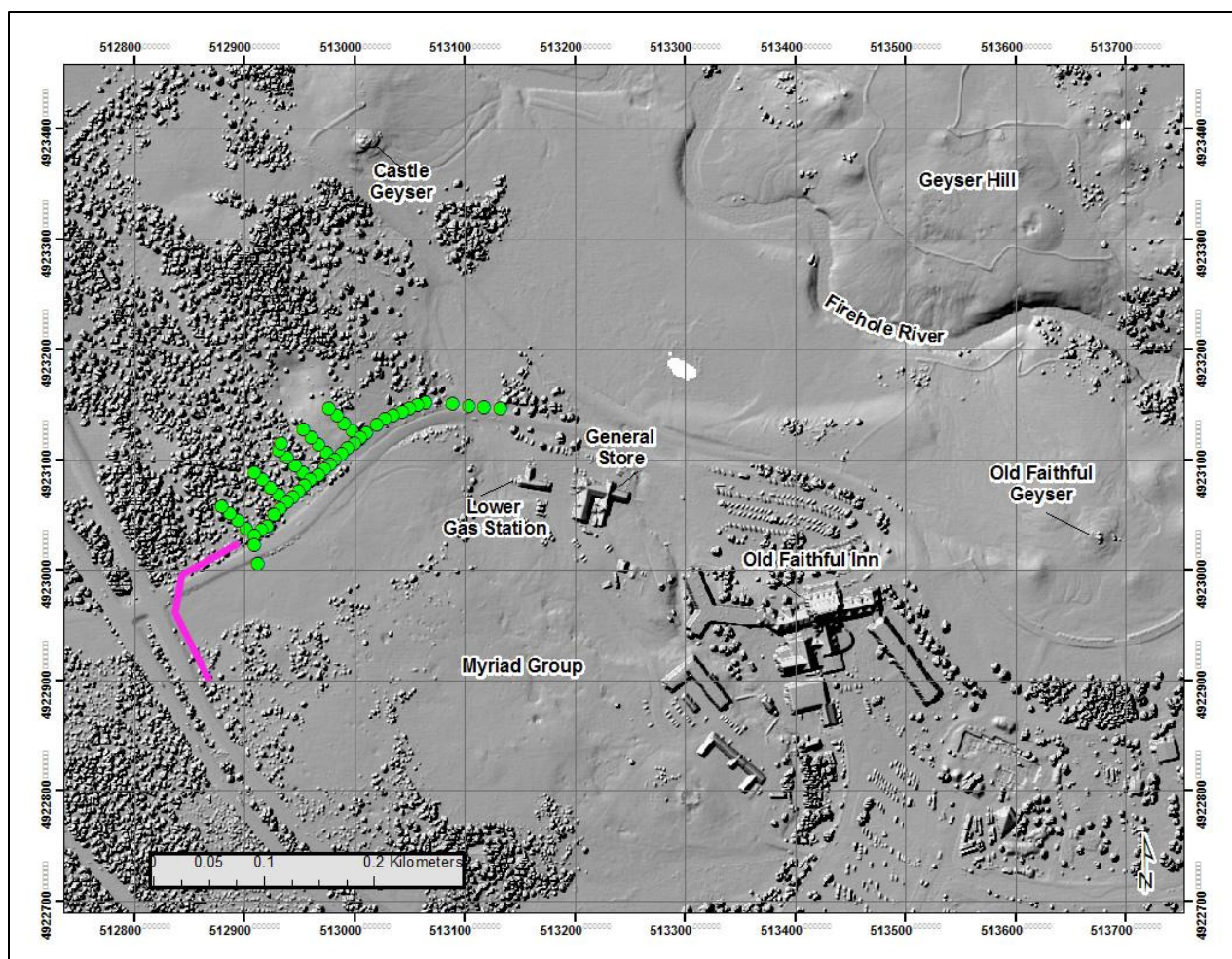


**Figure 2.** A LiDAR base map showing locations (green circles) assessed for temperatures and gases along proposed route of the Old Faithful sewer line. Approximate location of an alternate route is shown by the solid purple line. Notice the General Store, lower gas station, roads, and trees shown on this 2008 digital elevation model. The Myriad Group, part of the Upper Geyser Basin hydrothermal system, extends south from the access road towards the Old Faithful Inn, the General Store, and the bottom of the image. Active hydrothermal features (Castle and Old Faithful geysers) and Geyser Hill are shown on the map. The NSF EarthScope project funded the acquisition of this geodetic-grade LiDAR imagery (LiDAR publically available at [www.opentopography.org](http://www.opentopography.org)) of the Upper Geyser Basin.

## METHODS

Three ground surveys were conducted on 15 May 2014, 24 June 2014, and 2 July 2014. The following paragraphs describe the techniques and instruments used during the 15 May 2014 and 24 June 2014 surveys. The survey conducted on 2 July 2014 was a reconnaissance due to the presence of ponded hydrothermal water and cavernous ground (see Appendix A).

On 15 May 2014, YNP geologists conducted a ground survey shortly after NPS personnel marked the proposed route for the OF sewer line (Figures 3 and 4). 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 subsurface 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 detect unsafe levels of gas and measure the amounts of hydrothermal gases in the 32 holes. Hydrothermal gases measured were carbon dioxide, hydrogen sulfide, and sulfur dioxide. Oxygen and methane also were measured. The Drager X-am meter was calibrated using fresh air before beginning gas measurements and calibrated three times during measurements. There were no detectable levels of hydrogen sulfide, sulfur dioxide, or methane. Temperature and gas (carbon dioxide and oxygen) data measured on 15 May 2014 are presented in Appendix B.

On 24 June 2014, YNP geologists conducted a second ground survey. The area of this geologic assessment was a roughly rectangular area to the northwest of the points measured on 15 May 2014. This area was chosen to determine *if* the hydrothermal system was less active to the northwest of the proposed route chosen in May. Temperature and gas (carbon dioxide and oxygen) data measured on 24 June 2014 are presented in Appendix C.

Along the potential routes (Figures 3, 4, and 5), 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.

The morning of both investigations, geologists located a site for a standard 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. The data from the temperature loggers were used to determine the effect of solar heating on the temperatures at 85 cm (33.5 inches) depth through the day. Both on 15 May 2014 and 24 June 2014, the temperature at 85 cm (33.5 inches) remained constant throughout the day. The constant temperature at 85 cm depth indicated that the temperature value of the drill hole was not affected by daily solar heating. The standard holes were not used for comparing subsurface temperatures or carbon dioxide gas concentrations.

After installation of the temperature logger in the hole, geologists drilled all measurement 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, geologists could not measure gas concentration because the hole filled with hydrothermal water (11.4 to 13.2 °C).

A mobile mapping unit recorded accurate 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  $\pm 5$  to 15 cm ( $\pm 2$  inches to 6 inches) along the proposed sewer line route that parallels the road. Due to data acquisition difficulties, the locations for holes 11 and 29 were estimated. For lines A through E, the horizontal accuracy of the corrected points (100%) varied between  $\pm 5$  and 30 cm ( $\pm 2$  inches to 12 inches).

In the office, geologists transferred the field notes (temperatures, gas, and stratigraphy) into an excel spreadsheet for analyses. Temperature and gas concentration data are presented in Appendices B and C.

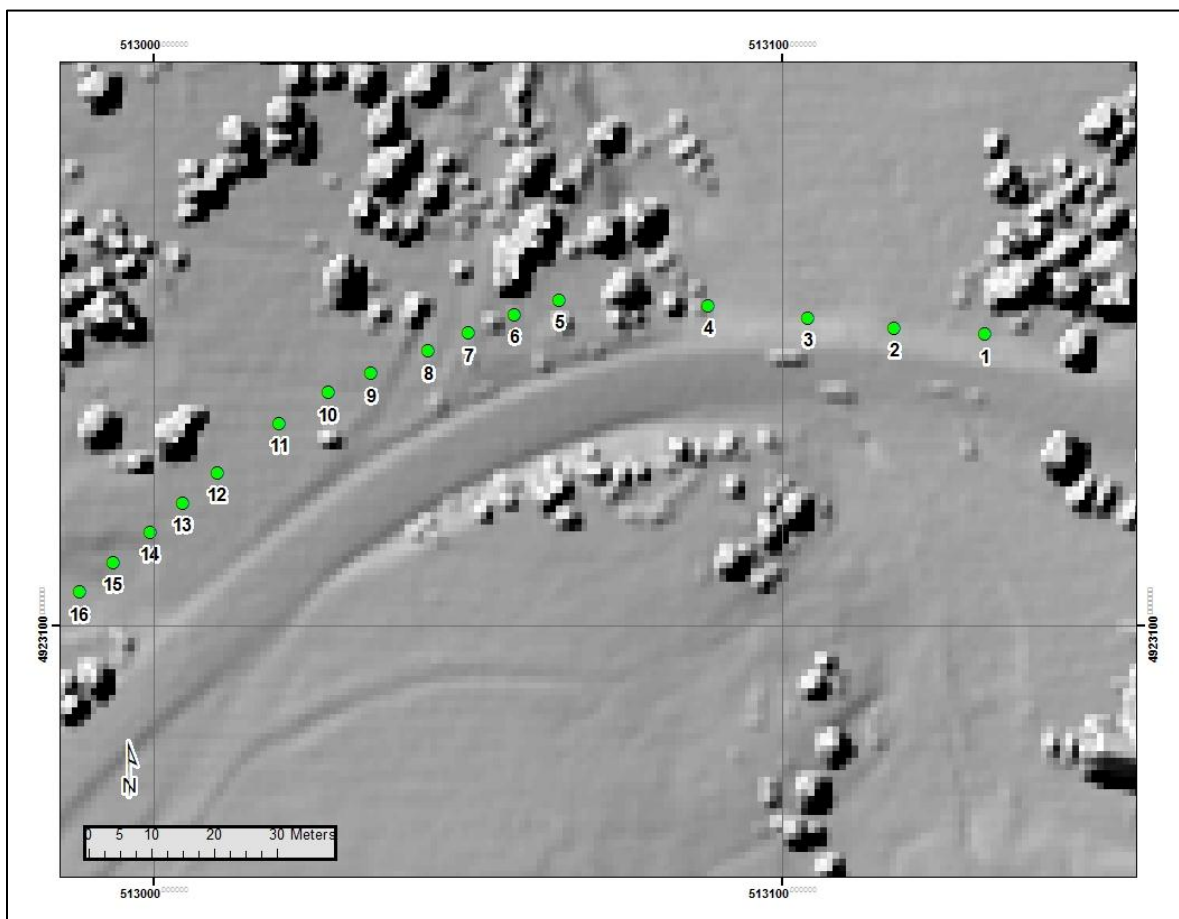


**Figure 3.** A LiDAR base map showing locations (1-16) assessed for subsurface temperatures, hydrothermal gases, and stratigraphy along proposed route of the Old Faithful sewer line on 15 May 2014. The NSF EarthScope project funded the acquisition of this geodetic-grade imagery (LiDAR publicly available at [www.opentopography.org](http://www.opentopography.org)) of the Upper Geyser Basin.

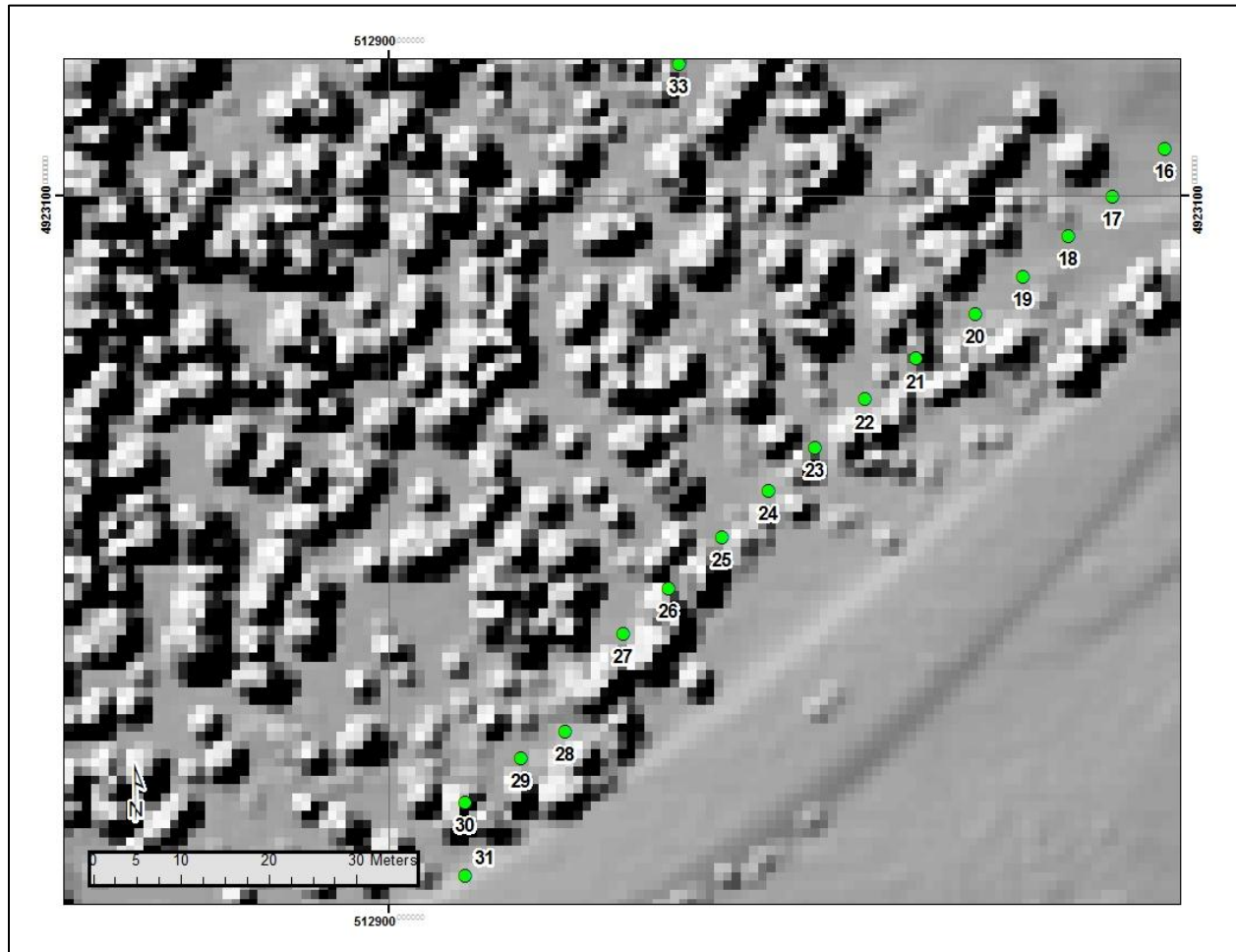


**Figure 4.** A LiDAR base map showing locations (16-31) assessed for subsurface temperatures, hydrothermal gases, and stratigraphy along proposed route of the Old Faithful sewer line on 15 May 2014. North-northwest of the Three Sisters, hole number 22 had the highest subsurface temperature for this propose route. Hole 33 was the location of the standard hole. The NSF EarthScope project funded the acquisition of this geodetic-grade imagery (LiDAR publically available at [www.opentopography.org](http://www.opentopography.org)) of the Upper Geyser Basin.

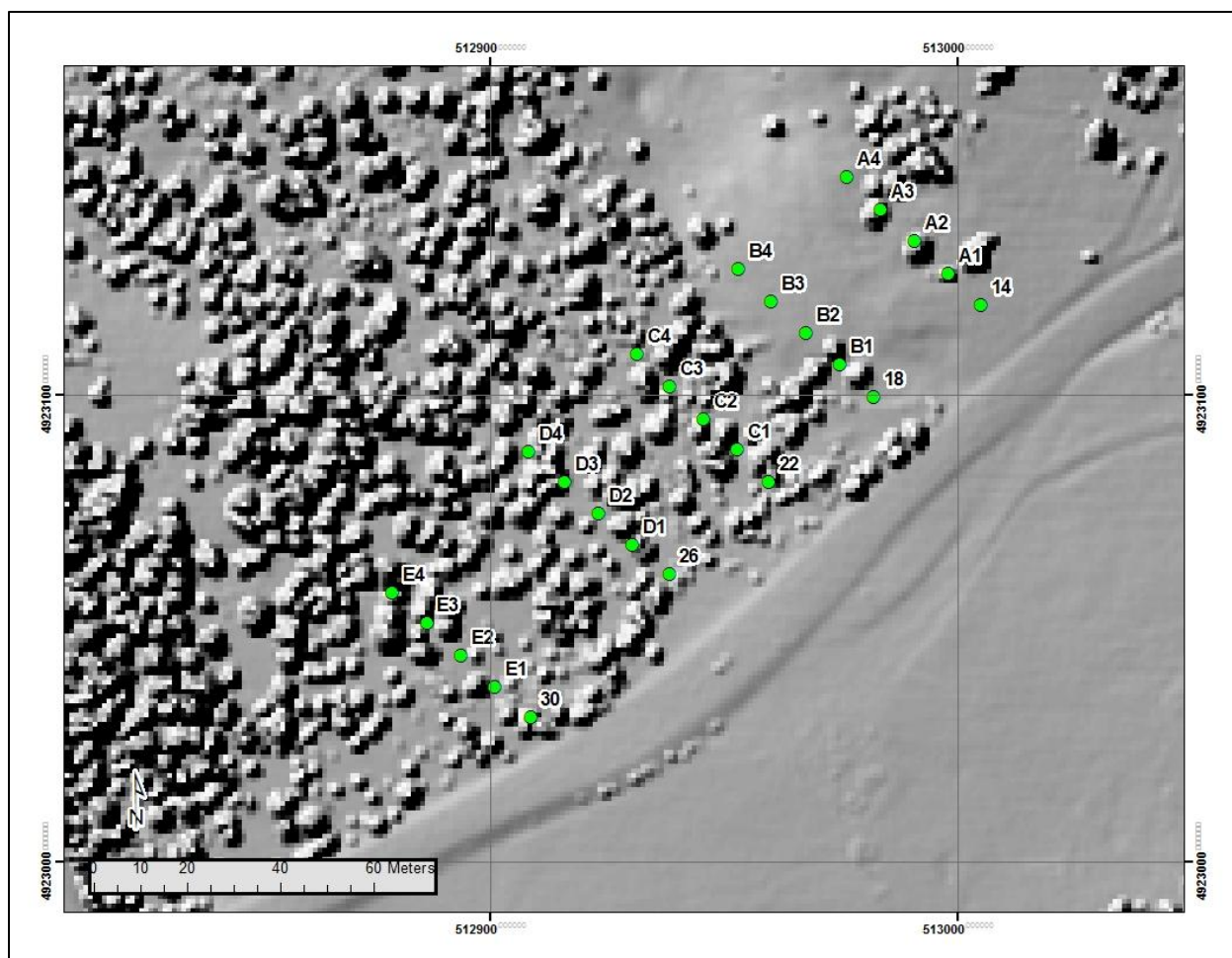


**Figure 5.** A LiDAR base map showing locations (A1-E4) assessed for subsurface temperatures, hydrothermal gases, and stratigraphy along proposed route of the Old Faithful sewer line on 24 June 2014. Holes 14, 18, 22, 26, and 30 from the 15 May 2014 assessment are shown as reference locations for the sewer line route. North-northwest of the Three Sisters, hole number B2 had the highest subsurface temperature (72.5 °C, 162.5 °F) for the 24 June 2014 assessment. The NSF EarthScope project funded the acquisition of this geodetic-grade imagery (LiDAR publicly available at [www.opentopography.org](http://www.opentopography.org)) of the Upper Geyser Basin.

## RESULTS

### Subsurface Temperatures

Temperatures were measured at 50 and 85 cm (19.7 and 33.5 inches) depth for ground surveys on 15 May 2015 and 24 June 2015. Temperatures for both depths are presented in Appendices B and C. However, because temperatures at 85 cm (33.5 inches) depth are more reliable indicators of hydrothermal activity, only the temperature data for 85 cm (33.5 inches) are displayed in the RESULTS section.

Figure 6 presents temperatures measured on 15 May 2014 at 85 cm (33.5 inches) depth along the route of the proposed sewer line (see Figures 3 and 4 for locations). At 85 cm (33.5 inches) depth, the maximum temperature was 39.7 °C (103.5 °F) in hole 22.

Figures 7-11 present temperatures measured on 24 June 2014 at 85 cm (33.5 inches) depth in a roughly rectangular area to the northwest of the points measured on 15 May 2014 (see Figure 5 for locations). At 85 cm (33.5 inches) depth, the maximum temperature was 72.5 °C, (162.5 °F) in hole B2.

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 approximately 92 °C (198 °F).

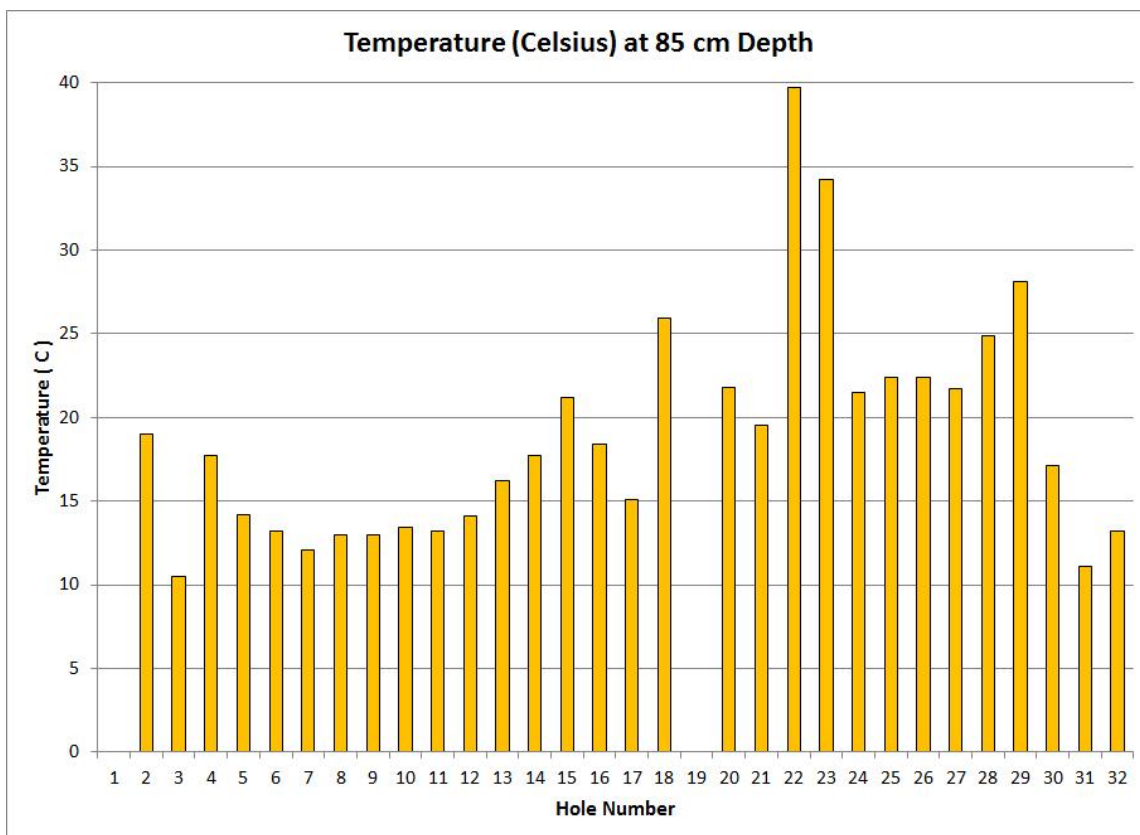


**Figure 6.** Graph showing temperatures at 85 cm (33.5 inches) depth for all holes along the sewer line route. Due to a hard substrate, measurements could not be drilled beyond 50 cm (19.7 inches) depth at hole 19. Note the high temperature value of 39.7 °C (103.5 °F) in hole 22. See Figures 3 and 4 for locations.

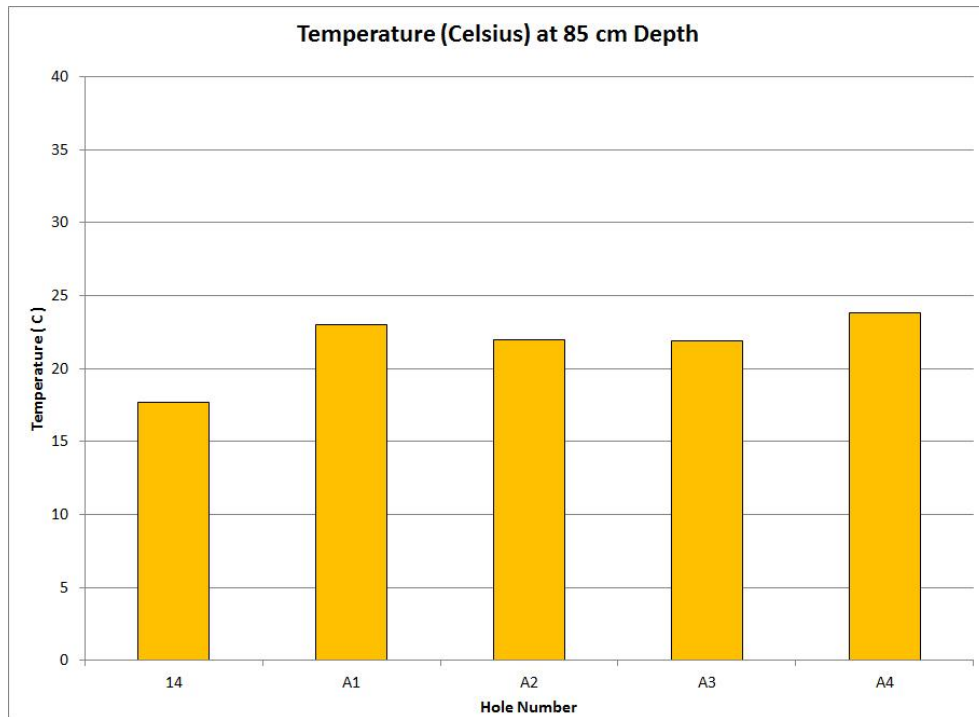


**Figure 7.** Graph showing temperatures at 85 cm (33.5 inches) depth for line “A” extending perpendicular (northwest) to the sewer line route. See Figure 5 for locations.

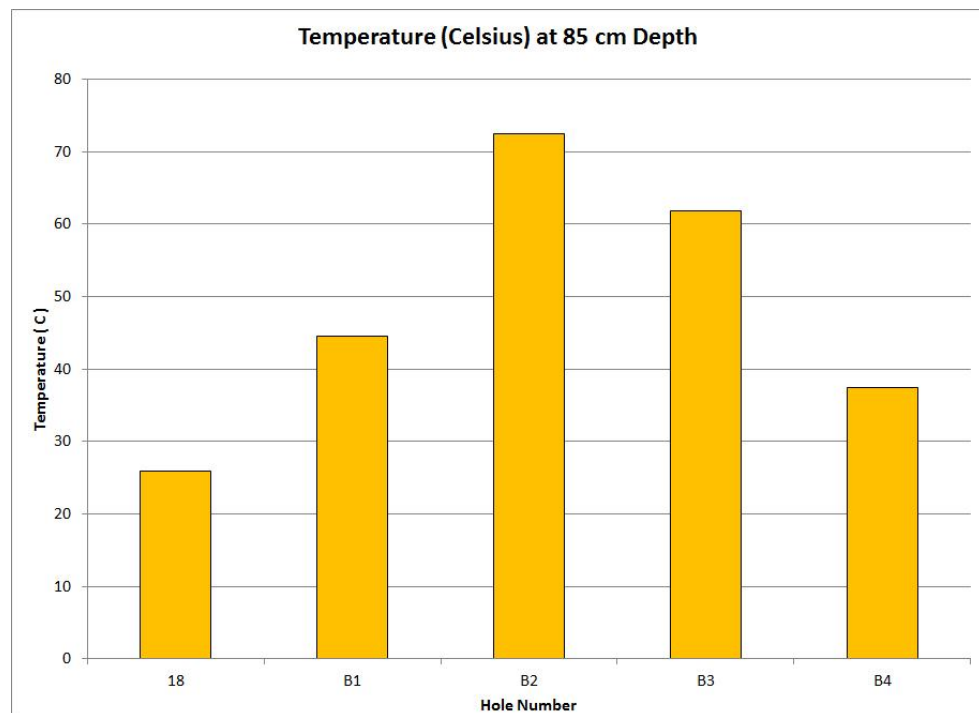


**Figure 8.** Graph showing temperatures at 85 cm (33.5 inches) depth for line “B” extending perpendicular (northwest) to the sewer line route. Note the increased temperature scale for this graph. A temperature value of 72.5 °C (103.5 °F) was measured in hole B2. See Figure 5 for locations.

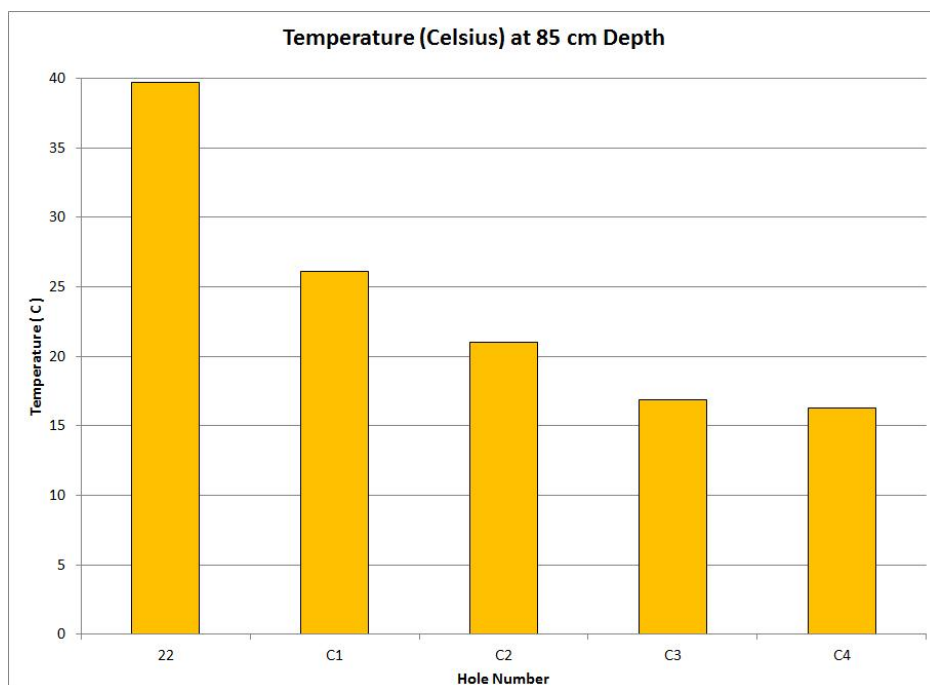


**Figure 9.** Graph showing temperatures at 85 cm (33.5 inches) depth for line “C” extending perpendicular (northwest) to the sewer line route. See Figure 5 for locations.

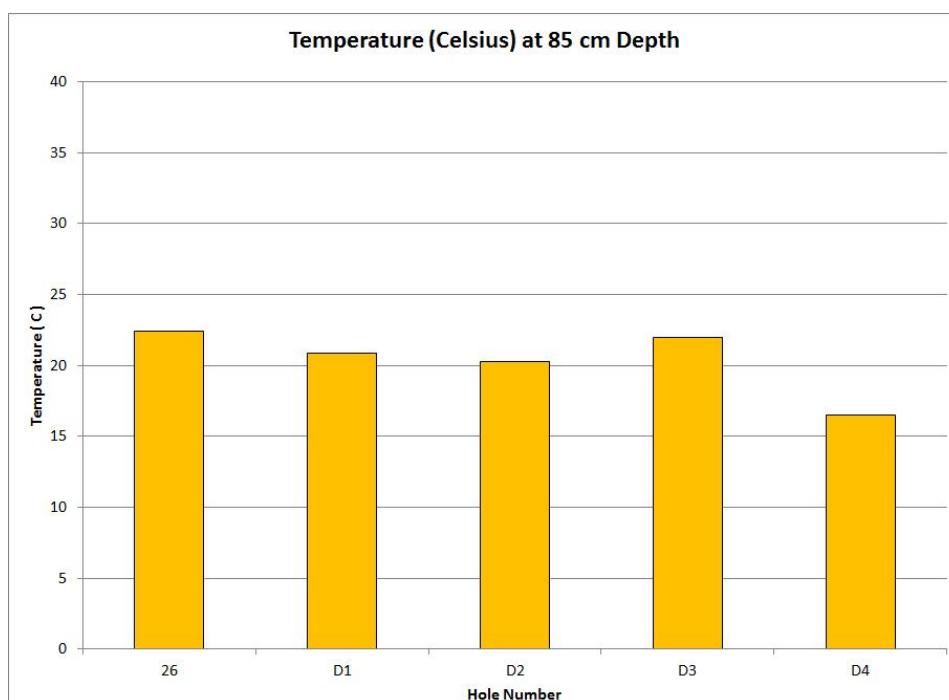


**Figure 10.** Graph showing temperatures at 85 cm (33.5 inches) depth for line “D” extending perpendicular (northwest) to the sewer line route. See Figure 5 for locations.

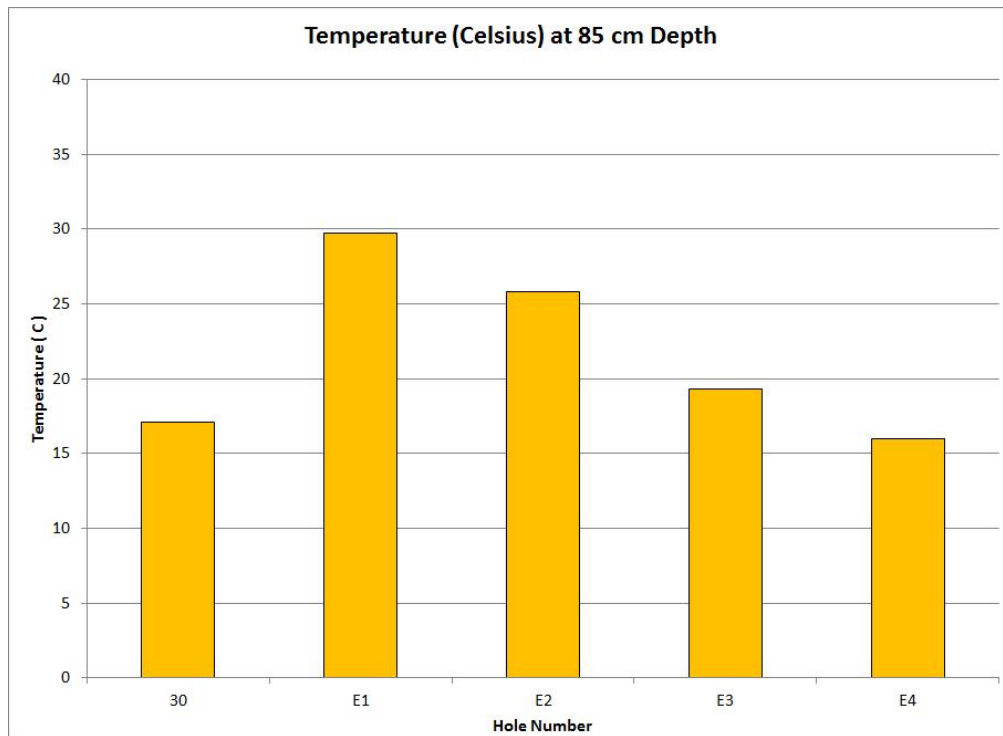


**Figure 11.** Graph showing temperatures at 85 cm (33.5 inches) depth for line “E” extending perpendicular (northwest) to the sewer line route. See Figure 5 for locations.

### Hydrothermal Gas Measurements

Hydrothermal gas concentrations at 42 locations along the proposed routes of the sewer line 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 and 24 June 2014, carbon dioxide was the primary hydrothermal gas detected (Appendices B and C). Gas measurements could not be made in all holes either due to the presence of water, collapsing of the hole, or inability to deepen the hole to 85 cm (33.5 inches).

Some background information on carbon dioxide gas will place the measured values in perspective. The concentration of carbon dioxide 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 carbon dioxide 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.

Elevated carbon dioxide levels at 85 cm (33.5 inches) depth generally is apparent in Figure 12 and Figures 14-17. At 85 cm depth, the highest measured carbon dioxide level on 15 May 2014 was 3.5 % in hole 22 (see Figure 4 for location). On 24 June 2014, the highest carbon dioxide level measured was 2.7% in hole C1 (see Figure 5 for location).

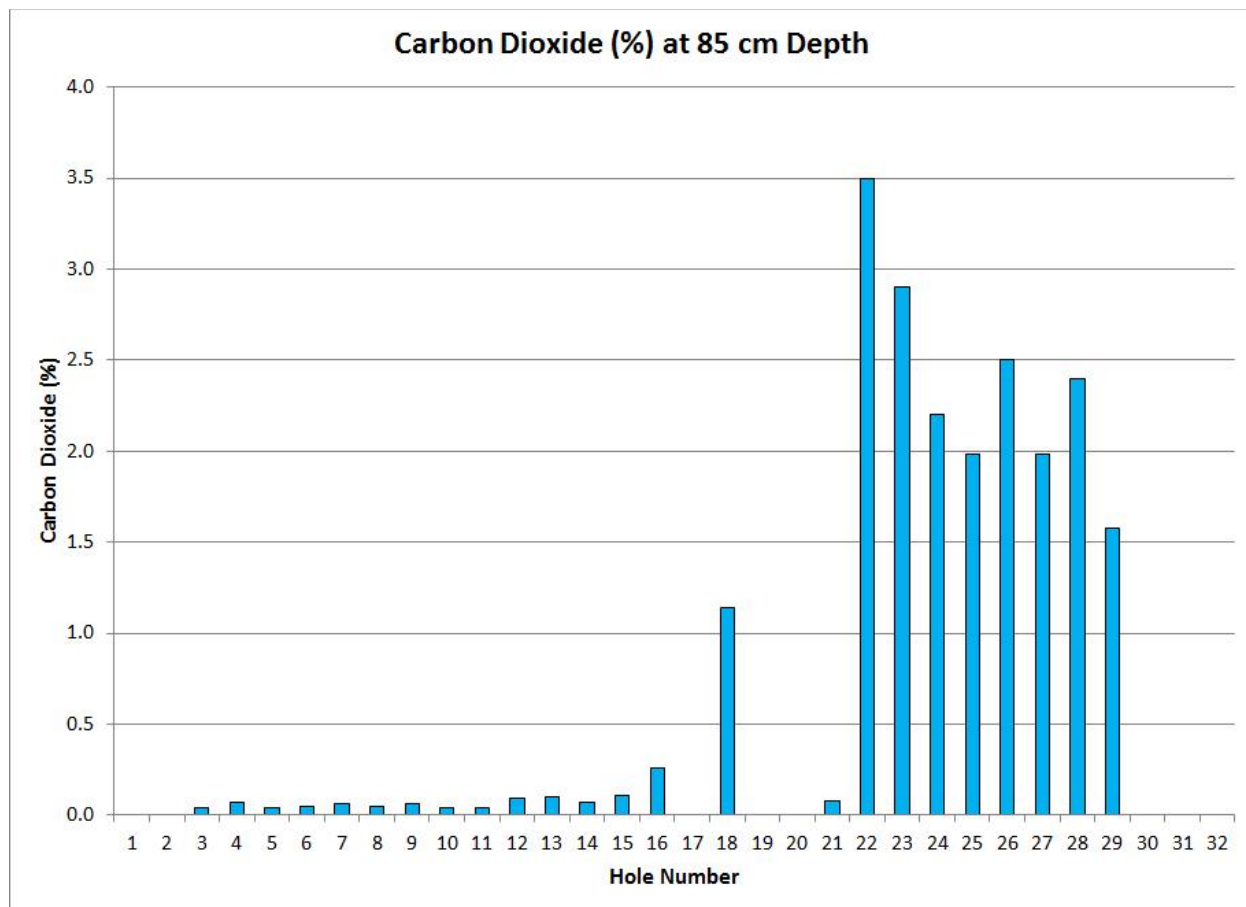


**Figure 12.** Graph showing carbon dioxide gas concentration (%) at 85 cm (33.5 inches) depth for all holes along the sewer line route. Gas measurements were not possible in all holes either due to water in the holes, collapsing holes, or holes that could not be drilled beyond 50 cm (19.7 inches) depth 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. See Figures 3 and 4 for locations.

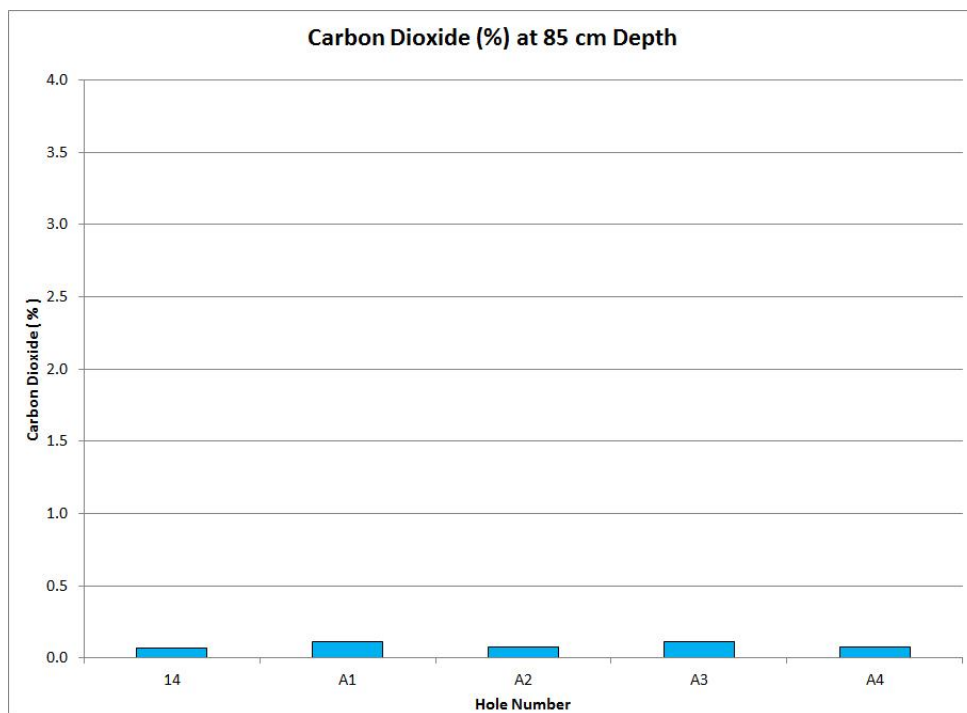


**Figure 13.** Graph showing carbon dioxide concentrations (%) at 85 cm (33.5 inches) depth for line “A” extending perpendicular (northwest) to the sewer line route. See Figure 5 for locations.

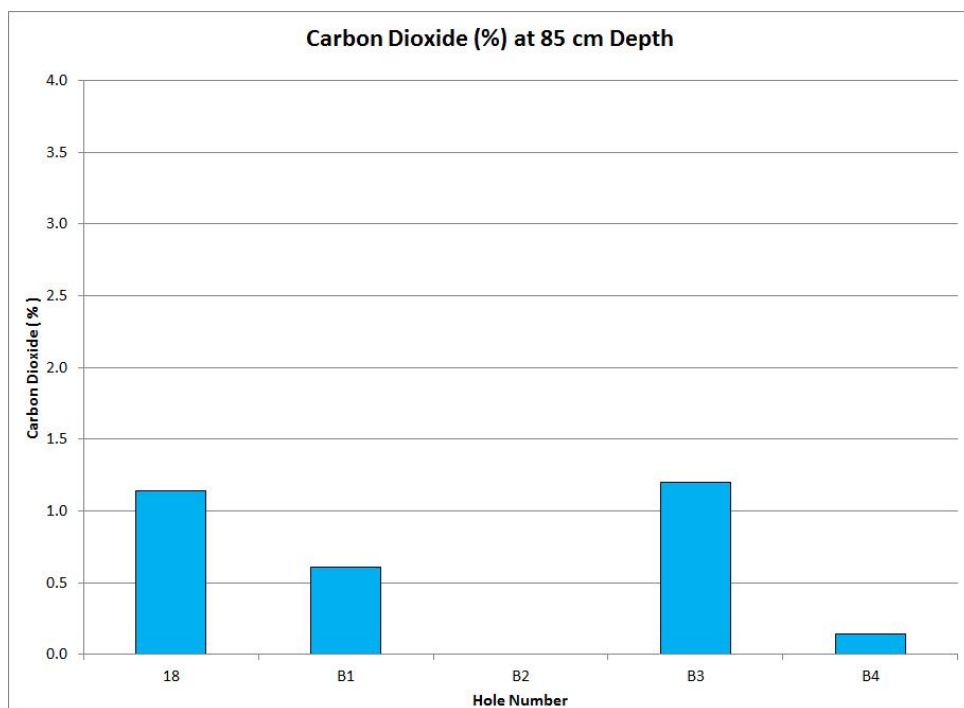


**Figure 14.** Graph showing carbon dioxide concentrations (%) at 85 cm (33.5 inches) depth for line “B” extending perpendicular (northwest) to the sewer line route. See Figure 5 for locations.

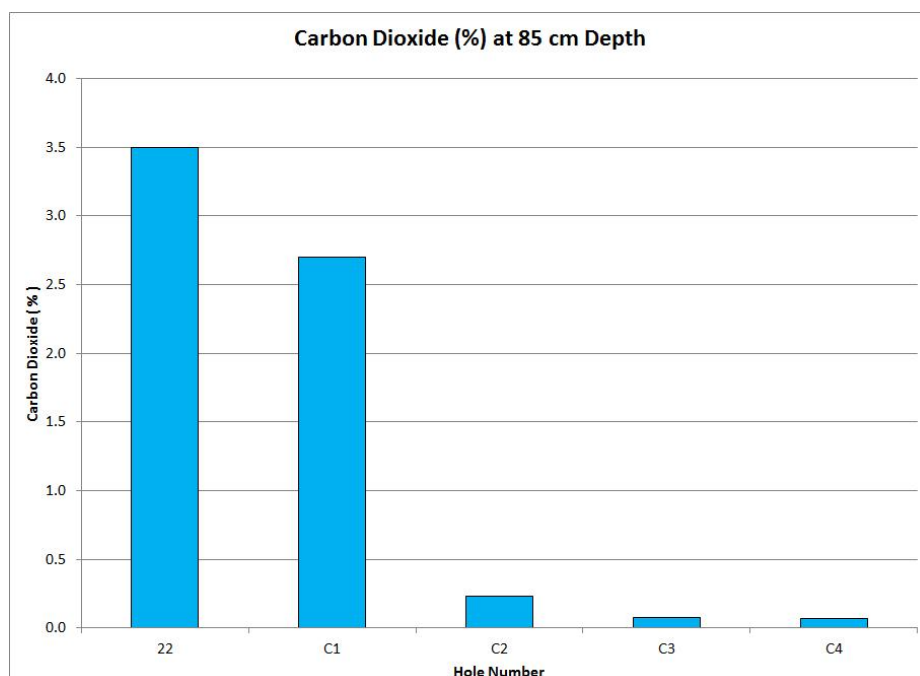


**Figure 15.** Graph showing carbon dioxide concentrations (%) at 85 cm (33.5 inches) depth (line “C”) and perpendicular (northwest) to the sewer line route. The highest carbon dioxide gas concentration (3.5 %) in hole 22 measured on 14 May 2014 is adjacent to the highest gas concentration (2.7%) in hole C1 measured on 24 June 2014. See Figure 5 for locations.

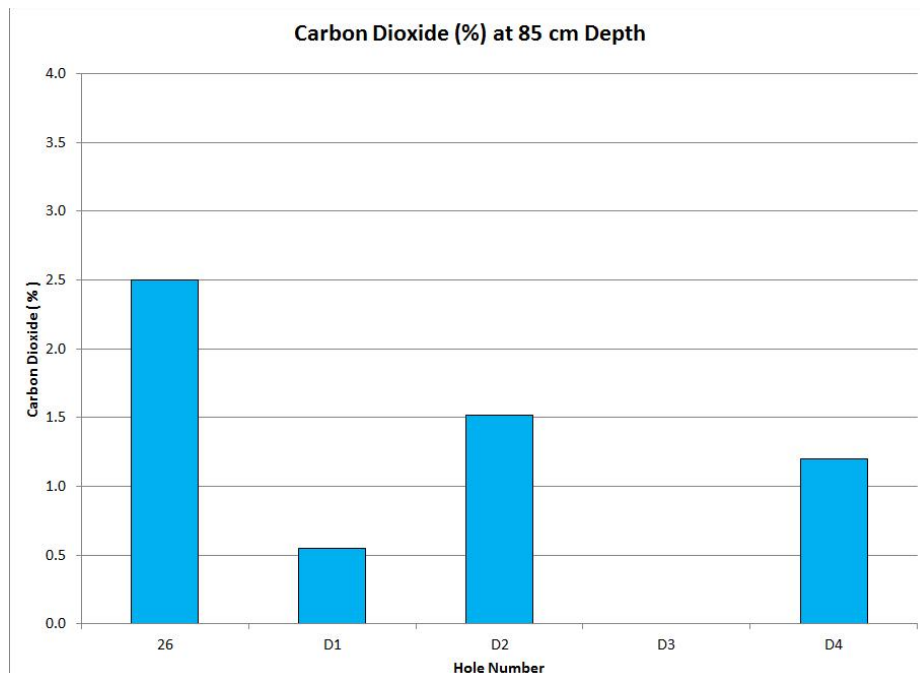


**Figure 16.** Graph showing carbon dioxide concentrations (%) at 85 cm (33.5 inches) depth for line “D” extending perpendicular (northwest) to the sewer line route. See Figure 5 for locations.

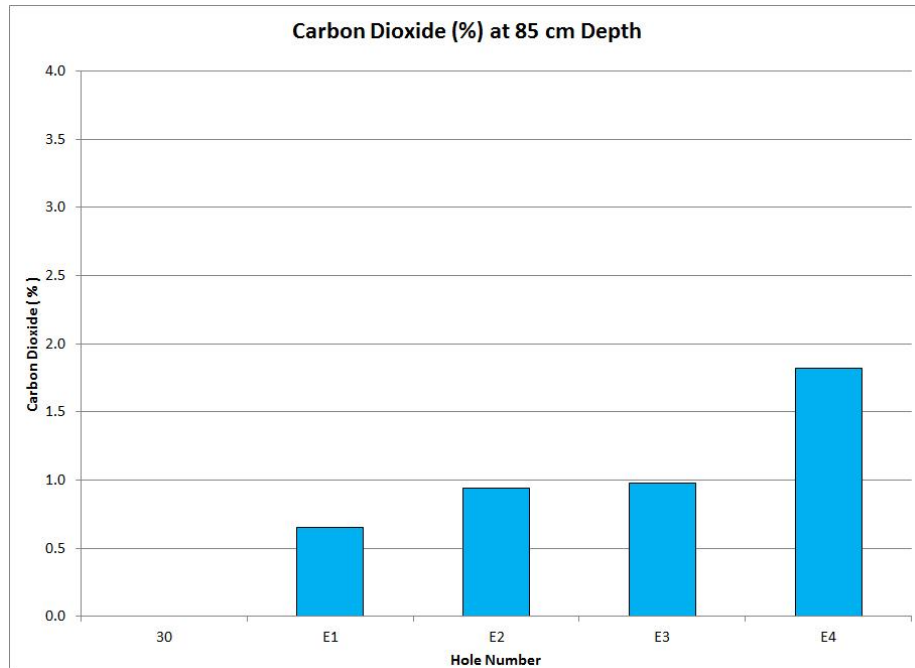


**Figure 17.** Graph showing carbon dioxide concentrations (%) at 85 cm (33.5 inches) depth for line “E” extending perpendicular (northwest) to the sewer line route. See Figure 5 for locations.

### Temperature and Gas Concentration Maps

Temperatures in degrees Celsius and carbon dioxide concentrations in percent for 85 cm (33.5 inches) depth are shown in Figures 18-23. In general, temperatures and carbon dioxide gas concentrations increase to the southwest along the proposed sewer line route. This generally coincides with proximity to the Three Sisters hot springs. Isolated low temperature values shown on Figures 18, 20, and 22 coincide with the presence of cool surface water flowing into the drill holes.

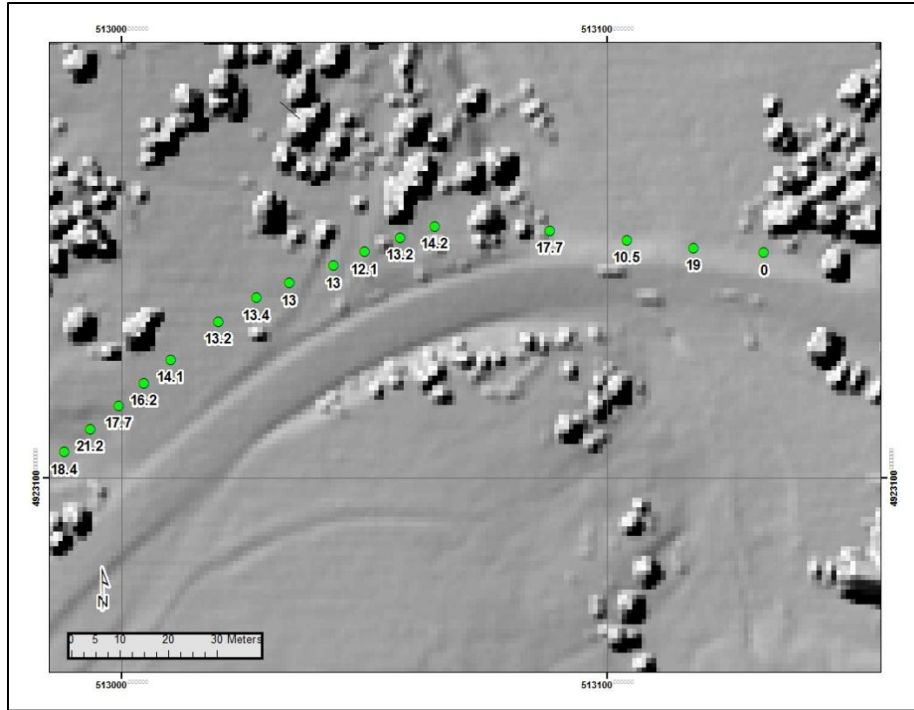


**Figure 18.** LiDAR image showing eastern access road and temperatures ( $^{\circ}\text{C}$ ) at 85 cm (33.5 inches) depth. See Figure 3 for locations. Zero values indicate no data. (LiDAR publicly available at [www.opentopography.org](http://www.opentopography.org)).

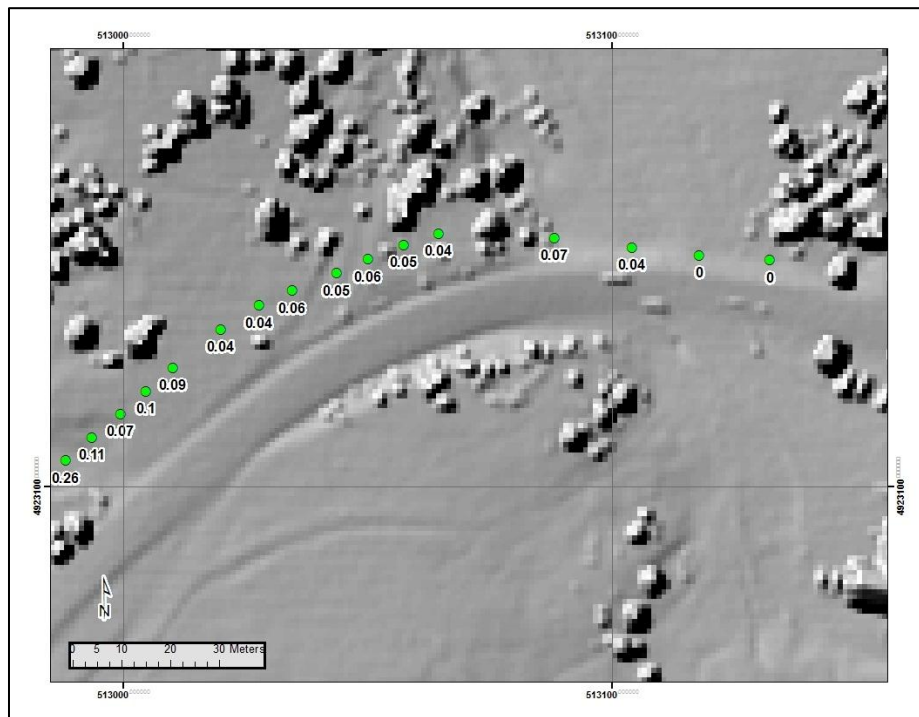


**Figure 19.** LiDAR image showing carbon dioxide gas concentrations (%) at 85 cm (33.5 inches) depth. See Figure 3 for locations. Zero values indicate no data. Compare figures 18 and 19. (LiDAR publicly available at [www.opentopography.org](http://www.opentopography.org)).

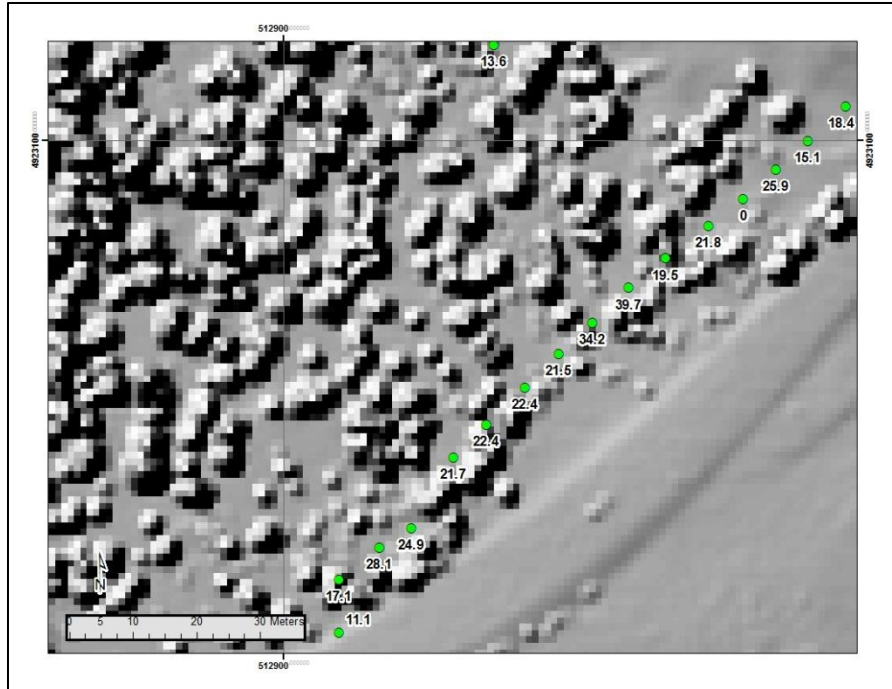


**Figure 20.** LiDAR image showing access road and temperatures ( $^{\circ}\text{C}$ ) at 85 cm (33.5 inches) depth. See Figure 4 for locations. Zero values indicate no data. (LiDAR publicly available at [www.opentopography.org](http://www.opentopography.org)).

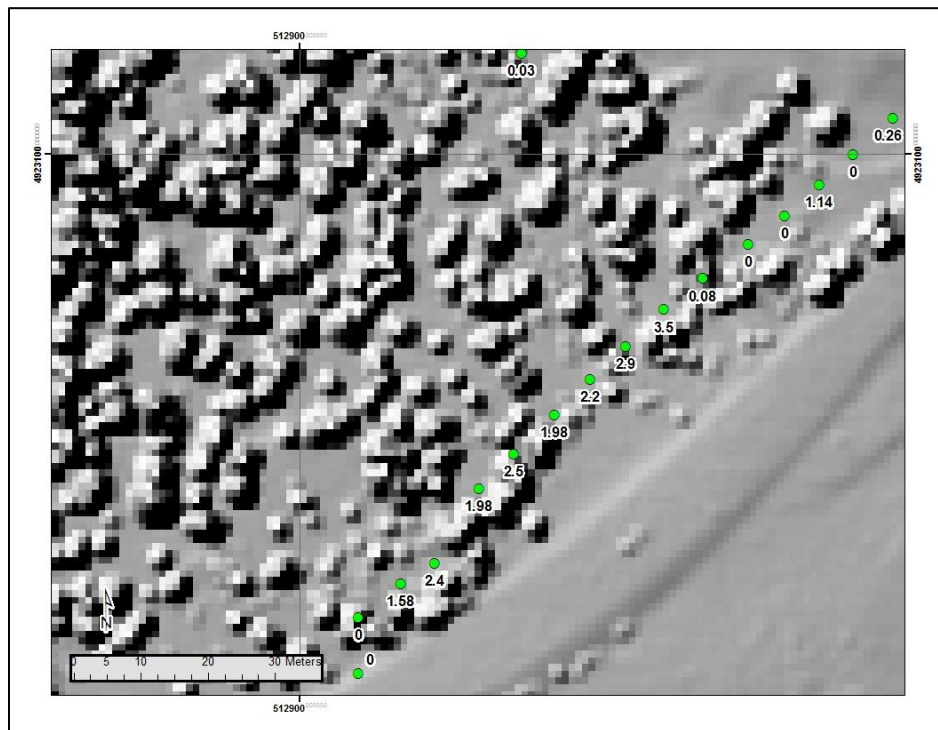


**Figure 21.** LiDAR image showing carbon dioxide gas concentrations (%) at 85 cm (33.5 inches) depth. See Figure 4 for locations. Zero values indicate no data. Compare figures 20 and 21. (LiDAR publicly available at [www.opentopography.org](http://www.opentopography.org)).

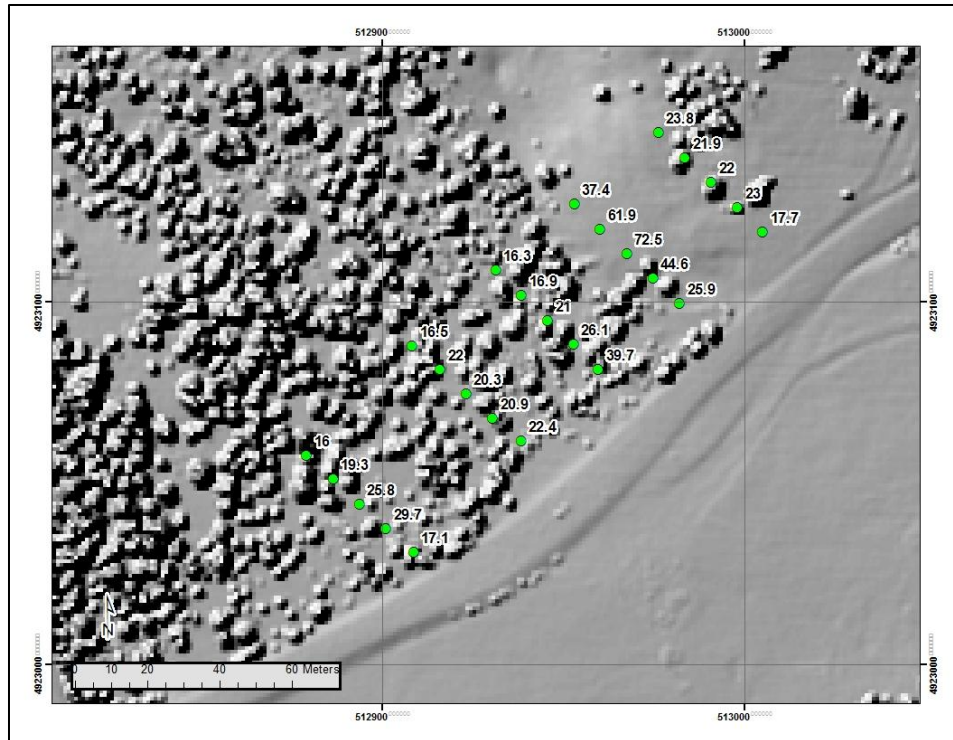


**Figure 22.** LiDAR image showing access road and temperatures ( $^{\circ}\text{C}$ ) at 85 cm (33.5 inches) depth. See Figure 5 for locations. (LiDAR publicly available at [www.opentopography.org](http://www.opentopography.org)).

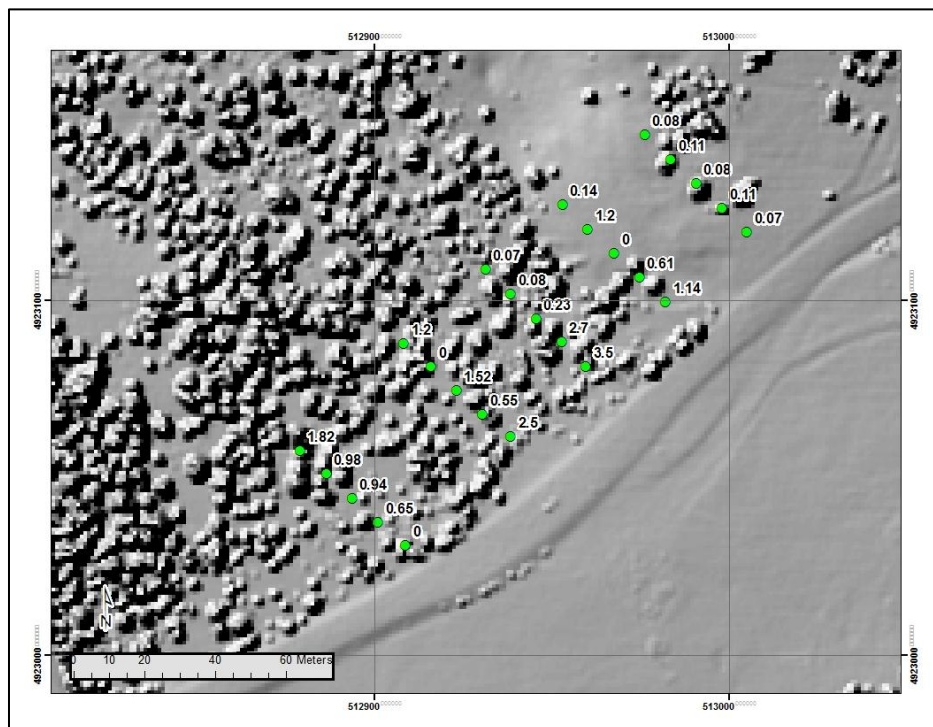


**Figure 23.** LiDAR image showing carbon dioxide gas concentrations (%) at 85 cm (33.5 inches) depth. See Figures 5 for locations. Zero values indicate no data. Compare figures 22 and 23. (LiDAR publicly available at [www.opentopography.org](http://www.opentopography.org)).

## SUMMARY

Fifty-two ½ inch holes were drilled to assess temperatures and carbon dioxide gas concentrations (Appendices B and C). Forty-eight holes had reliable temperature measurements at 85 cm (33.5 inches) depth. Forty-two holes had reliable gas concentration values at 85 cm (33.5 inches) depth.

Figure 24 presents the temperatures for all measurable holes at a depth of 85 cm (33.5 inches). All but two temperatures (holes 3 and 31) indicate an active hydrothermal system with a high heat flow. Holes 3 and 31 encountered surface water and are not considered reliable subsurface temperatures. Anomalous high temperatures in this active hydrothermal system are considered any temperature greater than or equal to 20 °C. This criteria applies to holes 15, 18, 19, 22-29, A1-C1, D1-D3, E1 and E2 (Figure 24).

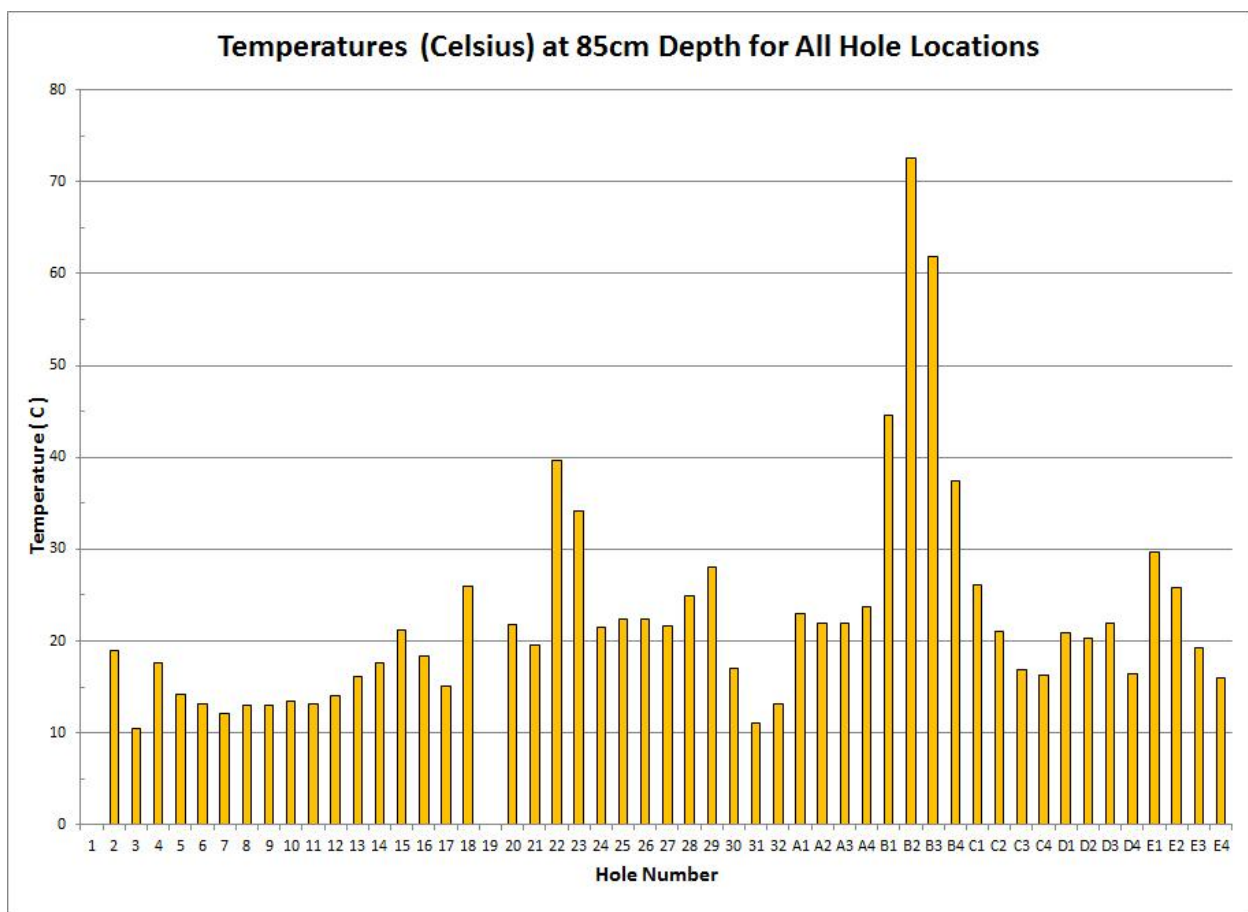


**Figure 24.** Graph showing temperatures at 85 cm depth (33.5 inches) for all holes. See Figure 3–5 for locations of the holes.

Concentration of carbon dioxide gases are an indication of an active hydrothermal system. Figure 25 displays carbon dioxide concentrations for all measurable holes at 85 cm depth (33.5 inches). The concentration of carbon dioxide in fresh outdoor air is approximately 330 ppm

(0.033%). Indoors or within a trench, carbon dioxide can become slightly elevated where there is insufficient ventilation. 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). Consequently, we considered a concentration of carbon dioxide greater than or equal to 1 % as an estimate of anomalous carbon dioxide values. Holes that meet or exceed this value are 18, 22-29, B3, C1, D2, D4, and E4.

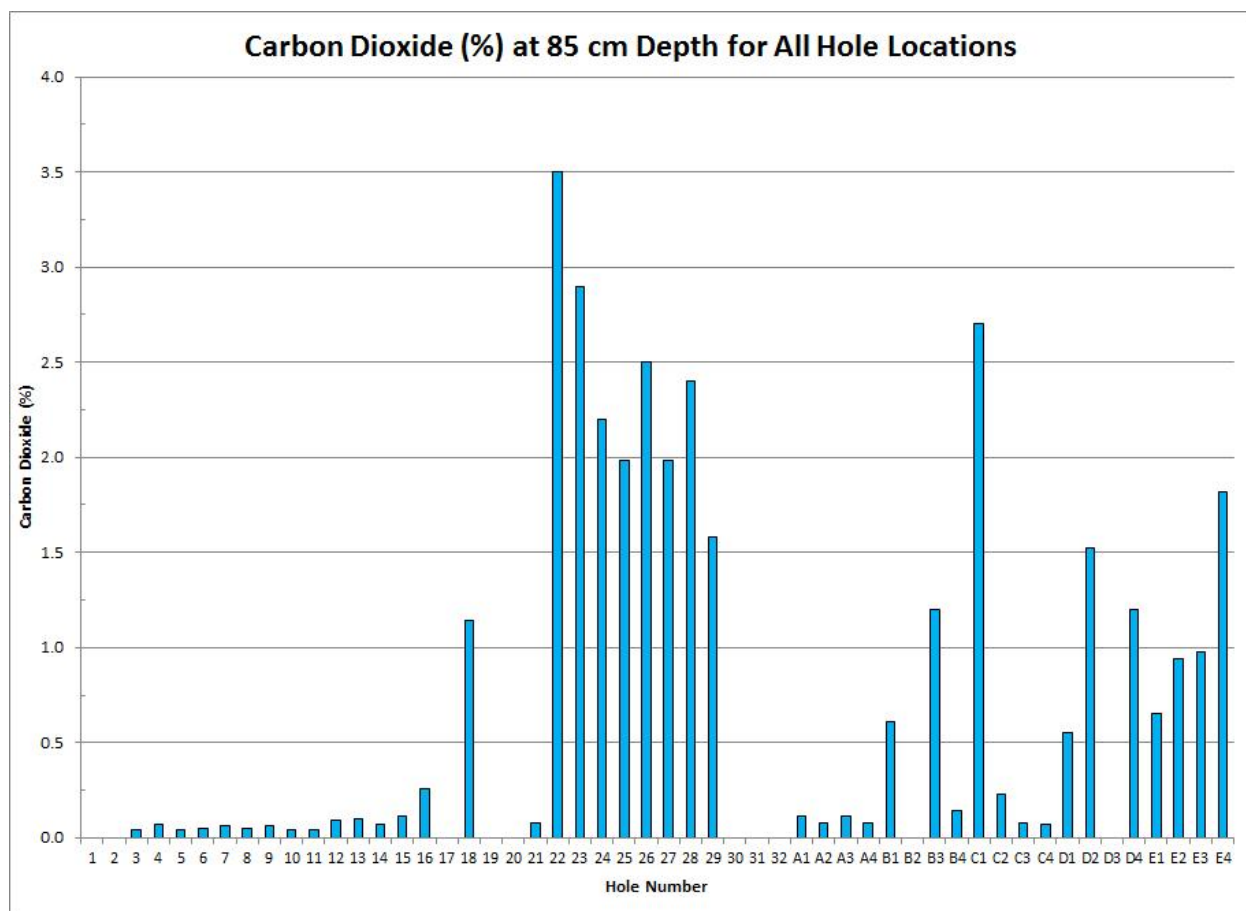


**Figure 25.** Graph showing carbon dioxide gas concentration at 85 cm depth for all holes. See Figure 3–5 for locations of the holes.

The geologic assessment indicates that the area along the access road is within an active hydrothermal system. Figure 26 is a map showing all holes with anomalously high temperatures or carbon dioxide gas concentrations for the active hydrothermal system. The map shows a discontinuous pattern of anomalous values. For example, the eastern portion of the proposed sewer line shows temperatures lower than 20°C and gas concentrations lower than 1% carbon dioxide. In contrast, the western portion of the proposed sewer line generally shows temperatures greater than 20°C and gas concentrations greater than 1% CO<sub>2</sub>. Along lines perpendicular to the access road, temperatures generally are greater than 20°C and gas concentrations greater than 1% carbon dioxide.

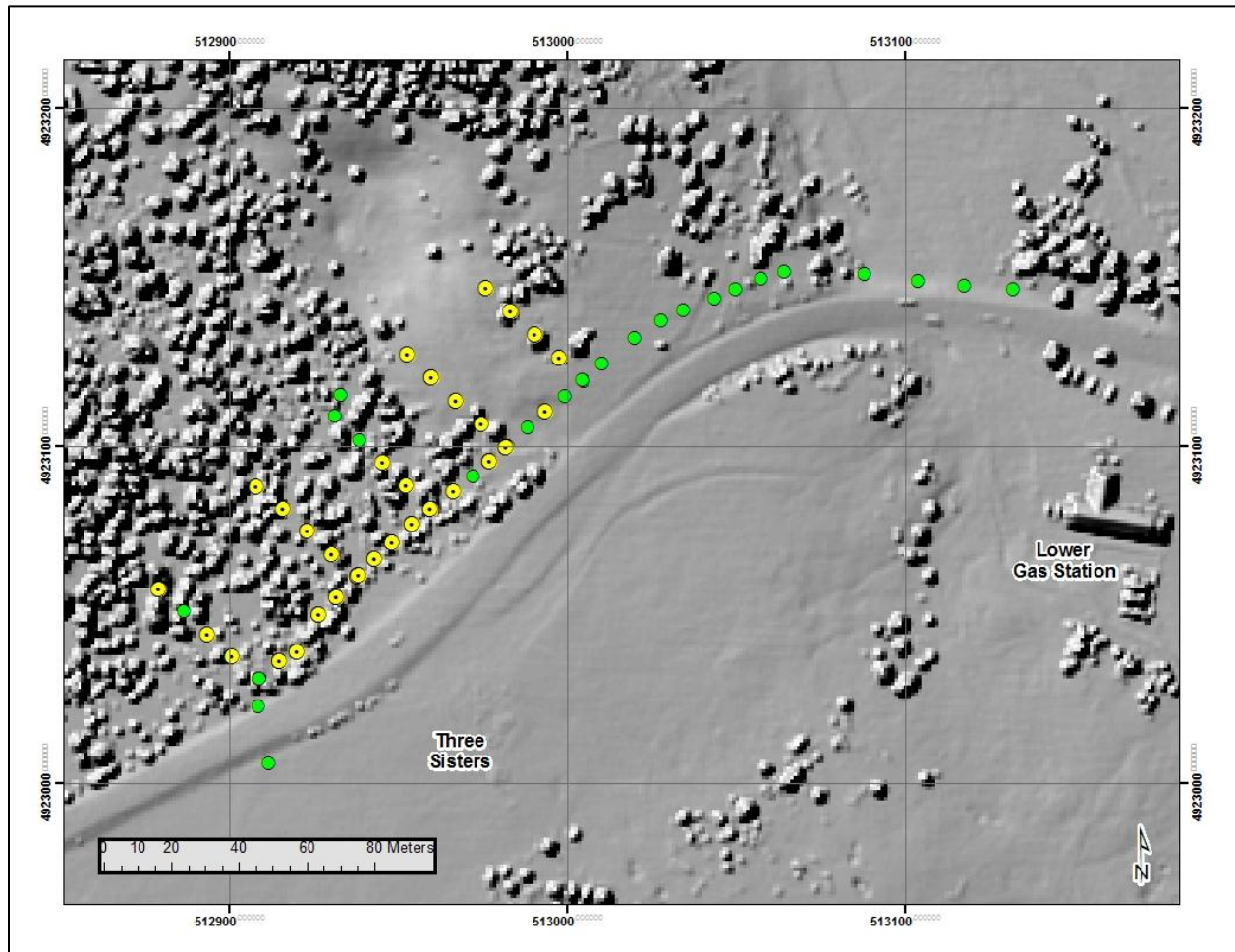


**Figure 26.** LiDAR image of all holes showing anomalously high temperatures at 85 cm depth (temperatures greater than or equal to 20°C) or anomalously high CO<sub>2</sub> gas concentrations (greater than or equal to 1 %) for the active hydrothermal system. Yellow circles with center dots show the locations that meet both criteria. (LiDAR publically available at [www.opentopography.org](http://www.opentopography.org)).

The proposed Old Faithful Inn sewer line replacement occurs within an active hydrothermal system. Evidence supporting this statement includes elevated subsurface 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 individual hydrothermal features and the hydrothermal system. At this time, potential anthropogenic impacts to the hydrothermal resource and individual features cannot be determined with certainty.

## REFERENCES CITED

- Christiansen, R.L., 2001, The Quaternary and Pliocene Yellowstone Plateau Volcanic Field of Wyoming, Idaho, and Montana: U.S.G.S. Professional Paper 729-G, 145 p.
- Christiansen, R.L., and Blank, Jr., H.R., 1974, Geologic Map of the Old Faithful Quadrangle: U.S. Geological Survey Geologic Quadrangle Map GQ1189, Scale 1:62,500.
- Heasler, Henry, and Jaworowski, Cheryl, 2014, Hydrothermal Assessment of the Proposed Old Faithful Inn Sewer Line Route, Yellowstone National Park, Geology Program, Yellowstone Center for Resources, Yellowstone National Park, June 2, 2014: YNP Geology Program report, 20 p.
- Heasler, Henry, and Jaworowski, Cheryl, 2005, Investigation of Shallow Ground Water Movement in the Immediate Area of the Old Faithful Visitor Center, Geology Program, Yellowstone Center for Resources, Yellowstone National Park, February 28, 2005: YNP Geology Program report, 48 p.
- Heasler, Henry, Jaworowski, Cheryl, Feeney, Chelsea, and Foley, Duncan, 2009a, Temperature Measurements at the Historic Old Faithful Pub, Yellowstone National Park, Geology Program, Yellowstone Center for Resources, Yellowstone National Park, 27 July 2009: YNP Geology Program report, 8 p.
- Heasler, Henry, Jaworowski, Cheryl, Feeney, Chelsea, Carr, Brett, and Foley, Duncan, 2009b, Preliminary Geothermal Analyses of the Area at the Historic Old Faithful Pub, Yellowstone National Park, Geology Program, Yellowstone Center for Resources, Yellowstone National Park, 24 August 2009: YNP Geology Program report 19 p.
- Muffler, L.J.P., White, D.E., Beeson, M.H., and Truesdell, A.H., 1982, Geologic Map of the Upper Geyser Basin, Yellowstone National Park, Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I-1371, Scale 1:4,800.
- Old Faithful Science Review Panel, 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, 28 p., <http://dx.doi.org/10.3133/ofr20141058>.
- OSHA, 2006, Limits for Air Contaminants, [http://www.osha.gov/pls/oshaweb/owadisp.show\\_document?p\\_table=STANDARDS&p\\_id=9992](http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9992), web site accessed on March 26, 2008.
- Waldrop, H.A., 1975, Surficial Geologic Map of the Old Faithful Quadrangle: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-649, Scale 1:62,500.
- Watts, K.E., Bindeman, I.N., and Schmitt, A.K., 2012, Crystal scale anatomy of a dying supervolcano: an isotope and geochronology study of individual phenocrysts from voluminous rhyolites of the Yellowstone caldera: Contributions to Mineralogy and Petrology.

## **Appendix A**

### **Hydrothermal Assessment of the 2 July 2014 Alternate Sewer Line Route**

## Hydrothermal Assessment of the 2 July 2014 Alternate Sewer Line Route

On 2 July 2014, Yellowstone National Park geologists examined a proposed alternate sewer line route within the Old Faithful area. The proposed alternate route extended approximately 75 m west-southwest from the previously measured temperatures, crossed the access road (approximately 50 m) and paralleled the two-lane road for an additional 75 m (See Figures 1 and 2 in main text).

The west-southwest portion of the proposed re-route traversed an area (approximately 7 by 8 m) containing several hydrothermal vents and depressions. This area was approximately 6-13 m from the edge of the lower service road. The size and shape of the hydrothermal vents or depressions varied (Figures A1-A5; Table A1); some were roughly circular and others were oblong (Table A1). Additionally, hydrothermal feature “D” contained an inclined vent (approximately 1.5 by 1 m extending to a depth of approximately 1.9 m) that trended to the southwest for a distance of 4 m. No hydrothermal gases or temperatures were measured. This area, centered on UTM 12 T 0512866 E and 4923008 N (NAD83 datum), clearly indicated past hydrothermal activity as well as minimal hydrothermal activity at the ground surface currently.

**Table A1. Measurements of Hydrothermal Vents and Depressions**

| Name | Width (m) | Length (m) | Depth (m) | Comments                   |
|------|-----------|------------|-----------|----------------------------|
| A1   | 1         | 1.8        | NA        | depression                 |
| A2   | 1.5       | 1.8        | NA        | depression                 |
| B    | 1.5       | 1.8        | NA        | depression                 |
| C    | .8        | .8         | 1.5-2     | 2.5 m cavern               |
| D    | 1.5       | 2.5        | 2.5       | Moss or lichen around edge |



**Figure A1.** Photograph of hydrothermal depressions “A1 and A2” on 2 July 2014. Notice the green depressed areas with vegetation. The black-and-white portion of the north arrow is 10 cm in length.



**Figure A2.** Photograph of hydrothermal vent “C”. The two-lane service road is visible in the background. View to the south on 2 July 2014.



**Figure A3.** Photograph of hydrothermal vent “C” on 2 July 2014. Notice the green vegetation at the mouth of the cavern potentially indicating the presence of water vapor. The black-and-white portion of the north arrow is 10 cm in length.



**Figure A4.** Photograph of hydrothermal vent “D”. The two-lane service road is visible in the background. View to the south on 2 July 2014.

After crossing the two-lane service road, the next portion (approximately 38 m N-S; 24 m E-W) of the alternate sewer line route traverses an area with flowing hydrothermal water. Some hydrothermal water (~15-20 gpm, visual estimate) exits through a culvert while other hydrothermal water stagnates near the road embankment (Figure A5). Various plants grow on the wet, siliceous sinter (Figures A5 and A6).

The gas measurement technique used on 15 May 2014 and 24 June 2014 is not applicable in the area of cavernous ground shown in Figures A1-A4. Caverns and vents form conduits for the collection of hydrothermal gases. Thus, a network of drill holes would not provide reliable values of carbon dioxide concentration.

Also, the temperature measurement technique used on 15 May 2014 and 24 June 2014 is not applicable in the area of cavernous ground shown in Figures A1-A4. The presence of air in the caverns drastically changes the temperature pattern in the ground making the temperatures difficult to interpret.

Yellowstone geologists would not be able to measure temperatures nor hydrothermal gases in the area shown in Figures A5 and A6 due to the presence of water. Water flowing into drilled holes invalidates temperature measurements and precludes the measurement of gases.



**Figure A5.** Photograph showing an alternate sewer line route. The alternate route crosses the two-lane service road near the intersection of the two-lane service road with the four-lane road. The YNP staff near the upper center of the photograph is standing near the four-lane road and along the proposed alternate route. Hydrothermal water from the Three Sisters flows towards the culvert and stagnates by the road embankment. View to the west on 2 July 2014.



**Figure A6.** Close-up of YNP staff in Figure A5 showing sea arrowgrass (*Triglochin maritima*; Roy Renkin, Yellowstone National Park, 17 July 2014) in bloom and growing on wet, siliceous sinter near the four-lane road embankment. The YNP staff is standing near the proposed route and is pointing in the approximate direction of the alternate sewer line route. View to the south on 2 July 2014.

## **Appendix B**

### **Locations and Hydrothermal Assessment Data for 15 May 2014**

Data for Temperature, gas survey, 15 May 2014, Old Faithful Sewer Line Project

Datum WGS84

| Name | Northing | Easting | Depth (cm) | Temp (°C) | CO2 (%) | O2 (%) | Depth (cm) | Temp (°C) | CO2 (%) | O2 (%) |
|------|----------|---------|------------|-----------|---------|--------|------------|-----------|---------|--------|
| 1    | 4923146  | 513132  | 25         | 11.3      | 0.03    | 20.9   |            |           |         |        |
| 2    | 4923147  | 513118  | 50         | 14.7      | 0.06    | 20.9   | 80         | 19.0      |         |        |
| 3    | 4923149  | 513104  | 50         | 9.1       | 0.04    | 20.9   | 60         | 10.5      | 0.04    | 20.9   |
| 4    | 4923151  | 513088  | 50         | 13.5      | 0.07    | 20.9   | 85         | 17.7      | 0.07    | 20.9   |
| 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   |
| 8    | 4923144  | 513044  | 50         | 12.3      | 0.05    | 20.9   | 85         | 13.0      | 0.05    | 20.9   |
| 9    | 4923140  | 513035  | 50         | 14.0      | 0.04    | 20.9   | 85         | 13.0      | 0.06    | 20.9   |
| 10   | 4923137  | 513028  | 50         | 13.7      | 0.05    | 20.9   | 85         | 13.4      | 0.04    | 20.9   |
| 11   | 4923132  | 513020  | 50         | 12.5      | 0.03    | 20.9   | 85         | 13.2      | 0.04    | 20.9   |
| 12   | 4923124  | 513010  | 50         | 13.2      | 0.05    | 20.9   | 85         | 14.1      | 0.09    | 20.9   |
| 13   | 4923119  | 513005  | 50         | 13.9      | 0.04    | 20.9   | 85         | 16.2      | 0.10    | 20.9   |
| 14   | 4923115  | 512999  | 50         | 15.2      | 0.04    | 20.9   | 85         | 17.7      | 0.07    | 20.9   |
| 15   | 4923110  | 512994  | 50         | 15.2      | 0.21    | 20.9   | 85         | 21.2      | 0.11    | 20.9   |
| 16   | 4923105  | 512988  | 50         | 14.8      | 0.15    | 20.9   | 85         | 18.4      | 0.26    | 20.9   |
| 17   | 4923100  | 512982  | 50         | 12.8      | 0.06    | 20.9   | 85         | 15.1      |         |        |
| 18   | 4923095  | 512977  | 50         | 20.2      | 2.65    | 20.1   | 85         | 25.9      | 1.14    | 20.6   |
| 19   | 4923091  | 512972  | 48         | 20.5      | 0.06    | 20.9   | 85         |           |         |        |
| 20   | 4923087  | 512967  | 50         | 18.0      | 0.22    | 20.9   | 85         | 21.8      |         |        |
| 21   | 4923081  | 512960  | 50         | 16.6      | 0.05    | 20.9   | 65         | 19.5      | 0.08    | 20.9   |
| 22   | 4923077  | 512954  | 50         | 28.0      | 1.96    | 20.1   | 85         | 39.7      | 3.50    | 19.8   |
| 23   | 4923071  | 512949  | 50         | 24.0      | 1.82    | 20.1   | 85         | 34.2      | 2.90    | 19.8   |
| 24   | 4923066  | 512943  | 50         | 14.8      | 0.07    | 20.9   | 85         | 21.5      | 2.20    | 19.5   |
| 25   | 4923061  | 512938  | 50         | 16.0      | 1.12    | 20.1   | 85         | 22.4      | 1.98    | 19.6   |
| 26   | 4923055  | 512932  | 50         | 16.6      | 0.43    | 20.5   | 85         | 22.4      | 2.50    | 19.2   |
| 27   | 4923050  | 512927  | 50         | 16.2      | 0.96    | 20.2   | 85         | 21.7      | 1.98    | 19.3   |
| 28   | 4923039  | 512920  | 50         | 18.8      | 1.40    | 20.0   | 85         | 24.9      | 2.40    | 19.4   |
| 29   | 4923036  | 512915  | 50         | 21.7      | 1.50    | 18.9   | 85         | 28.1      | 1.58    | 19.7   |
| 30   | 4923031  | 512909  | 50         | 14.0      | 0.06    | 20.9   | 85         | 17.1      |         |        |
| 31   | 4923023  | 512909  | 50         | 9.7       | 0.06    | 20.9   | 85         | 11.1      |         |        |
| 32   | 4923006  | 512911  | 50         | 11.4      |         |        | 85         | 13.2      |         |        |

## **Appendix C**

### **Locations and Hydrothermal Assessment Data for 24 June 2014**

Data for Temperature, gas survey, 24 June 2014, Old Faithful Sewer Line Project

Datum WGS84

| Name | Northing | Easting | Depth (cm) | Temp (°C) | CO2 (%) | O2 (%) | Depth (cm) | Temp (°C) | CO2 (%) | O2 (%) |
|------|----------|---------|------------|-----------|---------|--------|------------|-----------|---------|--------|
| A1   | 4923126  | 512998  | 50         | 21.8      | 0.05    | 20.9   | 85         | 23.0      | 0.11    | 20.9   |
| A2   | 4923133  | 512991  | 50         | 19.8      | 0.04    | 20.9   | 85         | 22.0      | 0.08    | 20.9   |
| A3   | 4923140  | 512984  | 50         | 18.7      | 0.01    | 20.9   | 85         | 21.9      | 0.11    | 20.9   |
| A4   | 4923146  | 512976  | 50         | 23.4      |         |        | 85         | 23.8      | 0.08    | 20.9   |
|      |          |         |            |           |         |        |            |           |         |        |
| B1   | 4923106  | 512975  | 50         | 32.7      | 1.20    | 20.6   | 85         | 44.6      | 0.61    | 20.6   |
| B2   | 4923113  | 512967  | 50         | 54.4      | 0.25    | 20.9   | 85         | 72.5      |         |        |
| B3   | 4923120  | 512960  | 50         | 48.6      |         |        | 85         | 61.9      | 1.20    | 20.4   |
| B4   | 4923127  | 512953  | 50         | 31.9      | 0.31    | 20.9   | 85         | 37.4      | 0.14    | 20.9   |
|      |          |         |            |           |         |        |            |           |         |        |
| C1   | 4923088  | 512953  | 50         | 22.8      | 0.24    | 20.9   | 85         | 26.1      | 2.70    | 18.9   |
| C2   | 4923095  | 512946  | 50         | 19.4      | 0.30    | 20.3   | 85         | 21.0      | 0.23    | 19.9   |
| C3   | 4923102  | 512938  | 50         | 17.8      | 0.07    | 20.9   | 85         | 16.9      | 0.08    | 20.9   |
| C4   | 4923109  | 512931  | 50         | 17.4      | 0.10    | 20.9   | 85         | 16.3      | 0.07    | 20.9   |
|      |          |         |            |           |         |        |            |           |         |        |
| D1   | 4923068  | 512930  | 50         | 20.0      | 0.51    | 19.9   | 85         | 20.9      | 0.55    | 20.1   |
| D2   | 4923075  | 512923  | 50         | 20.0      | 1.24    | 19.0   | 85         | 20.3      | 1.52    | 18.4   |
| D3   | 4923081  | 512916  | 48         | 20.5      |         |        | 85         | 22.0      |         |        |
| D4   | 4923088  | 512908  | 50         | 15.7      | 0.22    | 20.6   | 85         | 16.5      | 1.20    | 19.2   |
|      |          |         |            |           |         |        |            |           |         |        |
| E1   | 4923038  | 512901  | 50         | 24.4      | 0.21    | 20.6   | 85         | 29.7      | 0.65    | 20.1   |
| E2   | 4923044  | 512894  | 50         | 22.3      | 0.19    | 20.5   | 85         | 25.8      | 0.94    | 18.5   |
| E3   | 4923051  | 512886  | 50         | 17.4      | 0.30    | 20.5   | 85         | 19.3      | 0.98    | 19.7   |
| E4   | 4923058  | 512879  | 50         | 15.9      | 0.51    | 20.3   | 85         | 16.0      | 1.82    | 18.3   |