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Preliminary constraints of thermal conditions within the Cornell University Borehole Observatory (CUBO)

Ivanakbar Purwamaska[1], Patrick M. Fulton[1]

[1]Cornell University, Earth & Atmospheric Sciences, Ithaca, New York, 14850, USA

ip246@cornell.edu

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ABSTRACT

Borehole temperature measurements are disturbed by borehole circulation during drilling & take considerable time to re-equilibrate to background formation values. Therefore, we estimate the equilibrium formation temperature near the bottom of the borehole at 2.95 km depth using a modified Horner plot analysis which takes into account the duration of borehole circulation at that depth & the time since circulation completed. We use 5 bottomhole temperature values recorded during wireline logs immediately after drilling & estimate a bottomhole formation temperature of at least 80 degrees Celsius. This value is within the anticipated range for potential low temperature reservoirs for deep direct-use applications. Subsequent higher resolution temperature logs recorded as part of hydrologic testing are affected by subsequent borehole circulation effects but provide insights into depth-variations & the influence of thermal property variations & advection due to fluid inflow or outflow between the borehole & formation. Large advection signals Indicative of formation fluid flow are not immediately apparent. However, analysis of 7 high-resolution downhole temperatures reveals 9 separate depth zones between 2.5 to 3.0 km depth with distinct thermal gradients that do not directly correlate lithostratigraphic boundaries. Assuming a constant vertical conductive heat flow we evaluate the thermal conductivity variations implied. Although these profiles are complicated by secondary circulation effects, by looking at the thermal recovery over time at various depths we assess intervals potentially affected by fluid flow within the formation. Further assessment of natural thermal conditions will be improved by the availability of time-series downhole temperature measurements from a fiber-optic distributed temperature sensing (DTS) cable, anticipated to be installed in late 2022.

1. INTRODUCTION

Cornell University is pursuing the Earth Source Heat (ESH) project to demonstrate the viability of direct-use deep geothermal energy for district heating of its main campus in Ithaca, NY (e.g., Tester et al., 2010; Beckers et al., 2015; Tester et al., 2023, this session). ESH plans to harness the accessible low-temperature (50-100°C) thermal resource at 2-3 km depth, well within deep sedimentary and basement rocks (e.g., Smith, 2019; Tester et al., 2019; Gustafson et al., 2019; Jordan et al., 2020). These studies, however, are based on regional petrophysical and stratigraphic data. Recently, in summer 2022, the university collected *in situ* data from the drilling and testing of a 3-km deep (TD = 9790 ft) exploration borehole on its Ithaca, NY campus. This borehole ESH#1 is referred to as the Cornell University Borehole Observatory (CUBO). In the cased intervals of the borehole, geophysical well logging was performed to assist with lithostratigraphic mapping and correlation with off-set wells and geophysical surveys (Figure 1). Within the open hole section which spans a region where potential geothermal reservoirs are being sought (2.37-3.00 km, 7776-9790 ft), a more extensive suite of geophysical wireline logs and an additional hydrologic testing was performed.

Here, we perform thermal analyses on CUBO data to provide preliminary constraints on thermal conditions at depth, including temperature and thermal gradient, and the hydrology of potential geothermal reservoir formations for Cornell's ESH. To estimate formation temperature at depth, we analyze bottomhole temperature collected during geophysical well logging (Table 1) and correct for the thermal effects of drilling-related circulation. To understand the relationship between thermal conditions and lithostratigraphy, we evaluate temperature profiles collected by pressure-temperature wireline logging during hydrologic testing and look for changes in thermal gradients. Lastly, to characterize the hydrology, we evaluate other features within these thermal profiles and identify advective thermal signals that may correspond to zones with increased permeability and/or background fluid flow.

This paper is part of a series on Cornell's ESH and CUBO analysis, and we encourage interested parties to see companion papers: Clairmont and Fulton 2023, Fulcher et al., 2023, Pinilla et al., 2023, and Tester et al., 2023 (summary overview paper).

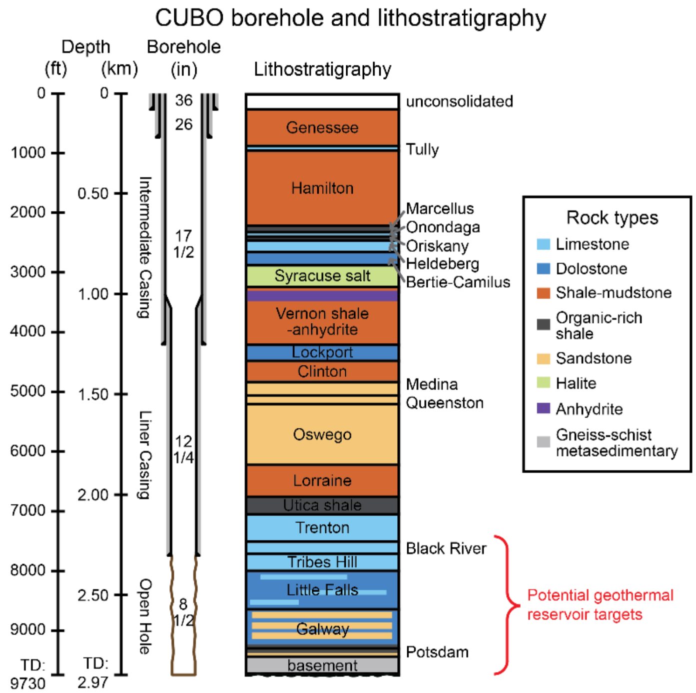

Figure 1. CUBO borehole geometry and lithostratigraphy, which represents the Cornell and Ithaca, NY subsurface. To allow for more extensive testing, CUBO was completed with an open hole section (2.37-3.00 km, 7776-9790 ft) that span the potential geothermal reservoir targets based on previous ESH studies.

2. DATA AND METHODS

To constrain the thermal conditions and hydrology of potential ESH reservoirs, we evaluate temperatures collected during geophysical wireline logging and hydrologic testing.

2.1 Equilibrium bottom-hole temperature

Temperatures were measured as part of geophysical logging runs immediately after the completion of drilling and hole circulation. However, these temperatures are relatively low-resolution do not represent equilibrium formation temperatures; instead at the time of measurement the hole remains thermally disturbed by the effects of hole circulation. The re-equilibration of formation temperature from drilling-related thermal disturbance is known to take considerable time, on the order of months (e.g., Lachenbruch and Brewer, 1959; Ramey Jr, 1962; Fulton et al., 2010; 2013). Assuming a re-equilibration entirely by conductive heat flow, equilibrium temperatures can be estimated through a projection of raw temperature data into infinite time.

Here, we analyze five raw bottom-hole temperatures (BHTs) at 2.96 km (9710 ft) depth were measured via five separate wireline runs during the initial suite of wireline logging runs in the open borehole. These wireline logs were performed 7-26 hours after drilling-related circulation. To estimate the equilibrium BHT, we use the modified Horner plot method (Bullard, 1947; Horner, 1951; Peters and Nelson, 2012) to project raw bottom-hole temperatures (BHTs) into infinite thermal equilibration time, when the thermal disturbance caused by drilling-related circulation have conductively diffused. This modified Horner plot is a semi-log graph that shows BHT on the vertical axis and a logarithmic function of time on the horizontal axis. Short times after the end of circulation are to the right of the x-axis and longer times are to the left. The extrapolated BHT at infinite time after circulation, i.e., the time of full BHT equilibrium, plots on the far left. The method assumes that temperature rises in the same way as pressure and therefore a semi-log plot of BHT vs. log function of time can be projected by least-squares fit along a line of a slope to yield equilibrated BHT (at 0 in the x-axis).

2.2 High resolution temperature logs, thermal conditions, and hydrology

In addition to the bottom-hole temperatures recorded as part of other wireline geophysical logs, we also analyze higher-resolution temperature profiles collected via pressure-temperature (P-T) wireline logging during subsequent hydrologic tests (Figure 2) (Table 1). These data are higher resolution and therefore provide greater insight into persistent depth variations in geothermal gradient and hydrologic signals. However, these data are affected by at least a second round of well circulation and well cleaning before the hydrologic tests such that they are not easily incorporated into the equilibrium formation temperature analysis described above. Instead we first analyze these data to characterize persistent variations in thermal conditions at depth across the various surveys conducted during hydrologic testing and also utilize them to identify advective signals indicative of likely permeable zones described below.

Three hydrologic tests were performed after the geophysical logging and cleaning of the borehole described above: one airlift test in which the hydraulic head (i.e. water level) was progressively lowered in the well to try to induce fluid flow into the well and two injection tests in which water was returned to the well returning the water level back to ground level and then a modest back pressure was applied to try to induce fluid flow into the formation (Table 1). During the hydrologic testing, seven high-resolution P-T logs were ran at the following times: (A) before the start of the airlift test (static condition); (B) after the airlift test; (C) after the airlift test but before the injection test 1 (pre-injection condition); (D) after the injection 1 test; (E) after the injection 2 test; (F) slightly longer after injection 2 test (post fall-off condition); (G) post bleed-off condition. Out of the 7, the temperature profiles collected during the static and airlift conditions span from surface depth to 2.90 km (9505 ft) ft while the others span the open-hole (from 2.32 km, 7625 ft to 2.90 km, 9505 ft). To understand the relationship between thermal conditions and lithostratigraphy, we look for changes in thermal gradient.

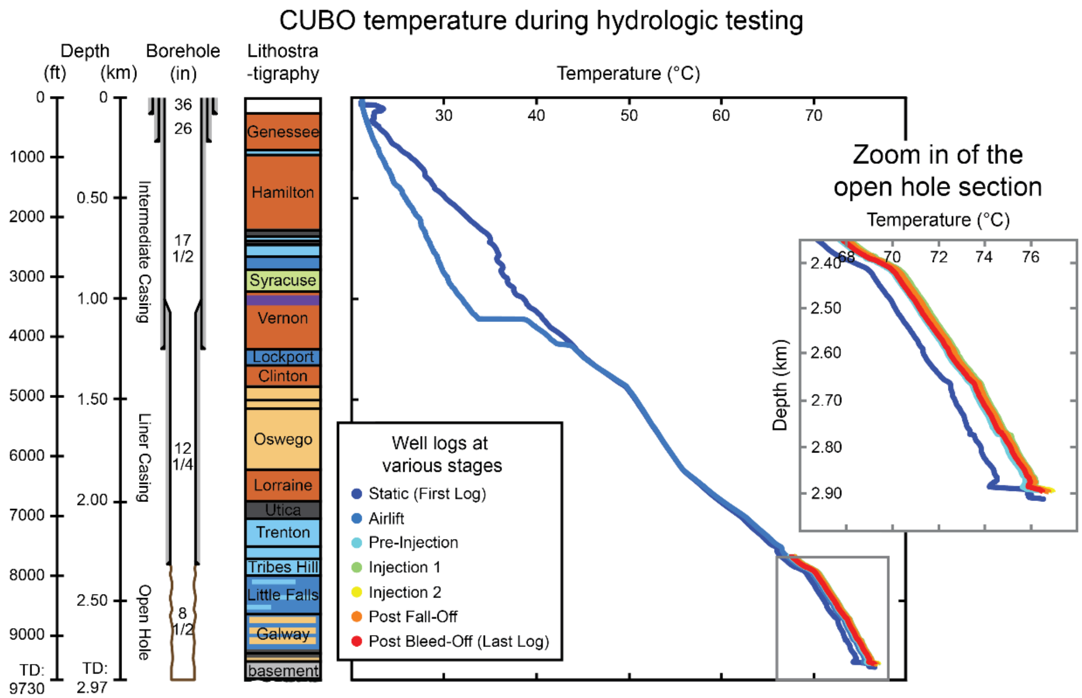

Figure 2. High-resolution temperature recorded via pressure-temperature (P-T) wireline logs during hydrologic testing, compared to CUBO borehole geometry and lithostratigraphy. 7 P-T logging runs were performed at various stages of the hydrologic testing.

Table 1: Timeline of thermal-related geophysical wireline logs and pressure-temperature logs during hydrologic testing.

Name			Time	Time post-circulation
End of drilling-related circulation			8/13/22 10:00 PM	-
Geophysical wireline logs in the open hole section, which record bottomhole temperatures	1	FMI main run, 4B	8/14/22 5:12 AM	7 hours
	2	PEX main run, 4C	8/14/22 4:09 PM	18 hours
	3	UBI repeat run, 4D	8/14/22 11:17 PM	25 hours
	4	UBI main run, 4D	8/15/22 12:14 AM	26 hours
Pressure-temperature logs during hydrologic tests, which record temperature profiles	1	Static conditions	8/20/22 9:16 AM	~6.5 days
	2	Airlift test	8/21/22 7:35 AM	~7.0 days
	3	Pre-injection conditions	8/21/22 6:12 PM	~8.0 days
	4	Injection 1 test	8/22/22 12:25 AM	~8.0 days
	5	Injection 2 test	8/22/22 1:19 AM	~8.0 days
	6	Post Fall-Off conditions	8/22/22 2:33 PM	~8.5 days
	7	Post Bleed-Off conditions	8/22/22 3:20 PM	~8.5 days

To investigate indications of hydrology in permeable zones, we identify potential advective thermal signals in the temperature profiles from P-T logs ran during hydrologic testing (Figure 2). Fluid flow can cause temperature increases or decreases relative to the surroundings in permeable zones depending on the relative difference between the fluid and the surroundings, and whether fluid flow is into the formation or into the well. Because depth variations (i.e. anomalies in temperature-depth profiles) can result from both hydrologic signals and variations in thermal properties (e.g., Tanaka et al., 2007), it is important to evaluate how temperature anomalies vary through time and potentially change due to various types of fluid circulations during the hydraulic testing (Fulton et al., 2013; Li et al., 2015) . For example, insights and discriminating signals can be gleaned by determining whether depth variations and assorted anomalies are persistent and/or similar throughout the experiment or whether they change differently than the surroundings or change direction depending on the direction of hydraulic testing. Here we analyze the raw data and look for anomalies and clear advective signals across the data.

In addition, we also identify finer resolution advective thermal signals be removing a reference geotherm. Our selection of the reference geotherm is based on the following: We choose our reference to be the pre-injection log collected after a short rest period after the airlift (i.e. production) testing and before injection testing. Our selection of the reference geotherm is based on the following: (A) Of particular interest for fluid flow analysis are temperature anomalies in the static profile that captures drilling-related effects, the airlift profile that captures the airlift-related effects, and the injection profiles that capture the injections-related effects. Thus, the reference geotherm should be selected between the pre-injection, post fall-off, or post bleed-off temperature profiles. (B) To retain the clearest advective thermal signals upon the removal of a reference geotherm, we examine the remaining options and select the temperature profile that is the least influenced by fluid advection as the reference. By choosing the pre-injection temperature profile as the reference, differences in direction of signal between production versus injection may be more apparent.

3. RESULTS AND DISCUSSION

3.1 The equilibrium bottom-hole temperature estimate is > 80.8 °C

From the projection of bottom-hole temperatures (BHTs) in the modified Horner plot, we estimate that the equilibrated BHT at 2.96 km (9710 ft) to be > 80.8 °C (Figure 3). The modified Horner plot projection uses a least-squares fit and in Figure 3, the trend line correlates well to the BHTs (r-squared of 0.966) and suggests that our estimate of equilibrium BHT is reasonable.

However, the equilibrated BHT may be greater than 80.8 °C because our modified Horner-plot-projection is based on 5 BHTs recorded immediately after CUBO drilling-related circulation. This analysis would benefit from additional BHT measurements at longer times-since-circulation relative to the currently available BHTs (Peters and Nelson, 2012). A future effort to measure additional BHTs is anticipated to utilize a downhole fiber-optic distributed temperature sensing (DTS) cable.

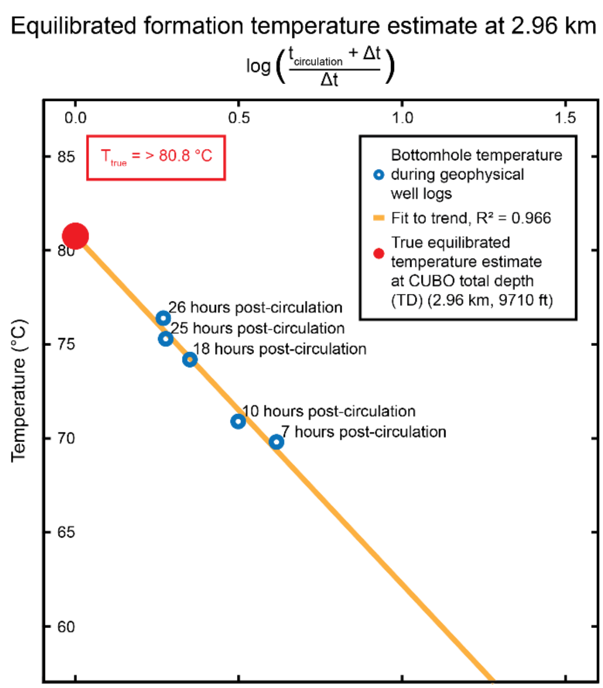

Figure 3. Equilibrated formation temperature estimate of > 80.8 °C at CUBO total depth (TD) (2.96 km, 9710 ft). This is based on a projection of 5 BHTs to infinite thermal equilibration time (labeled 0 in x-axis), when the drilling-related effects have diffused.

3.2 The depth-variations in thermal conditions match the lithostratigraphy

On the static temperature profile in Figure 4, we observe depth-variations in thermal conditions that correlate with the independently-determined lithostratigraphy. These depths of thermal gradient changes: (1) 0.70 km (2310 ft); (2) 1.07 km (3500 ft); (3) 1.43 km (4680 ft); (4) 1.88 km (6180 ft); (5) 2.41 km (7897 ft); (6) 2.87 km (9400 ft). Assuming constant vertical thermal heat flux (q), Fourier's Law of Thermal Conduction ($q = \lambda * dT/dz$) suggests that changes in thermal gradient (dT/dz) result in depth-variations in thermal conductivity (λ). Because changes in Figure 4 are in line with stratigraphic boundaries, we expect that they reflect thermal conductivity differences.

Specifically, these depths of thermal gradient changes correspond to the boundaries between rock types with typically substantial differences in thermal conductivities based on Robertson, 1988. At (1) 0.70 km (2310 ft), a boundary exists between shale-mudstone and a combination of organic-rich shale and limestone rocks (typically a 2x-4x relative difference in thermal conductivity). At (2) 1.07 km (3500 ft), a boundary exists between anhydrite and shale-mudstone rocks (typically a 3x-5x relative difference in thermal conductivity). At (3) 1.43 km (4680 ft) and at (4) 1.88 km (6180 ft), boundaries exist shale-mudstone and sandstone rocks (typically 3x-4x relative differences in thermal conductivity). At (5) 2.41 km (7897 ft), a boundary exists between limestone and dolostone rocks (typically a 1.5x-2.5x relative difference in thermal conductivity). At (6) 2.87 km (9400 ft), an unconformity boundary exists sandstone and basement rocks (typically a 1.5x-4x relative difference in thermal conductivity. Further analysis of thermal properties is anticipated to be completed on drill cuttings and side wall cores.

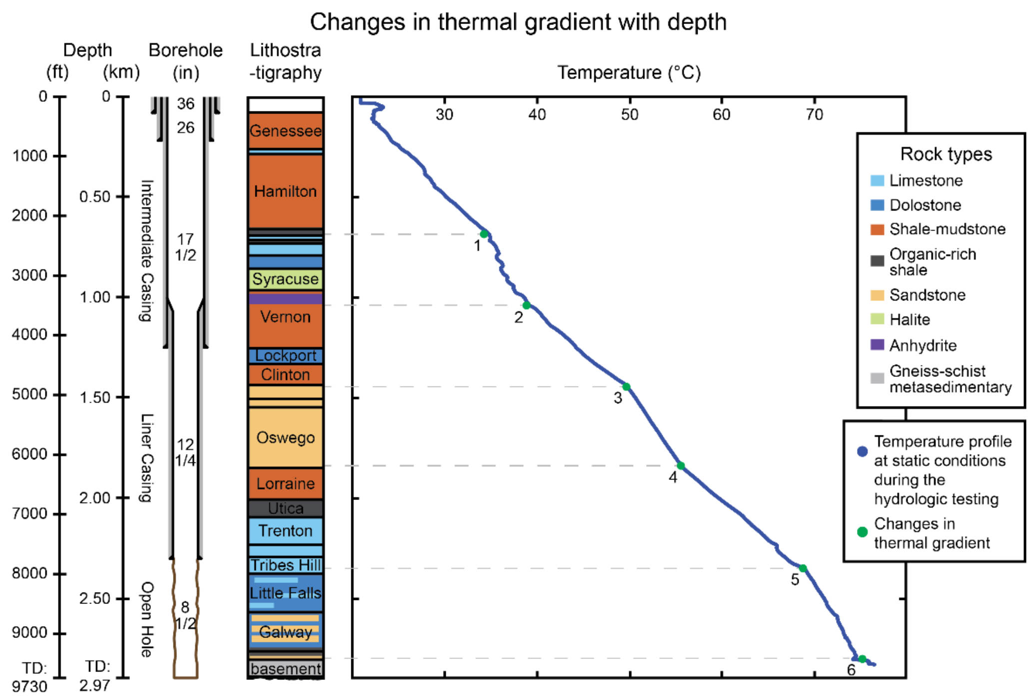

Figure 4. Changes in thermal conditions with depth, as observed from the static temperature profile. We focus on the static profile for this analysis because it most closely reflects the natural formation temperatures relative to other profiles. The depths with observable changes in thermal gradients include (1) 0.70 km (2310 ft), (2) 1.07 km (3500 ft), (3) 1.43 km (4680 ft), (4) 1.88 km (6180 ft), (5) 2.41 km (7897 ft), (6) 2.87 km (9400 ft), and they correlate with the independently-determined lithostratigraphy.

3.3 Potential thermal signals of fluid flow in permeable zones exist

The gradually increasing raw temperature profiles from the first to last log during hydrologic testing is most likely caused by the equilibration of formation temperature from the drilling-related thermal disturbance (Figure 5). Beyond conductive heat flow, additional signals may be present and represent the localized effects of advection. By looking at anomalies in Figure 5 that are not easily explained by thermal conductivity variations, we identify potential signals of fluid advection either caused by fluid flow into the borehole or fluid infiltration into permeable zones within the formation. These signals consist of localized anomalies in the temperature profiles that occur at the same depth and persist over the entire hydrologic testing duration.

In Figure 5, an observable potential advective thermal signal is present below the boundary between the Potsdam sandstone and basement rock (2.87 km, 9430 ft) (labeled light gray arrow), which appears to be consistently cooler than adjacent temperatures throughout hydrologic testing. This continually cooler temperature anomalies may be a result of relatively higher levels of infiltration of cool drilling fluids, which is driven by circulation in the borehole during drilling. We interpret this signal to indicate a potentially permeable zone capable of naturally taking in fluids.

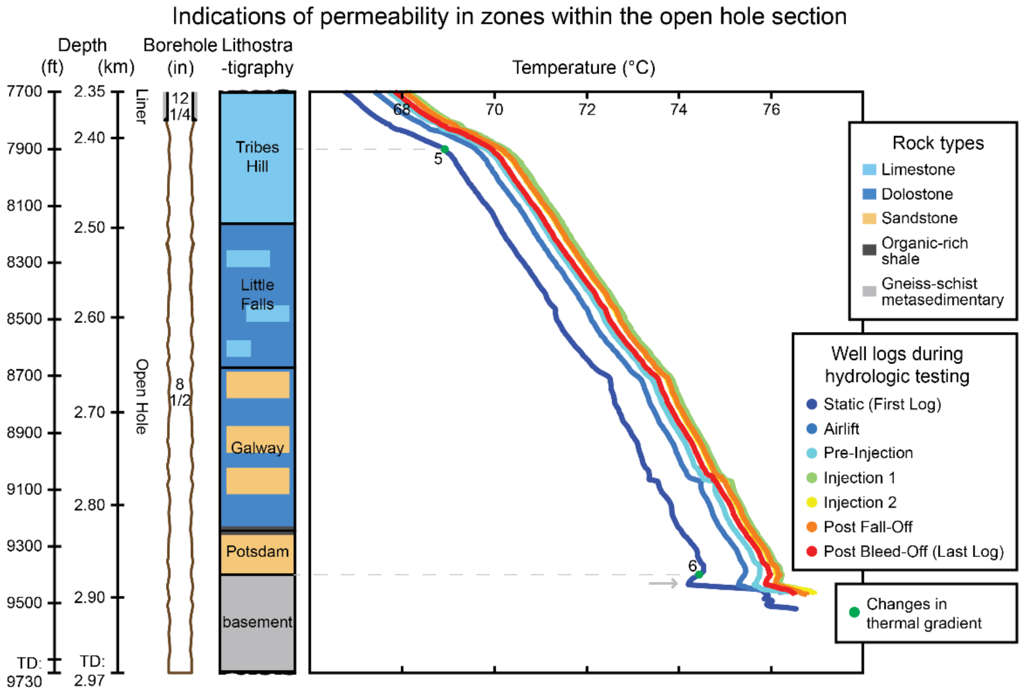

Figure 5. Thermal condition of the open-hole, which show thermal gradient changes (point 5 and 6) and signals that may represent the localized effects of fluid advection (light gray arrow). An advective thermal signal consists of anomalies in the temperature profiles that persist over time at the same depth, such as below the Potsdam and basement rock boundary (2.87 km, 9430 ft).

To further investigate indications of permeability, we remove a reference geotherm in order to see advective thermal signals more clearly. Figure 6 shows residual temperature profiles after the reference pre-injection profile was subtracted, and as a result, we see a greater number of potential thermal signals (labeled light and dark gray arrows) than in Figure 5. These include persistent temperature anomalies in the middle of the Little Falls (2.58 km, 8466 ft), below the Little Falls and Galway boundary (2.66 km, 8717 ft), in the middle of the Galway (2.76 km, 9071 ft), and below the Potsdam and basement rock boundary (2.87 km, 9430 ft) (also seen in Figure 5).

The advective thermal signals at 2.58 km (8466 ft) and at 2.87 km (9430 ft) are similar and appear as persistent localized cool, negative residual anomalies. As indicated earlier, these signals may be the result of relatively larger amounts of cool-drilling-fluid infiltration into the formation caused by drilling-related circulation in the borehole. We interpret these signals as indications of permeable zones in the middle of the Little Falls and below the Potsdam and basement rock boundary, which are capable of naturally taking in fluids.

In contrast, the advective thermal signal at 2.66 km (8717 ft) consists of persistent localized warm, positive residual anomalies. This may be the result of relatively greater production of warm formation fluids from the formation induced by airlift-driven circulation in the borehole. We interpret this signal, somewhat differently than before, as an indication of a permeable zone below the Little Falls and Galway boundary that is capable of naturally producing formation fluids.

Notably, the advective thermal signal at 2.87 km (9430 ft) is initially a localized cool, negative residual anomaly in the static profile that evolves into a warm, positive residual anomaly in the airlift profile and finally evolves into cool, negative residual anomalies for the remainder of hydrologic testing. These anomalies may be the result of a combination between relatively significant cool fluid infiltrations caused by the borehole drilling and the injection tests, and relatively great production of warm formation fluids induced by the airlift test. Thus, we interpret this signal as a permeable zone in the middle of the Galway that is capable of both naturally taking in fluids and producing formation fluids.

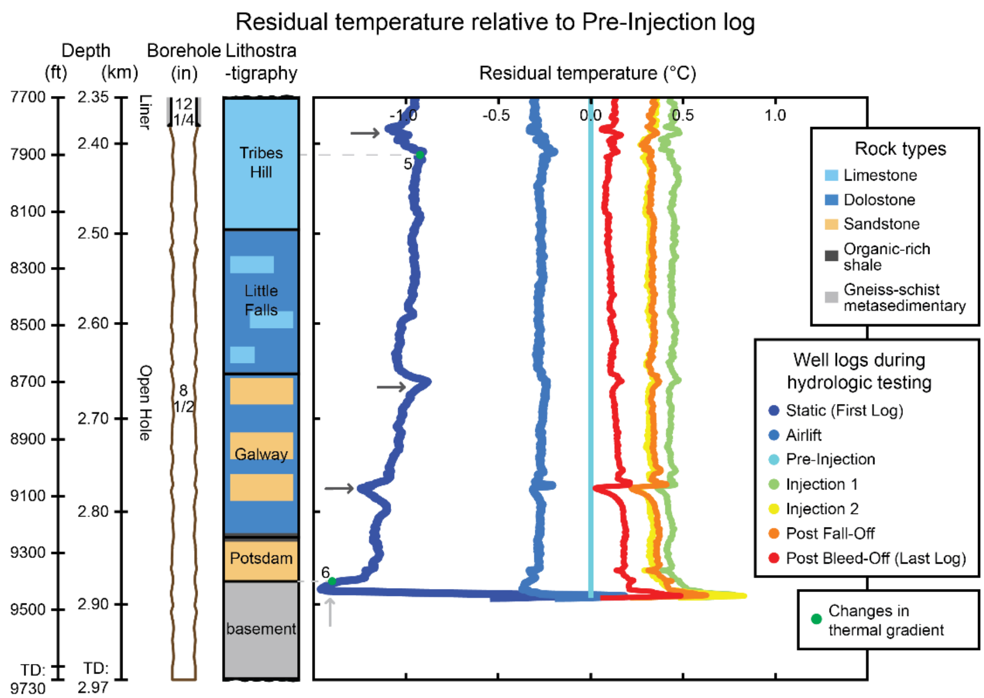

Figure 6. Residual temperature profiles after the subtraction of the pre-injection profile as a reference geotherm. Advective thermal signals consist of residual anomalies that persist over time at the same depth and appear in the middle of the Little Falls (2.58 km, 8466 ft), below the Little Falls and Galway boundary (2.66 km, 8717 ft), in the middle of the Galway (2.76 km, 9071 ft), and below the Potsdam and basement rock boundary (2.87 km, 9430 ft) (also seen in Figure 5). Of these signals, some are persistently cool, negative residual anomalies, others are persistently warm, positive residual anomalies, and one is a mix of both.

4. CONCLUSIONS

This paper provides preliminary constraints on thermal conditions at depth and the hydrology of potential geothermal reservoir formations for Cornell's ESH.

We estimate the equilibrium bottom-hole temperature of CUBO at 2.96 km (9710 ft) to be greater than 81 °C. This temperature is within the workable range for ESH direct-use geothermal application, presuming sufficient flow and surface area can be utilized. Also, this temperature is consistent with previous predictions of geothermal gradient in the region (Blackwell et al., 2011; Smith, 2019).

We find depth-variations in thermal conditions that correlate with the lithostratigraphy, which suggest that they are associated with thermal conductivity variations. Additional constraints on thermal properties are anticipated based on analysis of drill cuttings and side wall cores.

We interpret depth intervals of increased permeability from advective thermal signals that reflect the effects of localized increases of fluid inflow or outflow between the wellbore and surrounding formation. Of particular interest are permeable zones at the Tribes Hill formation (2.38 km, 7821 ft), the Little Falls and Galway boundary (2.85 km, 9357 ft), the Galway formation (2.76 km, 9071 ft depth), the Potsdam and basement rock boundary (2.85 km, 9357 ft). These depths are consistent with previous predictions of potential ESH reservoirs (e.g., Camp and Jordan, 2017; Tester et al., 2019) and correlate with other indications of permeability (Roberto and Fulton, 2023, this session).

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