Measuring the Geothermal Resource in the Steward Mineshaft

Jaewon Kim[1], James M. Tinjum[1], Dante Fratta[1], David J. Hart[2]

[1]1415 Engineering Drive, Geological Engineering, University of Wisconsin–Madison, Madison, WI 53706, USA

[2]3817 Mineral Point Road, Wisconsin Geological and Natural History Survey, Madison, WI 53705, USA

Corresponding Author: jmtinjum@wisc.edu

Keywords: abandoned mine, temperature profile, flow logging, low-temperature geothermal, SONAR, thermal pulse testing

ABSTRACT

Abandoned mines are potential and underutilized reservoirs for low-temperature geothermal heat pump systems. We are exploring the potential for a ground-source heat exchange system in the abandoned and flooded Steward Mine in Butte, Montana. This mine is located within the Butte Mining District, within 1000 m of the Berkeley Pit (a large feature within the Butte Area Superfund site). There is a steep groundwater flow gradient from the Steward mineshaft to the Berkeley Pit, creating the potential for vertical flows in the mineshaft as water flows between horizontal drifts and to the pit. Proper design of heat exchangers in the mine shaft and predictions on the possible energy return and sustainability require measurements of the shaft temperatures, water levels, water chemistry, water movement vertically in the shaft and horizontally across the shaft. Using tools typically applied to borehole geophysics, we collected vertically distributed water temperature, conductivity, and pH. In addition, we measured vertical flows in the shaft using a spinner flow meter. We also collected shaft dimensions using SONAR in the flooded sections of the mine. We then attempted to correlate those flows with mine construction records. We found that flow is variable from near zero m/s to around 0.030 m/s and moving downward in the mineshaft starting from near the surface of the water at 150 m below land surface to 396 m below land surface. Variations in flow are likely due to horizontal workings (drifts) that intercept the shaft, creating areas available for flow in the mineshaft.

1. INTRODUCTION

Abandoned underground mines represent a vast, underutilized geothermal resource. Historic mining operations often created extensive networks of shafts and drifts that can extend for thousands of miles (Pokhrel et al., 2025). During active mining, continuous dewatering is essential for safe working conditions; however, once operations ceased, groundwater gradually filled these spaces. This accumulated mine water along with the contact surface area created by the shafts and drifts offer an opportunity to harness thermal energy for heating and cooling applications through ground-source heat pump systems. Mine-water geothermal systems can support district heating and cooling networks, provide thermal energy for commercial or campus buildings, and even supply process heat for agriculture and industry. Despite these benefits, characterizing the subsurface thermal resource remains challenging. Digital mine maps rarely capture the detailed geometry of shafts and drifts, and while groundwater levels are generally known, flow paths and hydraulic connectivity are poorly understood. Ralston (1994) proposed a pipe network modeling approach for mine workings, but its accuracy depends on experimental validation.

Globally, most existing mine-geothermal projects have been implemented in abandoned coal mines, with notable developments in Europe. For example, The Netherlands aims to supply geothermal heat to 30,000 homes by 2030 using mine-water systems (Euroheat and Power, 2021). These installations typically employ open-loop configurations with wells spaced 25–30 meters apart. In the United States, the Orphan Boy mine in Butte, Montana hosted a pioneering heat exchange system that met 88% of a building's annual heating demand and reduced greenhouse gas emissions by 39% (Hagan, 2015; Hinick, 2016). Although the system operated successfully from 2013 to 2016, it was eventually decommissioned due to piping leaks, highlighting the need for robust design and maintenance strategies.

As part of the Federal Geothermal Partnerships (FedGeo) initiative, our University of Wisconsin–Madison (UW–Madison) team provided technical assistance to modernize the Mike Mansfield Federal Building in Butte, Montana. FedGeo partners with the Geothermal Technologies Office (GTO) with the Federal Energy Management Program (FEMP) to help expand geothermal heating and cooling at federal sites in the United States. The goal is to repurpose nearby abandoned mines as the heat reservoir for a geothermal heat pump system. The abandoned Steward Mine is about 200 m from the federal building. FedGeo research partners provide design guidance and related modeling capabilities for a ground heat exchanger in an advisory role to the General Services Administration.

UW–Madison led on-site characterization activities, including thermal property measurements and assessment of the in-shaft thermal resource an advisory role to the . On-site data are used to model and verify thermal and hydrogeological properties of the sites. The primary outcome of the on-site characterization is to measure *in situ* thermal and groundwater properties. This dataset will validate models and inform system design and ground heat exchange (GHE) sizing activities. The expected outcomes include obtaining comprehensive distributed thermal-hydrogeological property measurements and technical-economic analysis of a GHE installation using the thermal resource from an abandoned mine shaft in Butte, Montana. Overall objectives for the Steward Mine include:

- Collect and compile existing information about the mine

- Provide preliminary modeling of thermal capacity based on measured mine geometry and water temperature, depth, and quality data
- Perform onsite resource characterization to verify thermal conditions
- Update the modeling framework with data collected from the site
- Provide design guidance to selected mechanical design firms and information on the expected performance of the heat exchanger

This paper assesses the geothermal potential of the Steward mine shaft within the Butte mining district, addressing key challenges in resource characterization and system design. By leveraging historical mine data and modern analytical techniques, the study aims to advance understanding of mine-water geothermal systems and their role in geothermal development.

2. BACKGROUND

2.1 Mining History in Butte, Montana

The Butte mining district has one of the longest and most intensive mining histories in North America, beginning with the discovery of placer gold in 1864 in Missoula, Dublin Gulches, and Silver Bow Creek (Miller, 1978; USEPA, 1994). Early mining focused on placer and quartz gold, but then silver mining became prominent, followed by a rapid shift toward copper as the dominant commodity in the 1870s. By 1884, more than 300 copper and silver mines were operating in the district (USEPA, 1994). As mining expanded, operators pursued increasingly deep and laterally extensive copper veins. To manage groundwater inflows, mining companies interconnected underground workings and developed centralized pumping systems to keep mines dry (Daly and Berrien, 1923; Duaime et al. 2023). By the early 1900's, the Anaconda Copper Mining Company had consolidated control over most underground operations and began systematically interconnecting mines. Key shafts, including the High Ore, Leonard No. 2, and Kelley mines, served as central pump stations that discharged untreated mine water to Silver Bow Creek. Lime addition to mine water began in the late 1950s to reduce dissolved mineral content (Spindler, 1977; Duaime et al. 2023).

By the mid-twentieth century, underground mining in Butte encompassed several thousand miles of interconnected workings. Estimates suggest more than 3,000 miles of major shafts, drifts, and levels, with total workings potentially exceeding 10,000 miles within an area of approximately 6.75 square miles (James, 1980; USEPA, 1994). Open-pit mining began in 1955 with development of the Berkeley Pit, marking a major transition in mining methods. Underground mining continued in parts of the district, including the Kelley and Steward mines, until 1975. In 1982, underground mining and the extensive dewatering system that had artificially lowered groundwater levels by approximately 4,200 feet were suspended. The Berkeley Pit ceased active mining in 1982, followed by closure of the East Berkeley Pit in 1983. Open-pit mining resumed in 1986 when Montana Resources acquired and renamed the East Berkeley Pit as the Continental Pit.

The cessation of pumping in 1982 initiated widespread flooding of the 16,000 km (10,000 miles) of underground workings and the Berkeley Pit (Metesh, 2006). The Steward Mine is part of the East Camp underground mine system that consists of a series of underground mines that were connected to the Kelly Mine pump station for dewatering. Water-levels in the East Camp mines has risen over 3,200 ft since 1982, including 2,2000 ft in the Steward Shaft, reaching 5,371.71 ft MSL (NAVD29) by December 2024, while the Berkeley Pit water level was approximately 5,356 ft. Under the 2002 EPA Consent Decree, a Protective Water Level for the East Camp System was established, that states the water-level in none of the 14 points-of-compliance (POC) cannot exceed 5,410 ft MSL, to ensure flow remains towards the Berkeley Pit. The Steward Mine is one of the 14 POC's.

2.1.1 The Steward Mine

Among the most significant mines on the Butte Hill was the Steward mine, located within the Butte National Landmark District near North Main and Woolman Streets. Discovered by John Marshall Steward and later acquired by William Clark in the early 1880s, the mine became a prolific producer of copper and silver, with some zinc output as well (Woodruff, 2025). The site retains its characteristic steel headframe and brick hoist houses. The Steward mine was notable for its depth and productivity. The initial wooden headframe was replaced in 1898 by a 126-foot steel structure over a 1,300-foot, three-compartment shaft (Figure 1). By 1920, the shaft reached 3,633 feet, making it Anaconda Copper Mining Company's deepest mine at the time (Shovers, 1987). Ultimately, the Steward extended to a depth of 4,400 feet before operations ceased in 1973, with limited experimental mining continuing until 1980. The mine was infamous for extreme heat, with temperatures in deep stopes reaching 130°F. Despite these conditions, the Steward was a major copper producer throughout World War II. Today, the Steward Mine continues to play a role in environmental management as part of the East Camp Mines system, as part of the Butte Mine Flooding Long-Term Monitoring Program. It helps to monitor water levels under the EPA Consent Decree, and the effectiveness of the Berkeley Pit Pilot Project that pumps and treats water from the Berkeley Pit (Duaime et al. 2023). This evolution from a leading copper-silver producer to a critical component of mine water remediation underscores the Steward's enduring significance in Butte's mining legacy.
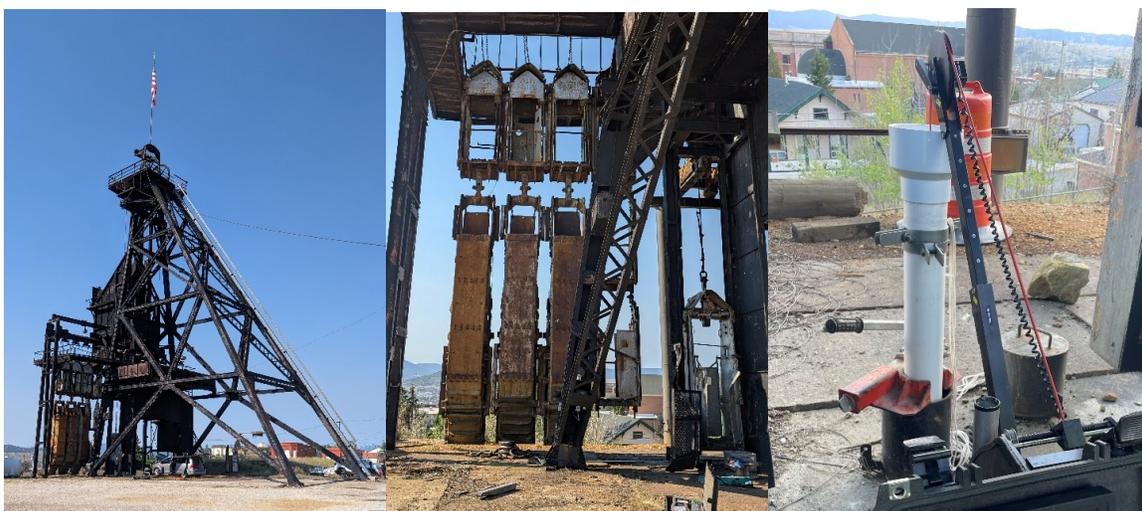
Figure 1. Photos of the Steward headframe (left), ore bins (middle), and access to the closed mine shaft (right).

2.2 Geologic Setting

The Butte mining district is underlain by igneous rocks of the Boulder Batholith (Figure 2), a formation composed primarily of quartz monzonite intruded by rhyolite and porphyry dikes (AIME, 1968; USEPA, 1994). This intrusive complex hosts extensive disseminated and vein-type ore deposits rich in copper, with associated silver, gold, and other metals. Mineralization is dominated by sulfide minerals, including pyrite. These sulphide minerals play a critical role in the generation of acid mine drainage when exposed to oxygen and water.
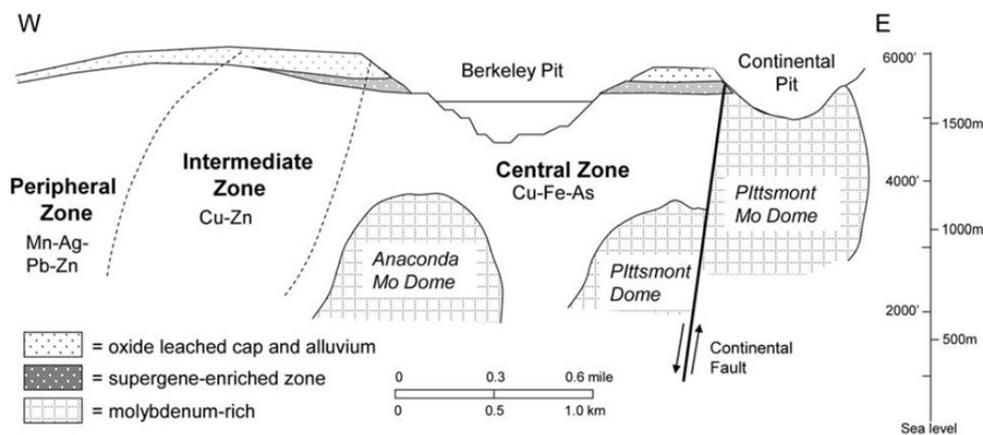

Figure 2. Simplified and schematic geologic cross-section through the Butte Mining District (from Gammons et al. 2006a).

Mining activities have extensively altered the bedrock through excavation of shafts, drifts, stopes, and open pits. The resulting subsurface has been described as an anastomotic or "Swiss cheese"–like system, with highly enhanced secondary permeability relative to natural bedrock conditions (USEPA, 1994). A number of underground workings directly intersect the Berkeley Pit, creating strong hydraulic connectivity between the pit and the surrounding bedrock aquifer.

2.3 Hydrogeologic Setting

Groundwater in the Butte area occurs primarily through fractures, joints, and the extensive network of underground mine workings. Prior to mining, groundwater levels reflected natural recharge and discharge conditions. During active mining, continuous pumping created an artificially lowered groundwater surface, establishing a controlled flow circuit through interconnected underground workings that kept both the mines and the Berkeley Pit dry (Metesh, 2006).

Following the cessation of pumping in 1982, groundwater levels began to rebound toward pre-mining conditions, resulting in flooding of underground mines and the Berkeley Pit at an average rate of approximately 3,785 m³/day (5 MDG) (USEPA, 1994). Inflow sources include surface water (approximately 6,360 m³/day - 1.68 MGD), alluvial aquifer contributions (about 2,195 m³/day - 0.58 MGD), and bedrock aquifer inflow (approximately 8,330–9,460 m³/day - 2.2–2.5 MGD), with additional minor contributions from direct precipitation and evaporation.

Hydrogeologic investigations indicate that groundwater flow within the bedrock aquifer, particularly west of the Berkeley Pit in areas such as the Kelley Mine, is best represented by a pipe-network model rather than a porous-media system (Ralston, 1994). The interconnected mine workings function as drainage galleries and conduits (Figure 3), dramatically increasing the storage capacity of the

bedrock aquifer. Estimates suggest storage volumes exceeding 25.5×10^6 m³ (900×10^6 ft³) within the mine network alone (USEPA, 1994 citing a personal communication with Stephenson, 1994).
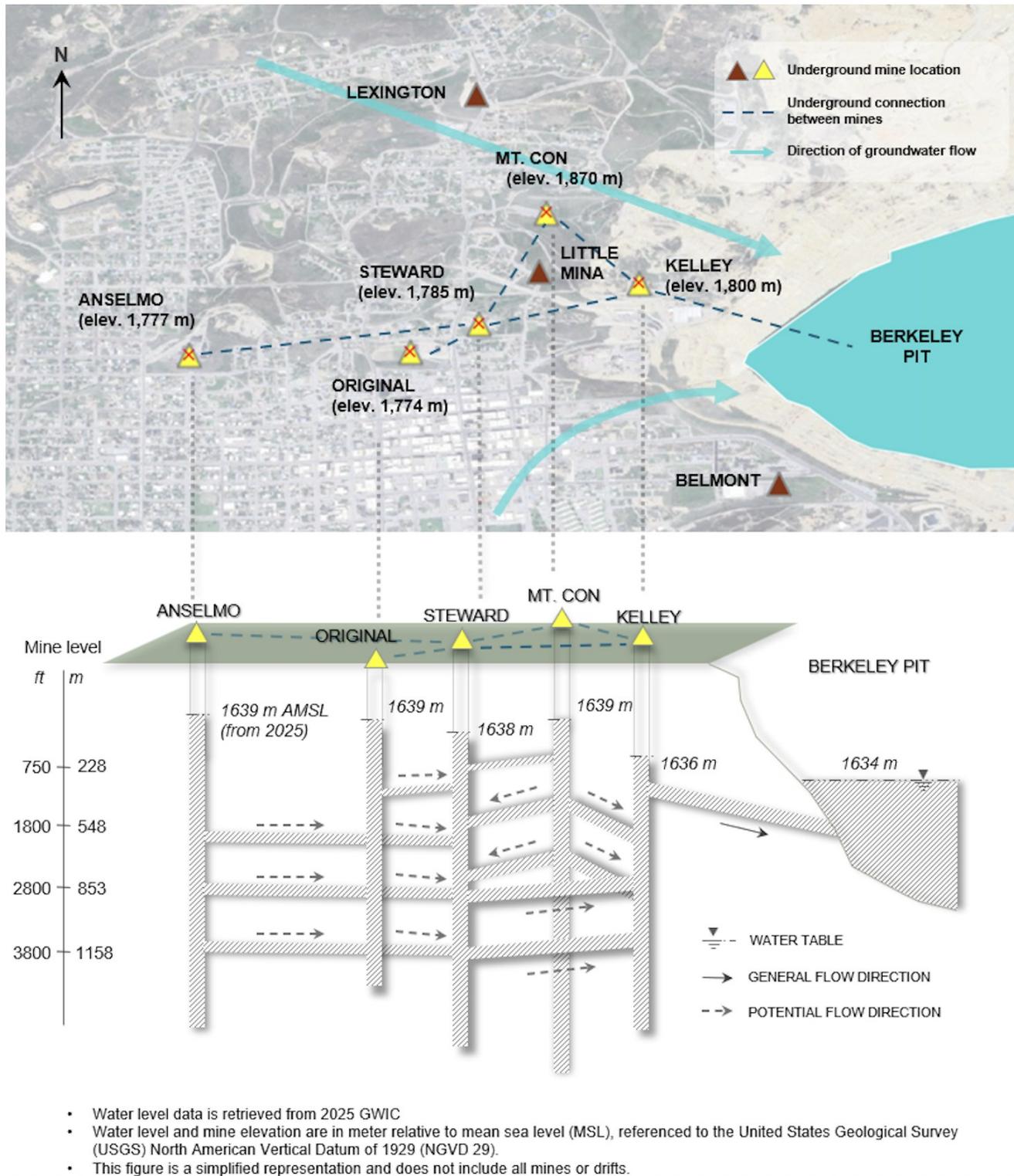

Figure 3. Conceptual schematic of flooded mine connections including the Steward Shaft and selected mines (concept from Canonie 1993 as found in Duaime et al. 2023).

At present, groundwater levels in the bedrock aquifer remain higher than the Berkeley Pit water level, resulting in a radial flow toward the pit. This condition has helped contain contaminated water within the East Camp system. However, if water levels were allowed to rise above established Critical Water Levels (1,649 m -5,410 ft- in the East Camp and 1,656 m -5,435 ft- in the West Camp), hydraulic

gradients could reverse, allowing contaminated water to Silver Bow Creek (USEPA, 1994). To prevent off-site migration, the selected remedial strategy maintains the Berkeley Pit as a long-term sink for acid mine drainage while controlling inflows and managing water levels through pumping and treatment. This integrated management approach is central to protecting human health and the environment while addressing the legacy impacts of more than a century of intensive mining in the Butte district

3. MATERIALS AND METHODS

We deployed three primary geophysical tests and jointly interpreted them to identify flow conditions and evaluate heat transfer performance in the Steward mine, together with chemical analyses of the mine water. The spinner flow meter provides rapid, depth-continuous measurements of flow rate and direction of mine water along with other environmental data including temperature and electrical conductivity. The acoustic video logging provided structural context to distinguish fracture-controlled flow from porous media exchange, change in radius of the mineshaft, and existence of connection to drifts. We also used mine stopes maps to support interpretation. Chemical analysis evaluated existing or potential chemical reactions in the mine water. Lastly, we deployed a thermal pulser to evaluate how fast and where heat transfers and dissipates within the water in the shaft.

3.1 Geophysical Mineshaft Data Collection

We used a QL40 spinner flow meter (SFM) to characterized vertical flow conditions in the mineshaft. The QL40 SFM measures the speed of impeller rotation induced by fluid movement within the borehole via a magnetically coupled pick-up to sense water flow (Advanced Logic Technology & Mount Sopris Instruments, 2015). We logged the spinner tool both upward and downward in the mineshaft at several logging speeds to capture flow disturbances. This approach assumes steady-state conditions in which the inflow to the spinner tool equals the outflow, allowing measured impeller rotation to be interpreted as representative of ambient borehole flow. The spinner tool records rotation direction and rotation speed in counts per second (cps) that are then converted to downward fluid velocity using the WGNHS's spinner-tool processing method as an alternative since no site-specific field calibration was available. As a result, the speed of (m/s) of vertical flow in the mineshaft was estimated and may differ by more than 50 percent from the actual flow. As part of the logging protocol, we also measured fluid temperature (C), electrical conductivity (µS/cm), pH, and redox potential (mV) were measured every 0.052 m (0.17 ft). We used these parameters to support flow interpretation by identifying thermal and geochemical anomalies indicative of hydraulically active intervals.

3.2 Down-shaft Imaging

An optical borehole imaging, Aries Explorer portable borehole inspection system equipped with a WC1200 camera imaged the shaft. The WC1200 camera provides continuous side-view and down-view imaging with 360° rotational capability and integrated LED illumination (Aries Industries, 2016). The recoded video data supports the interpretation of subsurface flow conditions, allowing visual assessment of fractures, possible inflow area, and structural irregularities along the mineshaft. Following the optical survey, subcontractor COLOG collected acoustic imaging logging using sonar below the water table. This method generates a 360° acoustic image of the borehole wall, enabling identification of fractures and cavities where the optical imaging is limited. During the sonar survey, the measurement detection range was set to 3 m, limiting the acoustic response to features within this radial distance from the mineshaft wall.

In addition to the geophysical imaging tests, the Steward Mine Stope Book (Montana Bureau of Mines and Geology, 2025) identified mine connections and shaft locations. The top-of-casing elevation at Steward Shaft is 1785.05 m (5856.45 ft) above mean sea level (AMSL), referenced to the NGVD 29 (1929 USGS) datum, and the casing above the ground surface is 0.298 m (11.75 in).

3.3 Chemical Analysis

Three aqueous samples were collected from the Steward mineshaft in Butte, Montana, for chemistry analysis. The samples were ice-preserved when they were shipped for lab measurements of pH, redox potential (Eh), and electrical conductivity (EC). Cation and anion concentrations were measured using inductively coupled plasma optical emission spectrometry (ICP-OES) for major elements, inductively coupled plasma mass spectrometry (ICP-MS) for minor and trace elements following USEPA Method 6010D and 6020B (USEPA, 2014a,b), and microbore ion chromatography (IC) for anions according to USEPA Method 300.1 (USEPA, 1997). For cation analysis, the sample was acidified using concentrated nitric acid (HNO_3, CAS#:7697-37-2) to 2% HNO_3 and filtered using a 0.22 µm polypropylene syringe filter. For anion analysis, the sample was only filtered using a 0.22 µm polypropylene syringe filter.

3.4 In-shaft Heat Pulse Testing

In-shaft heat pulser testing was performed to evaluate heat transfer performance of mine water within the mineshaft. The test aimed to quantify the magnitude of shaft warming, the rate of heat dissipation, and the dominant direction of heat transport. The experimental approach closely follows the in-well heat tracer method described by Sellwood et al. (2015). Tests began by lowering the heat pulser into the water column to a target depth and running the heat pulser until a temperature increase of 1–2 °C was observed in the water surrounding the heat pulser using fiber-optic distributed temperature sensing (DTS) measurements. The DTS system recorded temperature at regular spatial intervals along the fiber with repeated temporal sampling, allowing simultaneous observation of heat movement over the entire borehole length. Temperature data were processed and visualized as depth-versus-time plots, where inclined thermal anomalies indicate vertical migration of heated water (Sellwood et al. 2015).

A total of 650 m (2132 ft) of fiber-optic cable was deployed in a looped configuration and connected to an Oryx DTS interrogator to record temperature variations continuously with depth and time. In this configuration, the DTS system records temperature along both the forward and reverse directions of the cable; therefore, heat propagation was monitored to an effective depth of 250 m (814 ft) below the top of casing. The stainless-steel heat pulser feature a cone-tipped cylindrical geometry with surface protrusions designed to increase the effective surface area and enhance convective heat transfer to the surrounding water. The heat pulser had a length of 0.57 m and a diameter of 0.064 m with a heating rate of 2000 W. Some heat loss through the open-air wiring was recorded under field conditions.

The test began by lowering the heat pulser to a depth of 152 m below the top of casing, where heating was applied for 30 minutes followed by a 30-min cooling period while heat migration was recorded. After this initial test, additional heat pulser experiments were conducted at 9.1 m (30 ft) depth intervals. From the 180 m (590 ft) test, the protocol was modified to 30 min of heating followed by 15 min of cooling, based on observations of rapid cooling and rapid stabilization of water temperature in earlier experiments. For the final test at 244 m (800 ft), the heating duration was extended to 90 min to evaluate water temperature behavior under prolonged heating conditions.

4. RESULTS

Figure 4 presents the flow-velocity, temperature, conductivity, pH, and redox logging data as a function of depth. The average mine water temperature is approximately 31.4 °C and flow velocity is range from near zero m/s to around 0.06 m/s. The spinner log shows consistently positive velocities in the water column to 396 m below ground surface indicating net downward flow within the shaft. This pattern is characteristic of a cross-connecting well, in which water enters the borehole at shallower depths and discharges to deeper zones with lower hydraulic head. The inferred downward flow direction is supported by the hydraulic gradient between the Steward Shaft and the Berkeley Pit, which acts as a regional hydraulic sink at depth (Metesh, 2006).

The depth range between 229–238 m (750–780 ft) was identified as a zone of interest potentially influenced by groundwater inflow from connected mine workings, based on the observation of a slight temperature change accompanied by a corresponding change in electrical conductivity. Information from the Mine Stope Book indicates multiple connections, including a connection to the Mt. Con mine at approximately 230 m (753 ft), supporting the presence of enhanced hydraulic connectivity within this interval. These observations are consistent with the results of the algorithm-based segmentation analysis presented in the following section.
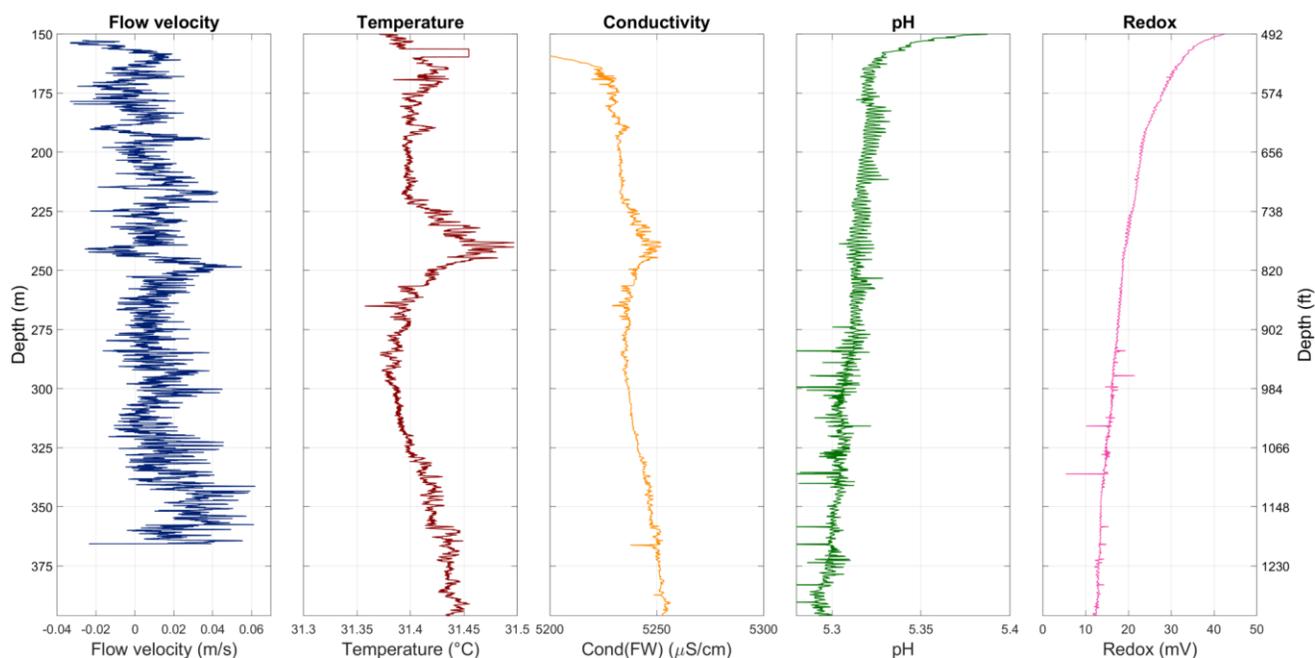

Figure 4. Depth profiles of temperature, electrical conductivity, pH, redox potential, and mineshaft fluid velocity. Positive velocity values indicate downward flow, whereas negative values indicate upward flow. 4.1 Geochemical Results

Results from geochemical measurements are presented in Figure 4 (*in situ* via logging) and Table 1 (laboratory analyses of discrete samples). Due to the presence of oxygen and water during and after mining, the release of naturally occurring sulfide minerals is susceptible to oxidation thus resulting in acidic conditions. This reaction is an exothermic process. Gammons et al. (2006b) reported that some shaft waters were anomalously warm, possibly due to the ongoing pyrite oxidation or bacterial reactions. In the central part of the Summit Valley District, there is an inverse correlation between pH and water temperature, possibly caused by these exothermic pyrite oxidation reactions (Gammons et al., 2006b).

The dominant rock type in Butte is the Late Cretaceous Butte Quartz Monzonite, the largest of several granitic plutons that make up the Boulder Batholith of western Montana (Gammons et al. 2006a). Hydrothermal alteration of the host granite was strongly zoned, with

pyrite-rich phyllic and advanced argillic alteration in the center near the Berkeley Pit, grading to less intense phyllic, argillic, and propylitic alteration in the outer portions of the district (Gammons et al. 2006a), see Figure 2.

Compared to sampling conducted by the Montana Bureau of Mines and Geology from 2000 to 2006, results from this field investigation show lower pH levels of 5.25 to 5.35 relative to the 5.97 pH average from 2000 to 2006. Recent results also show significantly higher levels of Fe and As. Many of the timbers were treated with arsenic trioxide as a preservative; thus, the presence of elevated As levels are expected. Previous work by MBMG has shown that some of the flooded mine shafts display vertical gradients in chemistry and temperature, whereas others have relatively minor changes with depth (Metesh and Duaime, 2002). Also, some mines have a thermocline or chemocline in the upper 20 m, probably due to inflow of surface water or shallow groundwater (Metesh 2004).

Table 1. Geochemical results from the Steward Shaft

Property / Element	Instrument	Unit	Depth: 160 m	Depth: 191 m	Depth: 221 m	2000-2006[1]
pH	pH meter	-	5.433	5.371	5.292	5.97
Redox Potential (Eh)	Eh meter	mV	85.2	88.6	92.9	+350
Electrical conductivity (EC)	EC meter	mS/cm	4.447	4.46	4.43	3.14
Anion-to-Cation Ratio	Calculation	-	0.98	0.97	0.96	
Ionic Strength	Calculation	mM	155.7	153.4	152.7	
RMD	Calculation	$M^{0.5}$	0.021	0.022	0.023	
Na	ICP-OES	ppm	65.1	70.1	70.3	44
Mg		ppm	254.4	252.4	249.3	153
K		ppm	46.6	51.4	51.6	31.7
Ca		ppm	561.5	551.1	559.6	491
Si		ppm	32.0	35.3	35.3	42
Fe		ppm	615.3	611.9	601.3	249
Be	ICP-MS	ppb	2.5	2.5	2.2	
B		ppb	137.4	121.9	106.3	
Al		ppb	736.8	661.1	599.8	691
Ti		ppb	61.9	56.5	56.5	
Cr		ppb	88.7	80.1	80.1	
V		ppb	1.2	1.1	ND	
Mn		ppb	89145.1	88604.8	89365.8	30.5
Co		ppb	222.5	219.3	210.4	
Ni		ppb	125.5	123.4	112.8	
Cu		ppb	14.0	9.7	7.7	47
Zn		ppb	52793.8	52194.5	52500.6	68900
As		ppb	7410.8	7285.1	6667.2	2650
Se		ppb	ND	ND	ND	
Sr		ppb	1251.8	1238.8	1246.6	
Mo		ppb	3.6	1.7	2.5	
Ag		ppb	79.3	79.3	79.3	
Cd		ppb	ND	ND	ND	18
Sb		ppb	3.9	3.7	3.2	
Ba		ppb	27.3	12.2	9.8	
Pb		ppb	5.7	5.6	4.3	
Tl		ppb	ND	ND	ND	
Li		ppb	-	-	-	
Rb		ppb	-	-	-	
W		ppb	-	-	-	
Zr		ppb	-	-	-	
F^-	IC	ppm	ND	ND	ND	
Cl^-		ppm	60.5	59.3	58.8	38
NO^{2-}		ppm	ND	ND	ND	
SO^{4-}		ppm	3669.0	3574.3	3571.3	2320
Br^-		ppm	ND	ND	ND	
NO^{3-}		ppm	ND	ND	ND	
PO^{4-}		ppm	ND	ND	ND	
HCO_3^-		ppm	-	-	-	156

[1]Chemical compositions from 2000-2006 as taken from GWIC (2006) and summarized by Gammons et al. (2006)

Notes: ND: not detected; -: not measured; J: estimated quantity above detection limit but below reporting limit; U: undetected quantity below detection limit.

4.2 Sonar Results

While sonar has limitations due to its forced vertical position along a vertical column for much of the downward deployment (and thus 360-degree field of view is not routinely possible), the return images very clearly indicate the shaft dimensions and some of the support structures. According to the stope book, the Steward shaft is a four-compartment shaft, likely consisting of three regular compartments

and one service compartment. These compartments are **"lined"**—this is confirmed in that timber bracing was observed in the video logs in 0.76 m (2.5 ft) vertical sections repeating every 1.52 m (5 ft).

The sonar log (Figure 5) illustrated that the mineshaft geometry has a repeating pattern of volumetric fluctuations associated with the presence of timber-supported structural elements within the shaft. Optical borehole imaging confirms the presence of these repeated internal structures; however, it is not possible to determine whether the spaces behind the timber represent voids, drifts, or active connections. The darker central regions represent the open void of the mineshaft, while the lighter surrounding regions correspond to widened sections associated with vertical structural features. From the sonar data, an average examined shaft radius of approximately 1.016 m was estimated. Using a downward velocity of 0.030 m/s and an average shaft radius of 1.016 m, the estimated volumetric flow rate is approximately 8,380 m³/day (2.21 MGD). This value is on the order of reported overall flow from the Eastern bedrock complex to the Berkeley Pit of 8,330–9,460 m³/day (2.2–2.5 MGD) (USEPA, 2004). It suggests a significant percentage of overall flow occurs in the Steward Shaft, a result that must be corroborated with additional measurements at the Steward Mine shaft to improve on our confidence value and in other shafts given the uncertainty in this single measurement.
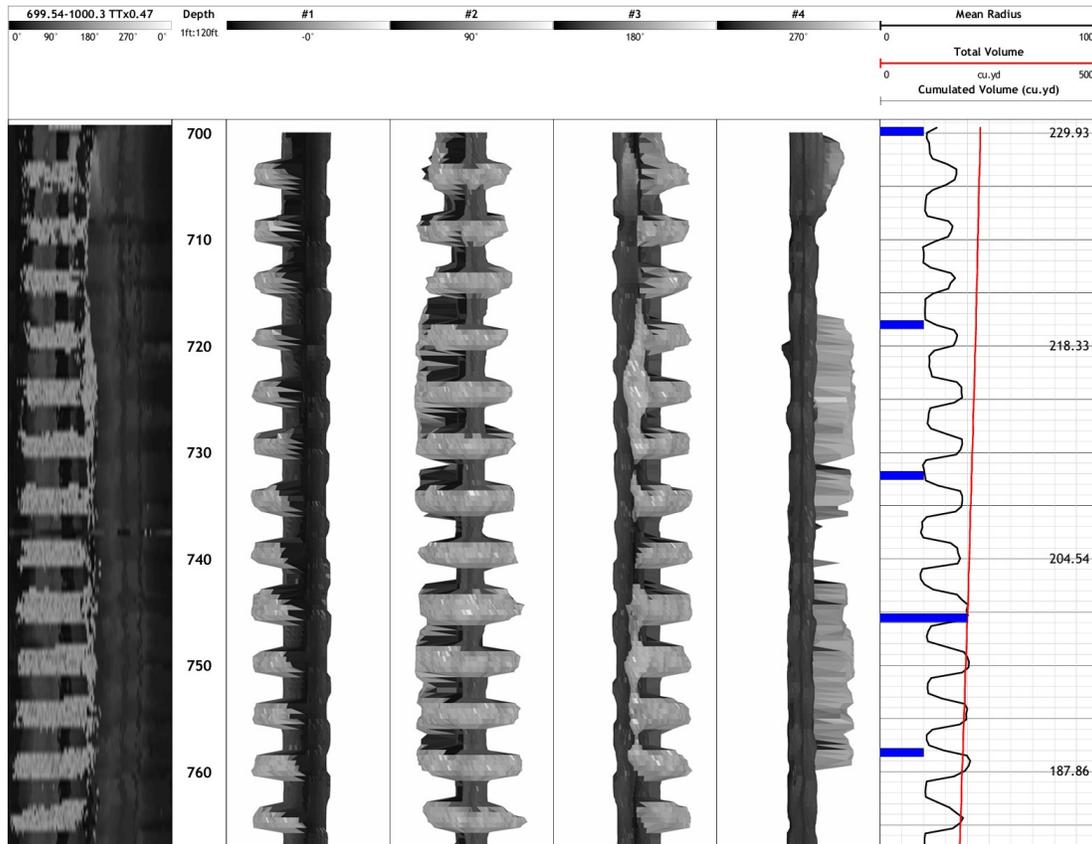
Figure 5. Sonar log results from depths between 213–235 m (700–770 ft).

5. ANALYSIS

5.1 Algorithm-based segmentation of flow-rate and temperature-depth profiles

We performed a segment-based environmental data analysis following a data-driven approach (Gökpinar and Heinze, 2024) including outlier removal, signal smoothing, and slope-based segmentation. First, we identified outliers and removed them using a moving median approach with a 31-point window. Data points exceeding three standard deviations from the local median were excluded from further analysis. Next, we smoothed the filtered flow-velocity profile using the Savitzky–Golay filter with a third-order polynomial and a 101-point window. Within each moving window, we fitted a third-degree polynomial to the data, and we kept the polynomial value at the center of the window, preserving local trends while reducing high-frequency noise. Finally, the smoothed temperature profile using the Matlab's findchangepts function with a linear statistic approach. We imposed an upper bound of nine change points (resulting in 10 segments) to identity locations where introduction of a new linear segment reduced the overall sum of squared residuals compared to a single-line representation. Because of the noisy flow data, we segmented the profile into eight representative segments to capture its dominant trends. This approach enabled us to objectively identify depth intervals with distinct temperature and flow gradients. Figures 6 and 7 present the temperature and flow-velocity profiles, respectively, both with slope-based segmentation.

We found that segment-wise temperature gradient indicates a slight increase near approximately 250 m (820 ft) depth. And while the flow rate data exhibit large noise, likely due to the large volume of the mineshaft, a slight fluctuation is also observed at approximately 250 m (820 ft) depth. According to the Stope Book, there's an active connection to Mt. Con mine near this depth. However, attributing this observation to warm water inflow requires additional testing within the Mt. Con mine, as well as temperature measurements over the full depth of the mine shaft.
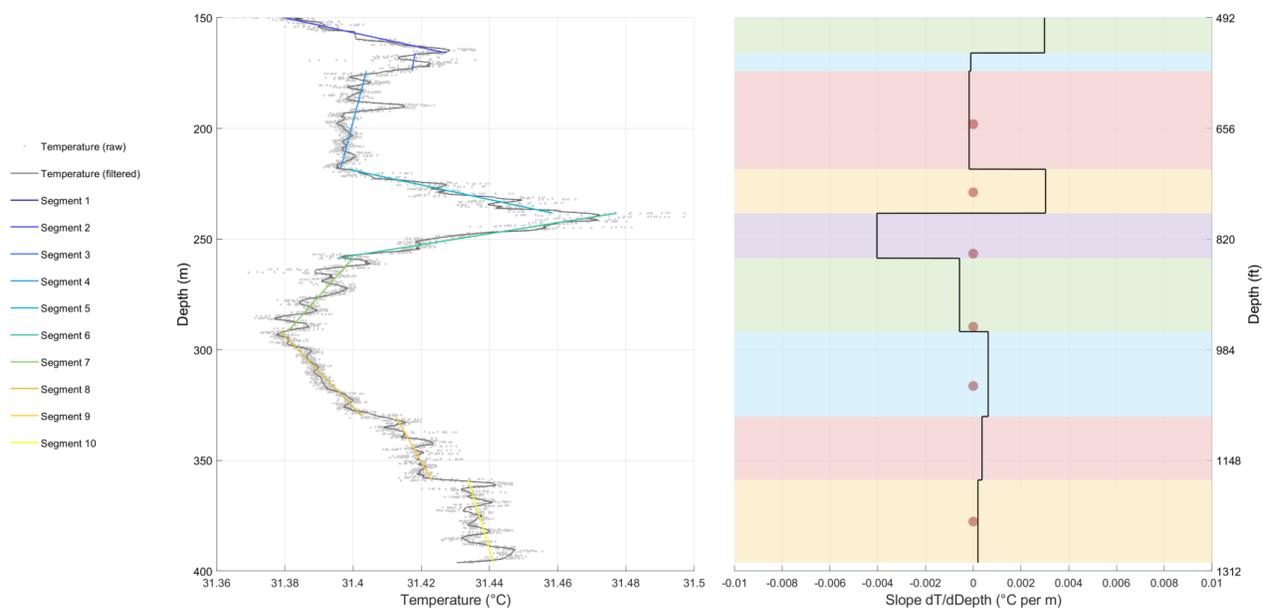
Figure 6. (Left) Filtered temperature–depth profile with slope-based segmentation. (Right) Temperature gradient (dT/dDepth) with color-patched segments; the red dot indicates mine work location obtained from mine stope book.
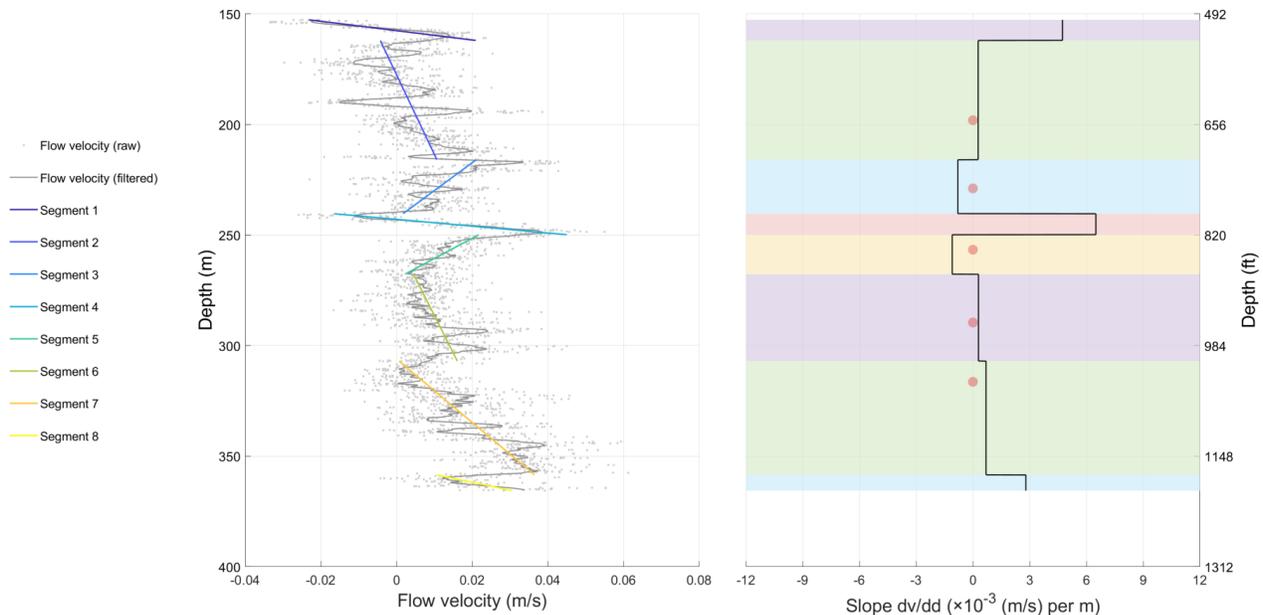
Figure 7. (Left) Filtered flow velocity–depth profile with slope-based segmentation. (Right) Flow velocity gradient (dv/dDepth) with color-patched segments; the red dot indicates mine work location obtained from mine stope book.

5.2 Mineshaft Chemistry

As shown in Figure 4, the mine water is corrosive with pH ranging from 5.25 to 5.35. Due to the oxidation of naturally occurring sulfide minerals. Equipment and piping which comes in contact with the water would have to take this into consideration. This would include pump casing, the pump itself, dropping, and the heat exchanger. Lower pH levels are likely influenced by pyrite oxidation, a reaction that

9

is strongly exothermic and is known to significantly raise the temperature of sulfide-rich waste rock or tailings piles undergoing microbially catalyzed oxidation.

5.3 Heat pulser testing

When the 2000-W heat pulser ran for 30 minutes, the water temperature locally increased approximately 1.5 °C around pulser. The magnitude of temperature increased was similar across all tested depths. After the heat pulser was turned off, heat dissipation occurred rapidly within few minutes. As shown in Figure 8, localized spike-shaped thermal anomalies indicate mine water heated by the heat pulser.
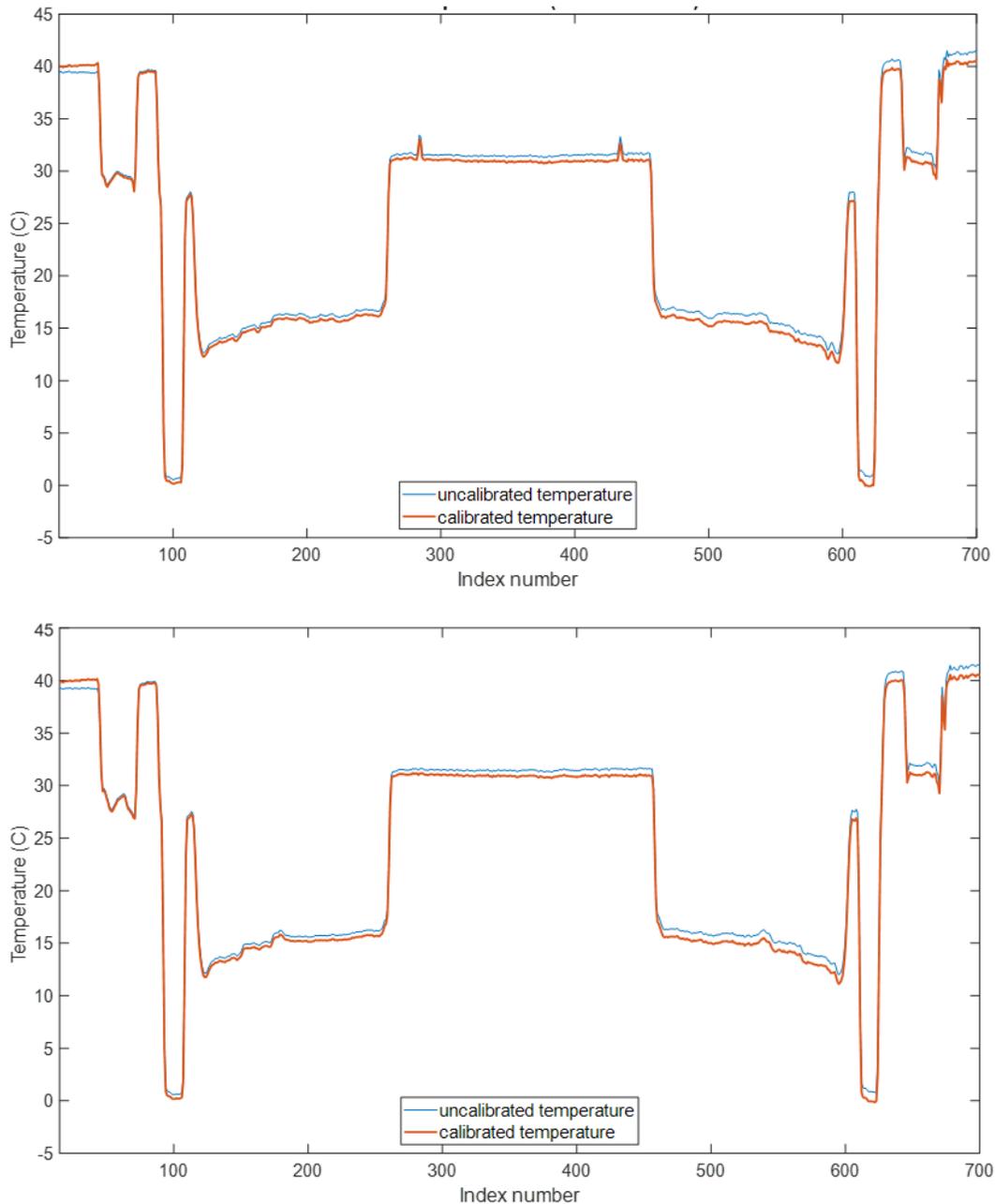
Figure 8. Fiber-optic DTS temperature profiles under heat pulser off (top) and on (bottom) conditions.

Figure 9 shows the DTS temperature data visualized as a depth-versus-time plot in the flooded shaft. Because the fiber-optic cable was installed in a looped configuration, descending and ascending along the shaft, the upper and lower portions of the figure exhibit near-symmetrical temperature patterns that represent the same physical depths measured in the forward and reverse directions. In principle, inclined thermal anomalies in such plots indicate vertical migration of heated water; however, in this dataset, no consistent upward or downward migration of heat is observed. Instead, thermal anomalies remain localized near the heat pulser depth and appear largely stationary over time. Under conditions dominated by natural convection and negligible background flow, heated water would be expected

to rise, producing a clear upward-propagating thermal signature. The absence of such behavior in this case is consistent with independently measured flow conditions, which indicate a predominantly downward flow direction with an average velocity of approximately 0.030 m/s (6 ft/min). This downward flow likely suppresses buoyancy-driven upward convection during the heat pulser tests, resulting in the observed confinement of heat near the source and an apparent lack of vertical heat transport.
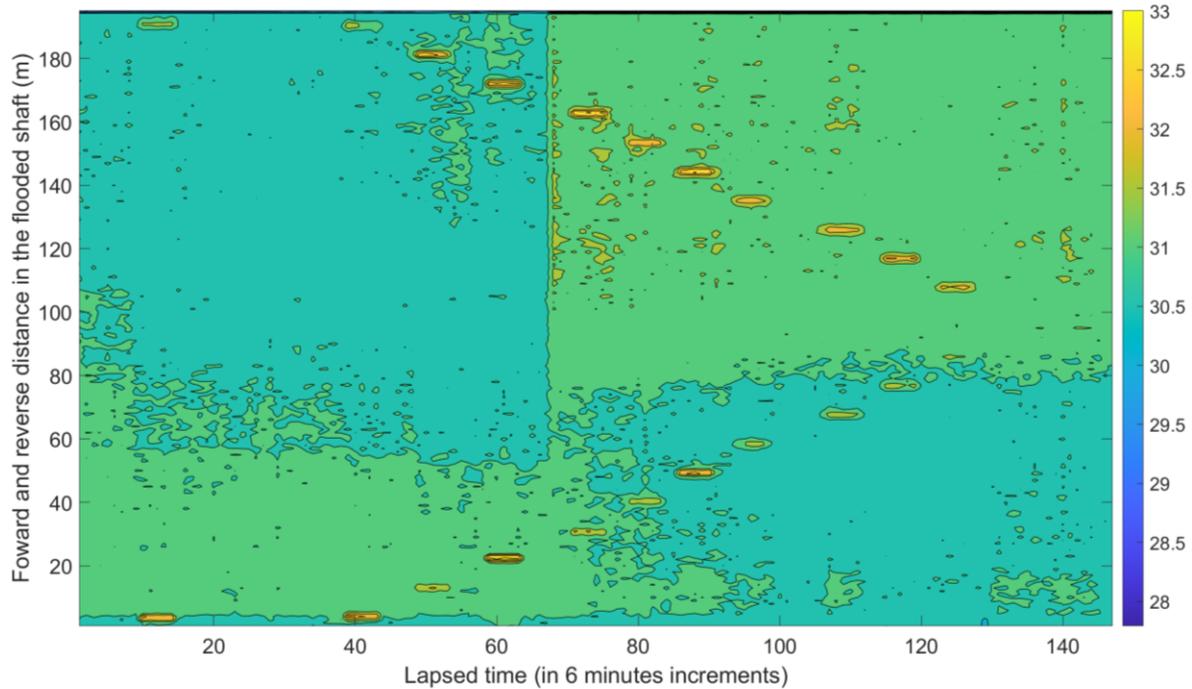

Figure 9. Depth-time temperature distribution in the flooded shaft.

6. CONCLUSIONS

Although this field investigation confirms that the Steward mineshaft in Butte, Montana, has been capped with approximately 12.2 m (40 ft) of fill over a wood/concrete bulkhead, access to the water column is still available via a 0.61 m (24 inch) steel pipe that extends from surface to a steel grating at 14.5 m (47.5 ft) below top of concrete. Spinner log data shows consistently positive velocities in the water column to the full depth explored (366 m bgs -1200 ft bgs), indicating net downward flow within the shaft. This pattern is characteristic of a cross-connecting well, in which water enters the borehole at shallower depths and discharges to deeper zones with lower hydraulic head. The inferred downward flow direction is supported by the hydraulic gradient between the Steward Shaft and the Berkeley Pit, which acts as a regional hydraulic sink at depth (Metesh, 2006). Further, there are many interconnected drifts which can network the flow.

The average Steward mine water temperature was approximately 31.4 °C. This is not surprising as the Steward Shaft was infamous for high temperatures during minging activities. Having access to water at this elevated temperature likely would lead to a greatly enhanced coefficient of performance (COP) in heating mode, upwards of 8.0 per the FedGeo team as compared to a more traditional heating COP of 4.0 for a typical ground-source heat exchange system (Heeg et al. 2024).

A segment-based environmental data analysis allowed for the identification of depth intervals with statistically significant temperature or flow gradients. This is important for selecting inlet and outlet elevations for any open-loop type of geothermal system that might be chosen. Due to the presence of oxygen and water during and after mining, the naturally occurring sulfide minerals are susceptible to oxidation thus resulting in acidic conditions and the release of sulfide; for example, via bacterial sulfate reduction. The mine water is acidic and thus equipment and piping which comes in contact with the water would have to take this into consideration. This would include pump casing, the pump itself, dropping, and the heat exchanger. Lower pH levels are likely influenced by pyrite oxidation, a reaction that is strongly exothermic and is known to significantly raise the temperature of sulfide-rich waste rock or tailings piles undergoing microbially catalyzed oxidation.

We used distributed temperature sensing (DTS) to monitor air and water temperatures in the shaft with a time resolution of 90 s per channel and a spatial resolution of 1 m. We used two fibers and two sensing directions to offset the channel location within the fiber, aiming to improve spatial resolution and image the direction of the heat plume in the water. We plan further use of the DTS data, along with other geophysical testing, to evaluate the conduction, convection, and advection mechanisms of heat transport within the column of water in this flooded shaft.

Kim et al.

6. ACKNOWLEDGEMENTS

References

Advanced Logic Technology & Mount Sopris Instruments: User guide: QL40 SFM - spinner flow meter, Version 08.09.15, Advanced Logic Technology (2015).

American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME): Ore deposits of the United States, 1933–1967, The Graton-Sales Volume, John D. Ridge, ed., New York, NY (1968).

ARCO: Butte Mine Flooding Operable Unit Remedial Investigation/feasibility Study Draft Remedial Investigation Report, Prepared by Canonie Environmental Services (1994).

Aries Industries, Inc.: User guide: Explorer portable borehole inspection system, Operation manual (EX1210 / EC1210 / WC1200), Aries Industries, Inc. (2016).

Butte Historical Society, Woodruff, N.: Steward Mine, Story of Butte, accessed Dec. 30, https://storyofbutte.org/items/show/3397, (2025).

Daly, W.B., and Berrier, C.L.: Mining methods and installations of the Anaconda Copper Mining Co. at Butte, Montana, Transactions of the American Institute of Mining, Metallurgical, and Petroleum Engineers, (1923).

Duaime, T.E., McGrath, S.F., and Icipini, G.A.: Forty Years of Water-Level Monitoring and Water-Quality Sampling, 2022 Consent Decree Update, Butte, Montana, 1982–2022, Montana Bureau of Mines and Geology Open-File Report 761 (2023).

Euroheat & Power: Mijnwater project in Heerlen, The Netherlands, accessed Jan. 8, 2026, https://www.euroheat.org/dhc/knowledge-hub/mijnwater-project-in-heerlen-the-netherlands, (2021).

Fratta, D., Tinjum, J.M., and Hart, D.J.: Evaluation of Distributed Temperature Sensing Results at the West Point Military Campus, PROCEEDINGS, 51st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 9-11, 2026. SGP-TR-230 (2026).

Gammons, C.H., Metesh, J.J., and Duaime, T.E.: An overview of the mining history and geology of Butte, Montana. Mine Water and the Environment, 25, (2006a), 70–75.

Gammons, C.H., Metesh, J.J., and Snyder, D.M.: A survey of the geochemistry of flooded mine shaft water in Butte, Montana. Mine Water and the Environment, 25, (2006b), 100–107.

Gökpinar, T., and Heinze, T.: Algorithm-based segmentation of temperature-depth profiles: Examples from a mine, Environmental Modelling and Software, 180, (2024), 106143.

GWIC: Montana Bureau of Mines and Geology, Ground Water Information Center http://mbmggwic.mtech.edu/ , (2006).

Hagan, T.: Temperature and Pressure Sensing in Three Flooded Underground Mine Workings in Butte, Montana, USA, Graduate Theses & Non-Theses, 21, http://digitalcommons.mtech.edu/grad_rsch/21, (2015).

Hinick, W.: Montana Tech uses mine water from Orphan Boy Copper Mine to heat buildings, Mining Connection, https://miningconnection.com/surface/featured_stories/article/montana_tech_uses_mine_water_from_orphan_boy_copper_mine_to_heat_buildings, (2016).

James, D.: Butte Memory Book, The Caxton Printers LTD, (1980).

Metesh, J.J.: Geochemical evolution of flooding mine waters in a zoned, sulfide-hosted ore deposit, Summit Valley Mining district, Butte, Montana, Ph.D. dissertation, Univ of Montana, Missoula, MT, 157 pp, (2004).

Metesh, J. J.: Using a water balance to determine the source of water in the flooding underground mine workings of Butte, Mine Water and the Environment, 25, (2006), 108–113.

Metesh, J.J., and Duaime, T.E.: The flooding of Butte's underground mines and Berkeley Pit: water-quality monitoring through 2001, Mont Bur Mines Geol, Open File 456, 55 pp, (2002).

Miller, R.N.: Production history of the Butte District and geological function, past and present, Guidebook for the Butte Field Meeting of Society of Economic Geologists, August 18–21, 1973, 2nd printing (1978).

Montana Bureau of Mines and Geology: O25 Vol. 7 Mountain Consolidated/Steward, Butte Stope Books, Accessed Dec. 30, 2025, https://mbmg.mtech.edu/Information/Collections/Butte-Stope-Books/items/bsb166.html#bsb173, (2025).

Pokhrel et al.: Opportunities and Technical Challenges for Thermal Energy Exchange from Abandoned Underground Mines, International Ground-Source Heat Pump Association Annual Conference, Urbana, IL (2025).

Ralston, D.R., Sprenke, K.F., Liou, J.C.P., and Petrich, C.: Evaluation of hydrologic impacts from operation of a pumping-injection program in the underground workings at Butte, Montana, prepared for the Kelley Resource Recovery Corporation (1994).

Sellwood, S.M., Hart, D.J., and Bahr, J.M.: An in-well heat-tracer-test method for evaluating borehole flow conditions, Hydrogeology Journal, 23(8), (2015), 1817-1830.

Shovers, B.L.: Miners, Managers, and Machines: Industrial Accidents and Occupational Disease in the Butte Underground, 1880–1920. Master's thesis, Montana State University, Bozeman, MT (1987).

Spindler, J.C.: The clean-up of Silver Bow Creek, Mining Congress Journal, June (1977).

Stephenson, S.: Personal Communication (1994).

Tinjum, J.M., Fratta, D., Hart, D.J., and Luebbe, A.K.: Characterizing the Geothermal Resource at the Detroit Arsenal, PROCEEDINGS, 51st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 9-11, 2026, SGP-TR-230 (2026).

USEPA: Record of Decision, Silver Bow Creek / Butte Area Operable Unit 03, Butte Mine Flooding Operable Unit, Sept.29 (1994).

USEPA: EPA Method 300.1: Determination of Inorganic Anions in Drinking Water by Ion Chromatography, Washington D.C (1997).

USEPA: EPA Method 6010D (SW-846): Inductively Coupled Plasma-Atomic Emission Spectrometry, Washington D.C (2014a).

USEPA: EPA Method 6020B (SW-846): Inductively Coupled Plasma-Mass Spectrometry, Washington D.C (2014b).