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Fracture Network Characterization and Permeability for Direct-Use Geothermal Energy – Cornell University Borehole Observatory ESH No. 1

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ABSTRACT

Space heating demand of the Cornell University campus in Ithaca, New York, reaches approximately 240,000 MWth-hrs/yr and is supplied by a natural-gas-fed district heating system, accounting for 50% of the annual Ithaca campus energy consumption. Cornell University plans to have a carbon neutral Ithaca campus by 2035 and is exploring the feasibility of providing the campus space heating demand with a deep direct-use (DDU) geothermal district heating system. Initial studies predicted development of a campus DDU district heating system would depend on the formation temperature and fracture permeability within Ordovician to Precambrian rock ranging from depths of 2.3 to 3.2 km beneath the Cornell University Ithaca campus. Understanding the nature and extent of natural fracture zones is paramount for thermal hydraulic reservoir modeling and economic geothermal energy extraction.

Cornell University recently completed drilling, construction, and testing of the 3-km deep exploratory Earth Source Heat Well No. 1 to aid feasibility assessment of potential DDU geothermal energy for campus wide district space heating. Here we present data and initial analysis of fracture networks within Ordovician to Precambrian rock underlying the Cornell University campus, based on newly acquired micro-resistivity and acoustic borehole image (BHI) surveys coupled with sidewall core data obtained from ESH No. 1.

Preliminary fracture analysis of BHI surveys identifies five depth intervals with increased fracture intensity spanning from sedimentary Ordovician formations into the Precambrian basement complex. Most identified fractures present low electrical resistivity values; however, high resistivity fractures are also observed in some depth intervals. Additionally, well drilling parameters and gas chromatography data are examined to further define and bracket permeable fracture zones within intercepted borehole rock. Last, stratigraphic relationships are further defined with additional offset well data to provide lithological facies and spatial extents of potential DDU geothermal reservoir zones.

1. INTRODUCTION

The Cornell University Ithaca, New York, campus space heating demand reaches approximately 240,000 MWth-hrs/yr and is supplied by a natural-gas-fed district heating system – accounting for 50% of the annual Ithaca campus energy consumption. Cornell University plans to have a carbon neutral Ithaca campus by 2035 and is conducting feasibility studies of the Corning-Ithaca Geothermal Play (CIGP) (Figure 1) for providing campus space heating demand via a deep direct-use (DDU) geothermal district heating system. The CIGP (Figure 1) is a 24,000 square kilometer area of south-central New York and north-central Pennsylvania exhibiting the combination of an elevated geothermal gradient, favorable prospects for natural reservoirs, and relatively low risk of induced seismicity, based on Play Fairway Analysis of regional borehole temperature (BHT) measurements (Jordan et al., 2016) (Figure 1). Predicted formation temperatures exceed >70°C at depths of 2.3 to 3.2 km beneath the Cornell University Ithaca campus (Tester et al., 2020).

Geothermal feasibility of the of the CIGP for DDU geothermal energy is being conducted in multiple phases under the Cornell University Earth Source Heat (ESH) project. Phase 1 of the ESH project was the drilling, construction, and testing in August 2022 of Earth Source Heat Well No. 1 (formally ESH No. 1, informally Cornell University Borehole Observatory [CUBO]), a 3 km (2,984 meters below ground surface [bgs]) deep borehole with an 8.5-inch diameter open section between the depths of 2,643 and 2,984 m bgs (Figure 2). ESH No.1 will serve as the first borehole of the Cornell University Earth Source Heat site for future subsurface demonstrations and data collection.

A crucial aspect of DDU geothermal feasibility of the CGIP is characterization of fracture networks within a structural and stratigraphic framework for future well pair development. Borehole image (BHI) surveys show discrete fracture zones within Ordovician, Cambrian, and Precambrian rocks intercepted by ESH No. 1 (open borehole section). Presented herein is an integrated analysis of borehole fracture data with additional geophysical wireline surveys, gas chromatography, and drilling parameters to provide an interpretation of borehole fracture morphology and permeability within a structural-stratigraphic framework.

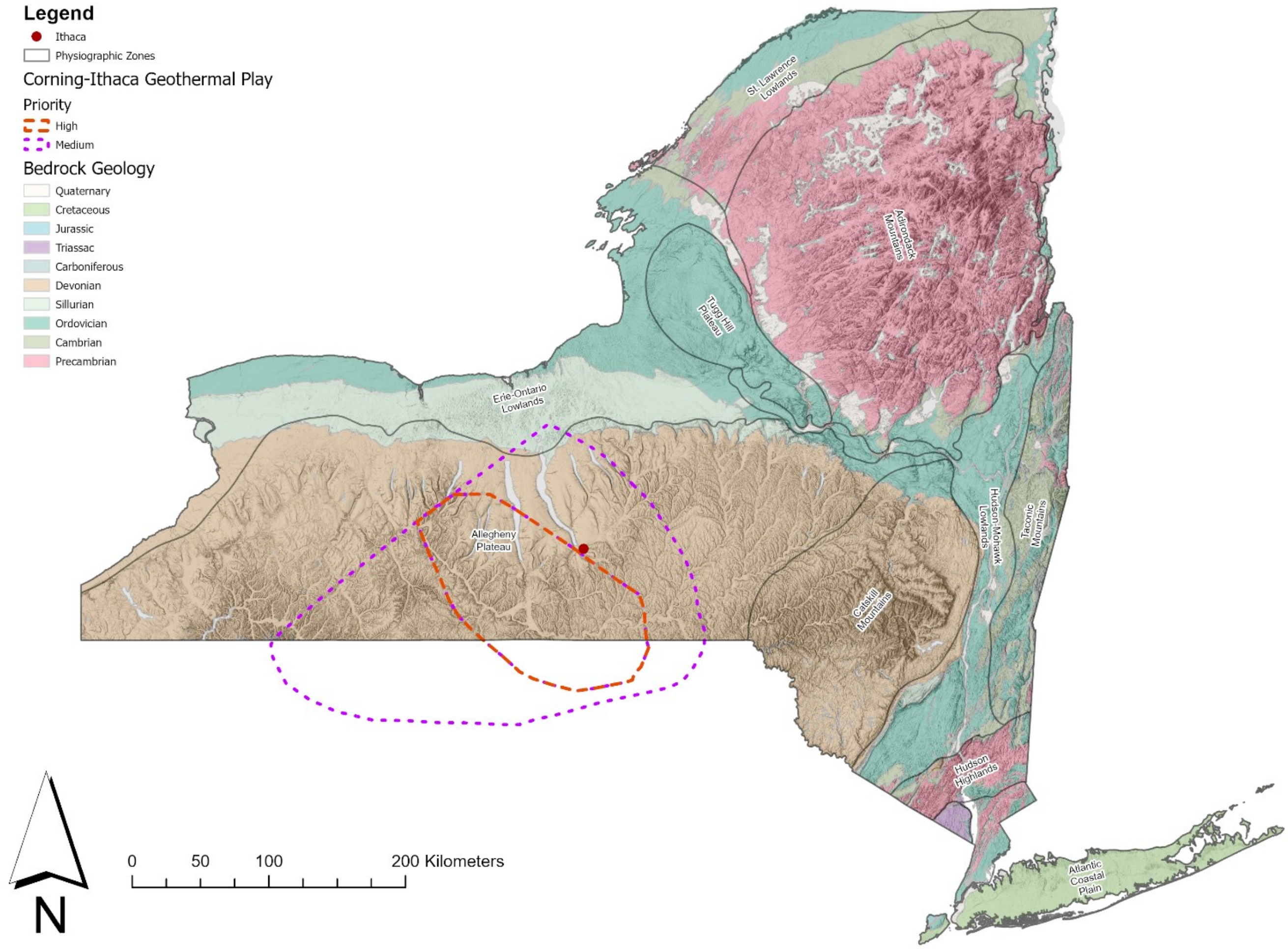

Figure 1: A regional chronostratigraphic map of New York State illustrating the location of Ithaca in relation to the Allegheny Plateau (the highlands of the southern third of New York) and the CIGP. Regional geologic data compiled from USGS SGMC.

2. GEOLOGIC SETTING

The CUBO site lies centrally within the Allegheny Plateau geomorphic province of the Appalachian Basin (Figure 1), where Devonian strata crop out. Cambrian to Devonian-age marine and terrestrial siliciclastics and carbonates unconformably overlie an igneous/metamorphic Precambrian basement (Figure 2). The Devonian to Cambrian-age units represent the preserved remnants of a 290 million year (ma) protracted history of deposition, lithification, and deformation related to an early passive margin basin and later foreland basin, affected by the regional Acadian, Taconic, and Alleghenian orogenies. Tectonically, the CUBO site is situated over 100 km from the Allegheny structural front, where low amplitude northeast-southwest oriented folds persist under the Allegheny Plateau (Figure 3) (Engelder & Geiser, 1980; Wedel, 1932). Most of this distal folding is due to detachment above the Salina décollement (Mount, 2014), and also causes minor thrust faulting (Scott, 1986). Based on interpolated bottomhole temperature data and regionally correlated stratigraphy, Lower Ordovician, Cambrian, and Precambrian stratigraphic units of Tribes Hill Formation, Little Falls Formation, Galway Formation, Potsdam Group, and Precambrian basement are of interest beneath the CUBO site (Tester et al., 2023).

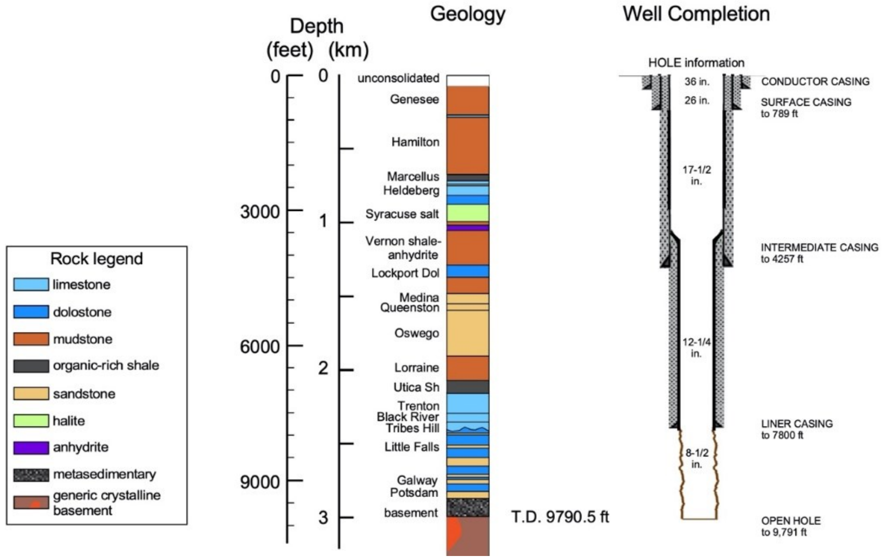

Figure 2: Stratigraphic column of formations intercepted by the ESH No.1 with a borehole casing diagram.

The Tribes Hill Formation is a Lower Ordovician dolostone-limestone deposited in a shallow marine environment, ranging from subtidal to supratidal. Ulrich and Cushing (1910) first described the Tribes Hill Formation in the Mohawk Valley as a separate formation overlying the Little Falls Formation, thereafter Fisher (1954) defined four members in ascending order: the Fort Johnson, Palatine Bridge, Wolf Hollow, and Fonda. The Fort Johnson Member is the basal stratigraphic unit of the Tribes Hill Formation—composed of dolomsiltite and dolomarenite with a predominant breccia or sandstone as the basal contact interface with the Little Falls Formation (Fisher, 1954). Overlying the Fort Johnson Member is the Palatine Bridge Member composed of shaley dololutite and a slightly silty calcilutite (Fisher, 1954). Conformably overlying the Palatine Bridge Member is the massive, thick-bedded, dolomitic calcilutite of the Wolf Hollow Member. The Wolf Hollow Member is widely recognized as the most exposed stratigraphic unit of the Tribes Hill Formation. Capping the Tribes Hill Formation is the Fonda Member, exhibiting highly variable lithologies ranging from phosphatic calcarenites to pebble conglomerates (Fisher, 1954).

Described as a shallow marine dolostone by Clarke (1903) and Cushing (1905), the Little Falls Formation is regionally a 400-ft thick succession of Cambrian dolostone hosting algal stromatolites and doubly terminating quartz (Herkimer diamonds). The formation type section is located in Little Falls, New York, where four informal units in ascending order, A through D, are defined by Zenger (1976). Unit A is the basal part of the Little Falls Formation, occurring as a 90- to 100-ft thick conglomerate and sandstone (Zenger, 1976). Unit B forms the majority of the Little Falls Formation as a 200-ft thick dark, fine- to medium-crystalline dolostone containing vuggy beds with stromatolitic dolostone and sandstone beds (Zenger, 1976). Units C and D are 25- to 40-ft thick sections of glauconitic dolostone and reddish gray finely-crystalline dolostone, respectively (Zenger, 1976).

The Galway Formation, sometimes referred to Theresa Formation in the literature, is an Upper Cambrian age dolomite hosting interbedded sandstones. Al Aswad (2019) simplified a host of local subdivisions into three regionally recognized members in descending order: the Rose Run, Yellowjacket, and Vespa. Clean sandstones of the Vespa Member form the lowermost portion of the Galway Formation while interbedded dolomite and sandstones of the Yellowjacket Member comprise the central portion of the Galway Formation (Smith et al., 2010). A 60-to-250-ft thick yellow arenite sandstone, known as the Rose Run Member, forms the top of the Galway and is equivalent to the Rose Run Formation in Ohio (Smith et al., 2010).

The Potsdam Group is a Cambrian to Lower Ordovician suite of transgressive passive-margin siliciclastic units unconformably overlying Precambrian basement (Landing, 2007; Lowe et al., 2015; Lowe et al., 2017). Basal contacts of the Potsdam Group with the underlying Precambrian basement represent a regional ~550 ma non-conformity. The Potsdam Group consists of three regionally recognized formations in ascending order: Altona, Ausable, and Keeseville.

The Altona Formation is the newest classified formation within the Potsdam Group and is considered the basal stratigraphic unit contacting the Precambrian basement. Locality and present extent of the Altona Formation were first documented by Landing et al. (2009). They described it as 20-m thick fossiliferous sandstone with reddish mudstone and carbonates underlying exposed Ausable arkosic sandstones near Altona, New York. Identified planolites, olenellids, and trilobite remnants bracket the Altona Formation to the Lower Cambrian (Landing et al., 2009).

Overlying the Altona Formation is the Middle Cambrian age Ausable Formation consisting of light gray to pale pink medium- to coarse-grained and pebbly arkosic sandstone (Fisher, 1968), referred to as the Covey Hill Formation in Ontario and Quebec, Canada (Sanford & Arnott, 2011). The Ausable contains up to 50% feldspar, showing thick cross-bedding, indicating a braided fluvial depositional environment (Fisher, 1968). Subordinate laminated bedforms are representative of inter-tidal deposition suggesting coastal proximity of braided rivers (Lowe et al., 2015). True thickness ranges from 300 to 400 m southwest of Montreal to over 450 m in the Valleyfield Trough (Sanford & Arnott, 2011).

The Keeseville Formation was first described by Emmons (1841) as the primary sandstone body of the Potsdam Group, consisting of buff to white silica-cemented supermature quartz arenite hosting ≤ 5% detrital feldspar. Quartzite clast cobble-boulder conglomerates with quartz arenite matrix are observed locally with lesser mudstone and dolostone (Lowe et al., 2017; Sanford & Arnott, 2011). The Keeseville Formation unconformably overlies the Ausable Formation in northern New York, but also overlies the Precambrian basement in portions of the Ottawa Embayment (Nepean Formation) and Quebec Basin (Cairnside Formation).

Widely, these Appalachian Basin strata overlie high grade metamorphic rocks of Grenville affinity, like those exposed in the Adirondack Mountains (McLelland et al., 2010; Chiarenzelli et al., 2011; Valentino et al., 2019). Based on sparse borehole cuttings data from prior deep exploration wells in central New York state and from Ithaca, New York, it was presumed that granulite facies metamorphic rocks would directly underlie sedimentary rocks like the Potsdam Group beneath the CUBO site (Jordan et al., 2020).

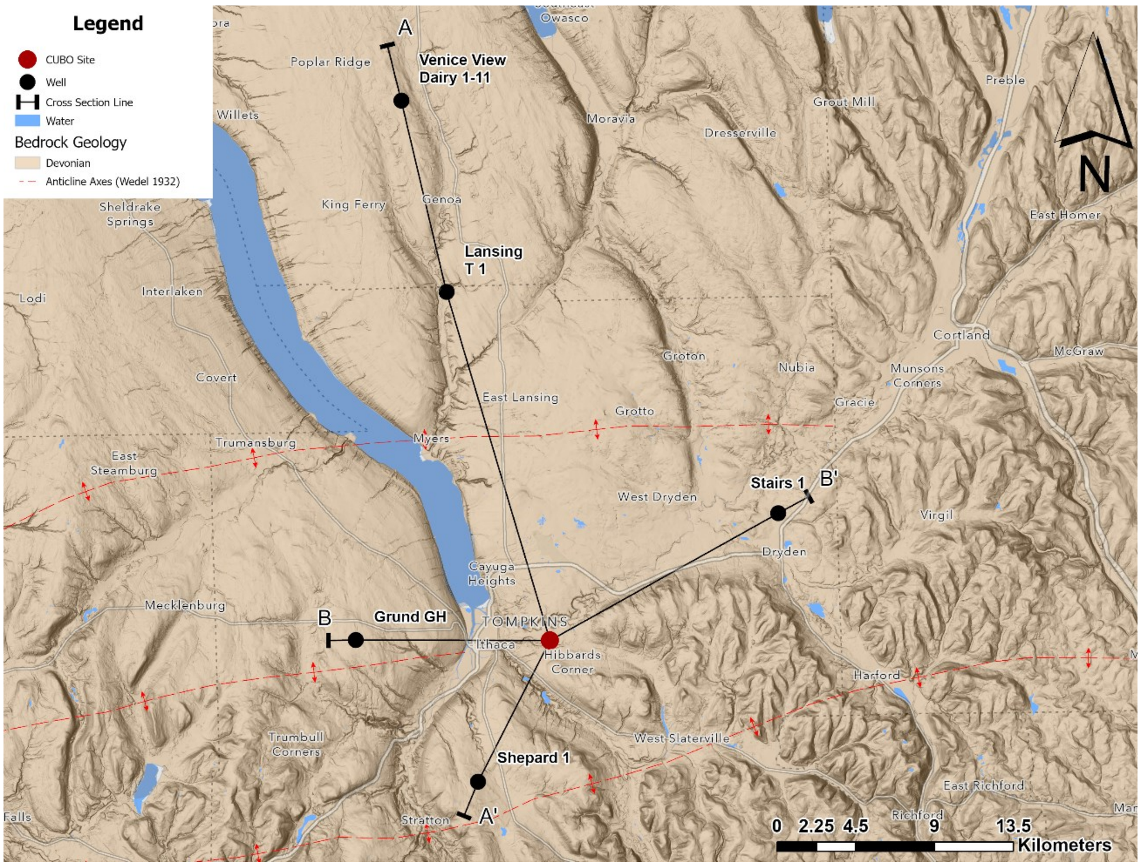

Figure 3: A local chronostratigraphic map of central New York State illustrating the location of the CUBO site in relation to the offset wells and regionally interpreted anticline fold axes. Regional geologic data compiled from USGS SGMC and ESOGIS data with regional anticlines plotted from Wedel (1932).

3. CUBO BOREHOLE DATA

Borehole data collected from ESH No. 1 open section are shown in Figure 4. These data sets provide the most current and complete set of geological and petrophysical subsurface data in the CUBO site locality. The following subsections present CUBO borehole petrological and geophysical data collected from the open borehole section.

3.1 Drill Cuttings & Sidewall Cores

Rock cuttings generated during drilling of ESH No.1 were conveyed to surface through circulation of water-based bentonite mud and phase separated via shaker tables equipped with No. 200 mesh screens. Drill cutting samples were point samples collected every 3 m (~10 ft) of drill bit advancement from 33.5 to 2,387 m bgs and every 1.5 m (~5 feet) from 2,387 to 2,984 m bgs. Geoservices of Schlumberger petrographically logged drill cutting samples using stereoscopic, mechanical, and geochemical techniques, forming a lithology percentage log. Drilling parameters, logged by the onsite Pason drill monitoring system, were cross-referenced with lithologic data obtained from logged drill cuttings to form an interpreted lithology per sample depth. Actual and interpreted lithologies, rate of penetration (ROP), mud weight, and calcimetry data are presented in Figure 4.

Drill cuttings reveal the intercepted Tribes Hill Formation to contain an upper shaley limestone unit overlying a sandy dolomitic limestone, consistent with the Palatine Bridge and the Fort Johnson Members, respectively. Lithologic units within the Little Falls Formation were predominantly sandy and dolomitic limestone and may represent Unit B of the type-section by Zenger (1976). The Galway Formation reached a thickness of 175 m and consists of interbedded fine- to medium-grained sandstone and dolostone. Ooids or peloids are identified between 2,760 and 2,792 m bgs, near the base of the Galway Formation.

The Potsdam Group drill cuttings exhibited white to dark grey color with medium, rounded, well sorted, and well cemented quartz grains that transitioned into weakly red basal shale. A minor unit of sandy dolomite is interpreted near the upper Potsdam contact with the Galway Formation. Below the Potsdam Group, five Precambrian units, A through E, are defined based predominantly on wireline logs. Units A through E are defined as low grade metasediments and possibly volcanics. Preliminary descriptions of units A through E are provided in Table 1.

Table 1: List of basement units with depth intervals and lithologic descriptions.

Basement Unit	Depth Interval (m bgs)	Unit Description
A	2,865 - 2,888	Low-grade metasediments of meta-arkoses to metashales with 10-20% carbonate fragments
B	2,888 - 2,925	Low-grade metasediments, quartzose meta-siltstone/ sandstone dominant, metapellite increases downward; vein or vug-filling quartz and minor oxides
C	2,925 - 2,946	Low-grade interlayered meta-quartzose, meta-siltstones, and metapellites with muscovite+biotite; phyllitic sheen increases downward
D	2,946 - 2,960	Low-grade metapellites, quarzitic metasandstone containing pyrite; meta-siltstone; vein quartz
E	2,960 - 2,984	Low-grade metapellites with compositional layering and local penetrative foliation, quartzitic metasiltstone with pyrite; minor coarsely crystalline quartz; trace tourmaline; phyllite decreases downward

A total of 24 XL-size (1.5 x 2.5 inch) sidewall cores were collected from ESH No.1 in Ordovician, Cambrian, and Precambrian rock using the Schlumberger XL-Rock wireline tool during a single sidewall core sampling event. Sidewall core sample depths range from 2,404 to 2,897 m bgs (Figure 4). Core recovery percentages vary from 66 to 107% with quartz arenite samples showing the highest recovery. Each sidewall core sample was depth verified and oriented using the Formation Microimager resistivity survey conducted after sidewall coring operations. Sidewall core composition from Ordovician and Cambrian strata is generally dolostone and sandstone (quartz arenite to sublitharenite) – exhibiting sedimentary structures ranging from massive to finely bedded. Precambrian sidewall core samples are chiefly meta-sediments containing chlorite, quartz, hornblende, and plagioclase with weak lineations and spaced foliation. Interestingly, two sidewall cores were extracted from the basal contact area between the Potsdam Group and basement complex showing a chloritized polymictic conglomerate and oxidized metasediment (Figure 5).

Fractures in sidewall cores are present at varying intensities. Partially infilled linear fractures with kinematic apertures ranging from 0.14 to 1.5 mm are measured in Ordovician-Cambrian sidewall core samples. Fractures identified in Precambrian sidewall cores are linear, with low and high angles to the core axis and have quartz-feldspar infills. Kinematic apertures of fractures in Precambrian sidewall cores were on average larger, varying from 0.215 to 3.3 mm.

3.2 Geophysical Surveys

Natural gamma ray, spectral gamma ray, neutron porosity, and density surveys are among the logs conducted by Schlumberger wireline services in the open borehole section after reaching a total depth of 2,984 m (Figure 4). Results of natural gamma range from 8.98 to 230.70 GAPI and exhibited sloped and peak signatures within the Little Falls Formation, Galway Formation, and Potsdam Group. Signatures of natural gamma were similar to regional gamma ray surveys, providing a basis for correlation of formation tops with offset wells. Elevated values of natural gamma compared with spectral gamma show that increases of thorium and potassium in the Little Falls Formation and of uranium in the Galway Formation explain the peaks in natural gamma. Similarly, a gradual increase of thorium is observed with depth in the Potsdam Group with respect to the gross natural gamma increase.

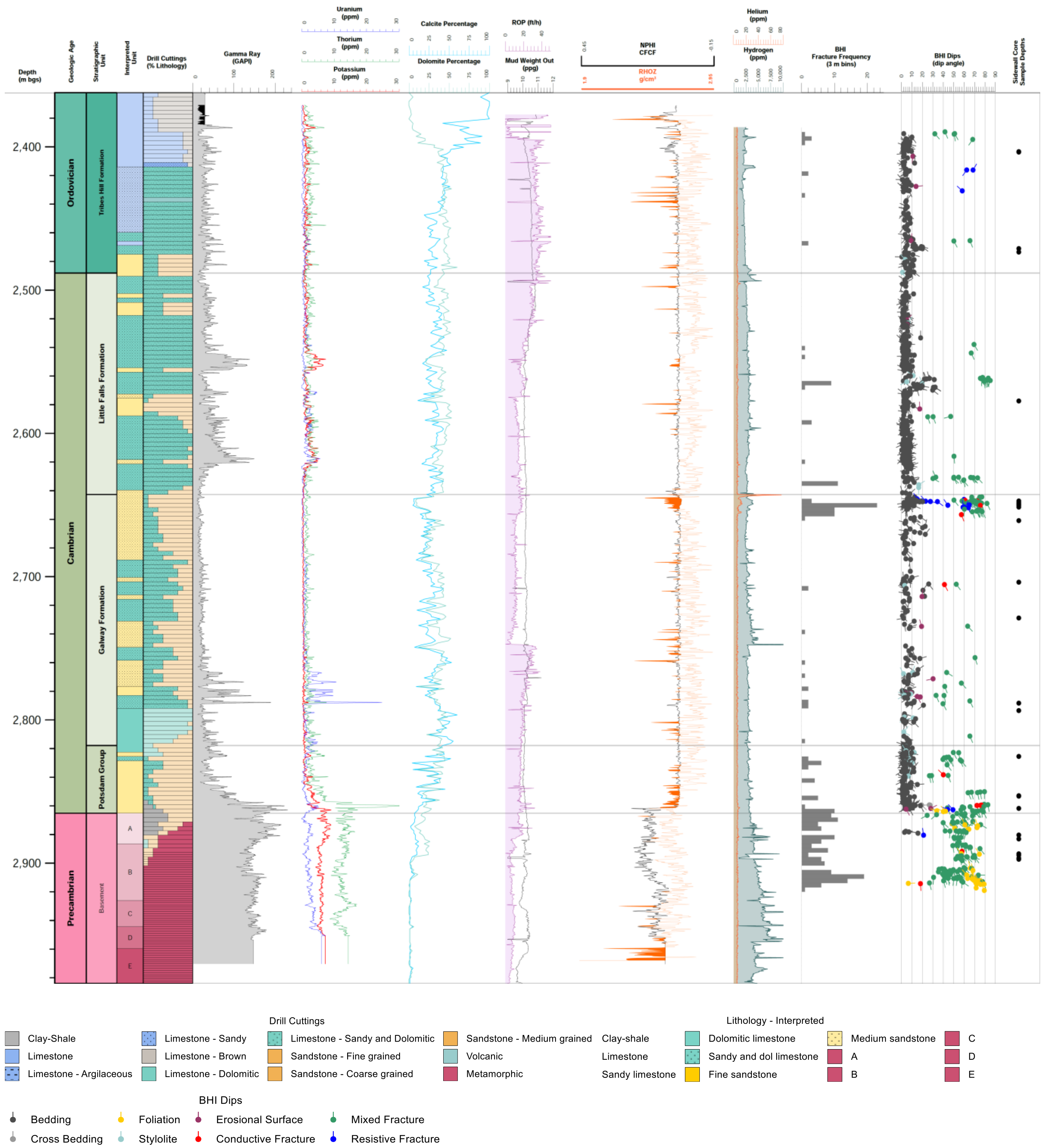

Figure 4: Compilation of logs of drill cuttings, fraction of cuttings reacting in HCl as is expected of calcite or dolomite, rate of drill bit penetration, mud weight, and wireline surveys. Wireline logs shown include natural gamma ray, spectral gamma (U, Th, K), neutron porosity (NPHI), and density (RHOZ). The abundance of gas emissions shown include helium and hydrogen, reported as concentrations of these gases among total gas extracted from the returned drilling mud. Fracture frequency based on BHI log analysis is plotted using 3-meter bins.

Neutron porosity measurements varied from 0 to 0.21 ft^3/ft^3. Throughout the Ordovician to Cambrian stratigraphic section, neutron porosity has an average value of 0.007 ft^3/ft^3 whereas peaks occur sporadically on the order of 0.03 ft^3/ft^3. There is a marked increase below 2,865 m bgs that persists through most of the basement interval, rising to 0.11 ft^3/ft^3. Density remained moderately consistent throughout the open borehole extent except in the basement. Below a depth of 2,865 m bgs, density values decrease from an average density of 2.79 to 2.62 g/cm^3, with depth variability similar to the neutron porosity though of opposite sign (Figure 4).

3.3 Borehole Image Surveys

BHI logs consisted of one acoustic televiewer survey and three microresistivity imaging surveys, conducted using wireline logging techniques. The acoustic televiewer survey was completed using the Schlumberger Ultrasonic Borehole Imager (UBI) to obtain the complete circumferential open borehole image profile. Microresistivity image surveys utilized the Schlumberger Formation Microresistivity Imager (FMI) tool for three separate surveys conducted prior to Modular Formation Dynamics tool (MDT) testing, after MDT testing, and after sidewall coring. The FMI utilized a 4-pad and 4-flap setup with 192 button sensors for microresistivity image acquisition, covering approximately 80% of the circumferential borehole profile.

BHI log data files were provided by Schlumberger in DLIS format and processed using Paradigm Geolog software by AspenTech. UBI survey data was first speed corrected using the onboard z-axis accelerometer sensor and frame time data to compute a speed-corrected depth for all logged UBI data. Depth corrections were applied to the acoustic images and their ancillary logs as a depth shift correction. Acoustic image data from Schlumberger's UBI tool were processed into single image logs for display and structural feature analysis in Geolog. Speed-corrected UBI survey data was processed to generate several data logs and images such as azimuth reference, radius image, static image, and diameter image. Generated UBI image logs were further normalized both statically and dynamically by rebinning the input data to match predefined frequency distributions collected from the speed-corrected data.

FMI survey data processing was similar to UBI processing but required additional equalization of generated images prior to normalization. Equalization processing altered the generated speed-corrected static images by adjusting the standard deviation and mean of each column (resistivity button) based on a window size. The equalization process allows for higher contrast to be achieved in the final BHI log, thereby aiding structural feature analysis.

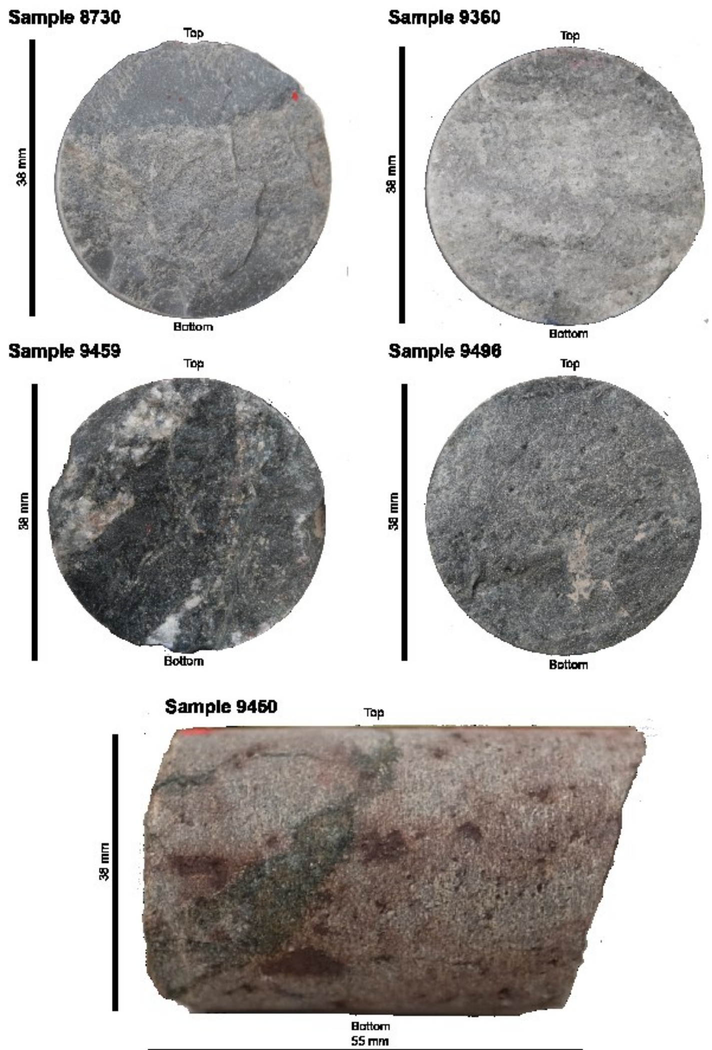

Figure 5: A plate of images of sidewall cores collected from ESH No. 1. Sample 8730 is an interbedded sandstone and dolomite from the Galway Formation. Sample 9360 is a quartz arenite sidewall core sample from the Potsdam Group. Meta-sedimentary units from the Precambrian basement are illustrated by samples 9459 and 9496. A profile image of Sample 9450 illustrates the oxidized basal metasediments contacting the Potsdam Group.

Structural feature analysis was completed using a three-step process to measure, orient, and interpret structural features observed in the processed BHI logs. Generated static and dynamic images of all log types and runs were compared for data consistency and continuity. UBI images appear mottled with lower resolution compared to the FMI images in the Cambrian stratigraphic sections (2,387 - 2,984 m bgs). Sections of the UBI image log improve intermittently within the Cambrian stratigraphic units; however, the majority of the UBI image log improvement is below 2,984 m bgs within Precambrian strata. FMI images show higher image contrast, resolution, and consistency than the UBI images throughout the open borehole section. The initial FMI log exhibits the highest contrast and image quality within Precambrian strata compared to FMI surveys conducted after MDT and sidewall coring.

Structural feature analysis focused on identifying linear and sinusoidal discontinuities with respect to primary sedimentary features and textures. Examples of structural feature analysis are shown in Figure 6. Sedimentary structures were first identified to serve as a basis for identifying fractures and other structural discontinuities. Bedding in FMI surveys appear as sharp continuous semi-horizontal planes arithmetically averaging a strike and dip of 97.6° and 5.7°, respectively. Bedding thickness ranged widely from 0.015 to 12.26 m. Stylolites appear as semi-planar wiggly features in FMI surveys, often coplanar with sedimentary bedding and laminations. Erosional surfaces were semi-planar, showing instances of scouring in the Little Falls Formation, Galway Formation, and lower Potsdam Group contact with the basement complex (Figure 6). Bedding and foliation observed in the basement quickly steepened to an average dip 54.4° and rotated to a northwest-southeast orientation.

Fractures identified in FMI images are categorized into three morphological groups based on electrical resistivity responses: resistive, mixed resistivity, or conductive. Resistive fractures consist of high resistivity sinusoidal structures cross-cutting sedimentary features. Resistive fractures are most prominent in the Galway Formation (Figure 4) and have varying northeast, northwest, and east-southeast dip directions (Figure 7). Mixed resistivity fractures exhibit both a resistive and conductive sinusoidal geometry in FMI surveys and account for most of the fractures observed throughout the open borehole section. A total of 219 mixed fractures were identified in FMI logs as either full or partial sinusoids constrained within bed forms or cross-cutting bedding planes. A consistent dip direction to southeast is observed having an average strike/dip orientation of 69.5°/58.1° (Figure 7). Conductive fractures were the least frequent and showed low resistive sinusoidal traces cross-cutting bedforms, averaging a strike/dip orientation of 84.8°/60.5°.

Fracture frequency, calculated on 3-meter bins using BHI structural feature analysis data (Figure 4), shows clustering in several distinct depth intervals. Increased fracture frequency is observed within the central portion of the Little Falls Formation (2,562 m bgs) consisting of clustered mixed resistivity fractures in an algal bed of a sandy dolomitic limestone. Within the lower zone of the Little Falls Formation is an additional fracture frequency increase of mixed resistivity fractures within bedded dolomitic limestone but with varying dip angles. The largest fracture frequency is located at the top of the Galway Formation (2,652 m bgs). This area is a 12 m thick zone of resistive, mixed resistivity, and conductive fractures hosted in a thinly bedded, medium-grained sandstone unit. Observed fractures below 2,652 m become less frequent until the Potsdam Group is intercepted. Fractures within the Potsdam Group are mainly mixed resistivity fractures crosscutting laminated sandstone bedforms between 2,826 and 2,829 m. From the lower Potsdam Group contact and into the basement complex, fracture frequency increases strongly without the intermittent paucity observed in the above sedimentary units. Fractures at the lower Potsdam contact are generally mixed resistivity types oriented similarly with fractures in the Galway Formation with a more consistent dip angle (Figure 4).

3.4 Sonic Scanner

Following FMI surveys, a sonic survey was conducted using the Schlumberger Sonic Scanner tool. The sonic scanner is a sonic tool emitting acoustic compression and shear waves orthogonally to each other. An array of 13 onboard sensors captures directionally oriented reflected and refracted wave lengths and frequencies as a continuous wireline survey. The sonic scanner survey was conducted by Schlumberger wireline services—and the data were processed by Schlumberger experts using inversion techniques to obtain structural discontinuities and their radial distance from the borehole bore. Identified structural continuities were interpreted as fractures based on the wavelength characteristics. Radial distances of interpreted fractures from borehole ranged from 3.4 to 48.2 m. Fracture orientations show a dominant northwest-southeast orientation with an average dip of 81.3° (Figure 7). An additional minor fractures set is also observed, oriented northeast-southwest with an average dip of 80.5°.

3.5 Gas Chromatography

Gas chromatography was conducted by Geoservices of Schlumberger during drill of the open borehole to semi-quantify concentrations of C_1–C_5 hydrocarbons, helium, argon, and hydrogen from drilling mud as a formation characterization parameter. Analysis of drilling mud gas utilized an inline constant volume degasser (gas trap) connected to a DQ1000 mass spectrometer via evacuated tubing. A 1.5 L/min mud flow rate constantly entered the gas trap where the exhaust product was conveyed to and analyzed by the DQ1000. Concentrations of gases are reported in ppm by the DQ1000 and are semi-quantitative as the gas concentrations originate from the drilling mud and not the formation directly.

Values of helium and hydrogen are plotted in Figure 4 and exhibit spikes at specific depths. Helium gas concentrations exhibit a spike of 77 ppm in the Galway Formation at 2,643 m bgs. Excluding this helium spike, values of helium remain fairly constant throughout the open borehole hole section, averaging 6 ppm. Hydrogen values were similar to helium values but show spaced peaks throughout the open borehole section reaching a maximum value of 22,721 ppm in the central Galway Formation. Hydrogen peaks and total hydrogen concentrations become higher and more frequent with depth, specifically within the basement complex.

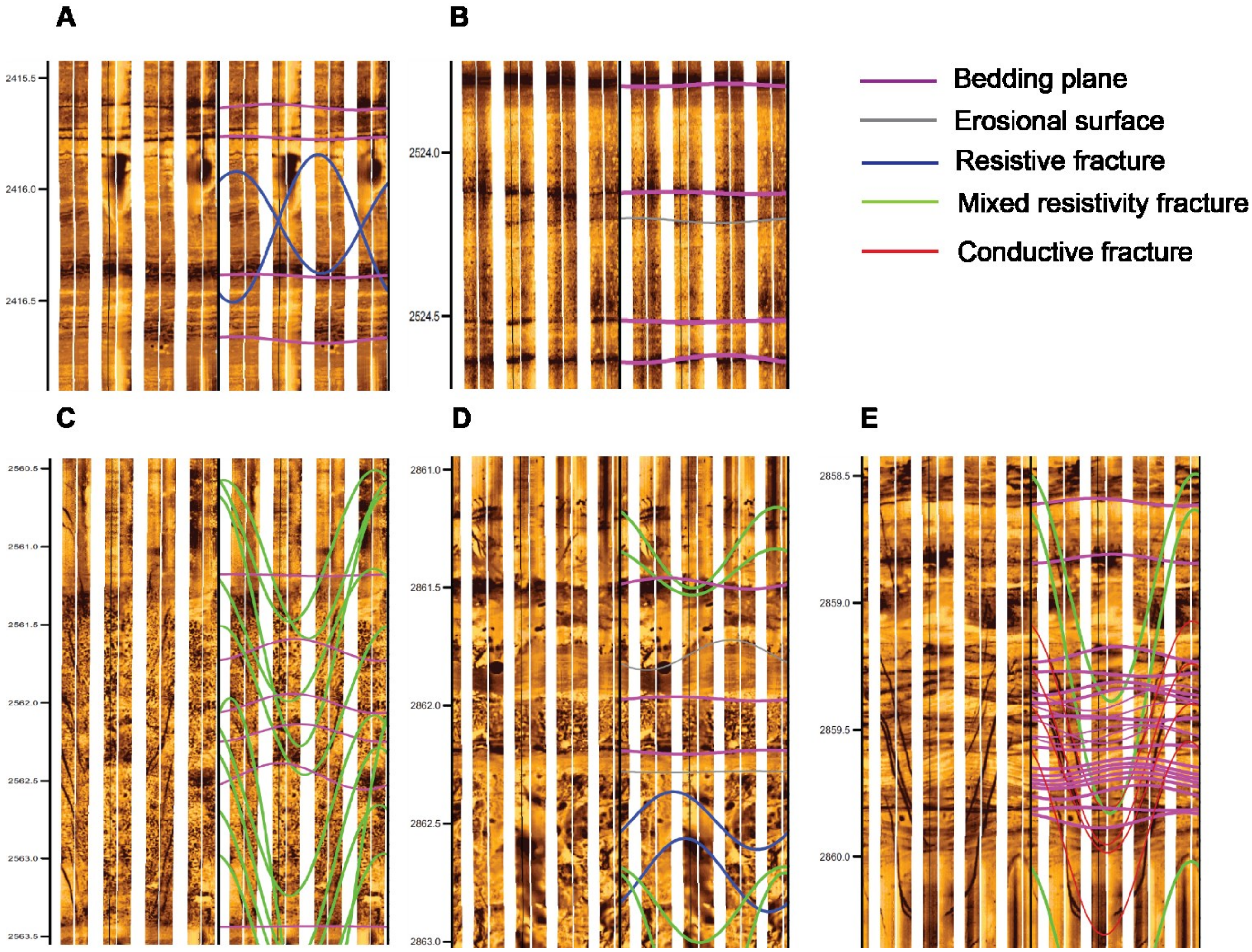

Figure 6: FMI image comparisons of dynamic resistivity images with and without structural feature selections. Image A is an example of resistive fractures and bedding planes within the Tribes Hill Formation. Horizonal bedding with an erosional surface from the Little Falls Formation is depicted in image B. Mixed fractures within the Little Falls Formation are shown in image C. The lower Potsdam Group contact with the basement is shown in D. Image E shows mixed resistivity and conductive fractures within a cross-bedded Potsdam Group interval.

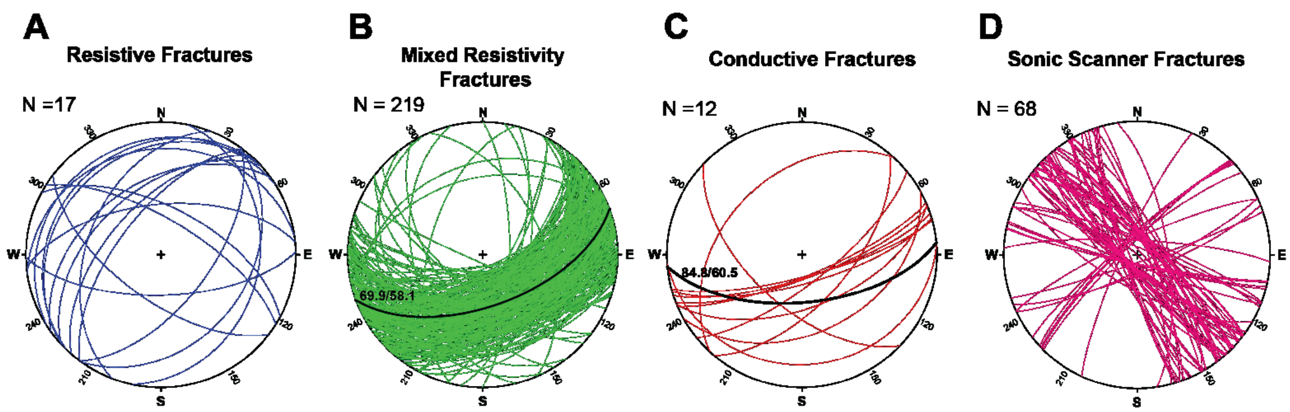

Figure 7: Equal area, lower hemisphere stereonets of categorized fractures with average dip planes plotted in black for mixed resistivity and conductive fracture data from BHI logs (A, B and C). Interpreted fracture data from the far-field sonic scanner survey are plotted in stereonet D (equal area and lower hemisphere). Stereonets for this figure were plotted using the program Stereonet (Allmendinger et al., 2011; Cardozo & Allmendinger, 2013).

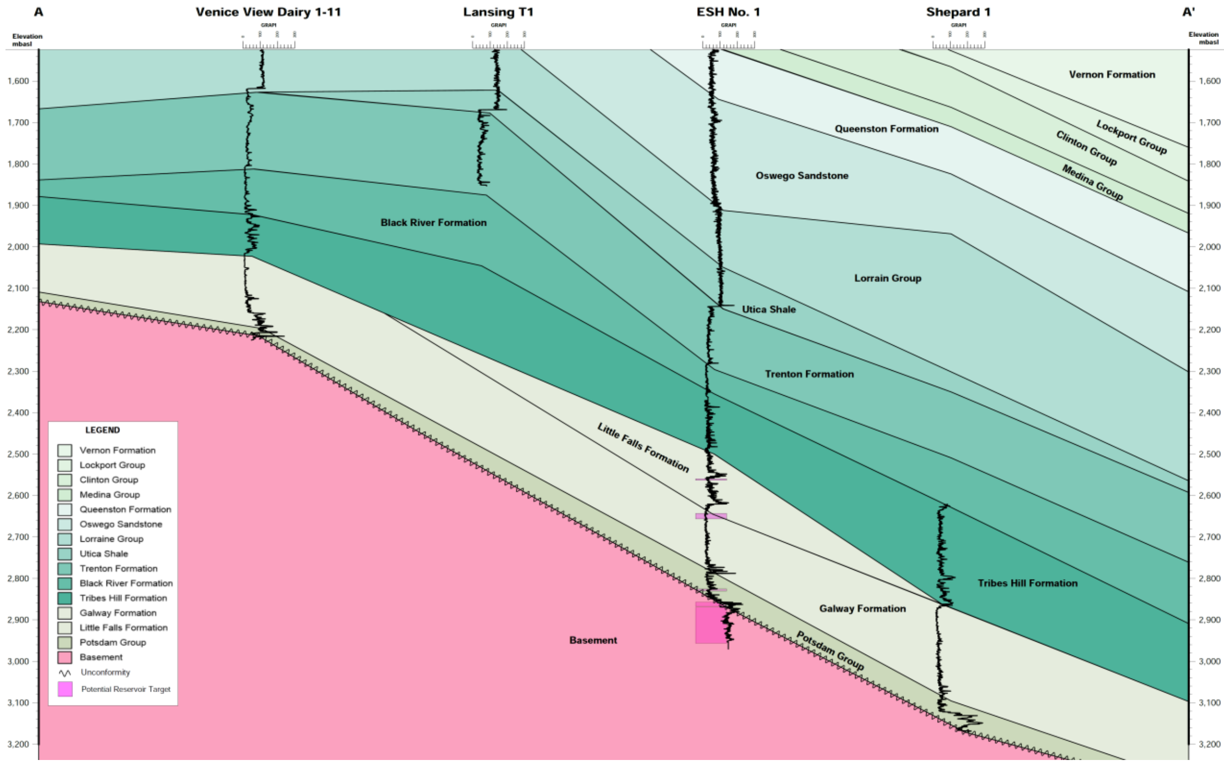

Figure 8: A north (left) to south (right) oriented cross-section of correlated formation tops based on natural gamma ray well logs obtained from the ESOGIS database.

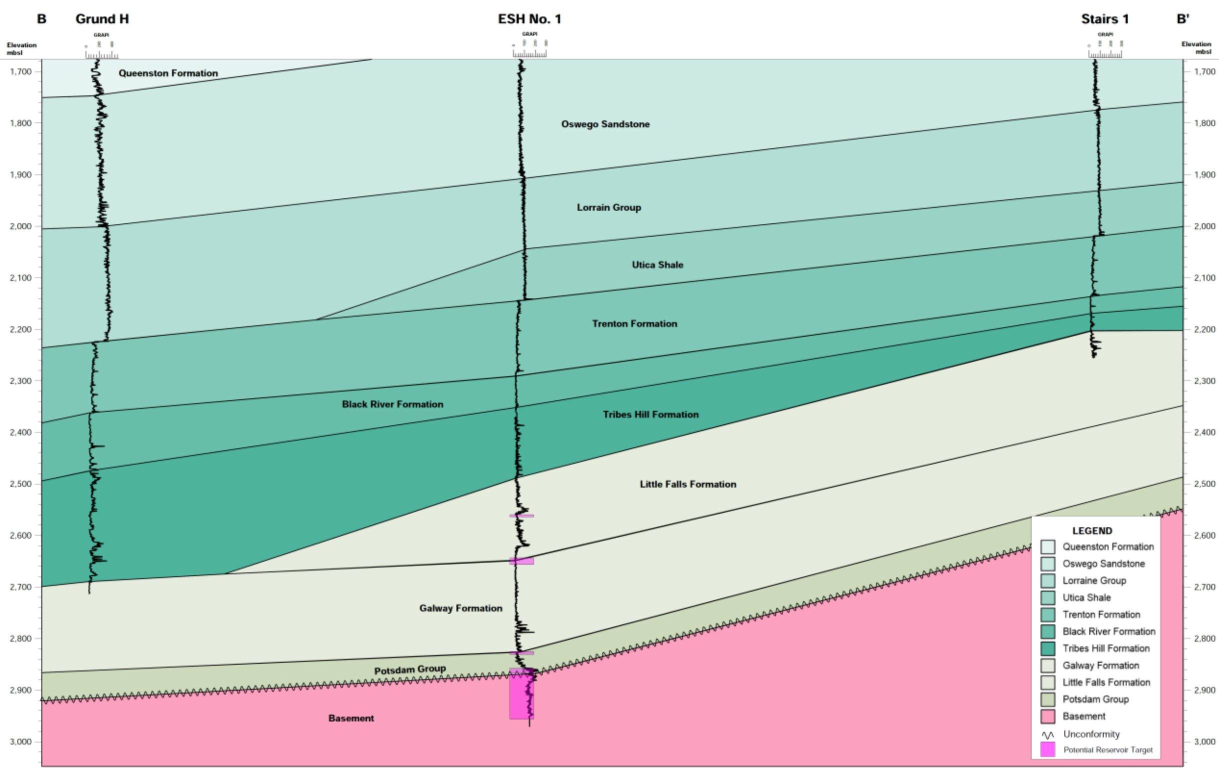

Figure 9: A west (left) to east (right) oriented cross-section of correlated formation tops based on natural gamma ray well logs obtained from the ESOGIS database.

4. OFFSET WELL DATA

Data for offset wells near the CUBO site locality are limited to geophysical logs and drill cuttings from historical oil and gas wells. Historical oil and gas well logs are managed by New York in the State Empire State Organized Geologic Information System (ESOGIS) database. Building off the regional correlations of Al Aswad (2019), formation tops were corelated utilizing natural gamma ray well logs from the ESOGIS database. Results of the correlations are presented in Figures 8 and 9 in cross-section form. Correlated tops in Figures 8 and 9 coupled with the BHI log data indicate conformable sedimentary units in both north-south and east west transects. Formation dips are relatively flat north of the CUBO site but dip southward at approximately 0.82° near the CUBO site moving southward to the extent of the Figure 8 cross-section. Formation dips along an east-west transect show a dip of approximately 0.69° to the west (Figure 9). The target formations (open borehole section) have good lateral continuity with the exception of the Little Falls Formation, which shows pinchouts north, south, and west of the CUBO site.

Drill cuttings for the Shepard 1 well, 9 km distant from CUBO, were obtained from the New York State Museum and offer the closest petrological data set of target formations in the CUBO site area. Stereoscopic analysis of drill cuttings shows a contrast to the CUBO basement complex compositions. Basement samples from the Shepard 1 well contain a granitic composition of k-feldspar (55%), plagioclase (20%), biotite (10%), amphibole (10%) and quartz (5%). Shepard 1 drill cutting mineral grain sizes are also coarser, ranging from 0.25 mm to 1 mm compared to ESH No. 1 mineral grain sizes that are less than 0.25 mm.

5. DISCUSSION

Compilation and review of petrological and geophysical data shows ESH No. 1 intercepted approximately 1,353 meters of Ordovician-Cambrian strata and 119 meters of underlying Precambrian basement. Interpreted lithologies from drill cuttings coupled with gamma ray and BHI logs provide the baseline petrological and stratigraphic data for the target formations in the open borehole section. The shallowest target formation, the Tribes Hill Formation, is composed of an upper 64 m of shaley limestone unit overlying a 74 m thick sandy dolomitic limestone – consistent with the Palatine Bridge and the Fort Johnson Member, respectively. Conformably lying below the Tribes Hill Formation are fine grained sandstone and sandy dolomitic limestone beds of the Little Falls Formation. Conglomerates and sandstones of Unit A and reddish gray glauconitic dolostones of Units C and D of the Zenger (1976) type section are not observed in drill cutting samples or BHI surveys. Observed stromatolite bedforms at 2,562 m bgs (Figure 6) from FMI surveys and the fine-grained nature of the sandstone and dolomitic limestone place the majority of the intercepted Little Falls Formation within Unit B of Zenger (1976) type section.

Interpreted lithologies of Galway Formation exhibit an interbedded nature of medium-grained sandstone, dolomitic limestone, and dolomite. The occurrence of ooids or peloids between 2,760 and 2,792 m bgs in conjunction with increased natural gamma and uranium concentrations (spectral gamma), suggest a different depositional environment compared to the regional basal Vespa Member. Potsdam Group strata are predominantly fine-grained sandstones ranging from quartz arenite to sublitharenite. The transition from the Postdam Group is marked by a chloritized basal conglomerate and oxidized upper Precambrian basement contact. Precambrian basement units from ESH No. 1 are metasediments and differ significantly from granitic basement drill cuttings of Shepard 1. This compositional juxtaposition between Shepard 1 and ESH No. 1 implies a structural or lithological discontinuity present in the basement complex south of the CUBO site, a contrast that is well expressed in aeromagnetic survey data (USGS, https://mrdata.usgs.gov/magnetic/map-us.html).

Porosity for the overall Ordovician-Cambrian target section appears low, averaging 0.007 ft^3/ft^3 based on neutron porosity values. Spikes of elevated porosity are intermittent and semi-correlative with fractures – indicating some matrix porosity on the order of 1 to 3 % in Ordovician-Cambrian units. Neutron porosity values increase from the basement contact downward and do correlate well with increased fracture intensity. However, the basement rocks contain a significant fraction of hydrated minerals, such as chlorite and micas, whose hydrogens are detected by the neutron tool, rending the NPHI value a mixture of mineralogy and pore water.

Fractures are interpreted to be the primary hosts of pore water. Fracture occurrences and intensity are not stratigraphically bound and occur in all target formations, predominantly in 5 discrete zones listed in Table 2.

Table 2: Depth intervals showing higher fracture intensity.

Fracture Interval	Depth Interval (m bgs)	Formation
1	2,560 - 2,564	Little Falls
2	2,644 - 2,657	Galway Formation
3	2,826 - 2,831	Potsdam Group
4	2,858 - 2,868	Potsdam Group / Basement Contact
5	>2,870	Basement

Fractures in FMI surveys overall occur as discontinuous mixed resistivity sinusoidal features in FMI surveys, oriented northeast-southwest with an average dip of 58° to the southeast. Conductive fractures show a similar orientation to mixed resistivity fractures having an average strike of 60°. The kinematic fracture orientation of both the mixed resistivity and conductive fractures are concordant to the Shmax orientation of 38° to 58° (Pinilla et al., 2023). In contrast, resistive fracture dip azimuths vary from northeast, northwest, and east southeast. This variation may reflect the low fracture population size or that additional fracture set geometries exist.

Fractures interpreted from the sonic scanner are in far field extents (3-48 m) of the ESH No. 1 bore and are oriented in a northwest-southeast orientation showing an average dip of 81°. Orientation of interpreted sonic scanner fractures are nearly orthogonal to BHI survey fractures and Shmax and have steeper dips. Approximately 12 fractures in the BHI surveys have similar, but shallower dips. The paucity of northwest-southeast oriented fractures in the BHI surveys may be due to the borehole vertical geometry or perhaps a larger fracture spacing occurs within the northwest-southeast oriented set compared to the northeast-southwest fracture set.

6. CONCLUSIONS

Petrological, geophysical, and drilling data presented provide a preliminary insight into target reservoir formations for DDU geothermal energy on the Cornell University Ithaca campus. Stratigraphic correlations show a mild southerly and westerly formation dip of Ordovician-Cambrian strata in the vicinity of the CUBO Site. The underlying Precambrian basement poses a complex lithostratigraphy that differs markedly from nearby wells. Porosity of the Ordovician to Cambrian strata appears low based on neutron porosity logs and stereoscopic analysis of sidewall cores. Structural feature analysis of BHI surveys identifies a northeast-southwest trend of southeast dipping fractures cross-cutting near horizontal beds. In contrast, interpreted fractures of the sonic scanner survey show a steeply dipping orthogonal fracture set 3- 48 m away from the well bore.

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8. DISCLAIMER

The views expressed in this paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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