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Geothermal Investigation on the UC Berkeley Campus

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ABSTRACT

The University of California, Berkeley, is building a clean, electrified heating and cooling plant utilizing shallow geothermal to reduce greenhouse gas emissions. To explore the feasibility of shallow geothermal as the core of the zero-carbon campus energy system, we conducted ground temperature monitoring, geophysical logging, and a distributed thermal response test (DTRT) for geothermal potential evaluation. The monthly temperature monitoring in four shallow geothermal boreholes using distributed fiber optic sensing (DFOS) shows that the subsurface temperature is influenced by daily and seasonal air temperature variation yet stabilizes below the depth of 50 ft. A 400-ft deep borehole with multiple sensors was drilled and installed. The subsurface of the Berkeley campus comprises a top layer of clay (0 ft to 10 ft) overlying a gravel layer (10 ft to 30 ft). Below 30 ft, the Franciscan Complex forms the primary bedrock. Shear zones are detected at depths of 75 ft, 200 ft, 280 ft, and 330 ft. The thermal conductivity (λ) for the sediment above 30 ft is measured at 1.23 Btu/hr-ft-°F, and for the bedrock from 30 ft to 250 ft, λ is 1.40 Btu/hr-ft-°F. Below 250 ft, λ approaches zero, indicating low heat transfer efficiency. This is probably attributed to the poor grouting quality. This research demonstrates the effectiveness of the DFOS technique in measuring continuous-in-space subsurface temperatures and characterizing geological features, underscoring its value in geothermal investigation.

1. INTRODUCTION

The University of California has its Carbon Neutrality Initiative against global climate change to reduce greenhouse gas emissions (http://sustainability.berkeley.edu/climate). To meet this target, the campus plans to replace its aged natural gas cogeneration plant with a new 100% clean energy system for heating and cooling the whole campus. The system's core is a clean, electrified heating and cooling plant, which can take advantage of shallow geothermal. By designing the GSHP system appropriately based on the campus's heating and cooling demands, the ground temperature can be balanced for the long-term operation of the system. Although the previous geothermal research by the authors has proven the potential of the shallow geothermal beneath the Berkeley campus through numerical simulations, in-situ tests are required to verify the simulation results and provide the geothermal properties of the campus ground for the detailed design of the proposed GSHP system.

A thermal response test (TRT) is an in-situ testing method characterizing geothermal properties. As heated water circulates through the U-pipe installed and grouted inside a borehole, the supply and return temperatures at the ground surface are recorded. The geothermal properties are then estimated from the change in the temperature inside the U-pipe with time. The conventional TRT mainly uses the line-source or cylinder-source model that Carslaw and Jaeger (1959) developed to calculate thermal conductivity and borehole resistance. However, the vertical heat transfer and the effect of heating rate fluctuation are ignored due to the infinite line source and constant heat rate assumptions.

In some cases, a numerical method is applied to consider the effect of borehole geometry, different properties of grout and ground, and varying heat transfer rates (Gehlin, 2002). It is usually combined with a parameter-estimation-based or inverse analysis method to evaluate the thermal conductivity value from TRT results (Signorelli et al., 2007; Raymond et al., 2011). Numerical methods also make the fracture and groundwater flow analysis possible (Raymond et al., 2011). However, since only outlet and inlet temperatures are measured, the conventional TRT only extracts the thermal conductivity of the whole tested subsurface section.

The recent development of the distributed fiber optic sensing (DFOS) technique makes the distributed thermal response test (DTRT) possible. Compared to the traditional TRT, DTRT can provide temperature change profiles along the depth during the tests and allow the vertical distribution of geothermal properties to be estimated. Analytical models (e.g., line-source model, cylinder-source model) can be applied to extract the geothermal properties in each sublayer from the temperature change profile measured by the distributed fiber optic sensors (Acuna et al., 2009, Fujii et al., 2009, Acuna 2013, Sakata et al., 2018, Beier et al., 2022). However, these analytical methods are based on the infinite line-source assumption and thus are inappropriate for use in layered subsurface conditions. Numerical simulation combined with the parameter-estimation-based process can be applied to DTRT results to overcome this issue (e.g., Raymond et al. (2013), Liu et al. (2020), and Beier et al. (2021)).

The study aims to conduct in-situ geothermal investigations and provide the geothermal properties of the campus ground to evaluate the geothermal potential. The specific tasks of the study include (1) monitoring the seasonal ground temperature changes across the campus, (2) exploring the site geology through a 400-ft investigation borehole, (3) installing the fiber optic sensor and conducting a distributed thermal response test for the geothermal property evaluation of the campus ground.

2. VARIATION OF THE GROUND TEMPERATURE

2.1 Acquisition of The Ground Temperature Using DFOS Technique

We drilled four ground temperature monitoring boreholes with fiber optic cables installed across the main campus (https://geomechanics.berkeley.edu/news/geothermal-cee/). ALICIA, an in-house developed BOTDR (Brillouin Optical Time Domain Reflectometry) based interrogator, was then used to read the temperature change in the cable installed inside the borehole. It works by injecting a laser impulse into the cable and measuring the Brillouin backscatter to estimate the temperature change (Figure 1). Since BOTDR measures the temperature based on the linear relation between the Brillouin frequency shift and temperature change, ALICIA can only record the temperature change, which will be the focus of the following analysis. The primary purpose is to monitor the seasonal ground temperature variation and provide data support for evaluating the campus's geothermal potential. Locations of boreholes are shown in Figure 2. The temperature variations along the depth have been logged every month since 2021.

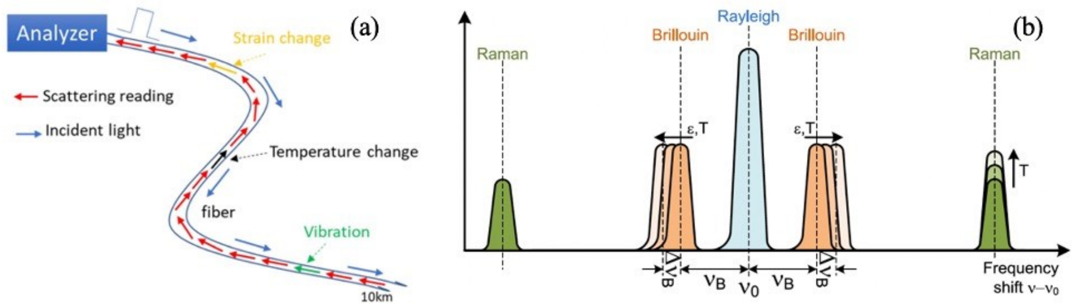


Figure 1: (a) A schematic of a distributed fiber optic sensor system and (b) three backscatter modes (Soga & Luo, 2018)

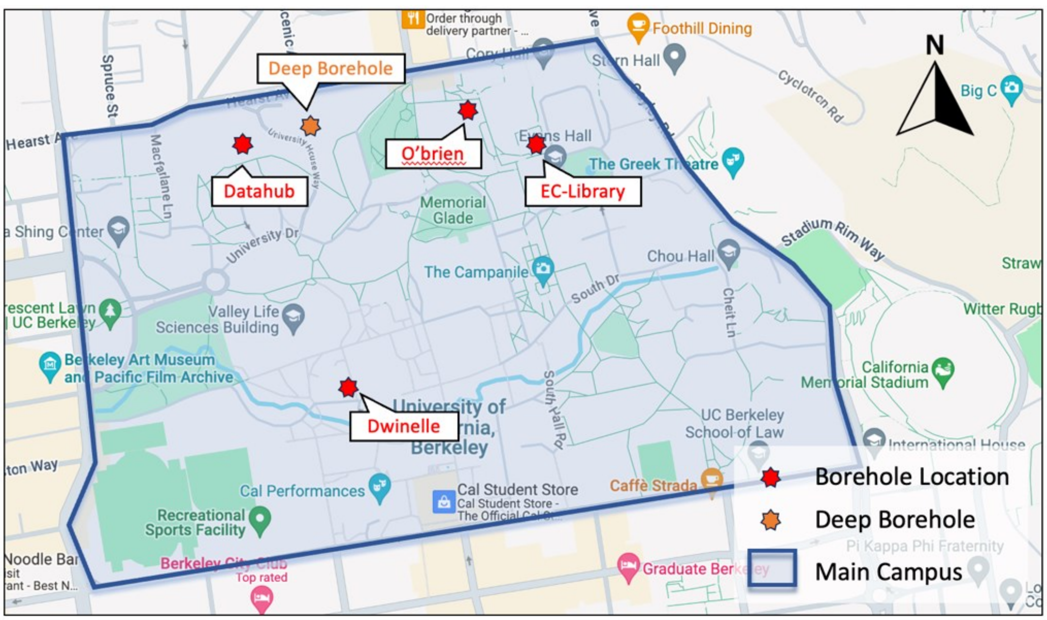


Figure 2: Locations of the ground temperature monitoring boreholes on the Berkeley campus

2.2 Variation Analysis of The Ground Temperature

The monthly ground temperature changes, recorded from March 2021 to September 2023, are presented in Figure 3. Notably, the boreholes at Dwinelle Hall and Engineering Centre Library were installed later than the others, resulting in fewer months of data for those two locations. Additionally, data gaps exist due to occasional borehole access issues and interrogator malfunction. The ground temperature in April 2022 is considered as relatively stable and has been selected as the baseline for the variation analysis. Near the surface above 10 ft, the temperature fluctuates because of daily atmospheric condition and solar radiation, thus reflecting the air temperature at the time of data recording. From 10 ft to 50 ft, the effect of atmospheric condition diminishes, and the temperature profiles more closely track the seasonal air temperature variation – generally warmer in summer and colder in winter. However, some temperature 'lags' can occur within this depth range. This lag is due to the time it takes for the heat transfer to occur, causing the ground temperatures change to sometimes trail behind the seasonal air temperature change. Considering an inherent random error of about 2 °C (3.6 °F) for most of commercial BOTDR interrogators (Soga and Luo, 2018), the temperature is generally stable at 50 ft and deeper into the ground. This study is still ongoing, and future analyzes will examine the year-on-year variation of the ground temperature.

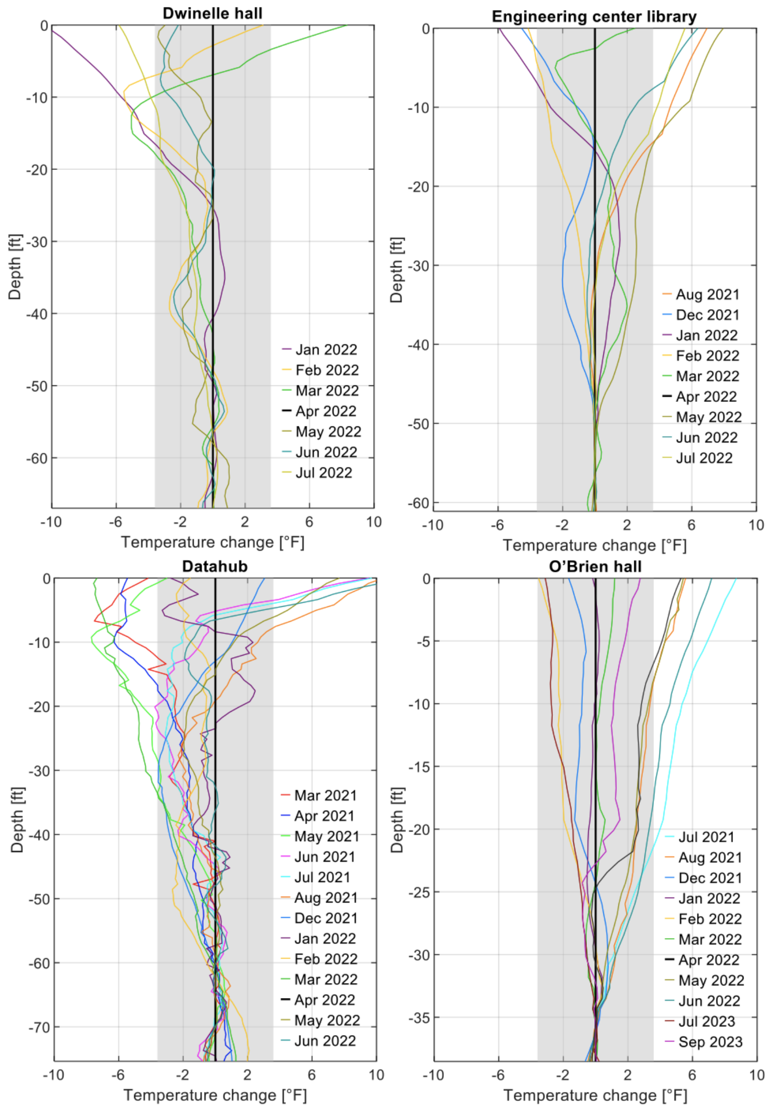
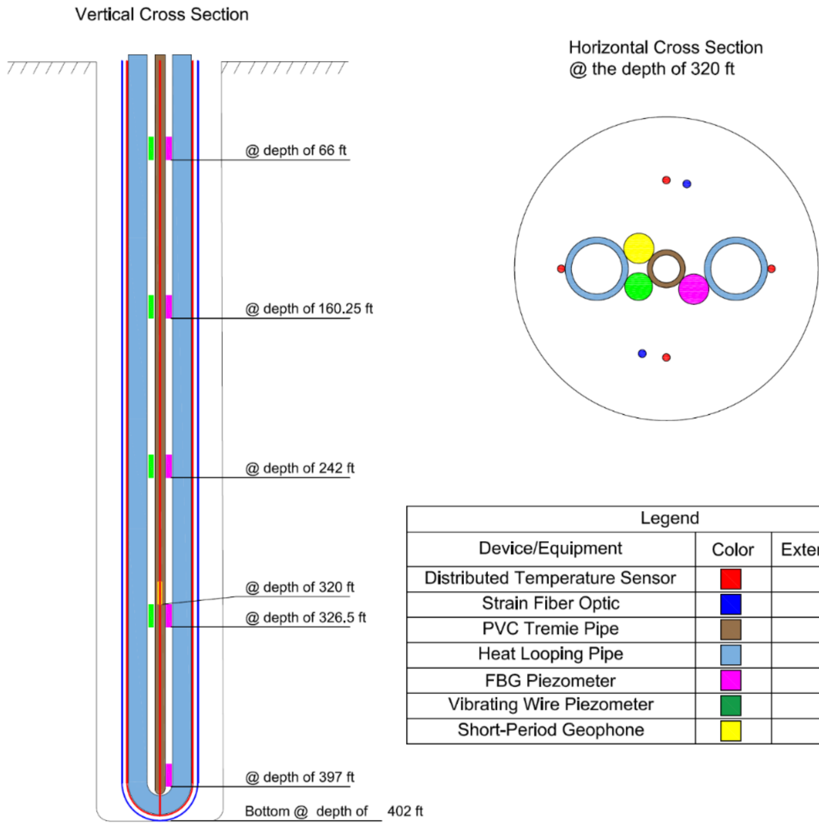


Figure 3: Temperature Change Readings [clockwise from top-left: Dwinelle Hall, Engineering Centre Library, O'Brien Hall & Datahub]; grey zones indicate accuracy zone of ± 2 °C (± 3.6 °F)

3. GEOLOGY INVESTIGATION IN A 400-FT BOREHOLE

3.1 Drilling and Installation of The Deep Borehole

In March 2022, a deep borehole drilling and investigation was conducted near University House, located in the north of the Berkeley campus (Figure 2). It was a 400-ft deep borehole with a diameter of 6 inches. Because the borehole was expected to penetrate hard bedrock, mud rotary drilling was selected as the appropriate drilling method. During the drilling process, the site geology was logged based on the cuttings returned by the mud. Upon completion of the drilling, the NORCAL team was hired to conduct geophysical loggings. The main scope of work included (i) a caliper survey for borehole stability analysis and diameter measure, (ii) a PS-wave Suspension survey to measure compression (P) and shear (S) wave velocity, (iii) a televiewer survey for discontinuity classification, and (iv) a natural gamma logging survey for stratigraphy mapping. Afterward, a U-pipe with multiple advanced sensors was installed into the borehole. A schematic of the borehole is shown in Figure 4. The sensors installed included a Distributed Temperature Sensor, a Strain Fiber Optic Sensor, five Fiber Bragg Grating (FBG) piezometers, four Vibrating Wire piezometers, and a Short-Period Geophone. The deep borehole equipped with these sophisticated sensors serves multiple purposes: it is an invaluable tool for geothermal investigations and applies to other research domains, such as vibration monitoring.



Legend		
Device/Equipment	Color	External Diameter
Distributed Temperature Sensor		0.354"
Strain Fiber Optic		0.197"
PVC Tremie Pipe		1.315"
Heat Looping Pipe		1.66"
FBG Piezometer		1.417"
Vibrating Wire Piezometer		1"
Short-Period Geophone		2"

Figure 4: A schematic of the 400-ft deep borehole with multiple sensors

3.2 Results of Geology and Geophysical Loggings

According to the borehole logging, the underground of the deep borehole site can be divided into three primary layers:

- *Clay layer*: 0 – 10 ft, yellowish clay with gravel and chert; oxidation due to water table fluctuation can be observed.
- *Gravel layer*: 10 – 30 ft, multicolor, well-graded sandy gravel, and trace clay can be found.
- *Franciscan Complex*: 30 – 400 ft, the bedrock is typically Franciscan Complex (the mélange of sandstone/greywacke, shale, and serpentinite). Sandstone is the primary material, and the content of interbedded shale varies according to depth. Trace serpentinite can also be found at some depths. Sheared zones with poorer mechanical properties were identified at 75 ft, 200 ft, 280 ft, and 330 ft.

Figure 5 presents a comparative analysis between results of the geophysical and borehole loggings. The changes in P-wave velocity (*Vp*), S-wave velocity (*Vs*), and natural gamma logging well match the geological features, such as interfaces between the bedrock and sediment and weak shale layer and sheared zones. For example, in the deposits above 30 ft, *Vs*, *Vp*, and natural gamma are roughly 1300 ft/s, 3000 ft/s, and 65 APICs, respectively. On reaching the sandstone/greywacke, these values show a notable increase, with *Vs*, *Vp*, and natural gamma rapidly escalating to 5500 *ft/s*, 13000 *ft/s*, and 80 API units, respectively. At depths of 75 ft, 200 ft, 280 ft, and 330 ft (marked as red lines in Figure 5), the existence of sheared zones or weak layers with higher content of shale causes a drop in the *Vs* and *Vp* profiles while a rise in the natural gamma profile. Since the borehole was logged based on the cuttings brought up by the mud, the boring log might not be accurate enough and probably missed several sheared zones at a depth of 170 ft and 240 ft, where *Vp* and *Vs* drop while natural gamma rises (marked by blue lines in Figure 5). Overall, the geophysical investigation results correlate well with the data recorded in the boring log, enhancing understanding of the subsurface geology encountered during the drilling process.

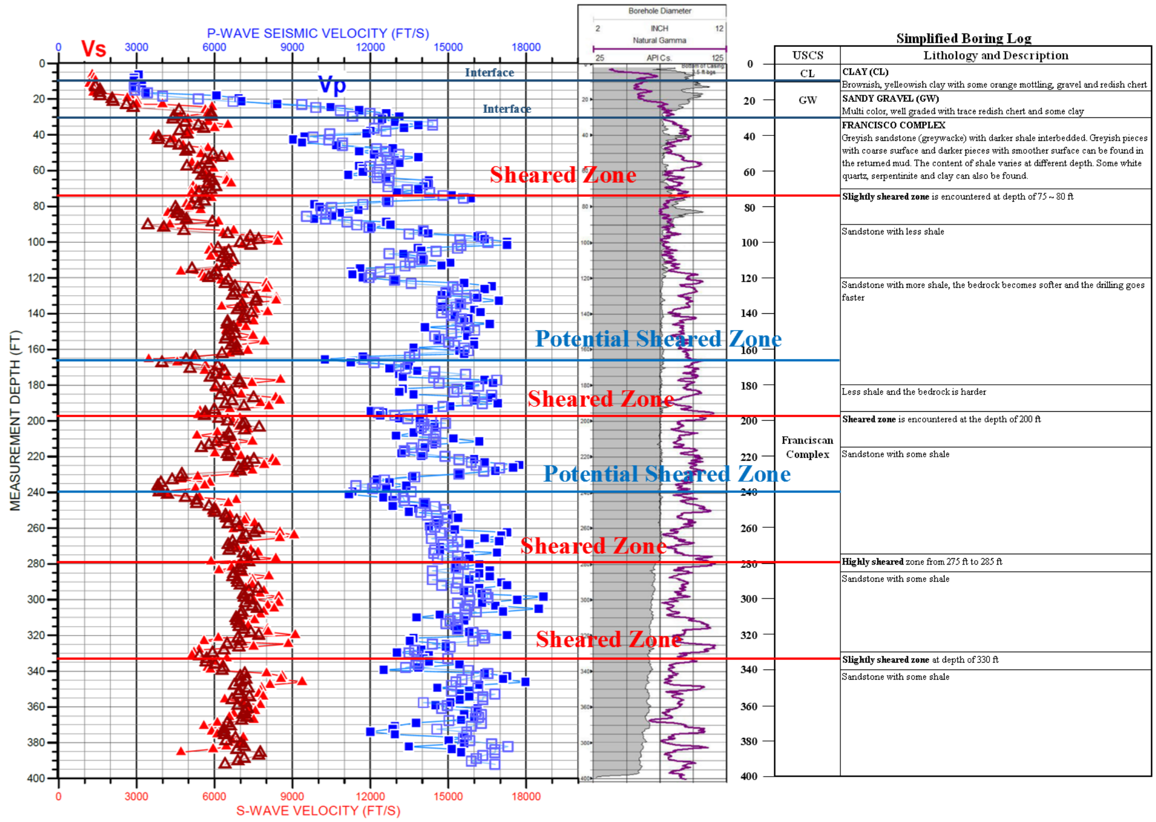


Figure 5: Comparison between the results of geophysical logging and the borehole log

4. DISTRIBUTED THERMAL RESPONSE TEST (DTRT) USING DFOS TECHNIQUE

4.1 DTRT Description

Compared with conventional TRT, DTRT utilizes a distributed temperature sensor – specifically, a temperature fiber optic (FO) cable in this study – to continuously record the temperature change along the depth throughout the test. To improve the accuracy of the test, FO cables are also inserted into the supply and return pipes, enabling precise measurement of water temperature changes. Those internal and external cables were connected to form a large loop, as shown in Figure 6. This configuration allows only one interrogator to read temperatures from the FO cable. The FO cable used was Belden cable FSSC002N0, and the TRT Rig is produced by Geothermal Resource Technologies, Inc. (GRTI). TRT Rig recorded the inlet and outlet temperature during the test, while ALICIA recorded the temperature change in the fiber optic cable along the depth. The test was carried out following the recommended Thermal Response Test (TRT) standards published by The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the International Ground Source Heat Pump Association (IGSHPA), and Table 1 summarizes the statistics of the test.

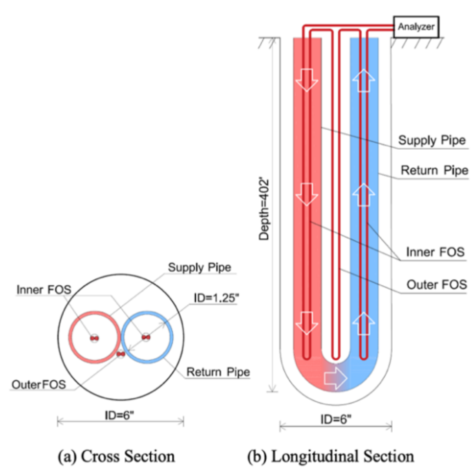


Figure 6: Setup of the distributed thermal response test using the DFOS technique

Table 1: Summary Test Statistics

Undistributed Formation Temperature	64.3 – 68.0 °F
Duration	47.5 hours
Average Voltage	238.7 V
Average Heat Input Rate Density	26,866 Btu/hr (7,872 W)
Average Heat Input Rate	66.8 Btu/hr-ft (19.6 W/ft)
Circulator Flow Rate	8.8 gpm
Standard Deviation of Power	0.50%
Maximum Variation in Power	1.94%

4.2 Results

4.2.1 Profiles of Temperature Change

Temperature changes (ΔT) in the heating and subsequent cooling phases were recorded using ALICIA. To enhance data quality for spatial-temporal analysis, a 2D anisotropic Gaussian Filter with σ_{time} of 3 hours and σ_{depth} of 20 ft was employed to smooth the data and reduce noise. Figure 7 presents the temperature variations in the heat and cooling phases at different depths. The temperature at the end of the heating phase increases by 32 – 37 °F, and ΔT_{supply} is higher than ΔT_{return}. The difference between ΔT_{supply} and ΔT_{return} is roughly 5 °F, decreasing with depth and approximating zero at 250 ft. Notably, a systematic temperature offset of approximately 1 – 2 °F can be found at 11 hours, caused by a sudden decrease in the input voltage of ALICIA. Figure 7 (e) compares ΔT near the ground surface (50 ft) measured by the TRT Rig and DFOS. In the supply pipe, the ΔT values measured by DFOS and GRTI Rig match each other, while in the return pipe, ΔT measured by DFOS is 2 – 3 °F higher. Different measuring positions probably cause the discrepancy in the return pipe temperatures.

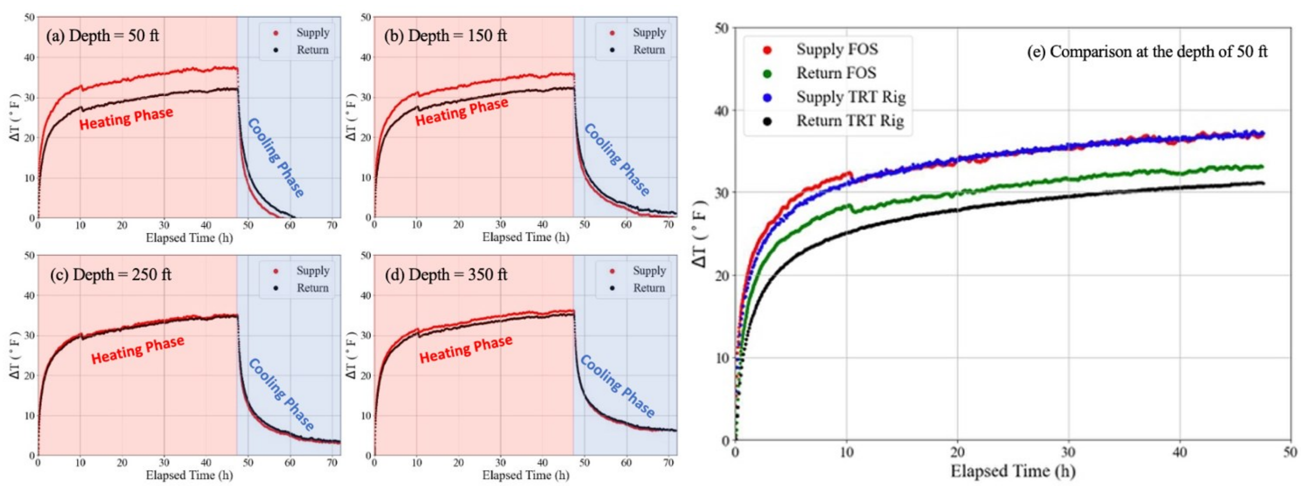


Figure 7: Temperature change (ΔT) vs elapsed time at different depths

Figure 8 displays the variations in ΔT recorded by internal and external fiber optic cables at various depths at different heating times. For temperature inside the pipes (Figure 8a), ΔT_{supply} decreases with depth while ΔT_{return} pipe increases with depth, indicating a distinct "V" shape. At the end of the heating phase, the temperature of the shallow surface increases by 34 – 38 °F, and the temperature near the bottom of the borehole increases by 35 °F. Significantly, the ΔT values in the supply and return pipes converge at a depth of 250 ft and below. This convergence suggests a nearly zero total temperature gradient, indicating a diminished heat transfer efficiency from the pipe to the ground. This may be related to sheared zones below 250 ft (250 ft, 275 – 280 ft, and 325 – 327 ft). Another possible reason is the poor grouting quality, likely resulting from interrupting the grouting process at a depth of 280 ft. Even after filtering, temperature fluctuation can be observed mainly in the return pipe. These fluctuations could be primarily ascribed to the varying grouting quality along the depth. Grouting quality can affect the heat transfer efficiency between the looping pipe and surrounding soil, thus leading to a variable temperature profile. Geological characteristics such as sheared zones can also affect the temperature by changing the thermal conductivity of the layers.

Contrasting with the ΔT profiles observed inside the pipes, the external ΔT profiles (as depicted in Figure 8b) do not exhibit the 'V' shape. Instead, at equivalent depths, ΔT_{supply} and ΔT_{return} are very close. This similarity can be attributed to the positions of the fiber optic cables. Figure 6b shows the cables attached to the middle of the supply and return pipes. Due to their proximity, not being perfectly isolated but relatively close and intertwined, the ΔT measurements they recorded tend to be nearly identical. At the end of the test, the temperature of the shallow surface increases by 27 – 30 °F, and the temperature near the bottom of the borehole increases by 27 °F, which is roughly 9 °F lower than the temperature increase measured by the cable inside the pipe. This difference highlights the impact of the sensor position on the temperature readings, underscoring the importance of their placement for accurate thermal profiling.

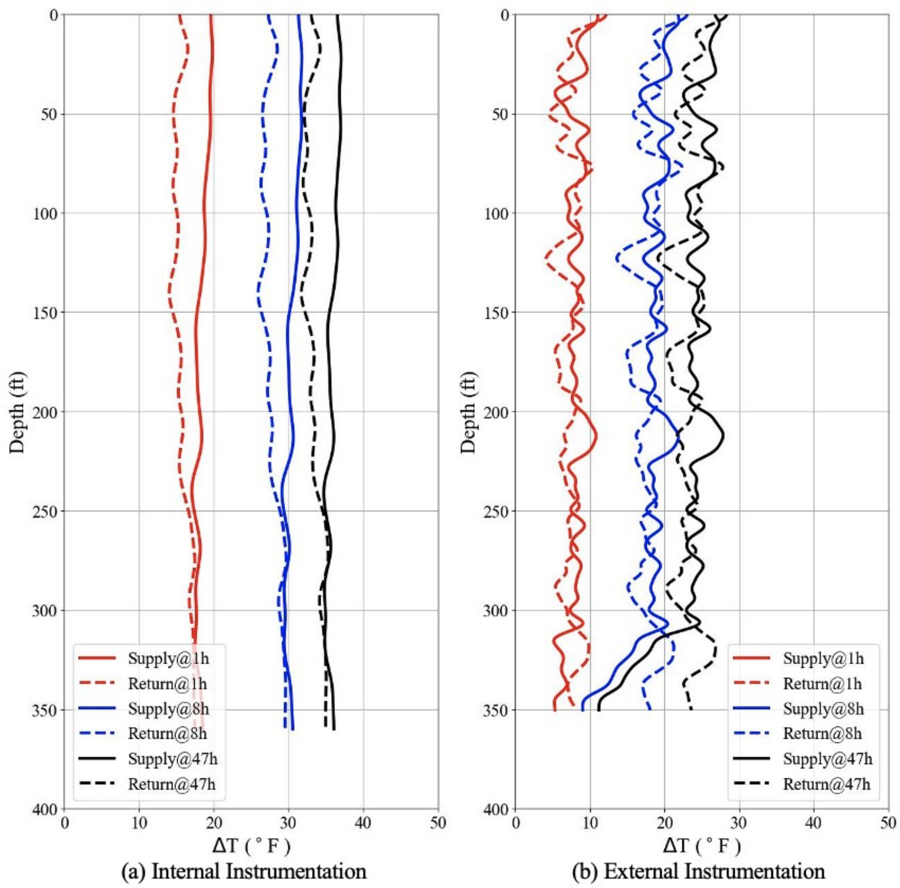


Figure 8: Temperature change (ΔT) vs depth at different times

4.2.2 Estimate of Geothermal Property

Thermal conductivity is usually calculated from the line source method, which assumes a constant heat input rate and ignores vertical heat transfer. Employing this method, thermal properties are calculated from the surface temperature recorded by TRT Rig as follows:

- Thermal conductivity: 1.35 Btu/hr-ft-°F
- The weighted average of heat capacity: 36.8 Btu/ft^3-°F
- Thermal diffusivity: 0.88 ft^3/day

However, the line source method fails to accurately characterize Thermal Response Tests (TRT) in stratified ground conditions. To address this, the analytical method developed by McDaniel et al. (2018), following the work of Molz et al. (1989), is applied in this study. The method assumes the radial temperature gradients from the U-tube to the subsurface are constant and uniform at the steady state. The thermal conductivity values at different depths can be calculated from the temperature gradient and total average thermal conductivity when the test reaches a steady state. The equations used in the method are as follows:

$$\frac{\lambda_i}{\lambda_{ss}} = \frac{\frac{\Delta Q_{H,i}}{\Delta z_i}}{\frac{QP_H}{B}} \tag{1}$$

$$\Delta Q_{H,i} = \Delta T * Q_w * \rho_w * C_{p,w} \tag{2}$$

where λ_i is the thermal conductivity of ith layer; λ_{ss} is the total average thermal conductivity from traditional TRT; $\Delta Q_{H,i}$ is the incremental heat flow; QP_H is the sum of $\Delta Q_{H,i}$; Δz_i is the thickness of ith layer; B is the depth of the borehole; Q_w is the flow rate; ρ_w is the density of water, and $C_{p,w}$ is the heat capacity of water. This equation can be reorganized as follows:

$$\lambda_i = \lambda_{SS}\left(\frac{T_{gradient,i}}{\frac{dT}{B}}\right) \tag{3}$$

where, $T_{gradient,i}$ is the temperature gradient of the ith layer; dT is the temperature between the supply and return pipes at the surface.

The subsurface was categorized into three primary layers, and regression lines were used to represent ΔT of the supply and return in each layer. Given the interface between sediment and bedrock at a depth of 30 ft and the low heat transfer efficiency below the depth of 250 ft, the tested ground is divided by the depth of 30 ft and 250 ft, and it is assumed that the ΔT value below 250 ft is constant. The ΔT profile at 47 hours is chosen as the steady state. The external DFOS data is not used in calculating thermal conductivity due to data fluctuation. Figure 9 presents the simplified temperature profile, temperature gradient, and thermal conductivity of the DTRT. The thermal conductivity (λ) for the sediment above 30 ft is 1.23 Btu/hr-ft-°F, and λ for the bedrock from 30 ft to 250 ft is 1.40 Btu/hr-ft-°F. Compared with conventional TRT, DTRT estimates higher thermal conductivities for sediment and bedrock above 250 ft. This is attributed to the lower heat transfer rate in the zone below 250 ft, a factor conventional TRT fails to account for, often leading to an underestimation of subsurface thermal conductivity. Notably, while the temperature gradient method provides a rapid estimation of the thermal conductivity profile, it is notably susceptible to fluctuations in data across various depths.

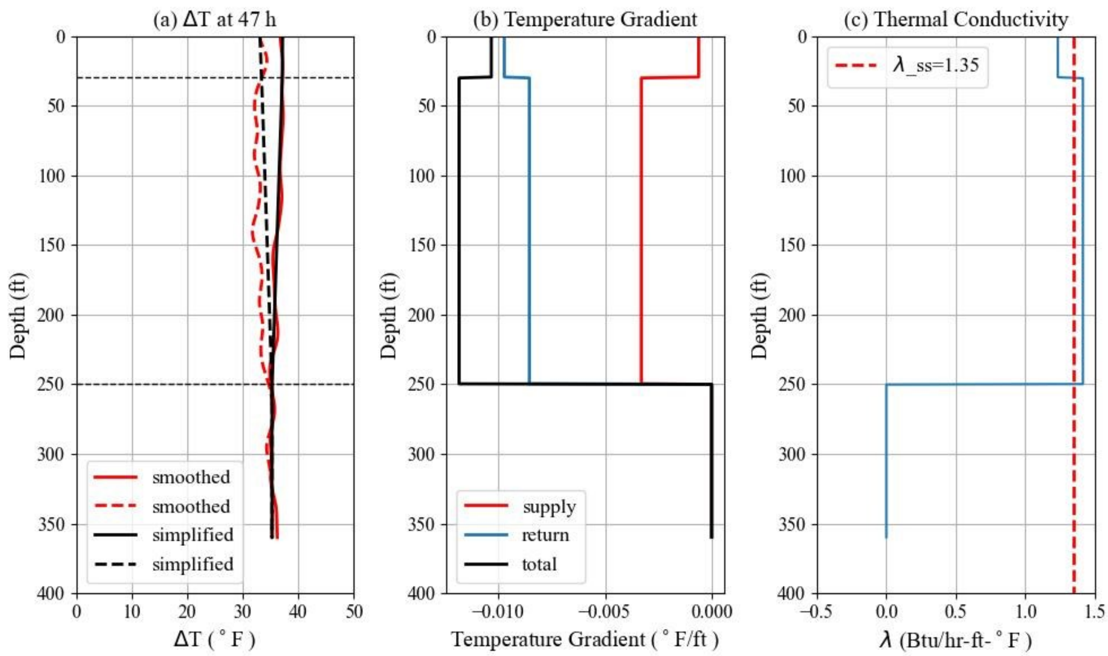


Figure 9: (a) temperature profile simplification, (b) temperature gradient, and (c) thermal conductivity profile

5. CONCLUSIONS

This paper describes the findings from the geothermal borehole investigations conducted on the UC Berkeley campus. Monthly temperature changes were recorded from four shallow boreholes across the main campus. A 400-ft deep borehole with multiple sensors was drilled and installed for geology investigation and distributed thermal response test. The main conclusions of the research are summarized as follows:

- Distributed fiber optic sensing technique enables the continuous-in-space measurement of subsurface temperatures along the entire depth of the borehole. On the Berkeley campus, the ground surface temperature (up to 10 ft) fluctuates daily; between 10 ft and 50 ft, temperature changes show seasonal variation but leg behind the seasonal variation of air temperature due to low heat transfer rate; below 50 ft, the temperature is relatively stable.
- The subsurface of the Berkeley campus comprises a top layer of clay (0 ft to 10 ft), overlying a gravel layer (10 ft to 30 ft). The primary bedrock is the Franciscan Complex, a mélange of sandstone, shale, serpentinite, etc. Shear zones can be identified at depths of 75 ft, 200 ft, 280 ft, and 330 ft. The results of geophysical loggings, especially the profiles of P/S-wave velocity and natural gamma value, match well with the geological features.
- In the 400-ft deep borehole, the thermal conductivity (λ) for the sediment above 30 ft is 1.23 Btu/hr-ft-°F, and λ for the bedrock from 30 ft to 250 ft is 1.40 Btu/hr-ft-°F. Compared with conventional TRT, indicating an average effective λ of 1.35 Btu/hr-ft-

°F, DTRT estimates higher λ for bedrock above 250 ft. This is attributed to the lower heat transfer rate in the zone below 250 ft, a factor conventional TRT fails to account for, underscoring the effectiveness of DFOS in geothermal research.

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