# Optimizing the Geothermal Resource at the Detroit Arsenal

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## ABSTRACT

As part of the Federal Geothermal Partnerships (FedGeo) initiative, the University of Wisconsin–Madison conducted *in situ* characterization of the low-temperature geothermal resource at the U.S. Army Garrison Detroit Arsenal to support techno-economic evaluation and borefield optimization. This study employed mud-rotary drilling, geophysical logging, and advanced monitoring techniques—including fiber-optic distributed temperature sensing (FO-DTS)—to assess thermal, physical, and hydrogeological properties along a 152-m test borehole. A conventional thermal response test (TRT) indicated a bulk thermal conductivity of 2.25 $W \cdot m^{-1} \cdot K^{-1}$, while the acquired FO-DTS data revealed significant variability in heat transfer, identifying high-conductivity formations such as the Birdsong Bay Limestone (67–78 m), Traverse Limestone (78–93 m), and cherty dolomite of the Dundee Group (140–152 m). Drilling performance demonstrated that a 152–168 m borehole can be advanced in a single workday using the mud-rotary drilling method. Completing the drilling in one workday optimizes the installation of the borehole, thus reducing contracting cost. Our testing results suggest that extending the borehole deeper to at least 168 m could increase thermal capacity by approximately 15% compared to a 152-m ground heat exchanger. These findings inform optimal borehole depth, spacing, and layout for geothermal borefields, which represent the most variable and costly component of ground heat exchange systems and thermal energy networks.

## 1. INTRODUCTION

The Federal Geothermal Partnerships (FedGeo) initiative, a collaboration between the U.S. Department of Energy's Office of Geothermal and the Federal Energy Management Program (FEMP), aims to expand geothermal heating and cooling at federal facilities nationwide. As part of this program, technical assistance was provided to the U.S. Army Garrison Detroit Arsenal (Detroit Arsenal) in southeastern Michigan to evaluate the feasibility of a borehole heat exchanger (BHE) system. Geoscientists and engineers working for the FedGeo initiative served as geothermal subject matter experts, offering design guidance and modeling support, while the University of Wisconsin–Madison led the on-site resource characterization with assistance from the Wisconsin Geological and Natural History Survey (WGNHS).

Accurate characterization of the subsurface thermal and hydrogeological properties is essential for optimizing borefield design, which represents the most variable and costly component of a geothermal system. At the Detroit Arsenal, site characterization included drilling, geophysical logging, and advanced monitoring techniques to measure the distributed thermal-physical-hydrogeological properties and assess expected system performance. These data informed the techno-economic analysis and guided the optimal borehole depth and spacing, and layout decisions in coordination with land-use planning.

Conventional thermal response tests (TRTs) provide bulk ground thermal conductivities but lack resolution along the borehole length. To address this limitation, fiber-optic distributed temperature sensing (FO-DTS) was integrated into a distributed thermal response test (FO-DTRT) enabling higher resolution thermal conductivities within 1–2 m intervals. This technologically advanced approach revealed variability in subsurface heat transfer and identified the zones with the highest thermal conductivity, supporting design optimization for energy efficiency and cost reduction.

The objective of this work is to document the site characterization activities at the Detroit Arsenal and present results that validate models and inform BHE sizing. Outcomes include comprehensive estimates of distributed thermal and hydrogeological properties and a techno-economic evaluation of vertical borefield installation, contributing to best practices for geothermal deployment at federal facilities.

## 2. BACKGROUND

### 2.1 Ground-Coupled Heat Pump Systems

Ground-Coupled Heat Pump (GCHP) systems use the thermal energy stored in the Earth and can be applied nearly anywhere to create an environmentally friendly and operationally low-cost solution that is a sustainable source for space heating and cooling (Ozenger et al. 2006, Chua et al. 2010). Using the ground as a heat source and sink is often more efficient than using the ambient air because the ground temperature is usually higher than the ambient air temperature in the winter and lower in the summer, thus improving the thermodynamic efficiency of heat pumps. Typically, the relatively constant ground temperature near the land surface results from homeostatic heat flux,

the rise and fall of the heat radiating from above (the sun) and the heat emanating below (radioactive decay within the Earth's interior). In the shallow subsurface (<10 m deep), the temperature fluctuates due to atmospheric interaction (Kusuda and Achenbach 1965), and at greater depth (>50 m), the temperature approaches that of the natural geothermal gradient (Grant et al. 1982, Ozdogan-Dolcek et al. 2014). However, the natural geothermal gradient was not observed in the borehole at the USAG Detroit Arsenal because of anthropogenic impacts at the land surface and flowing groundwater.

Operationally, GCHP systems reject heat to and extract heat from the ground using borehole heat exchangers (BHEs). Although a number of BHE configurations exist, vertical BHEs are most common in large GCHP systems. A vertical BHE typically consists of a high-density polyethylene (HDPE) U-tube inserted into a borehole. The space between the U-tube and borehole wall is typically grouted to provide better thermal contact between the loop and the surrounding ground, and also to prevent groundwater cross-contamination of aquifer. Typical boreholes have a depth between 40 m and 150 m and a diameter of 0.075 m to 0.15 m (Diao et al. 2004). A carrier fluid, typically a water-glycol mixture in northern climates is circulated between a borefield of BHEs and the heat pump.

Geothermal exchange systems, and the models used in their design, were originally intended for residential housing interiors rather than for large buildings or multi-building campuses. Consequently, special care must be taken when designing a commercial- or district-scale GCHP system (Kavanaugh 1995, Fan et al. 2015). The need for a much greater number of boreholes for these large GCHP systems requires that the thermal interactions occurring between the boreholes must be considered (IGSHPA 1991). Instead of heat dissipating from just a single borehole or a few boreholes, heat instead must be stored within or dissipated from borefields with tens to hundreds of boreholes. Furthermore, many office buildings being conditioned are cooling-dominated due to heat generated by employees, lighting, and computers. These factors have caused notable large-scale systems to overheat and lose efficiency over time (Florea et al. 2017, Herrera et al. 2018, McDaniel et al. 2018a, Yang et al. 2013, Zhou et al. 2014). Despite this challenge, the installation of large-scale GCHP systems have an enormous opportunity for energy (Heeg et al. 2024) and carbon emission savings (Tinjum et al. 2023, Thomas et al. 2020). Thus, if large BHE fields could reliably be designed to operate efficiently in the long term, GCHP systems could well become a preferred method for space heating and cooling of large-scale facilities.

## 2.2 Importance of Subsurface Geology for GCHP System Design

The geology of a BHE field plays a very important role in its effective design and management. The loop design must account for how heat is transferred in the ground (IGSHPA 1991 and 2005, Busby et al. 2009, ASHRAE 2011). Essentially all BHE design approaches (e.g., Ingersoll 1954, Eskilson 1987, IGSHPA 1991) rely on some estimate of thermal conductivity of ground ($\lambda_{ground}$). Subsurface geological conditions having higher thermal conductivities that maximize heat transfer and minimize the loop size in GCHP systems (Diao et al. 2004, Fan et al. 2007, Dehkordi and Schincariol 2013, Hecht-Mendez et al. 2013). An extensive design effort is conducted such that the loop length is not too small (resulting in exiting water temperatures from the field that are too high) or not too large (resulting in conservatively large and prohibitively expensive first costs).

The subsurface is normally assumed to have homogeneous conditions when a thermal response testing (TRT) analysis is made and when using building energy design tools. However, the subsurface commonly has a stratified geology through the borehole depth, with layers of different lithologies with varying thermal properties and creating different hydrogeological conditions. For example, in a comprehensive study of thermal conductivity of rock formations in Wisconsin, Walker et al. (2015) revealed a measured range of thermal conductivities (1.84 to 6.71 W m$^{-1}$ K$^{-1}$) and volumetric specific heat capacity (713 to 891 J kg$^{-1}$ k$^{-1}$) along boreholes. Even the thermal properties of broad rock types (e.g., sandstone, limestone, granite, basalt) cannot be viewed as homogeneous considering the plus-minus range of thermal conductivity within specific rock types may commonly be +/- 3 W m$^{-1}$ K$^{-1}$. Saturated conditions in unlithified sediments and bedrock aid in conducting heat better than where groundwater is absent (Horai and Simmons 1969, Zimmerman 1989, Clauser and Huenges 1995, Meyer 2013). The effect of subsurface heterogeneity on the performance of GCHP systems has been understudied, and it remains uncertain how variations in the lithological properties contribute to heat transfer in different depth intervals. As McDaniel (2018b) and others detail, the ground temperature profiles with depth in a borehole can vary significantly; therefore, variations in these properties along the length of BHE should be taken into consideration for any practical design of a GCHP system.

The number of boreholes and final drilling depth is highly dependent on $\lambda_{ground}$ which, in turn, strongly influences the initial cost of constructing borefields, particularly for large commercial buildings (Yavuzturk 1999). However, the determination of $\lambda_{ground}$ is a significant challenge. Design methods generally do not account for variable ground thermal properties or the deep geothermal gradient. Furthermore, and potentially of great importance, heat can also be carried away from the borefield by groundwater. Flowing groundwater results from a hydraulic gradient where groundwater moves the quickest through porous geological formations with a higher hydraulic conductivity. Dehkordi and Schincariol (2013) evaluated the long-term performance of BHEs in GCHP systems and the effect of thermo-hydrogeological parameters by modeling fluid temperature during a period of constant heat extraction (no seasonal thermal load) and 25 years of simulated operation. The results of this numerical study indicated that the thermo-hydrogeological parameters impacted the sustainability of the GCHP system. Studies by Walker et al. (2015) and Catolico et al. (2016) emphasized the importance of the undisturbed ground temperature and the ground thermal properties on GCHP system design and performance. However, software used to model GCHP systems (e.g., GLHEPRO) cannot resolve the impacts of flowing groundwater.

## 2.3 Geological Setting

The stratigraphy at the Detroit Arsenal reflects a sequence of formations typical of the Michigan Basin, each sequence of formations with distinct lithological and thermophysical characteristics relevant to geothermal resource assessment (Figure 1). The uppermost bedrock unit encountered is the Antrim Shale, a "black, fine-grained laminated shale interbedded with siltstone-shale couplets" (Harrison et al. 2018). This shale formation is well known as a natural gas reservoir, especially in the northern portion of Michigan's lower peninsula, having produced over 1.8 trillion cubic feet of gas since the mid-1980s (Wylie and Wood 2005). The Antrim Shale comprises several members—Upper, Lachine, Paxton, and Norwood—with porosity ranging from 2–7% in the Upper and Paxton members to 0.1–2% in the Lachine and Norwood members (Adeyilola et al. 2023). Mineralogical analysis through XRD, conducted by Adeyilola et al. (2023), indicates variable proportions of quartz, pyrite, feldspar, carbonates, and clay minerals. This variability in mineralogy contributes to heterogeneity in thermal conductivity.

Underlying the Antrim Shale is the Birdsong Bay Limestone, which consists of argillaceous limestone to calcareous shale (Harrison et al. 2018). The upper portion exhibits higher gamma-ray signatures due to the higher clay content, which transitions gradually from the overlying Antrim Shale (Voice and Harrison 2018). Beneath the Birdsong Bay Limestone lies the bedrock of the Traverse Group, which can be subdivided into the Traverse Limestone, Bell Shale and Dundee Limestone.

The Traverse Limestone is dominated by dolomite and limestone facies, including oolitic and skeletal shoals, reefs, lagoonal carbonates, and interbedded cherty carbonates, reflecting deposition in a shallow marine environment (Voice and Harrison 2018). The Bell Shale, also known as the Silica Formation by Harrison et al. (2018), consists of laminated shale to argillaceous lime mudstone with abundant fossils and pyrite inclusions.



**Figure 1: Expected geological stratigraphy in the Detroit Region of the Michigan Basin.**

The lowermost bedrock unit encountered during drilling at the Detroit Arsenal is the Dundee Limestone, a massively bedded limestone and dolomite with stylolites that is pelletal to fossiliferous (Harrison et al. 2018). This formation has been a major oil producer in Michigan (Wylie and Wood 2005). The Dundee Limestone includes the Rogers City and Reed City Members and can be distinguished by distinctive gamma-neutron log signatures and carbonate facies (Gardner 1974).

## 2.4 Thermophysical Properties

Given the variability in lithology—from shale and siltstone to limestone and dolomite—thermal conductivity estimates must rely on ranges rather than single values. Materials encountered during drilling at USAG Detroit Arsenal include unconsolidated glacial till—sand and gravel, silt and clay—and shale, siltstone, claystone, mudstone, limestone and dolomite bedrock that each contributing differently to geothermal performance (Luebbe 2024).

Thermal property values are available for specific glacial deposits and sedimentary bedrock types, as well as for the minerals that make up these rock types, but they should not be used to characterize the thermal properties for each bedrock unit. Past studies focused on the thermal properties of different sedimentary rock types such as Walker et al. (2015) and Stumpf et al. (2021) created a geologic repository of thermal properties, but these measurements cannot be generalized for sedimentary rock formations that have heterogenous properties. Similarly, study results for specific rock types cannot be used to generalize thermal properties of specific lithologies. For example, a fossiliferous limestone will behave differently to thermal loading than an argillaceous limestone and therefore using a thermal conductivity value for a generic "limestone" is not that accurate (Luebbe 2024). The specific bedrock formations encountered at Detroit Arsenal do not currently have published thermal properties.

Because each geologic formation likely to be encountered at the Detroit Arsenal includes different lithologies (Figure 1) with varying material properties, ranges must be used to represent their thermal conductivity values. The thermal conductivity of silty and clayey glacial tills ranges between 0.2 and 2.1 W m$^{-1}$ K$^{-1}$, of glacial silt and sand between 1.2 to 2.3 W m$^{-1}$ K$^{-1}$, and of glacial sand and gravel between 1.3 and 1.8 W m$^{-1}$ K$^{-1}$ (Stumpf et al. 2021). The thermal conductivity of dolomite ranges from 1.6 to 6.2 W m$^{-1}$ K$^{-1}$, of limestone from 1.4 to 4.5 W m$^{-1}$ K$^{-1}$, of siltstone from 1.4 to 2.4 W m$^{-1}$ K$^{-1}$, of shale from 1.0 to 4.0 W m$^{-1}$ K$^{-1}$, and of claystone from 1.9 to 2.9 W m$^{-1}$ K$^{-1}$ (Kavanaugh et al. 1997). The thermal conductivity of mudstone ranges from 1.4 to 2.8 W m$^{-1}$ K$^{-1}$ (Bloomer 1981).
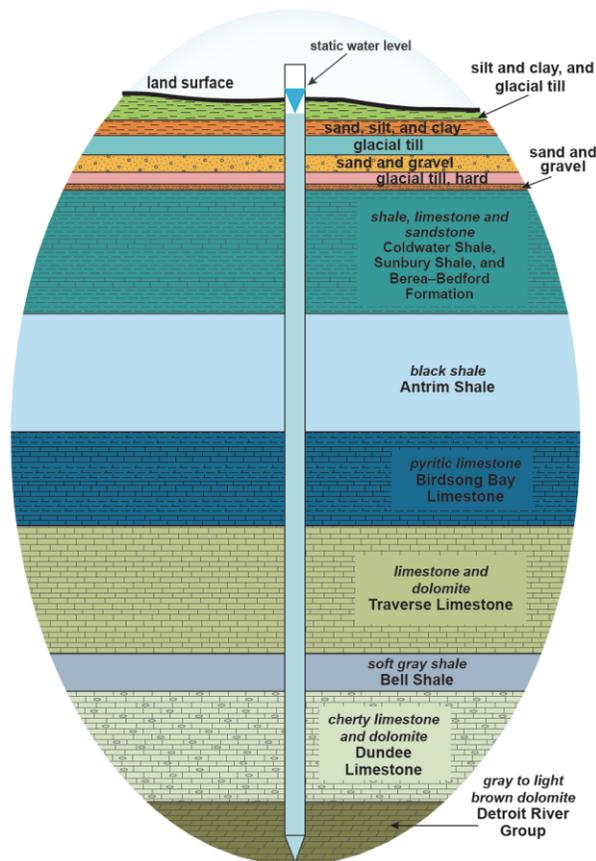
## 3. GEOLOGICAL INVESTIGATION

Several methods were used to characterize the thermal properties of the glacial deposits and sedimentary bedrock formations encountered in the test boring completed at the USAG Detroit Arsenal using the mud-rotary drilling method. One of these methods consisted of collecting cuttings from the recirculated drilling fluid for each formation and analyzing them visually at the same time reviewing the published geological information.

Shortly after reaching the final borehole depth of 152 m, downhole geophysical logs were collected. Due to the presence of drilling mud and the absence of casing in the bedrock, only a limited suite of logs was acquired. The natural gamma and normal resistivity logs delineate prominent lithological contacts that were correlated with descriptions of the drill cuttings. The drill cutting samples were further examined after being dried out. Because the drilling mud contaminated samples of unconsolidated glacial deposits, their detailed identification was prohibited.

### 3.1 Borehole Logging

To characterize the thermal properties of the geologic formations at USAG Detroit Arsenal, multiple methods were employed, including collection of drill cuttings during mud rotary drilling and geophysical logging. Samples were collected at approximately 1.5-m intervals based on rod length measurements from a datum at the driller's table. Although minor inconsistencies occurred due to drilling speed and slurry conditions, the sampling interval remained generally constant along the borehole.

Drill cuttings were retrieved using a long-handled kitchen sieve, rinsed briefly with water to remove the bentonite mud, and placed in plastic bags labeled with the depth. Field identification was performed immediately, using descriptive terms such as *trace* (≤15%), *some* (15–30%), and *with* (30–50%) to indicate relative proportions of the constituents. For example, "sand with clay" denotes a predominantly sand sample containing 30–50% clay. Hydrochloric acid (HCl) was applied to rock samples to distinguish carbonate-bearing formations (dolomite, limestone) from calcareous shale.

### 3.2 Geophysical Logging

Geophysical logging was conducted in the uncased, mud-filled borehole upon completion of drilling. Natural gamma and normal resistivity logs were acquired; these provided clear differences in lithology that correlated with field descriptions of cuttings. Matching geophysical signatures with cutting observations enabled a preliminary stratigraphic interpretation. Fluid temperature and conductivity, caliper, natural gamma, and normal resistivity logs were collected using a Mount Sopris Instrument Company logging system consisting of a Matrix logger, winch, and downhole sondes provided by WGNHS.

Each log was acquired by lowering the appropriate sonde into the borehole at a controlled speed of approximately $0.05–0.07$ m·s$^{-1}$ (3–4 m min$^{-1}$), resulting in an average run time of about 2 hours per sounding. During the downward pass, data was recorded and displayed in real time on a computer connected to the logger. After reaching the bottom, the tool was retrieved, exchanged for the next sonde, and the process repeated for subsequent logs. This procedure ensured comprehensive coverage of lithological, structural, and thermal characteristics necessary for the geothermal resource assessment.

#### 3.2.1 Natural Gamma Radiation

Natural gamma radiation logging measures the count rate (counts per second) of naturally occurring gamma radiation emitted from geologic materials surrounding the sonde (Telford 1990). Most natural earth radiation is generated from isotopes of Potassium-40 ($^{40}$K), and the natural decay series of Uranium-238 ($^{238}$U) and Thorium-232 ($^{232}$Th). The logs provide a highly visual and objective representation of the lithologic characteristics in the subsurface and are used to develop basic correlations and recognize subtle variations vertically in the subsurface (Keys 1990). Minerals such as clays and feldspars, which contain these elements, exhibit higher gamma activity. Consequently, these logs are effective for differentiating different lithologies (e.g., shale formations) that typically have higher gamma counts than dolomites due to their greater clay content.

#### 3.2.2 Normal Resistivity

Normal resistivity logging evaluates the electrical resistivity of the formation. Measurements are typically taken at multiple electrode spacings to minimize borehole fluid effects. Resistivity was recorded at 0.20- and 0.41-m electrode spacings. Intervals in the bedrock with higher porosity, conductive pore fluids, and clay minerals exhibit lower resistivity. Thus, shales generally appear less resistive than dolomites with lower clay content and porosity.

#### 3.2.3 Caliper

A three-arm caliper log was collected to measure the borehole diameter. The spring-loaded arms expand and contract as the tool moves upward, detecting changes in borehole diameter. Enlargements or "washouts" indicate zones of loose or weakly cemented materials, such as sand and gravel, while sharp increases in diameter may correspond to fractures in the bedrock.

### 3.2.3 Fluid Temperature

Fluid temperature was logged during tool descent. Because logging occurred shortly after drilling the residual mud circulation likely suppressed natural formation temperatures. Therefore, these measurements would not represent the ambient thermal conditions and thus the data were excluded from integrated analysis.

### 3.2.4 Fluid Conductivity

Fluid conductivity logging measures the electrical conductivity of borehole fluids, aiding the interpretation of resistivity logs, and identifying zones of fluid inflow or the presence of fractures. For this study, the conductivity readings exceeded the sonde's upper range, likely impacted by the drilling mud, and thus that data was also not reported.

## 3.3 Distributed Thermal Response Testing (DTRT)

During May and June 2024, UW–Madison deployed and interrogated Distributed Temperature Sensing (DTS) arrays to support the thermal characterization of the 152-m testing borehole drilled at the Detroit Arsenal. The DTS technique uses the rapid transmission of laser pulses into silica fiber while monitoring the return signals caused by Raman backscattering events. We deployed three multimode fiber optic cables and interrogated them using a Sensornet Sentinel DTS interrogator and a sixteen-channel interrogator to monitor the thermal profile in the borehole during and after the TRT.

We placed one of the fiber optic cables up and down the borehole on the outside of the HDPE U-tube that covered a distance of 304 m (Figure 2). We also placed two other fiber cables about ~68 m inside each of the legs of the HDPE pipe. We could not complete the fiber loop inside the HPDE pipe due to issues during drilling. This cable insertion was controlled by the friction against the inside of the HDPE pipe and the buoyancy force created by the water inside the pipe. Each fiber optic cable was protected by a 9.5-mm-OD PE tubing.

We deployed cold and hot water baths monitored with pt100 thermistors and thermocouples to calibrate the optical responses and obtain temperature distribution along each fiber optic run. The DTS interrogator, water baths (with temperatures controlled by a circulating pump for the hot water bath and a small refrigerator for the cold water bath), a data logger and computer, and an air conditioning unit (the DTS interrogators have a range of temperature operations that can be reached during the summer months in Michigan) were housed in a small shed to protect the instrumentation and peripheral of the environment (Figure 2).

We collected data with four DTS interrogator channels using single-ended configurations. Channels 1 and 2 collected single-ended data by sending laser pulses to each end of the fiber on the outside of the HPDE pipe. The beginning sections of each fiber optic cable ran through the cold and hot water calibration baths to provide a more robust contrast to the calibration algorithm. Channels 3 and 4 collected data on single-ended configurations from each of the two fiber optic cables inside the HPDE pipes.

## 4. RESULTS

The Detroit Arsenal geothermal test boring revealed a stratigraphy dominated by unconsolidated glacial deposits overlying sedimentary bedrock formations with varying thermal properties (Figure 3). The upper 43 m consisted primarily of glacial tills, that are interstratified with till, ranging from clay-rich layers of silt, sand, and gravel; the top 4.6 m of the borehole was drilled identified as fill material (Luebbe 2024). Between 4.6 and 23 m depths, the profile included alternating layers of silt, clay, and till were encountered, and this transitioned, with silt and sand from 23 to 26 m, before transitioning to sand and gravel from 26 to 32 m and returning to glacial till from 32 to 43 m. These unconsolidated materials generally exhibit lower thermal conductivities compared to bedrock (McDaniel et al. 2018b, Stumpf et al. 2021), limiting their contribution to the overall heat exchange potential.

Representative samples from the major lithologic units and high-conductivity zones were selected for further laboratory analysis. Identification of bedrock types relied on regional bedrock stratigraphic descriptions of Harrison et al. (2018) for Wayne County. An example of a log of the cuttings for the Antrim Shale and Traverse Limestone is shown in Figure 3. The combined field and laboratory observations, along with the geophysical logs and thermal response test data, informed our characterization of the subsurface thermal and hydrogeological conditions. Full results of the borehole characterization are found in Luebbe (2024).

Bedrock was first encountered at approximately 43 m, beginning with the Antrim Shale, which extended to 67 m depth (Figure 3). This unit consisted of dark gray to black shale and siltstone with minor quartz and pyrite inclusions, that has an estimated thermal conductivity in the range of 1.0–2.4 W m$^{-1}$ K$^{-1}$. Below the shale, the Birdsong Bay Formation (67–78 m) comprised argillaceous limestone to lime mudstone interbedded with calcareous shale and trace inclusions of limestone, dolomite, and pyrite as well as an increase in shale/siltstone content in the upper portion of this formation, with estimated conductivity between 1.9 and 4.0 W m$^{-1}$ K$^{-1}$. Fiber-optic distributed thermal response testing (FO-DTRT) identified a higher thermal conductivity zone near the contact with the Traverse Limestone (75–78 m), which is characterized by crystalline dolomite and limestone with minor chert and sulfide minerals as well as trace to some siltstone and shale layering.
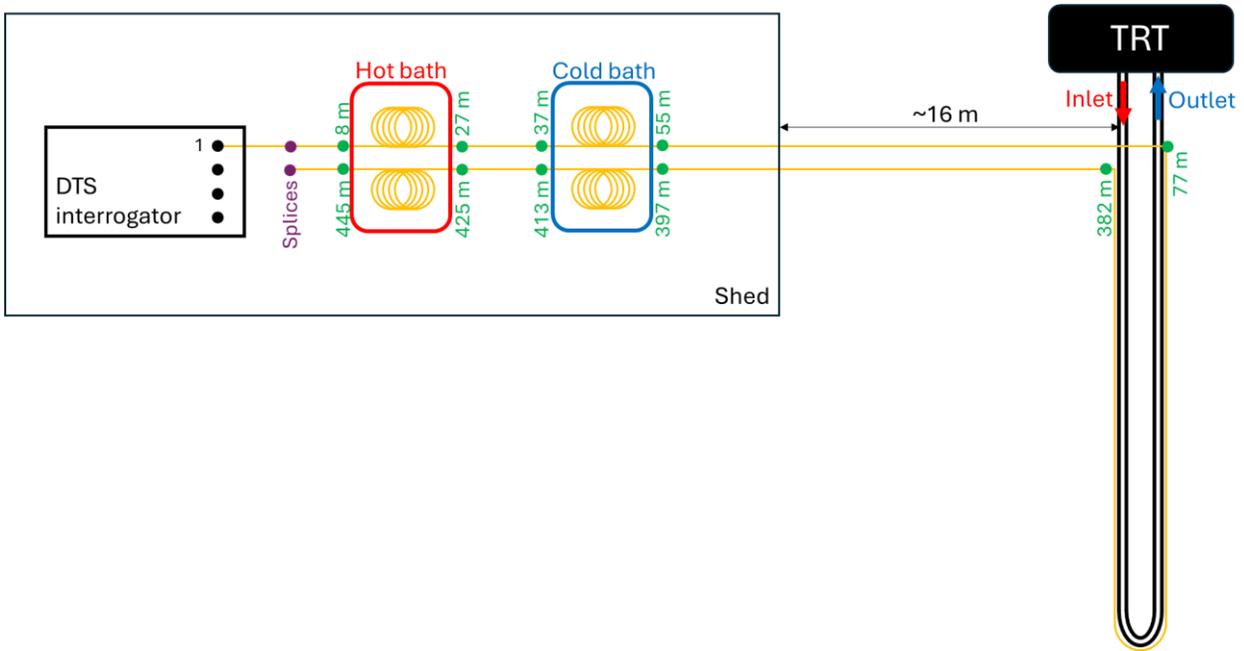
**Figure 2. Generalized DTRT Distributed temperature sensing setup with the fiber (top). The attached fiber optic cable ran outside the HDPE U-tube starting from the top to the bottom and back to the top of the borehole. View of the FO-DTS instrumentation and sensing peripherals (bottom).**
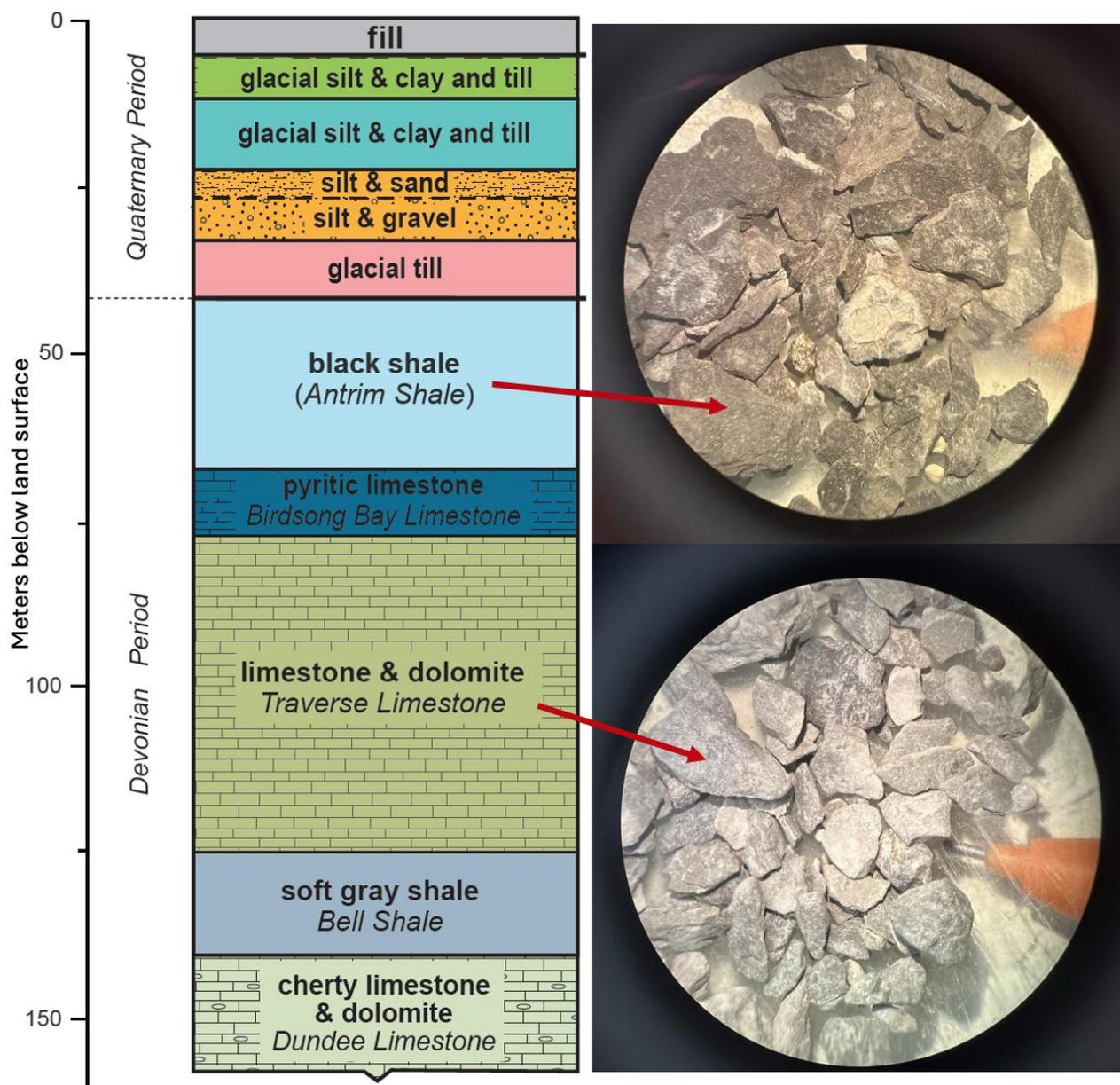
**Figure 3. (Left) Geologic log from the borehole at the Detroit Arsenal. (Top Right) Drill-cutting samples of black siltstone and shale with trace limestone and pyrite from the Antrim Shale were collected from a depth of 45.7–47.2 m. This shale was encountered from 42.7 and 67.1 m below ground surface (bgs). The rock fragments exhibited a weak or no reaction to HCl. (Bottom Right) Rock fragments of the Traverse Limestone were sampled from a depth of 85.3–86.9 m bgs. This unit was encountered between 77.7 and 93.0 m bgs and consists of gray to tan limestone with trace chert, siltstone, and shale. The tip of a 0.7-mm mechanical pencil is shown for scale. Sample images and descriptions are from Luebbe (2024).**

The Traverse Group (78–140 m) includes a 15-m interval of Traverse Limestone (78–93 m), which consisted of a gray to tan limestone with trace to some inclusions of materials such as chert, dolomite, sulfide minerals, fossils, and shale/siltstone, followed by Bell Shale (93–140 m), which consisted primarily of dark gray shale and lime mudstone with occasional limestone layers, with more limestone present at the top of the layer during the transition from the Traverse Limestone (Luebbe 2024). Thermal conductivity for these units would be between 1.4 and 4.5 $W \cdot m^{-1} \cdot K^{-1}$ for the limestone and 1.4 and 2.4 $W \cdot m^{-1} \cdot K^{-1}$ for the shale. The deepest interval, the Dundee Limestone (140–152 m), was primarily dolomite and limestone with some shale and trace fossils, with some difficulty in logging due to the sampling method (Luebbe 2024), offers the highest thermal potential with conductivity between 1.6 and 4.5 $W \ m^{-1} \ K^{-1}$. These findings indicate that extending borehole depth into the Dundee Limestone could significantly enhance geothermal capacity. A greater depth of exploration would be needed to confirm formation thickness but, based on the description by Harrison et al (2018), this formation can extend up to 41 meters thick.

The borehole geophysics helped differentiate between the different lithologies encountered in the boring log (Figure 4). In general, fine grained rock and sediments such as clays, silts, and shales have higher gamma counts than sands and gravels or limestones. Also, fined

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grained rock and sediment such as clays, silts, and shales are generally more conductive than sands and gravels and limestones. Using these two logs we can identify fine-grained zones in the glacial sediment (labeled as clay in Figure 4). Also labeled in Figure 4 are thin layers of glacial sands and gravels. The presence of these materials in the borehole can be correlated to sections where the borehole was enlarged or washed out. Because sand and gravel are not as cohesive or stiff as the finer-grained sediment (clays and glacial till) they are more susceptible to wash-outs. The upper bedrock lithology encountered was a shale at 43 meters corresponding to the Antrim Formation. Below this thick shale is an interval having alternating layers of limestone and shale (Figure 4). The shaly intervals have higher gamma counts and lower resistivity than the limestone.

## 5. ANALYSIS

Identifying thermal conductivities of distinct layers in the subsurface where a potential geothermal borefield may be located can require a combination of thermal response testing, collection of drill cuttings and laboratory analyses, DTRT surveys, and borehole geophysical logging. While examination of cuttings and their identification is useful for determining the lithology, it is difficult to resolve the thermal conductivity of each layer using this method alone, especially since there is often a lag time for sampling with the mud-rotary drilling method. Identifying the general lithology of each layer is helpful for determining conductivity ranges for further modeling but without further testing—such as X-ray fluorescence, X-ray diffraction, or thin-section mineral sections—it is difficult to determine rock mineralogy that would give insight for precise thermal conductivities.

By combining logs from the natural gamma radiation, normal resistivity, and caliper sondes on the same plot (Figure 4), we were able to differentiate between shales and carbonates units (dolomites and limestones) and between the glacial clay and sand and gravel deposits, that aided the identification of the drill cuttings. The logs indicate layering in the glacial materials and in the bedrock (Figure 4) along with interpretations of the likely lithologies. It also shows the caliper log which "kicks" corresponding to glacial sands and gravels above the bedrock. Those materials were washed out during drilling resulting in a larger-diameter borehole. There are additional caliper "kicks" in the bedrock at depths of approximately 90.5 m, 107.0 m, and 123.7 m. It is uncertain whether these features are related to drilling effects or to weathered zones. The caliper "kicks" at 107.0 m and 123.7 m occur at the tops of gamma-ray lows and resistivity highs—intervals labeled as thin limestones on the gamma log (Figure 4)—and therefore may be indicative of weathering.

Given that FO-DTS data are only available in the annulus of the borehole (i.e., we do not have distributed temperature data in the loop itself and no delta temperature within the well flow in the U-tube), we can only conduct an interpretive (qualitative) assessment of distributed thermal conductivity. We identified specific depths intervals where conductivity points on the graph of temperature decrement rate ($°C\ s^{-1}$) shown in Figure 5 to expected thermal conductivities based on mineralogical and geophysical analysis (Luebbe 2024) and assigned the relative temperature decrement rate with depth to match the overall borehole thermal conductivity value obtained from the traditional TRT.
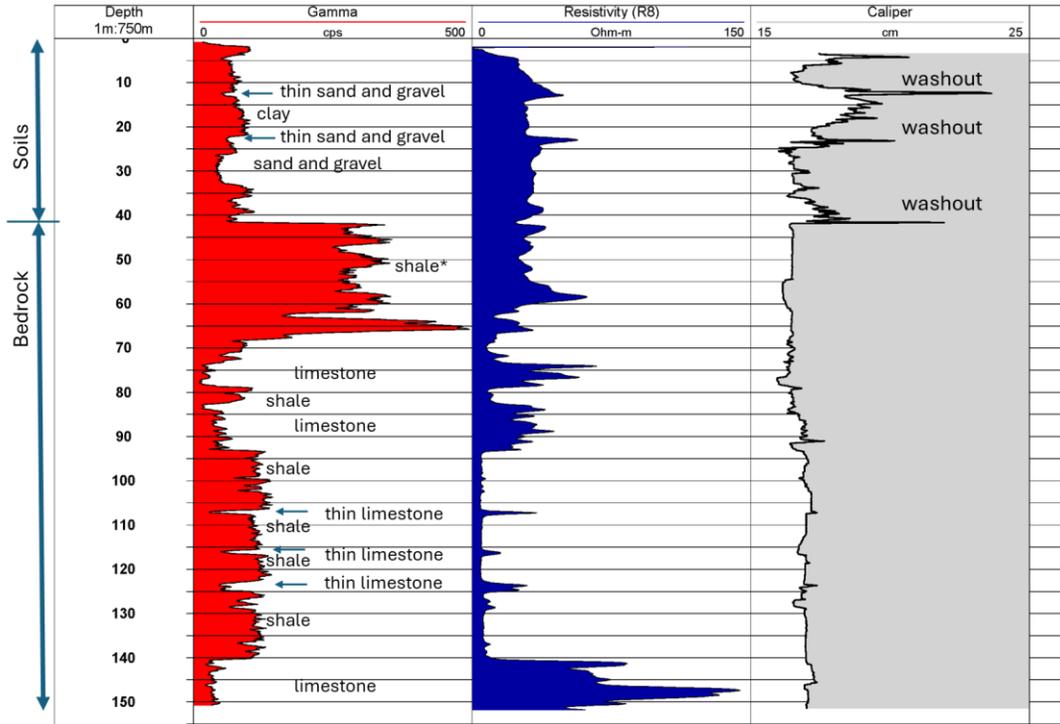
**Figure 4. Borehole logs of natural gamma radiation (left), normal resistivity (middle), and caliper (right). Shale is found in the intervals where the natural gamma radiation is the highest and resistivity is lower. Intervals with low gamma radiation and high normal resistivity values are characteristic of limestone or dolomite. The caliper log shows washouts in the glacial deposits.**
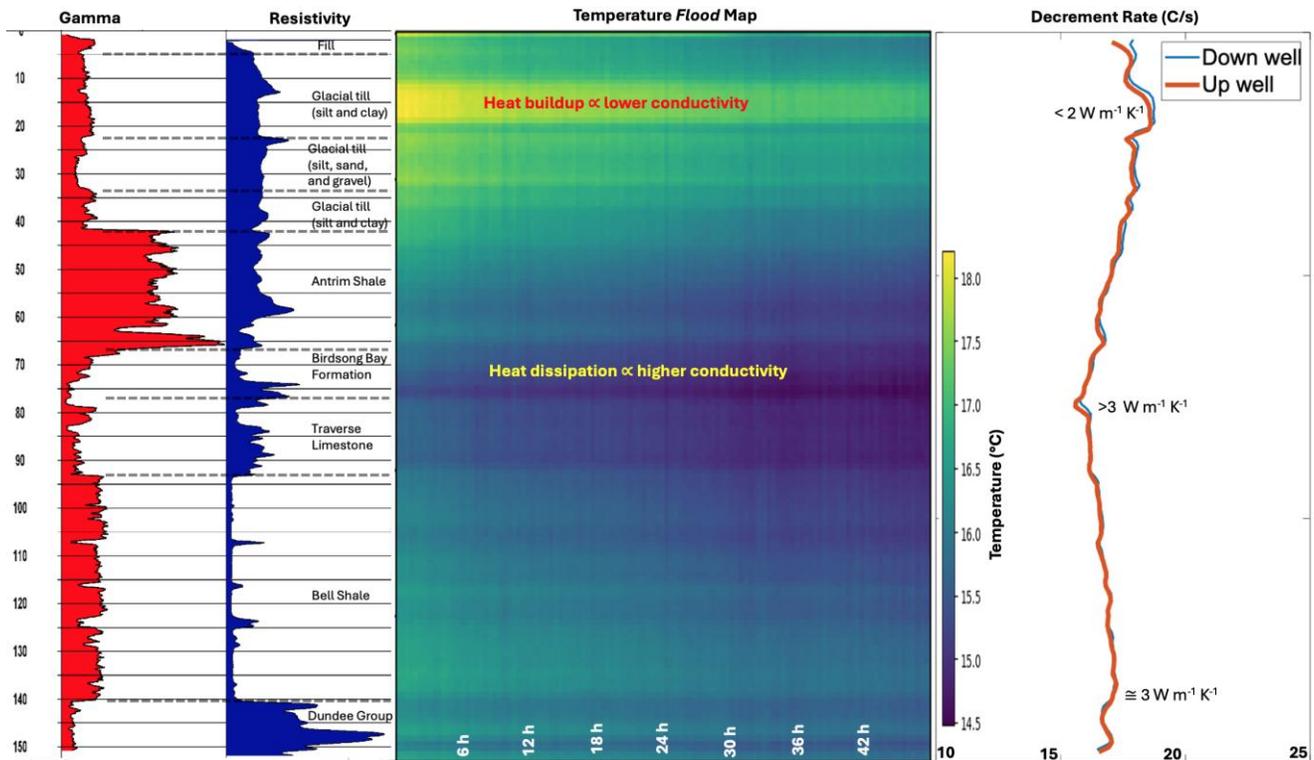


**Figure 5. Interpreted FO-DTS data using qualitative data. Natural gamma and resistivity logs (left) are shown for correlation with the temperature response. The ground temperatures recording during the DTRT are shown in the temperature color *flood* map (middle) over the 48-h testing period. The decrement rate (right) is correlated, relatively, to thermal conductivity. Heat dissipation was highest in bedrock of the Birdsong Bay Limestone, Traverse Limestone, and Dundee Group.**

Based on the results of this study, Table 1 presents the thermophysical properties as recommended for use in groundwater and heat transfer modeling at USAG Detroit Arsenal.

**Table 1. Geological data recommended for use in coupled groundwater and heat transfer modeling**

| Geological Material | Material Description | Thickness, m | Thermal Conductivity[1], W m⁻¹ K⁻¹ | Permeability, mD |
|---|---|---|---|---|
| Clayey glacial deposits | Clayey till, silt and clay, stiff | 12.2 | 2.10 | 0.4 |
| Clayey glacial deposits | Silty to sandy till soft to stiff, may include interbedded lake sediment | 10.1 | 2.10 | 100 |
| Sand and gravel | Sand and gravel, saturated | 10.7 | 1.90 | 1000 |
| Glacial till | Till sandy, hard | 8.8 | 1.90 | 50 but use 1000[2] |
| Antrim Shale | Black shale | 25.0 | 1.50 | 0.1 |
| Birdsong Bay Limestone | Limestone and shale, contains pyrite | 10.4 | 2.80 | 5 but use 10[2] |
| Traverse Limestone (includes the Ten Mile Creek Dolomite) | Limestone and dolostone | 16.2 | 2.80 | 10 |
| Bell Shale | Shale and mudstone | 46.9 | 2.30 | 0.3 |
| Dundee Limestone | Cherty limestone | 12.2 | 2.90 | 10 |

[1]Values taken from mineralogical laboratory analysis (Luebbe 2024) and adjusted to be consistent with TRT test value for entire borehole: 2.25 W/(m K) = 1.3 BTU/(h ft F).
[2]Permeability values are estimated as typical for geological material and description. Range due to coarseness of model resolution in vertical depth. These values were used for separate modeling work by Lawrence Berkeley National Laboratory in a parallel portion of the FedGeo Partnership.

## 6. CONCLUSIONS

The 152-m-deep geothermal test borehole was advanced in just over one field day using mud rotary drilling. Approximately 143 m was drilled on the first day before operations were halted due to non-subsurface limitations (i.e., fuel availability). On the second day, after cleaning out the borehole, the remaining depth was quickly drilled. Based on this performance, it is reasonable to predict that a single mud-rotary drill rig could complete a 152–168 m deep borehole in one approximately 10-hour workday. Standardizing the daily drilling depth helps maximize the workflow.

A TRT estimated a ground thermal response test indicated a bulk borehole thermal conductivity of 2.25 W·m⁻¹·K⁻¹. Geophysical logging and a DTRT improved on this estimate by locating favorable formations with a high-conductivity ($\geq 2.9$ W·m⁻¹·K⁻¹) including the Birdsong Bay Limestone (67–78 m), Traverse Limestone (78–93 m), and the Dundee Limestone (140–152 m). Extending the BHE to a greater depth, say 168 m, would allow for intersection with additional high-conductivity zones within the Dundee Limestone Group, thus increasing the BHE thermal capacity—for example, by approximately 15% for 168-m compared to a conventional 152-m BHE. This gain in thermal capacity is partially from the additional BHE depth in addition to the enhanced thermal conductivity of the Dundee Limestone that starts at 142 m bgs. A greater depth of exploration would be needed to confirm formation thickness but, based on the description by Harrison et al (2018), this formation can extend up to 41 meters thick.

## 6. ACKNOWLEDGEMENTS

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