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Subsurface Insights from the Cornell University Borehole Observatory (CUBO): A 3km Deep Exploratory Well for Advancing Earth Source Heat Deep Direct-Use Geothermal for District Heating

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ABSTRACT

Motivated by Cornell University's aspiration to use geothermal heat to replace fossil fuels to heat campus buildings, a 3-km deep geothermal exploratory well, the Cornell University Borehole Observatory (CUBO), was drilled on the Ithaca, NY campus in the summer of 2022. CUBO extends through largely low porosity and low permeability Paleozoic sedimentary rocks above low-grade metamorphic basement rocks. In order to assess the potential for and inform the design of an operational deep direct-use geothermal system within the US Northeast, the main objective of CUBO is to characterize the subsurface and potential fracture-dominated reservoir targets in both the sedimentary units and basement within a temperature range between 70 – 90 °C. Here we report results of our analysis which provide insight into the hydrologic, thermal, and mechanical conditions at depth and the associated physical rock fracture properties and characteristics. This integrative work incorporates regional well logs and geologic and geophysical data, as well as the CUBO-specific downhole logging and borehole image data collected during drilling operations, subsequent borehole temperature profiling and fluid sampling, downhole dual-packer mini-frac stress tests, and microstructural and physical property analysis of sidewall cores and cuttings. Altogether the knowledge from this information guides decisions regarding the design, depth, and orientation of subsequent injection and production wells at Cornell, as well as highlighting University, and highlights particular geologic targets and strategies for developing an effective and efficient enhanced geothermal reservoir. These comprehensive results, as well as lessons learned regarding the overall approach, can help de-risk decisions regarding the development of deep geothermal energy systems both at Cornell University and elsewhere.

1. INTRODUCTION

Through its Climate Action Plan, Cornell University in upstate New York has committed itself to a goal of achieving carbon neutrality by 2035. As part of a multi-faceted approach, Cornell has been exploring the potential for enhanced deep direct-use geothermal energy, referred to as Earth Source Heat, for campus heating needs (Tester et al., 2023). Earth Source Heat would complement an operational Lake Source Cooling system that facilitates district cooling on campus and ongoing efforts towards renewable low-carbon sources of electricity that include existing hydroelectric and solar facilities on and off campus (Figure 1).

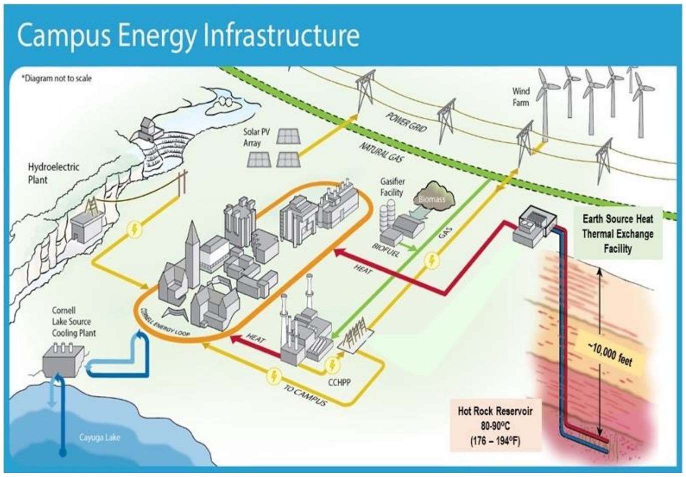

Figure 1: Cornell University Ithaca, NY campus energy infrastructure. An Earth Source Heat thermal exchange facility is not yet realized.

Cornell's energy challenges and goals are similar to those of the state and region as a whole: roughly 35% of New York state's primary energy is consumed for space heating needs, amounting to 30% of the state's greenhouse gas emissions (NYSERDA, 2019; Jordan et al., 2020 and references therein). To address heating needs, Earth Source Heat envisions using deep geothermal well pairs (injectors and producers) to facilitate fluid flow and heat extraction along flow paths within the deep subsurface geology. A heat exchanger and industrial-scale heat pump can transfer heat collected deep underground for use in the university's separate district heating system while returning the produced fluids back into the ground cold (Tester et al., 2023; Figure 2). We term this an "enhanced deep direct-use" system due to the utilization of hot temperatures at depth along with the incorporation of heat pump.

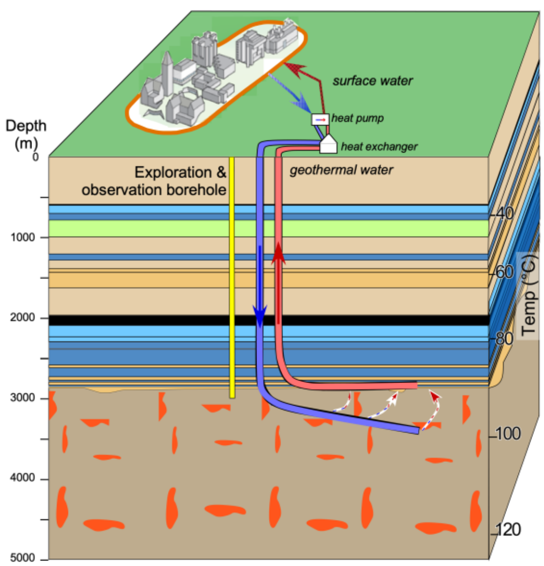

Figure 2: Schematic diagram of the Earth Source Heat concept for a deep direct-use geothermal energy system on Cornell University's Ithaca NY campus. CUBO is represented as the dedicated vertical "Exploration & observation borehole" in yellow.

The potential for Earth Source Heat in the northeast and at Cornell University is informed by a Play-Fairway analysis which combines estimates of the thermal resource based on heat flow maps and temperature projections along with other critical factors including potential reservoirs, hazards, risks, population centers and existing infrastructure and need, and general uncertainties (Jordan et al., 2016; 2020; Camp & Jordan, 2017). The results of this work suggest that despite the relatively low heat flow in the tectonically-quiet northeast USA, access to suitable rock temperatures is feasible. In addition, despite the general low porosity and permeability of the Paleozoic rocks at depth, there may be potential to utilize fracture-dominated reservoirs within either Paleozoic units or the Precambrian basement by directly using or enhancing existing fracture networks. Cornell University's Ithaca, NY campus resides within the Appalachian Basin and within one of the identified priority play regions (See Jordan et al., 2020).

Within the realm of geothermal projects, Cornell's Earth Source Heat concept is a low-temperature, deep direct-use, enhanced geothermal system. Drilling an exploration well is an important step towards the practical demonstration of a geothermal district heating for the campus. Technical uncertainties associated with the limited knowledge regarding the deep subsurface hydrogeology (including the distribution and orientation of fractures and the permeability and surface area of potential reservoir flow networks at depth), along with uncertainty in the stress conditions (magnitude and direction) and rock strength, present particular implementation challenges. An understanding of these subsurface characteristics is important for the design of injector and producer wells, development of strategies for potential hydraulic stimulation if necessary, assessment and mitigation of seismic hazard, and optimization of operational parameters once complete.

To address these uncertainties, the Cornell University Borehole Observatory (CUBO), a 3-km, nearly 10,000-foot-deep vertical characterization well was drilled on the Cornell campus in summer 2022 supported by funds from the US Department of Energy and Cornell University. This well, also referred to as ESH-1, serves as a dedicated exploration well to characterize the subsurface properties and conditions, provide information to guide the development of additional wells that can serve as injectors and producers, and to function as a long-term observatory to monitor how the subsurface responds over time. Before moving onto the next phase of ESH development, characterization of the subsurface using direct measurements in the CUBO well reduce the technical risks of developing a viable ESH system capable long term heat production at sufficiently high rates.

Here, we report findings from logging, testing, and sample collection within CUBO which provide greater insight into the geologic, thermal, hydrologic, and mechanical properties and conditions at depth and guide the next stages of decisions and development towards an operational Earth Source Heat (ESH) geothermal system. The resulting subsurface characterization is essential to properly locating, designing, drilling, and stimulating an injection and production well network to ensure economically sustainable reservoir thermal energy extraction production rates and lifetimes.

2. WELL DRILLING AND COMPLETION

Figure 3 illustrates the well completion of CUBO. CUBO was drilled over the course of 65 days in summer 2022 to a depth of 9791 ft below rig floor. The hole was completed with several levels of casing to ensure groundwater protection, promote hole stability around particularly challenging formations, and to prevent inflow from gas-bearing units. Cement extends the full length behind each casing string. The bottom 8.5” section of hole from 7800’ – 9791’ was left open to the surrounding rock to enable exploration and testing of potential target reservoirs.

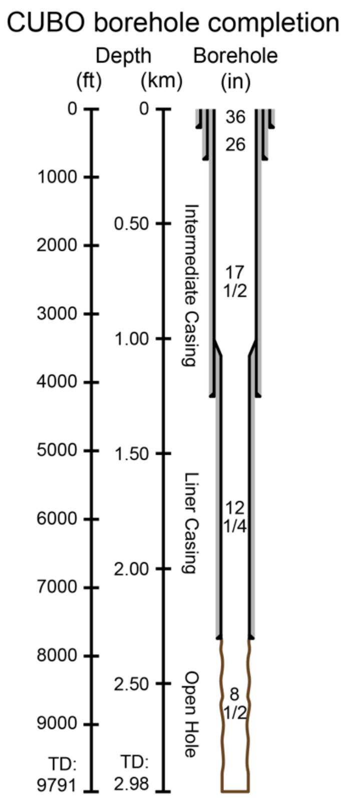

Figure 3: Schematic diagram of CUBO borehole completion. An 8.5” – diameter section was left as open-hole from 7800’ to TD at 9791’.

Prior to drilling, expectations regarding the lithostratigraphy, temperature range, and target intervals for exploration of reservoir potential were guided by regional geologic analysis, geophysical surveys including seismic reflection profiles, and other regional wells (Jordan et al., 2020). However, the basement and its character presented particular unknowns as it has not been well characterized within the region, and its relationship, if any, to basement exposures in the Adirondacks mountains ~200 km away has been uncertain.

3. LITHOSTRATIGRAPHY

During drilling, cuttings were collected from the circulated mud roughly every 5 to 10 feet of advancement. Figure 4 describes the lithostratigraphy and primary compositions of the subsurface encountered by CUBO as determined through integrated analysis of the drill cuttings, downhole geophysical logs, and a limited set of twenty-five 2”-diameter side wall cores in the 8.5” open hole section.

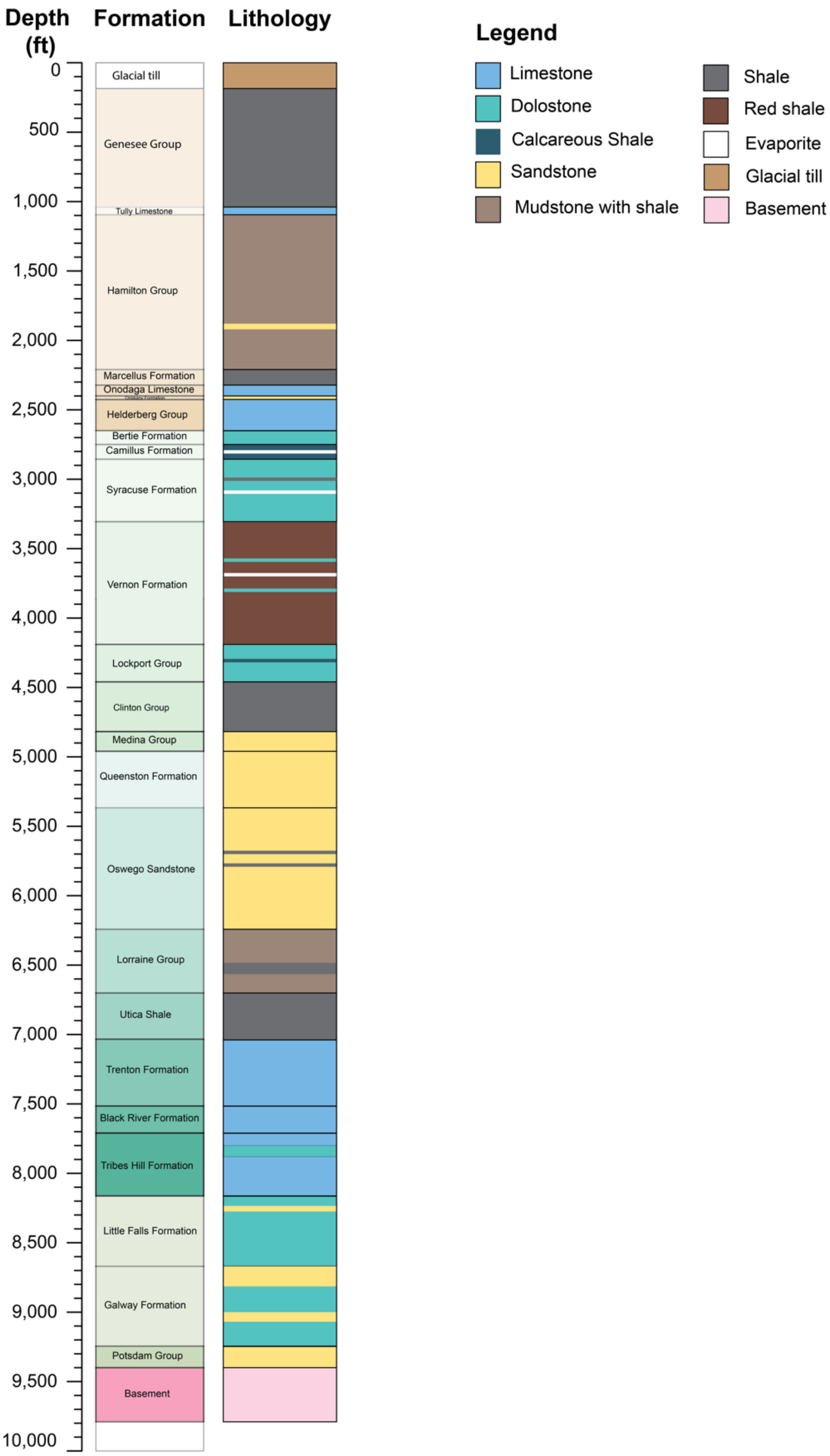

Figure 4: Formations and lithologies of the geology surrounding CUBO as determined by drill cuttings, a limited number of side-wall cores, and geophysical logs.

Beyond the roughly 200' of glacial sediment and till near the surface, CUBO extends through Paleozoic sedimentary formations consisting of shales, carbonates, sandstones, and some evaporites to a depth of ~9400'. CUBO then crosses a major unconformity and extends ~370' into metamorphic Pre-Cambrian basement to a total depth of 9791'. Positions of formation tops were relatively similar to those predicted ahead of time, and the basement intervals drilled consist of low-grade meta-sediments (Valentino et al, 2023).

4. THERMAL CONDITIONS

Circulation during drilling temporarily disturbed borehole temperatures, but Bullard-plot analysis of bottom-hole temperatures measured during various logging tool runs in the days after reaching total depth and cessation of circulation have previously provided an estimate of >80 °C at 9710' depth (Purwamaska & Fulton, 2023).

In December 2022, a brief deployment of a fiber-optic cable enabled distributed temperature sensing estimates of re-equilibrated temperature, but only within the cased section of the borehole <~7800'.

Figure 5, however, reflects results of a high-resolution survey of equilibrated temperatures to a depth of 9400' conducted in November 2023. This survey follows the Stop-Go methodology of Harris & Chapman (2007) in which temperature sensors were lowered to a particular depth, held for at least 2 minutes to enable extrapolation of the formation temperature accounting for instrument response and disturbance by the survey itself, and then incrementally lowered further.

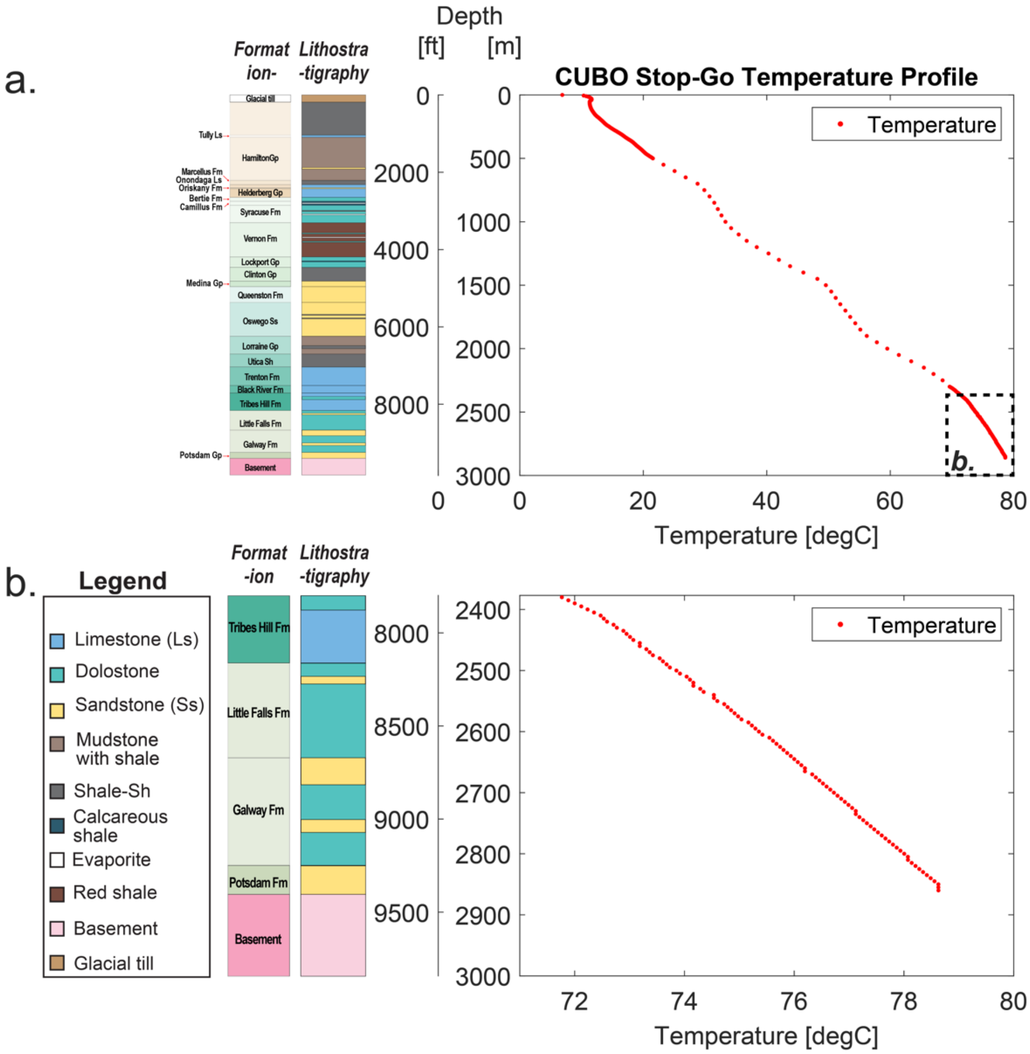

Figure 5: Results of November 2023 high-resolution stop-go temperature survey revealing borehole temperature distribution after re-equilibration with the formation following disturbance resulting from drilling 14-16 months prior. Panel b is a zoomed in section of panel a.

This 2023 survey confirms that open hole section conditions were sufficient to enable easy instrument access to and retrieval from approximately the depth of the basement contact at ~9400'. The maximum recorded temperature at this depth is 78.9 °C. Extrapolation to either 9710' where bottom hole temperatures were previously made or to 9842' (~3 km) both result in values >80 °C.

5. HYDROLOGIC CONDITIONS

To assess the overall permeability or transmissivity of the open hole section between 7800 – 9791' and to identify particular permeable zones, hydrologic tests were conducted after completion of drilling, logging, and coring operations. The hole was cleaned out and the drilling fluid / mud in the hole was replaced with fresh water. An airlift test was then conducted in which the water level inside the well was progressively lowered to 4116' below ground level in an attempt to drive flow into the well. No measurable excess water was produced, and the water level did not appreciably change in the hours after drawdown. The water that was removed and held in tanks was then returned to the well and a backpressure of 1400 psig was applied to see if the open-hole formations would take fluid. Again, water level / pressure at the wellhead did not appreciably change (i.e. diffuse) over several hours (Clairmont et al., 2023). The observations imply that the open hole section has low hydraulic diffusivity and low transmissivity.

During these tests pressure-temperature logs were run to assess where fluid inflow or outflow may be occurring. Issues with the tool prevented collection of reliable spinner / flow rate measurements and the tool had trouble accessing the basement due to encounters with ledges, possibly resulting from shifting blocks of rock within a highly fractured or brecciated interval within the basement. Figure 6 shows the temperature survey results from these tests.

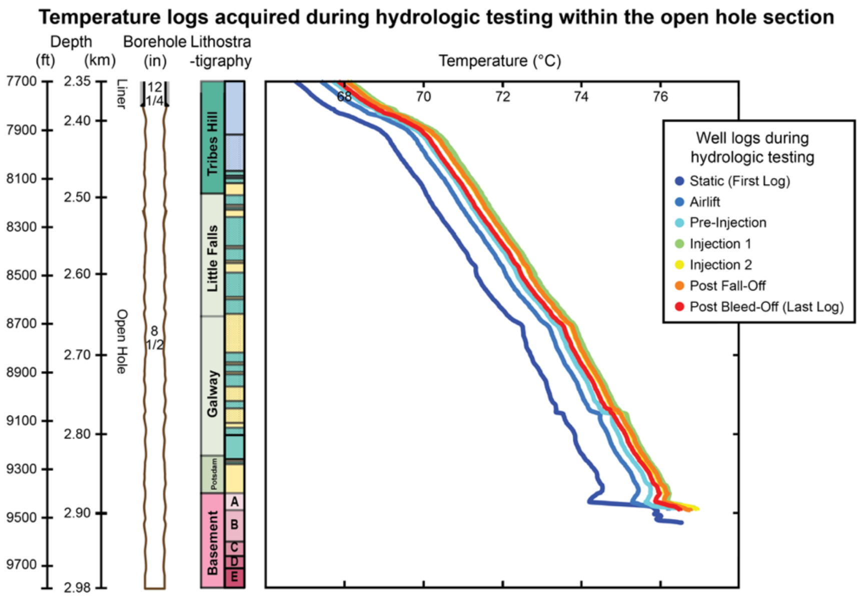

Figure 6: Temperature logs acquired during hydrologic testing within the open hole section of CUBO. Adapted after Purwamaska & Fulton (2023).

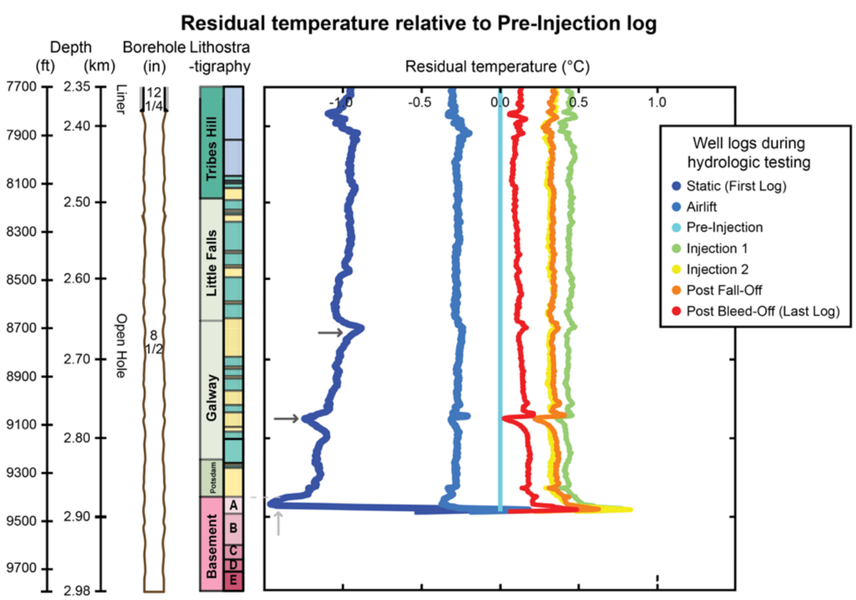

Figure 7: Residual temperature data (relative to the pre-injection log) acquired during hydrologic testing within the open hole section of CUBO. Similar to Figure 6, but with the pre-injection log subtracted off each to highlight anomalous differences between logs reflecting the effects of fluid advection. Adapted after Purwamaska & Fulton (2023).

By subtracting the pre-injection temperature as a reference, the residual temperature logs reveal several depth intervals with anomalous temperature responses. These signals are interpreted to suggest that these intervals correspond with localized zones of relatively higher permeability that produced and/or accepted small volumes of fluid during the hydrologic tests (Purwamaska & Fulton, 2023). Notable signals include a couple within the Galway Formation and a relatively strong signal, observable in the raw data as well, near the basement-sediment contact around 9400'. Unfortunately, there is not much data extending into the basement.

However, marked increases in hydrogen and helium within the mud gas, measured with a mass spectrometer connected to an inline constant volume degasser, were observed during drilling at the same two intervals within the Galway formation where temperature perturbations were observed during the hydrologic tests,. Similar H as well as He spikes were observed throughout the basement. These observations are interpreted to suggest that these intervals have permeability that extends away from the borehole enabling accumulation of inorganic gases and their subsequent release when these zones were intersected by the borehole (Clairmont et al., 2023).

Additional insight into the deep hydrogeology comes from wellhead monitoring. The open hole appears to be slightly overpressured such that it produces water at a rate on the order of tens of liters of water per week.

In November 2023, several liters of fluid were collected from deep within the open hole section of CUBO using a downhole point source bailer system. The system enabled collection of fluid from 9387', right around the depth of the basement-sediment contact and where temperature data suggest there may be localized permeability. Preliminary results of geochemical analysis confirm that the samples represent formation fluid in the form of brine. Specific conductivity of brine fluids ranged from 2700 to 23,560 µS cm^{-1} with field and measured pH values of 7.31 ± 0.23. Major anion analyses yielded a chloride (Cl^-) dominant brine hydrochemistry (268 ± 28 mmol L^{-1}) with elevated concentrations of sulfate (15.4 ± 3.7 mM), fluoride (190 ± 20 mM), and nitrate (14.03 ± 0.68 mM). In addition, initial cell enumerations reveal large concentrations of microorganisms within the samples (~10^5 cell/mL) potentially reflecting the presence of an active microbial community and a persistent interconnected deep fluid-flow network.

Together these data suggest that a) a relatively permeable zone naturally exists around the sediment-basement contact and perhaps deeper into the basement, b) these rocks are not dry, but rather contain brines, and c) the fluid pressure conditions are just slightly greater than hydrostatic.

6. FRACTURE DENSITY AND ORIENTATION

Because the intrinsic porosity and permeability of most of the rocks beneath Cornell is inferred to be quite small, fractures and fracture networks either currently present and/or engineered in the future, likely control permeability and reservoir potential. Thus, a major objective of CUBO is to characterize the distribution and orientation of existing fractures within the subsurface.

Identification of fractures and other structural features intersected by the borehole was completed utilizing a suite of borehole image (BHI) logs acquired within the open hole – including three Schlumberger Formation Microresistivity Imager (FMI) surveys and one Schlumberger Ultrasonic Borehole Imager (UBI) survey (Fulcher et al., 2023a). In addition, analysis of Stonely wave data from sonic scanner logs provides evidence of large-scale fractures several meters away from the borehole (Fulcher et al. 2023b).

Figure 8 shows a summary of identified fractures incorporating both borehole data sets and additional lithologic data and updated in late 2023.

Fractures identified within the FMI logs are characterized as either resistive, mixed resistivity, or conductive based on their electrical resistivity responses. Resistive fractures are most prominent in the Galway Formation (Figure 8) with varying northeast, northwest, and east-southeast dip directions. Mixed resistivity fractures occur predominantly in the basement complex – totaling 57 compared to the seven in the Ordovician-Cambrian section. Conductive fractures were the most frequent in the basement complex totaling 61 and with an average strike/dip orientation of 70.1°/50.8°.

Fracture frequency, based on 10-foot bins using the updated fracture analysis data (Figure 8), shows clustering in three distinct depth intervals situated at 8700, 9375, and below 9400 ft. The largest fracture frequency in the Ordovician-Cambrian sections is located at the top of the Galway Formation (8700 ft) in a thinly bedded, medium-grained sandstone unit that coincides with a helium gas peak as described above (Fulcher et al 2023).

Observed fractures below 8,700 ft become less frequent until the Potsdam Group is intercepted. Interpreted fractures within the Potsdam Group are mainly conductive and mixed resistivity type fractures near the basal unconformity. Fracture frequency increases strongly below the unconformity into the basement.

Far-field fractures identified by Stonely waveform analysis show subvertical dipping fractures oriented NNW-SSE orientation and a ENE-WSW orientation. These represent a separate set of fracture orientations than what is directly intersected by CUBO and thus provide insight into potential large-scale fracture networks (Fulcher et al., 2023b).

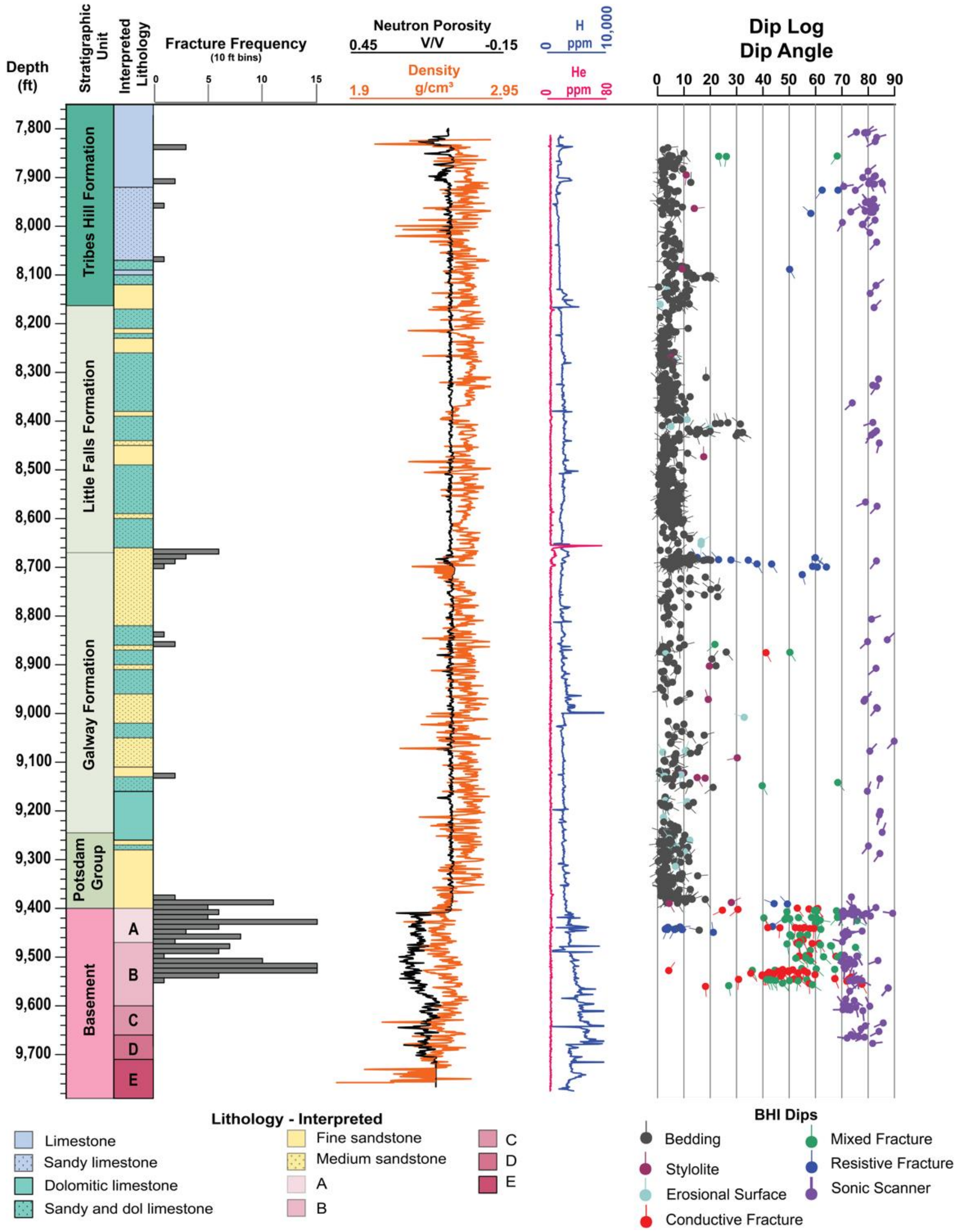

Figure 8. The depth and dip of identified fractures and other structural features on the right compared with hydrogen and helium data on a relative scale, geophysical logs, and lithostratigraphy. Bin counts of fracture frequency reveal the large numbers of fractures within the basement and around basement – sediment unconformity. For fracture data set after revisions late in 2023.

7. STRESS STATE

Understanding which fracture orientations are most susceptible to hydraulic stimulation or shear failure requires knowledge of the stress state – the magnitude of each principal stress and their orientation.

Four-arm caliper logs collected in each major drilled section along with borehole image logs in the open hole section reveal borehole breakouts throughout. These data constrain the maximum horizontal stress direction to a roughly NE-SW orientation both at depth and throughout the borehole (Pinilla et al., 2023a,b; Figure 9).

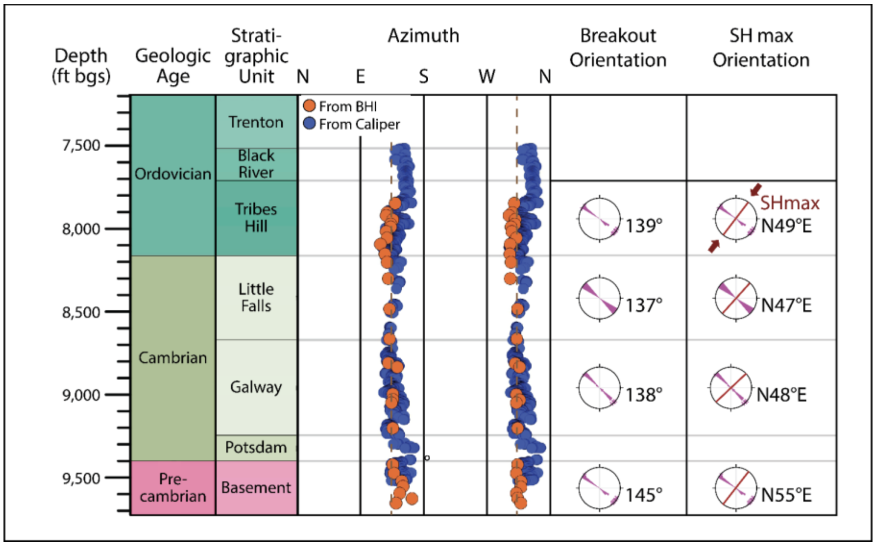

Figure 9. Borehole breakouts in the open hole section. From left to right in each panel: geological units in the CUBO bottom section, azimuth of borehole breakouts measured with caliper and image logs, average breakout orientation in each geological unit, and interpretation of SHmax orientation which is perpendicular to the breakout's azimuth. Caliper data extending to shallower depths reveal similar orientations throughout the borehole (Pinilla et al., 2023a, b).

Determination of stress magnitudes is made possible through dual-packer mini-hydraulic fracture testing completed within CUBO immediately after drilling cessation (Pinilla et al., 2023a, b). Figure 10 shows data from the key measurement station at 8695' depth.

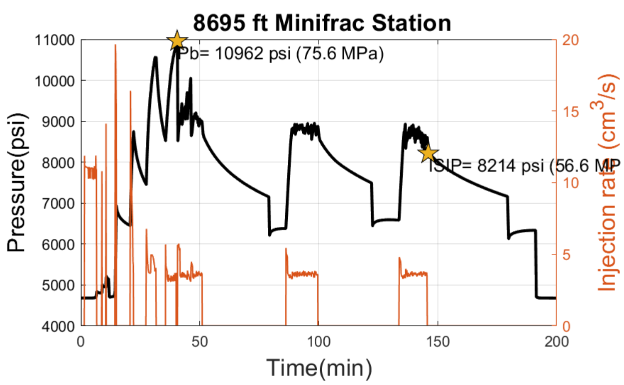

Figure 10: Pressure-time curves associated with a minifrac test centered at 8695 feet. The black curve represents the pressure data (y-axis on the left), while the orange curve represents the injection rate of the fluid pump (y-axis on the right). A measurement of ISIP of 56.6 MPa and Pb of 75.6 MPa are pointed out in the graph.

Measurements of breakdown pressure (Pb) and Instantaneous shut-in pressure (ISIP) allow for the determination of the maximum and minimum horizontal stresses (e.g. Schmitt & Zoback, 1989) assuming the test resulted in a pure tensile fracture perpendicular to the minimal principal stress. Comparison of borehole image logs before and after the minifrac tests confirms a vertical fracture was created during the experiment at 8695'. In contrast, new fractures were not observed at two other stations, at which ISIP values comparable to estimates of the overburden derived from from density logs are interpreted to suggest that these other experiment stations resulted in failure along relatively weak horizontal bedding planes rather than being able to overcome the combined minimum stress and cohesive strength of the rock in that direction.

Analysis of these data results in values of 82 MPa = σ_1, 68 MPa= $\sigma_2 = \sigma_v$, and 57 MPa= σ_3 (Pinilla et al., 2023b). These results, along with determinations of the cohesive strength and observations suggesting near-hydrostatic pore fluid pressure, enable the construction of a Mohr circle diagram (Figure 11) which reflects the current stress state at 8695' depth relative to a brittle frictional failure criterion. The data suggest that the present-day background stress state deep within CUBO is not critically stressed, but rather far from failure.

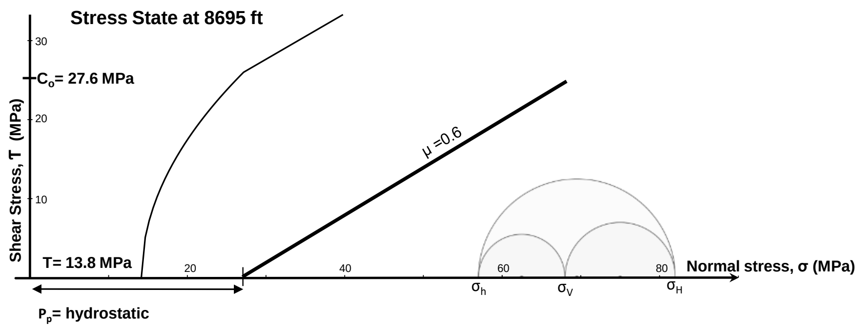

Figure 11: Mohr Circle representation of stress state at 8695 ft in CUBO (after Pinilla et al, 2023,a,b). The magnitude of the principal stresses is plotted on the x-axis. 82 MPa = σ1, 68 MPa= σ2, and 57 MPa= σ3. The thin black line is the Mohr-Coulomb envelope, including cohesion, and the bold black line represents a failure envelope without cohesion and a friction coefficient, μ = 0.6.

With knowledge of the relative magnitudes of the principal stresses and their orientations, the particular shear and normal stress conditions acting on individual fractures can be determined and their propensity for failure assessed.

Normalizing by the effective vertical stress allows for the relative stress conditions of individual fractures from various depths to be assessed in the same diagram as well as their potential for hydraulic stimulation. In Figure 12, we separate fractures identified in the sedimentary units within the open hole from fractures identified within the basement and plot their projected shear and normal stress based on their orientation relative to the principal stress tensor. Those fractures with theoretical potential for hydraulic stimulation are plotted in red whereas those plotted in black are oriented beyond the "lock-up" angle (e.g., Collettini & Sibson, 2001) and thus unlikely to be hydraulically stimulated. In addition to having both more prevalent and more conductive fractures in the basement, the orientations in the basement seem generally better suited for hydraulic stimulation than those within the sedimentary units above.

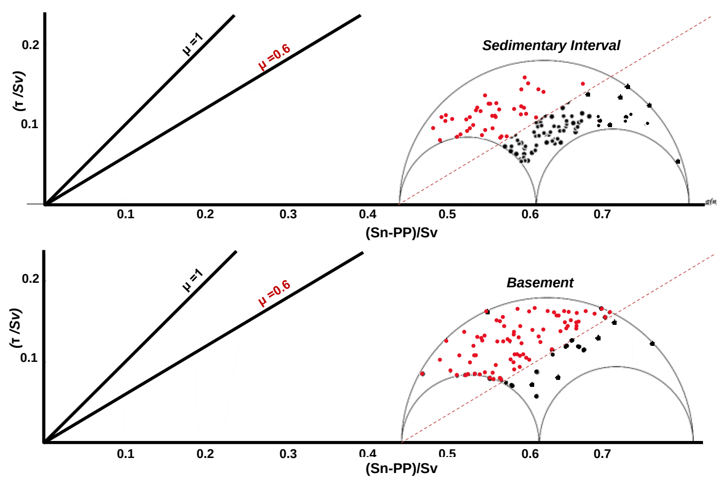

Figure 12. Normalized shear vs. effective normal stress based on CUBO results and resolved stress state of mapped fractures in the a) sedimentary interval of the bottom section between 7839-9400 ft depth, and b) the basement between 9400 – 9561 ft depth (Pinilla et al., 2023b, based on mid 2023 fracture interpretation). Red dots are fractures with orientations that would potentially allow them to be hydraulically stimulated.

8. CONCLUSIONS AND NEXT STEPS

The combination of geologic, thermal, hydrologic, and mechanical characterization of the subsurface enabled by CUBO provides important insights that help reduce technical uncertainties and guide progress towards designing and developing an operational geothermal well pair for deep direct-use district heating. CUBO observations imply temperatures at 3 km exceed 80 °C , which is well within the range that was anticipated and appropriate for enhanced direct-use operations. Sufficient surface area and flow would also need to be achieved between operational wells. The rock formations at depth are generally low porosity and have very little intrinsic permeability. However, local zones of permeability – likely controlled by fractures – exist at depth. Of particular interest are zones around the basement-sediment unconformity contact and others deeper into the basement. In combination with several lines of evidence for localized permeable zones extending away from the borehole, these depth intervals also correspond with locations where many natural fractures are observed, particularly within the basement. The fractures within the basement have high spatial density and are generally more suitable for potential hydraulic stimulation.

Together the data have focused attention towards further exploration of the basement for reservoir potential and possible stimulation / engineering of fracture flow networks. Thus, Cornell University is planning to return to CUBO for an additional phase of exploratory operations. The preliminary objectives are to a) drill deeper into the basement, b) install casing through what is now the open hole section with fiber-optic cables on the outside of casing for distributed temperature, strain, and acoustic sensing, and c) perform diagnostic fracture injection tests (DFITs) within the basement. Fiber-optic sensing behind casing will enable further characterization of the subsurface and insights into how the subsurface responds to stimulation and long-term operations. DFIT testing will enable assessment of the difficulty or ease with which permeable pathways can be created and maintained such that reservoir target depth(s) can be identified and future injector and producer wells can be designed, installed, and implemented.

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