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Temperature and Pressure Sensing in Three Flooded Underground Mine Workings in Butte, Montana, USA

Tyler Hagan
Montana Tech of the University of Montana

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TYLER D. HAGAN

Department of Geological Engineering, Montana Tech of the University of Montana, 1300 W. Park Street, Butte, Montana 59701

Abstract

Temperature and pressure were measured in several flooded underground mine shafts in order to assess the potential for the development of additional mine-based geothermal heating in Butte, Montana, USA. Temperature was sensed using both optical fibers, functioning as a distributed sensor, and thermistors, functioning as point sensors; while pressure was sensed using a piezoresistive strain gauge. Upon observing good agreement between the continuous and discrete temperature sensors, we found no significant change in temperature with increasing depth within the water column. This suggests the thorough transfer of heat throughout the mine shaft via convection. Moreover, we found water temperature (T) is directly proportional to total mine shaft depth (z) via the equation: $T = 0.0225*z + 3.0194$, where T is in degrees Celsius and z is in meters – demonstrating an observed geothermal gradient of 22.5 ˚C per km.

Introduction

Geothermal heating is the direct use of geothermal energy for heating applications. As of 2007, 28 GW of geothermal heating power are installed around the world, satisfying approximately 0.07% of our primary energy consumption (Fridleifsson et al., 2008). The extraction of this heat from the Earth is accomplished with ground source heat pumps (also known as geothermal heat pumps). Thermal energy can be extracted from any source at any temperature although higher temperature sources permit higher efficiencies.

In recent years, flooded underground mine shafts and horizontal workings have been developed as heat sources to accommodate heat pumps (Kranz and Dillenardt, 2010). Using water, refrigerant, and/or antifreeze as the working fluid(s) in the heating, ventilation, and air-conditioning (HVAC) cycle, coefficients of performance (COP) ranging between 3.0 and 5.0 are practical. One example of such an installation exists in the Orphan Boy mine shaft, located in the outer mining camp of Butte, Montana (Thornton et al., 2013). See figures 1 and 2 on the next page. In winter, warm (25 ˚C) water in the mine shaft is used as the heat source, and the floors of Montana Tech's Natural Resources Building are the heat sink. Placing a closed loop geothermal heat pump between the heat source and sink increases the temperature of the working fluid from 25 ˚C to upwards of 50 ˚C. In the summer, when cooling is needed, the heating cycle is reversed: mine water becomes the heat sink, and the system becomes a refrigeration cycle. Figure 3 displays a schematic of the type of closed loop heat pump employed in the Orphan Boy mine. In this case, a closed-loop heat pump is advantageous to an open loop heat pump because it is undesirable to use mine water as the working fluid in the system (Watzlaf and Ackman, 2006).

In order to convert abandoned, flooded mine shafts into heat sources for geothermal heating, it is important to evaluate both the temperatures, and pressures, in the mine workings so thermal efficiency can be maximized (Toth and Bobok, 2007). Additionally, the cost of materials needed to install a mine-based heat pump must be weighed against the maximum temperature in the mine shaft as a means to build the most economic heating application.

The remainder of this paper describes two methods used to measure temperature and pressure, provides depth vs. temperature profiles for three flooded mine shafts, and supplies a discussion proposing sensor precision, mine shaft water convection, seasonal temperature variation, and an observed geothermal gradient for Butte, Montana, USA.

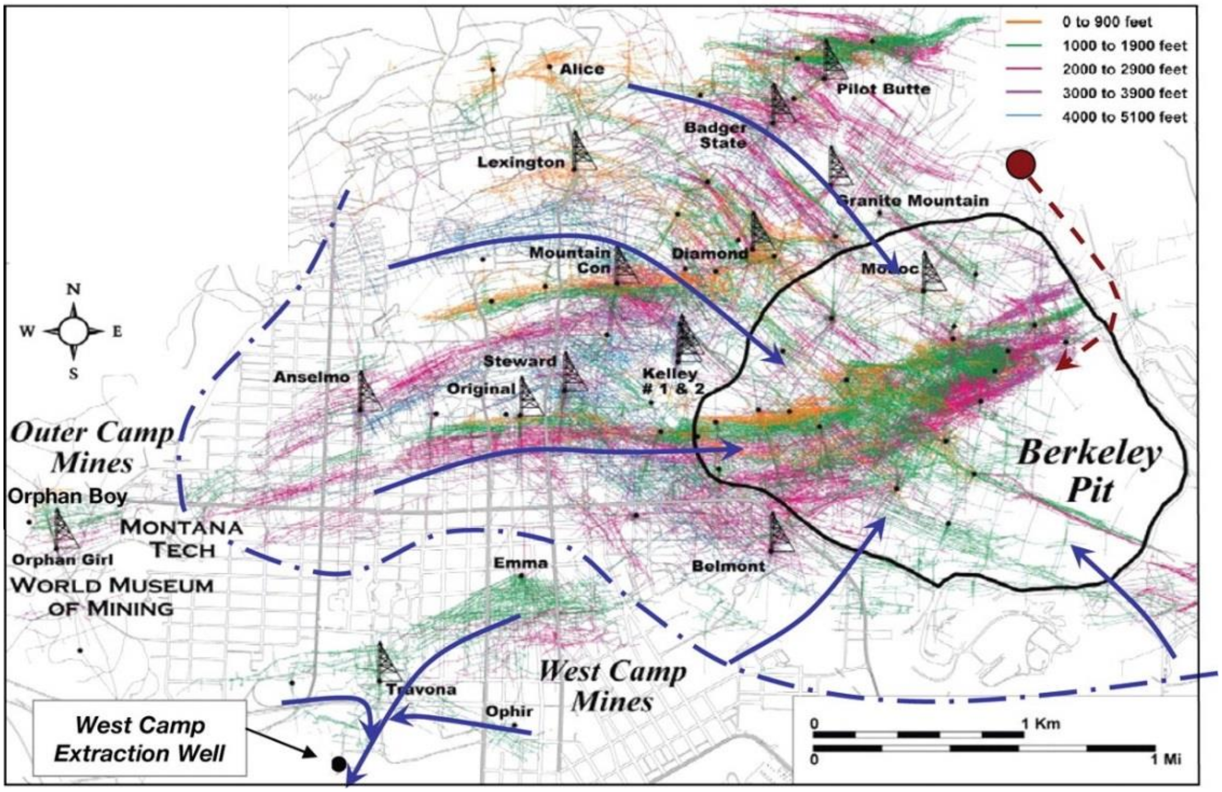

Figure 1. A plan view map shows mine shafts (head frames) and horizontal workings (colored lines) at depths between 0 and 5000 ft below the ground surface (Duaime et al. 2004 and revised by Gammons et al. 2009). The Kelley mine is located near the center of the figure and the Orphan mines are located on the left-most side of the figure.

Figure 2. Pictured is the closed-loop heat pump as it sits above the Orphan Boy mine shaft in Butte, Montana, USA. The 2011 installation of this mine-based heat pump was funded by the American Recovery and Reinvestment Act of 2009.

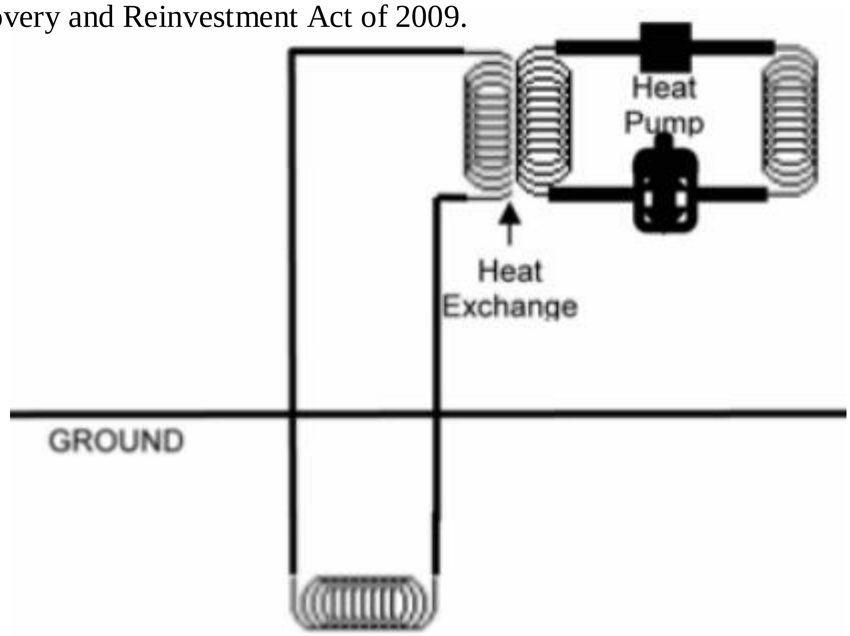

Figure 3. From Watzlaf and Ackman (2006), a closed-loop geothermal heat pump system is utilized to avoid using mine water as the working fluid. Instead, the heat pump loop (right) contains refrigerant, and the ground loop contains an antifreeze solution.

Methods

Temperature and pressure were measured in the Orphan Boy, Orphan Girl, and Kelley mine shafts (see figure 1 for locations). The two, connected, Orphan mines are located in Butte's outer mining camp on the west side of Montana Tech; these mine shafts and their respective horizontal workings constitute the underground mining education center (UMEC). The Kelley mine (located on the western margin of the Berkeley Pit) was the last of the operating mine shafts in Butte, halting operations in 1983; it was considered technologically advanced for its time, boasting a concrete-lined shaft and a cage that could hold 50 miners. A summary of the characteristics of each of the three mine shafts is outlined in the table below.

Table 1. The measured dimensions and attributes of the Orphan Boy, Orphan Girl, and Kelley mine shafts are outlined (Montana Bureau of Mines and Geology, unpublished records). Effective depth refers to the maximum depth at which temperature was sensed in this study. All three shafts have three compartments: one for miners, one for waste and ore, and one for ventilation and utilities.

	Orphan Boy	Orphan Girl	Kelley
Depth (m)	100	1000	1600
Width (m)	4	4	4
Length (m)	4	4	4
Effective depth (m)	100	400	450
# of compartments	3	3	3
Concrete lining?	No	No	Yes
Average temperature (˚C)	27	27	36

Two methods were utilized to measure temperature in the three aforementioned flooded mine shafts: distributed and point temperature sensing. Distributed (also known as continuous) temperature sensing was accomplished in the Orphan Boy mine shaft with an Omnisens DITEST STA-R™ and approximately 600 feet of fiber optic cable (see Figure 4). These instruments, in unison, record Brillouin frequency shifts of laser light along the length of the cable; the frequency shift is caused by a change in density of the glass fibers; and, the change in density is caused by thermally or mechanically induced strain (MacLaughlin and Wang, 2013). The system is, therefore, best suited for detecting changes from a baseline value rather than absolute values. The fiber optic cable is installed in a loop so that the light source/detector measures strain on the way down and on the way up. The loop configuration allows measurements to be recorded because the sensing technology requires the laser light to be sent simultaneously from each end, with one light pulse serving as the pump, to illuminate the fiber, and the other as the probe, to detect the frequency shift. This sensing technique is employed on a semi-permanent basis, and can be used to measure the seasonal variation in mine water temperature (Aminossadati et al., 2010).

Point (also known as discrete) temperature sensing was accomplished in all three mining shafts with two Hobo Tidbit thermistors/loggers, one Seastar combination thermistor-piezoresistive strain gauge, and approximately 650 meters of nylon rope (see Figure 5). All three point sensors were fastened to the rope with duct tape. A 10 kg slug was used to overcome the buoyant force of the rope; it also proved useful for dodging obstructions in the mine shafts. Point temperature sensing was implemented for three reasons: firstly, as a means to verify temperatures measured by the distributed temperature sensor, secondly, to gather temperature data in mine shafts where temperature-sensitive fiber optic cable is not installed (e.g. in the Orphan Girl and Kelley mine shafts), and thirdly, to measure temperature at greater depths.

Equipped with a piezeoresistive strain gauge, the Seastar temperature logger also provided a means to measure pressure in the static water columns. This proved to be an invaluable asset while discretely measuring temperatures. Pressure was calibrated to atmospheric pressure at Butte, Montana's ground surface elevation of 1690 m. Depth within the water column, z, was calculated by dividing the measured pressure, P, by the density of water, ρ, and Earth's gravitational acceleration, g (i.e. the specific weight of water):

$$z = \frac{P}{\rho g} = \frac{P}{\gamma}$$

where, the density of water was calculated (based on temperature and conductivity measurements) to be 996.5 kg/m^3 and the gravitational acceleration constant is approximately 9.81 m/s^2. The maximum depth to which temperature and pressure were measured was 100, 380, and 425 m in the Orphan Boy, Orphan Girl, and Kelley mine shafts, respectively. Obstructions in the Orphan Girl mine shaft and a lack of cable in the Kelley mine shaft prevented the discrete samplers from being lowered below these depths. Temperature and pressure were logged while lowering and also while raising the slug and sensors; this enabled us to retrieve two temperature profiles per each sensing session.

The Seastar logger also contains a built-in electrical conductivity (also known as specific conductance) meter. Specific conductance was measured both in the middle and left compartments of the Orphan Girl mine shaft. This enabled us to determine if a chemical stratification within the mine shaft's water column is present, and calculate a more accurate value for the mine water's density. As a means to check the accuracy of our primary sensors, a Hydrolab multiparameter water quality instrument was used to measure temperature, pH, EC, and Eh in the top 140 m of the Orphan Girl mine shaft.

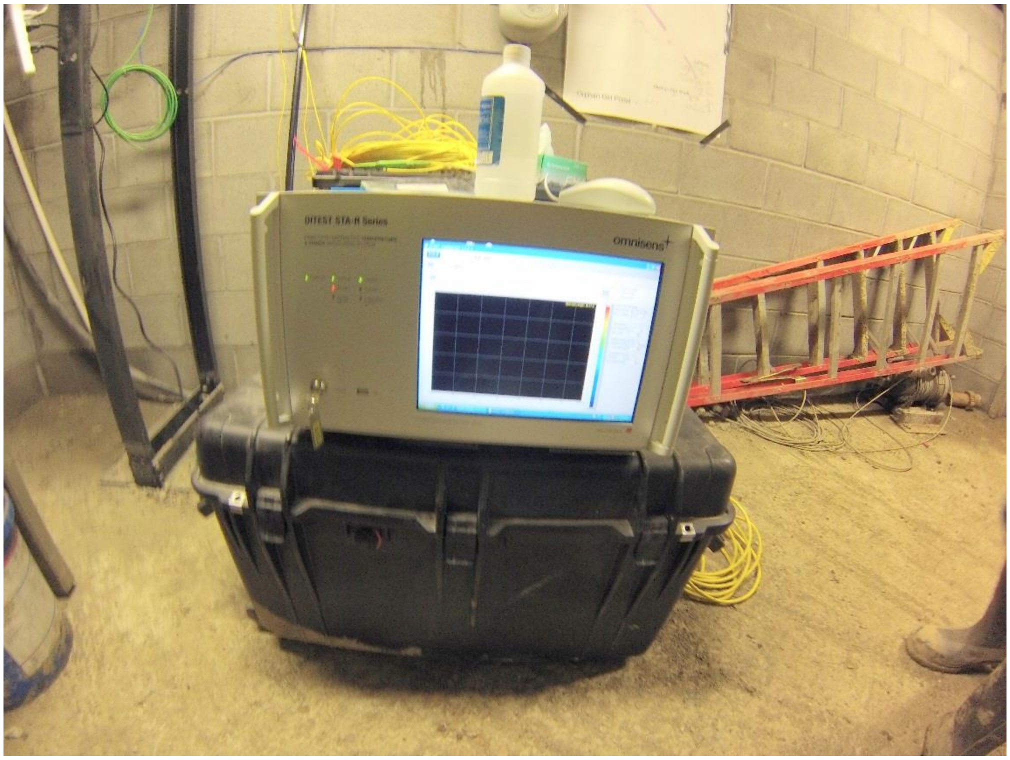

Figure 4. Pictured above is an Omnisens DITEST STA-R™ high-performance Brillouin-based fiber optic distributed temperature and strain analyzer collecting temperature data in the Orphan Boy mine shaft.

Figure 5. Pictured here (from left to right) is: one 20 kg slug, one Hobo Tidbit temperature logger, one Star-Oddi Seastar DST CTD miniature salinity/temperature/depth logger, another Hobo Tidbit, and 3/8” nylon rope.

Results

Point sensing was utilized to measure temperature in all three mining shafts: the Orphan Boy, Orphan Girl, and Kelley mines while distributed sensing was employed to measure temperature in only the Orphan Boy mining shaft. The following four pages of figures display temperature (in degrees Celsius) on the x-axis and depth (in meters of water column) on the y-axis. These are henceforth referred to as temperature profiles. The following table summarizes the content of figures 6 to 13.

Table 2. This list describes the figures displayed on the following four pages.

Figure #	Description
6	Seasonal variation in the Orphan Boy mine using the distributed sensor
7	Comparison of distributed and point sensing in the Orphan Boy/Girl mine
8	Variation in temperature between compartments in the Orphan Girl mine
9	Temperature variation among Hobos, Hydrolab, and Seastar in Orphan Girl
10	Point sensing in the Kelley mine
11	Variation in temperature between the Orphan Girl and Kelley mines
12	Seastar vs. Hydrolab specific conductance values in the Orphan Girl mine
13	Hydrolab temperature, pH, conductance, and Eh profiles

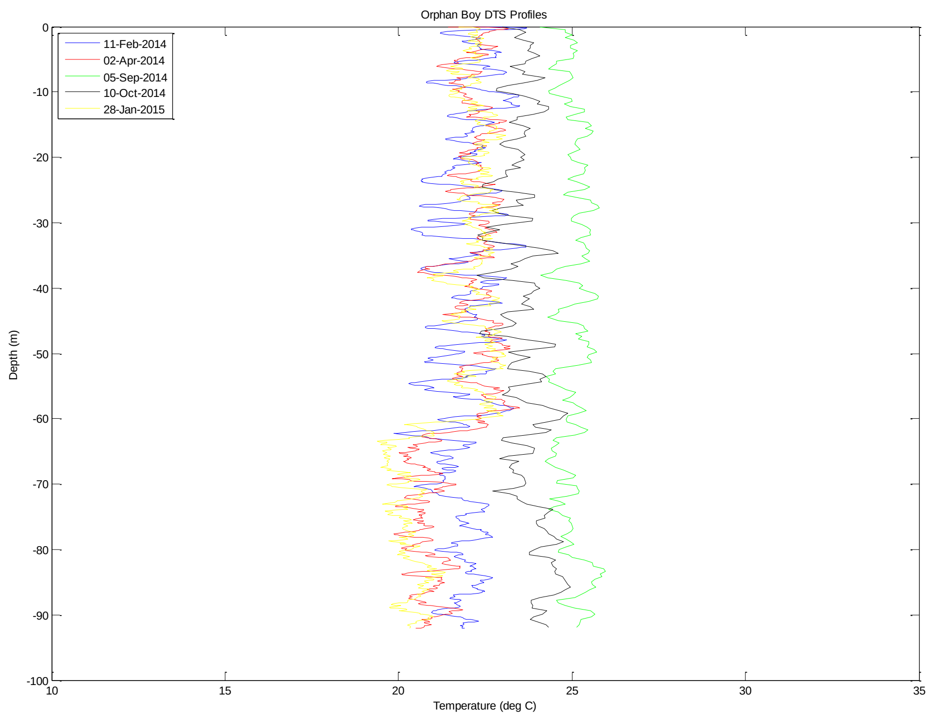

Figure 6. Distributed Temperature profiles, recorded using the distributed temperature sensing setup, are shown from February 2014 to January 2015 in the Orphan Boy mine shaft.

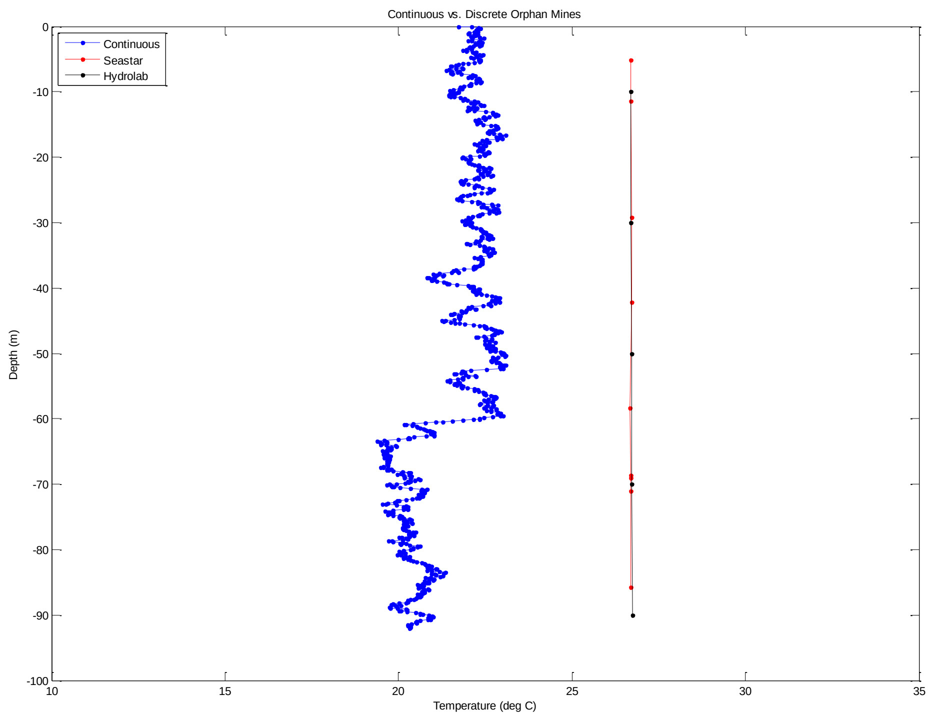

Figure 7. A comparative plot of distributed (blue) and point (red and black) temperature sensing as a function of water column depth in the Orphan Boy mine shaft shows fair agreement between the three measuring techniques. The distributed temperature profile shows the 28 January 2015 scan. The discrete profiles recorded temperatures in the top 90 m of the Orphan Girl shaft as the sensor was being raised to the surface on 13 February 2015.

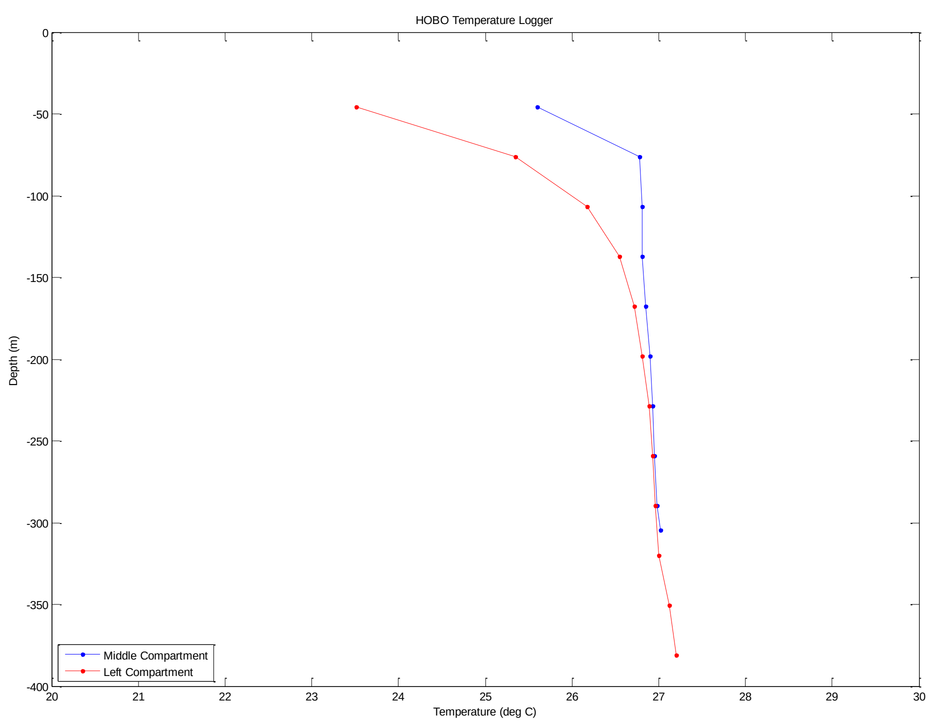

Figure 8. Temperature profiles, as measured by the Hobo loggers, in the Orphan Girl mine shaft do not vary between the middle (blue) and left (red) compartments. Temperatures shown are an average of two Hobo temperature loggers as the sensors went down on 13 February 2015.

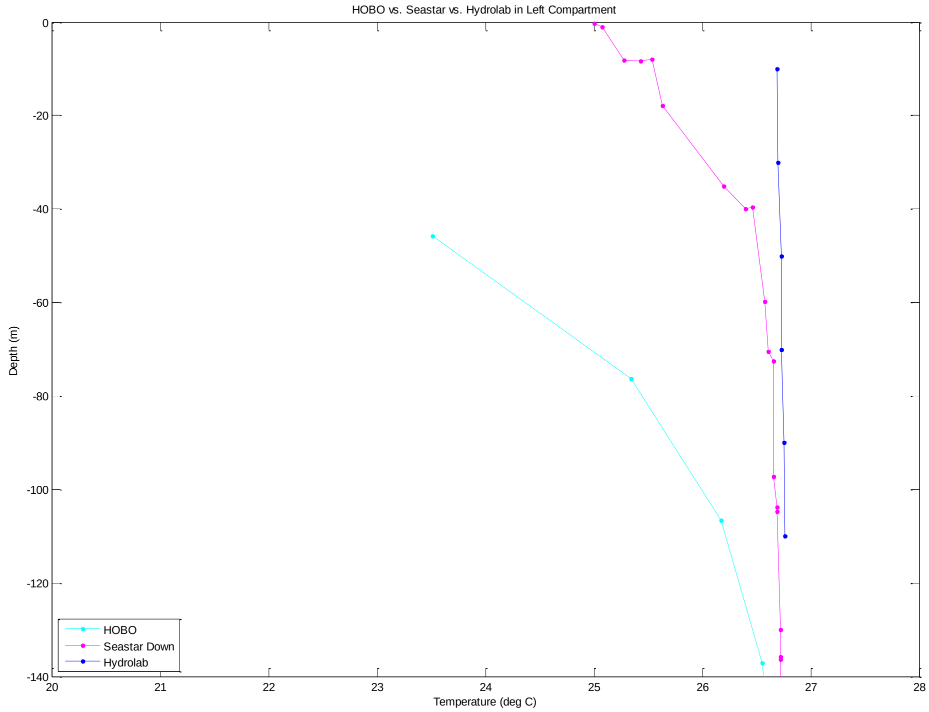

Figure 9. A comparison of the three point temperature sensors shows the Hobo Tidbit sensor is the slowest to equilibrate to the elevated temperature in the Orphan Girl mine shaft as the sensors are going down on 13 February 2015.

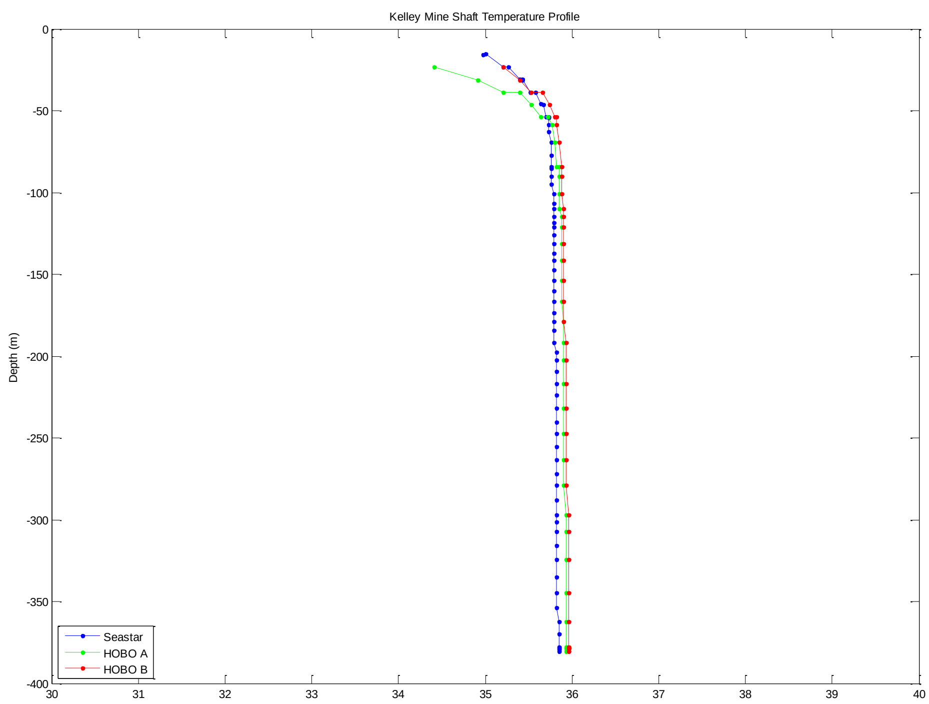

Figure 10. A plot of water depth vs. water temperature in the Kelley mine shaft shows a slight, but systematic, discrepancy between the three point temperature instruments as they sensed temperature on their way down the mine shaft on 13 February 2015.

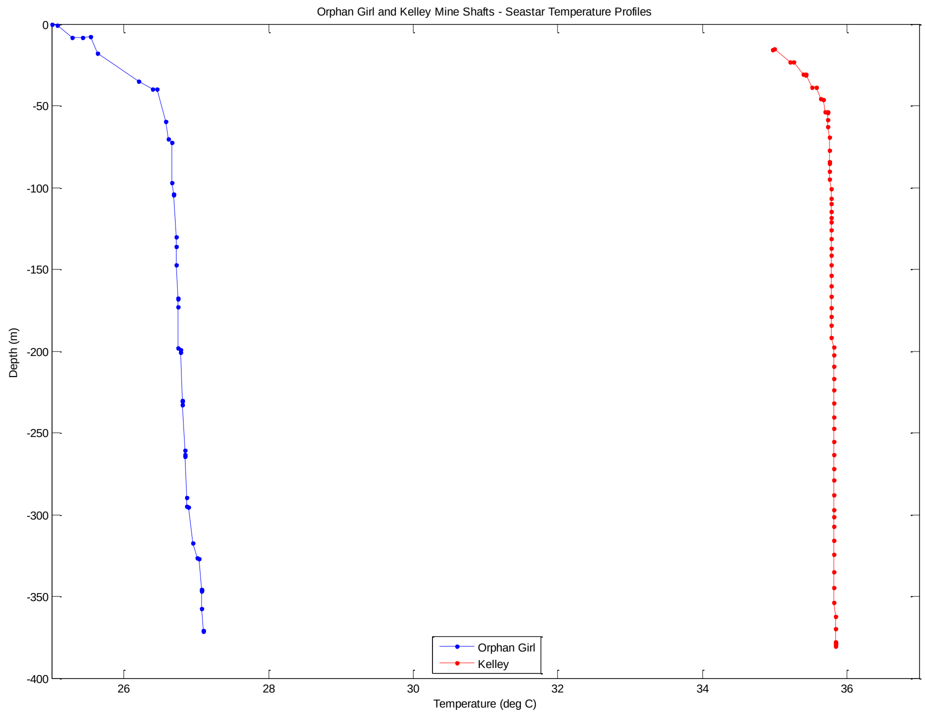

Figure 11. Orphan Girl (blue) and Kelley (red) mine shaft depth vs. temperature profiles are plotted together to show the ~9 ˚C temperature difference on 13 February 2015.

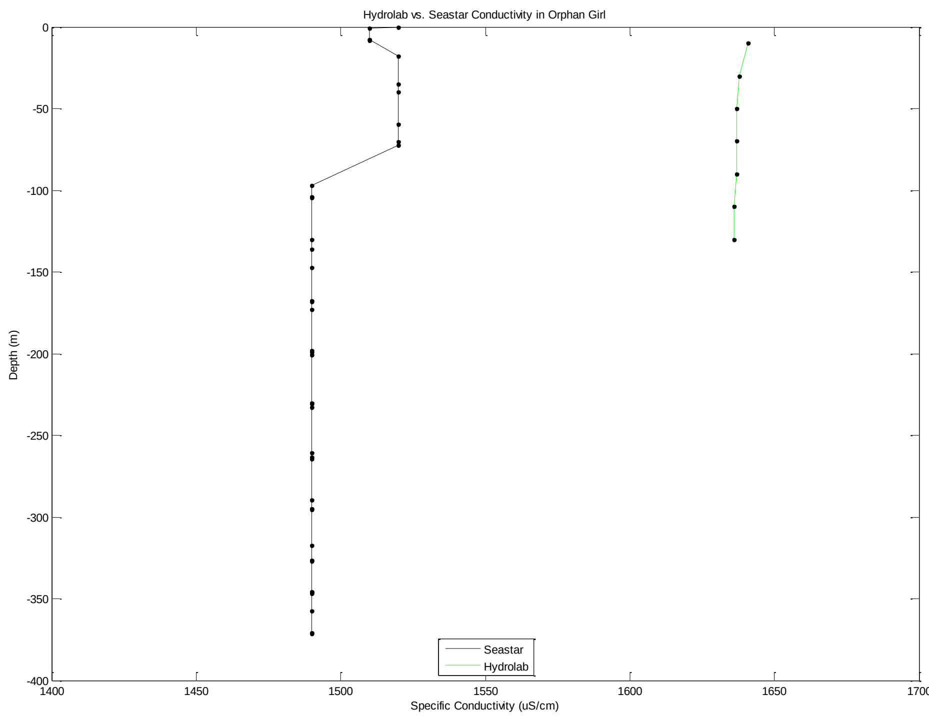

Figure 12. A comparison of the specific conductivity profiles, as measured by the Seastar (black) and Hydrolab (green) instruments, shows systematic error between the two sensing devices in the Orphan Girl mine shaft on 13 February 2015 and 20 February 2015, respectively.

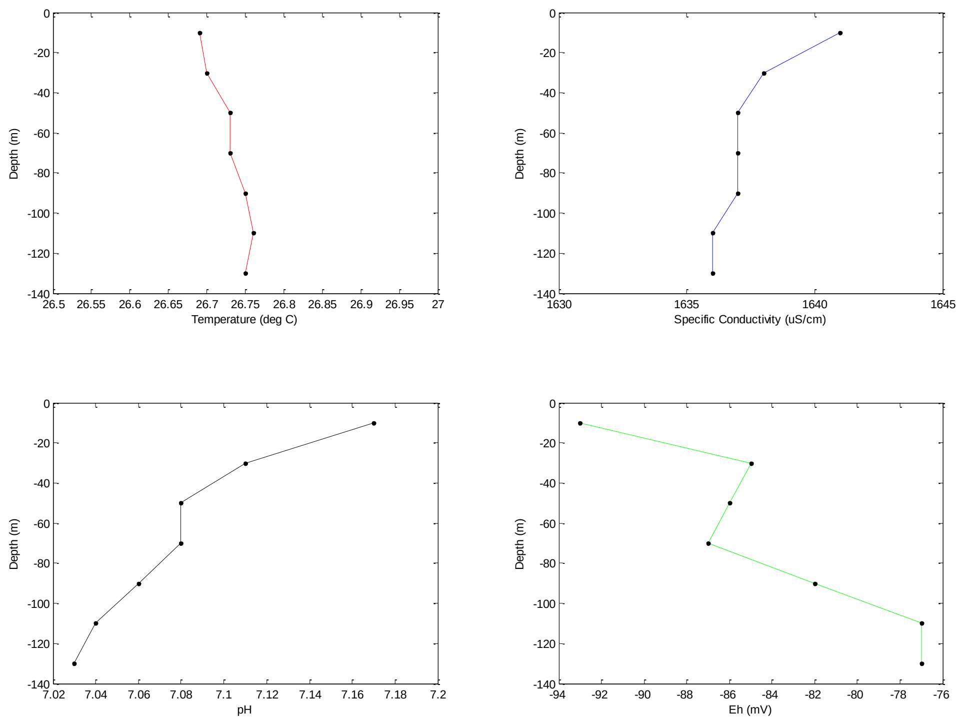

Figure 13. Temperature, SC, pH, and Eh were measured with the Hydrolab multiparameter water quality instrument in the middle compartment of the Orphan Girl mine shaft on 20 February 2015.

Discussion

The results show, first and foremost, that fair agreement between point and distributed temperature sensing in the Orphan mine shafts. The distributed temperature data are more scattered due to errors that are an artifact of the fiber optic cable deformations. The agreement between the point sensors, however, is spectacular. It should be noted that none of the temperature sensors were calibrated properly. Calibration is especially important for the fiber optic setup because the particular cable used in this study was not manufactured to measure temperature with good accuracy. The Hobo and Seastar thermistors/temperature loggers, on the other hand, should hold their factory calibration well. The observed temperature differences in Figure 7 could be due to the lack of agreement of the instruments, or it could be real; the lack of data from both types of instruments in the same shaft at the same time precludes definitive interpretations.

Secondly, it is obvious there is little to no increase in temperature with increasing depth within the water column, suggesting the thorough transfer of heat throughout the flooded mine shafts via convection. This suggestion is also supported by a lack of change in chemistry within the mine waters (Gammons et al., 2009). Additionally, Reichart et al. (2011) and Wolkersdorfer et al. (2007) have proposed convection takes place in flooded mines in Lorraine, France and Freiberg, Germany. Thus, it is rational to claim the waters in Butte's flooded underground mine shafts are undergoing convection and these waters are chemically and thermally well-mixed. The distributed temperature data in Figure 7 suggest the possibility of a drop in temperature of several degrees centigrade at a depth of approximately 60 m in the Orphan Boy shaft; this was not verified with the more accurate devices, however, and the Orphan Boy water temperature could be influenced by the heat exchanger.

Thirdly, Figure 6 shows water temperature in the Orphan Boy mine shaft varies seasonally: increasing in the summer and decreasing in the winter. Temperature variation of this sort implies the influence of meteoric water into the mine shafts, either directly, or via a connection with the local groundwater table.

Fourthly, Figure 9 signals the effect of total mine shaft depth on water temperature; namely, temperature increases with mine shaft depth. This trend does not necessarily occur between the Orphan Boy and Orphan Girl mine shafts because these two mine shafts are connected by a horizontal working; that is, the water is the same in both shafts. By plotting average temperature vs. total mine shaft for the Orphan Girl and Kelley mine shafts, an observed geothermal gradient beneath Butte, Montana can be determined (see Figure 14).

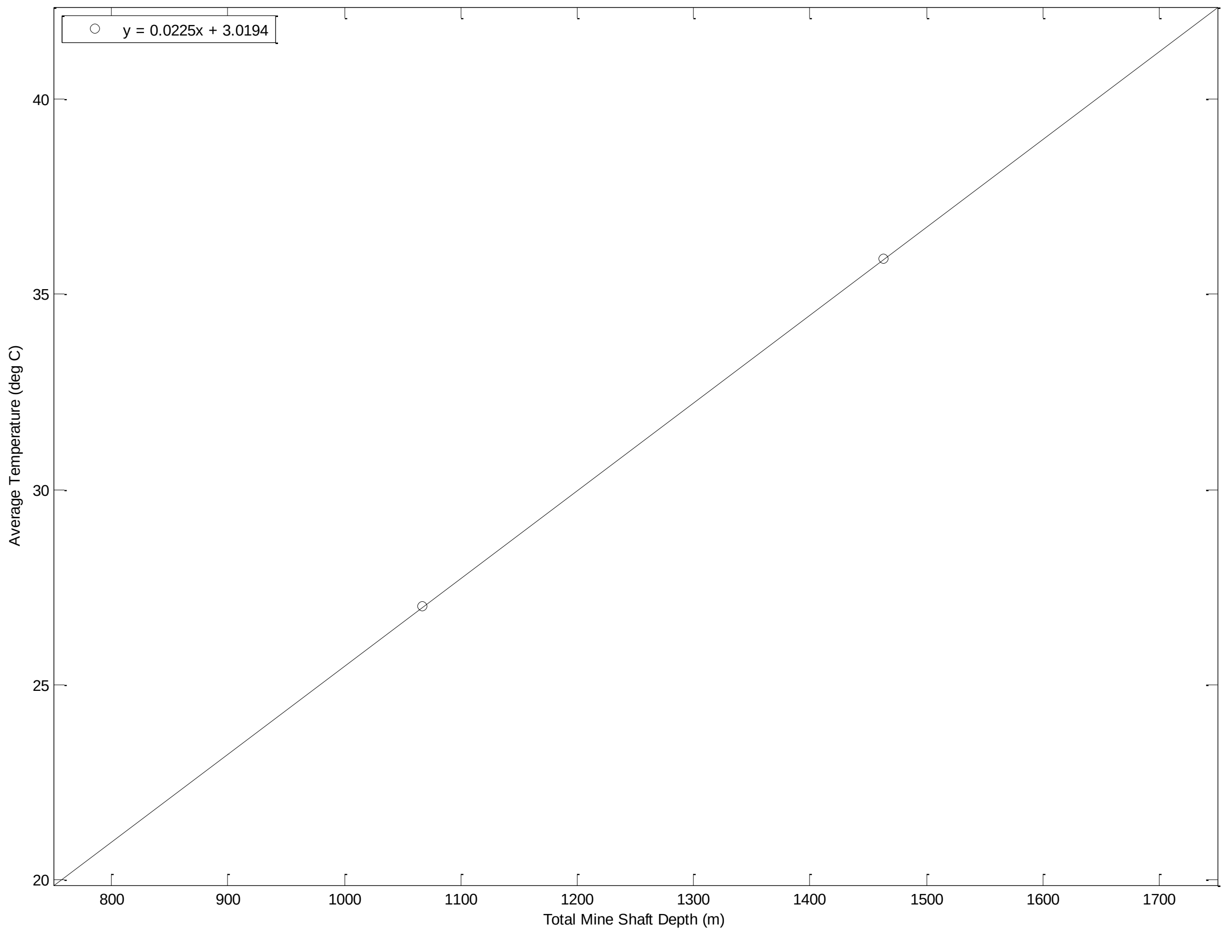

Figure 14. Average water temperature and total mine shaft depth are plotted for the Orphan Girl and Kelley mine shafts to determine the approximate geothermal gradient beneath Butte, Montana.

The equation of this line is:

$$T = 0.0225\left(\frac{°C}{m}\right) * z(m) + 3.0194(°C)$$

where, T is the temperature in degrees Celsius and z is the depth below the ground surface in meters. Therefore, based on the slope in the equation above, the observed geothermal gradient is 22.5 ˚C per kilometer. According to Fridleifsson et al. (2008), the average geothermal gradient of continental crust (away from tectonic plate boundaries) is approximately 25.0 ˚C per kilometer. Therefore, the percent difference between the observed value and this average value is 11.1%. Additionally, the computed y-intercept of 3.0194 ˚C closely matches Butte's annual mean air temperature of 3.9 ˚C (NOAA National Climatic Data Center).

It should be noted that the Orphan Girl and Kelley mine shafts contain anomalously high-temperature water, as compared to the other flooded underground mine shafts in Butte, Montana. In fact, Figure 16 in Gammons et al. (2009) shows the Anselmo, Belmont, Emma, Lexington, Ophir, Pilot Butte, Steward, and Travona mine shafts all fall on thermal gradients between 10 °C and 20 °C per kilometer.

Water in the Kelley mine shaft may be much hotter than the other shafts because it is lined with concrete: a feature no other mine shaft possesses. A concrete-lined mine shaft prevents water from entering along the length of the shaft. Therefore, if the concrete is still relatively intact, water can only infiltrate from the bottom or via horizontal workings (stopes and adits). Since block caving was used in the Kelley mine, most (if not all) of the horizontal openings must have been sealed, and consequently, water may only enter at the bottom of the mine shaft. If this is the case, heat would strictly transfer from bottom to top, and the influence of meteoric or ground water would be negligible.

Water in the Orphan Girl mine shaft may be hotter than the other shafts (with the exception of Kelley) because it is completely hydraulically separated from the rest of Butte's underground mine workings (refer to Figure 1). As a result of its location on the boundary of a small drainage basin, the Orphan Girl mine shaft receives very little rain and ground water input. As shown in the hydrographs in Figure 15, the water table elevation in the outer mining camp has decreased from 2012 to 2014; this differs significantly from the main zone and west mining camps.

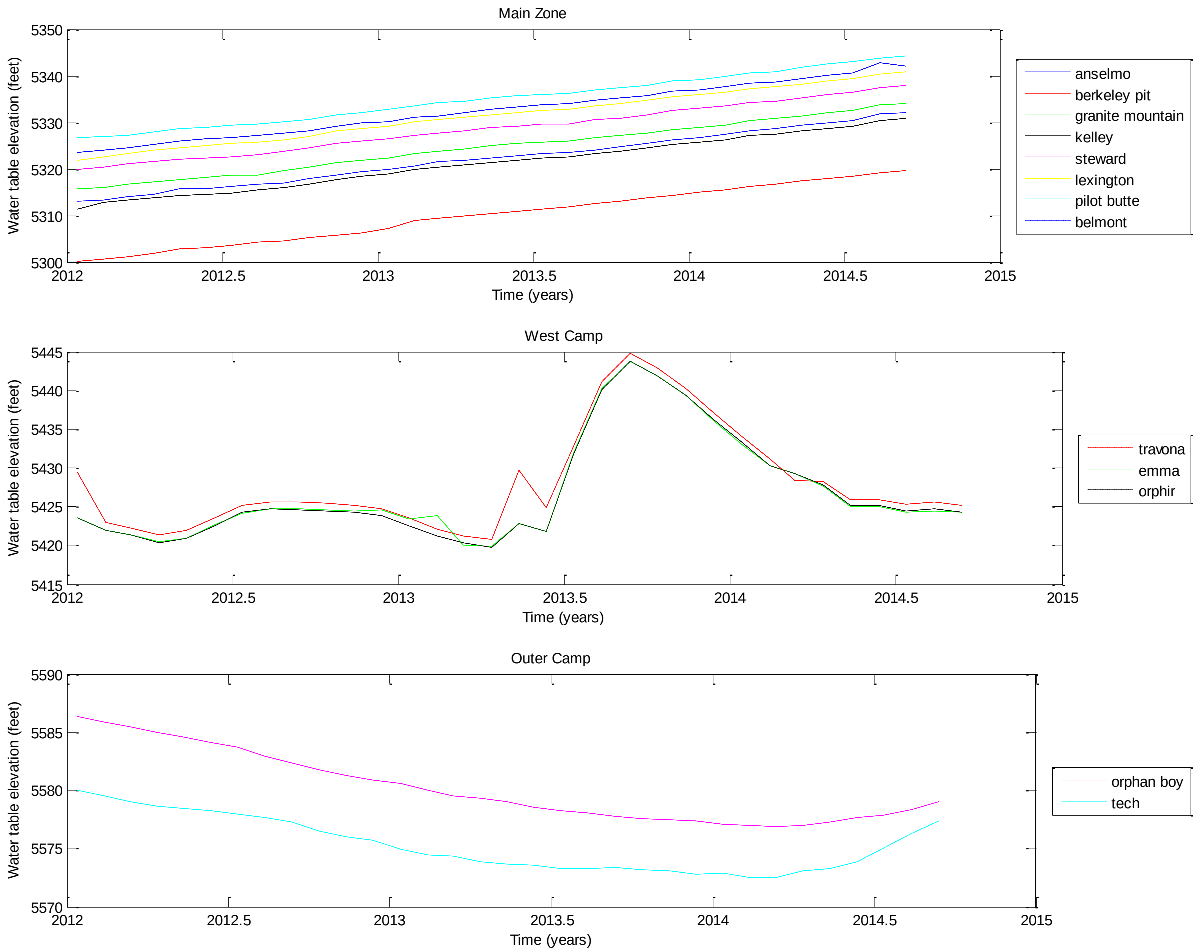

Figure 15. Plots of water table elevations vs. time (hydrographs) for the main zone, west, and outer mining camps show dramatically different flooding scenarios. Data sourced from monthly, open-file monitoring reports by Contract No. 400022-TO-35, Butte Mine Flooding-September 2014. These reports are available at pitwatch.org.

Lastly, a practical comparison of the different temperature sensing technologies is outlined in Table 2 below. The fiber optic temperature sensing setup is the most robust because it can be installed semi-permanently without much physical effort; however, the initial cost of this system is substantial compared to the point temperature sensors. This cost could be justified if the application requires frequent sensing over long periods of time is needed, because its ease of use will save countless hours of work.

Table 2. A comparison of the three methods used to measure temperature in the flooded mine shafts shows each sensor's primary functions, cost, setup time, ease of use, and durability.

	Omnisens DITEST STA-R™ + Fiber Optic Cable	Star-Oddi Seastar CTD logger	HOBO Tidbit Temp. Logger
Primary functions	temperature and strain	conductivity, temperature, and pressure	temperature
Cost	$$$$	$$$	$
Setup time	days to weeks	minutes	minutes
East of use	install and forget	tedious to repeat	tedious to repeat
Durability	very durable	very durable	very durable

Conclusions and Recommendations

This paper described two methods used to measure temperature and pressure, provided depth vs. temperature profiles for three flooded mine shafts, supplied a discussion proposing sensor precision, mine shaft water convection, seasonal temperature variation, and an observed geothermal gradient for Butte, Montana, USA. The findings show first, for this application, point temperature sensing, using thermistors, is more accurate and precise than distributed temperature sensing using fiber optic cable. Secondly, it was found that water in the three studied mine shafts is both thermally and chemically well-mixed. Thirdly, water temperatures in the Orphan Boy mine shaft vary seasonally. Fourthly, it has been shown that there is a hydraulic disconnect between the mine shafts in the main zone and the mine shafts in the outer and west mining camp; although, a complete water balance for Orphan mine system has not been realized. Finally, measuring temperature and pressure in Butte's flooded underground mine shafts provide a means to determine the observed geothermal gradient of 22.5 °C per kilometer beneath southwestern Montana.

Based on the data collection and interpretation experience gained by participants in this project, and on the conclusions drawn from the results, three main recommendations have been developed for further work:

- Complete a rigorous temperature calibration for the fiber optic setup and/or perform a side-by-side comparison of point vs. distributed temperature sensing in the Orphan Boy mine shaft. This could be accomplished by fastening the Hobo temperature sensors at systematic intervals along the fiber optic cable and logging temperature, with both devices, over a period of a few months. Unfortunately, this strategy could not be implemented in this study because there is currently limited access to the Orphan Boy mine shaft.

- Use the fiber optics and/or discrete temperature sensors to monitor long-term changes in water temperature when Montana Tech's mine-based heat pump system is active and inactive. Information gathered, as a result of this recommendation, is important for the prediction of the heat pump's expected lifetime and efficiency during extended periods of continuous heating and cooling operations.

- Use the aforementioned methods to measure temperature in other flooded mine shafts in the Butte Montana's main zone and west mining camps. Gammons et al. (2009) looked at eight different mine shafts, but they did not have a piezoresistive strain gauge to measure depth and did not attempt to lower their temperature loggers below the top 300 m of the mine shafts' water columns.

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