Utility of Ambient Groundwater Temperature Profiling within Sealed Bedrock Boreholes for Fracture Flow Characterization in Seasonally Dynamic Environments

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Abstract

Utility of Ambient Groundwater Temperature Profiling within Sealed Bedrock Boreholes for Fracture Flow Characterization in Seasonally Dynamic Environments

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Temperature profiles were collected in 3 angled and 3 vertical, FLUTe™-lined boreholes, drilled to 24-32 mbgs, in a dolostone bedrock aquifer adjacent to and extending beneath a bedrock river to study system hydrodynamics of a bedrock groundwater-surface water interface. Ambient borehole temperature data collected every 1-8 weeks over a 12 month period were shown to be effective at identifying zones of hydraulic activity during periods of intra-seasonal stability. Fourier spectra analysis of thermal deviation logs provided a novel way to observe the shallow bedrock flow system’s temperature evolution, identify noise caused by free convection, and represents a diagnostic tool to improve confidence in identifying hydraulic activity from thermal data sets. Seasonal atmospheric effects provided evidence of a strong vertical flow component in the upper 8-10 mbgs of the system. Free convection extended the depth of detection to 26 mbgs, as opposed to 14 mbgs when free convection was not present.
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Declaration of Work Performed

I declare that with the exception of the items listed below, all work presented in this thesis was performed by me.

Celia Kennedy, PhD., G360 Institute for Groundwater Research, University of Guelph, collected and processed lithology and feature logs for the 6 study site boreholes.

Andrey Fomenko, MASc., G360 Institute for Groundwater Research, University of Guelph, collected and processed geophysical logs for the 6 study site boreholes.

Colby Steelman, PhD., Celia Kennedy, PhD., Tara Harvey, MSc., Keelin Scully, MSc., Dan Elliott and myself periodically conducted the wireline temperature trolling.
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1.0 – Introduction

1.1 – Motivation

Bedrock aquifers represent an important source for fresh water supplies, readily available for many communities around the world. As attention paid to water availability issues grows, both locally and globally, so too does the importance of understanding the hydrogeologic conditions sustaining this valuable resource. Less studied than their alluvial counterparts, bedrock groundwater systems are more complex, with flow and transport governed by the occurrence of many connected fractures through which the bulk movement of water occurs. Fracture networks in sedimentary rocks are heterogeneous and anisotropic by nature due to variability in fracture aperture and connectivity, resulting in a more complex network of flow paths than that observed or predicted by a granular medium (e.g. sand and gravel). Due to the relatively discrete nature of these small aperture fractures, it is their connectivity that influences the bulk conductivity, anisotropy and hydrologic system unit boundaries, and responsiveness to hydrologic events, hence the importance of understanding their discrete distribution and of high-resolution data sets essential to their identification and characterization.

High-resolution spatial and temporal groundwater temperature measurements are a viable characterization method and can be an integral component in the quantification of groundwater flow and solute transport in fractured sedimentary rock (Parker et al. 2012; Bense et al. 2016). Temperature logging has been shown to be very effective at detecting and quantifying groundwater flow under open borehole conditions in (Ge 1998; Anderson 2005; Pehme et al. 2010; Sellwood et al. 2015) and forced gradient conditions (e.g., Banks et al. 2014; Klepikova et al. 2014; Hausner & Kobs 2016) in fractured rock systems. However, borehole temperature measurements are susceptible to vertical convective flows in the form of forced convection (hydraulic gradient-driven) and/or free-convection (buoyancy-driven) (Ge 1998; Anderson 2005; Pehme et al. 2007; Cermak et al. 2008a; Borner and Berthold 2009a; Pehme et al. 2010; Colombani et al. 2016) . This cross-connection or mixing across geologic units with long open boreholes can complicate the interpretation of hydrogeologic conditions if not realized when it is occurring.

Recent advancements in temporarily sealing bedrock boreholes with flexible, impermeable fabric liners such as those manufactured by FLUTE™ (Flexible Liner Underground Technologies, Alcalde,NM, USA) (Keller et al. 2014) provide a means of temporarily sealing an open bedrock borehole or long screened well, thereby restoring the groundwater flow system to
its natural state (Cherry et al. 2007). Under these sealed borehole conditions, natural groundwater flow within an aquifer can be re-established and observed by measuring subtle variations in the temperature within the liner’s stagnant water column where heterothermic conditions (temperature variations) exist within the aquifer in the adjacent formation. The utility of flexible fabric liners for improved collection of high-resolution temperature logs in bedrock environments has only recently been explored (Pehme et al. 2007, 2010, 2013, 2014; Coleman et al. 2015).

These works have involved ambient methods, using temperature variations induced by atmospheric variability (Pehme et al. 2007a), and active-line source methods, whereby a borehole water column is heated and the decay is monitored using wireline probes equipped with thermistors (e.g., Pehme et al. 2010, 2013, 2015), and fiber-optic Distributed Temperature Sensing (DTS) systems (Coleman et al. 2015; Bense et al. 2016), through which hydraulically active zones can be identified based on abrupt temperature changes over short distances.

Given the limited depth range of ambient methods, a great deal of emphasis by Pehme et al. 2010, 2013, 2014 has been placed on wire-line temperature trolling coupled with an Active Line Source (ALS). Here, the static water column within a FLUTE™ lined borehole is heated using a constant input at 20 Watts per meter (with approximate change in the water column temperature profile by less than 2 degrees Celsius) using an electrical heating cable. After heating is stopped, the associated temperature decay of the water column equilibrating with the local ambient groundwater occurs at different rates and at discrete depths due to variable rates of groundwater flow in discrete fractures, fracture zones, and possibly a permeable rock matrix; this is monitored via profiling the borehole at 8, 32, 56-hour intervals over a 72+ hr period. This borehole heating technique enhances sensitivity to subtle, yet resolvable temperature fluctuations with depth to one-thousandth of a degree Celsius at multiple time snapshots in the cooling cycle. As such, this method has an increased resolution and effective depth compared to an ambient temperature log (Pehme et al. 2013).

Ambient temperature techniques (e.g., Pehme et al. 2010) within a sealed bedrock borehole capture seasonal effects and atmospheric-induced temperature dynamics within temperature profiles, which are lost when disequilibrium is induced via ALS. Ambient temperature logs preserve the relative magnitude of spatiotemporal temperature variations associated with active flow zones intersecting the borehole, minimizing potential biases associated with borehole heating methods relating to spatial variations in specific heat capacity of geologic or hydrogeologic features that may or may not be hydraulically connected to the local flow system.
Recent uses of temperature measurements in shallow hydrogeologic fractured rock environments for quantification of groundwater discharge patterns or groundwater-surface water exchange (Hatch et al. 2006; Briggs et al. 2012; Rosenberry et al. 2016) and assessment of anthropogenic activities on the environment (Bayer et al. 2016; Bucci et al. 2017) demonstrates the importance of developing frameworks that improve interpretation of ambient temperature logs in shallow dynamic environments. Ambient temperature logs can improve confidence in ambient flow characterization, warranting more physically-based conceptualizations of local flow dynamics. These attributes of ambient temperature data have the potential to contribute to the refinement of both the technique and its applicability to characterize the variability in fracture connectivity and hydraulic activity at the borehole scale in groundwater flow systems under the direct influence of atmospheric and surface water conditions. This in turn may be used at multiple boreholes to support interpretations of heterogeneity and anisotropy in these less understood systems and is the premise of this study.

1.2 – Study Approach and Research Goals

This thesis evaluates the utility of ambient temperature profiles (i.e. temperature variability with depth due to heterogeneity in flow and attenuation of temperature associated with a disequilibrium between surface water and ambient air temperatures and the shallow subsurface groundwater systems) collected in small-diameter, sealed bedrock boreholes completed in vertical and angled orientations with respect to the regional fracture network (Munn 2012; Fomenko 2015) to better understand the variability of groundwater flow in discretely fractured, shallow bedrock environment. Time-lapse borehole temperature profiles were collected over a 1-year period in paired boreholes (one angled and one vertical) at three locations along a bedrock river. This study builds upon the Discrete Fracture Network (DFN) approach developed by (Parker 2007; Parker et al. 2011, 2012), which aims to characterize the individual or collective flow features dominated by discrete fractures or dissolution enhanced fractures and matrix porosity in a dolomitic sedimentary rock through the collection of multiple borehole-derived data sets. Therefore, multiple data types or lines of evidence are used in this study to assess the utility of the time-lapse, ambient temperature profiles throughout an annual cycle for the conceptualization of groundwater flow in an environment under the direct influence of thermodynamic atmospheric and surface water influences.

As ambient temperature profiles of a groundwater flow system are often subject to seasonal variations (Taniguchi 1993), there is currently no quantitative method to assess
whether these ambient subsurface temperature deviations are due to or influenced by hydrodynamic processes in a ‘presumed stagnant’ water column within the borehole (temperature-density induced vertical convective flows) or simply reflect the inherent flow variability in the adjacent formation. This study aims to address this gap in distinguishing influences on the temperature profiles by applying statistical methods to quantitatively compare ambient temperature profiles collected within lined boreholes over a wide range of seasonal conditions. The approach developed in this thesis will improve confidence in the characterization of thermal profiles collected in dynamic groundwater flow systems and subsequent quantification of thermal deviations.

A suite of statistical techniques were used to evaluate seasonal temperature trends observed in three vertical and three angled boreholes open in the shallow subsurface immediately adjacent and below a bedrock riverbed and their dynamic behaviour over a 1 year period. The goal of this thesis is two-fold: develop a statistical diagnostic data analysis approach that will improve confidence in the interpretation of temperature logs indicative of hydraulically active flow zones under ambient conditions (recognizing its transient nature due to seasonal conditions) that is transferable to other shallow bedrock groundwater environments; and demonstrate the utility of this approach through a conceptual model for groundwater flow and groundwater-surface water temperature conditions and their interaction in a temperate climate within a well-monitored fractured bedrock river environment. Ultimately, this thesis addresses three elements of the ambient temperature trolling method within lined boreholes in fractured rock:

1. **How does seasonal atmospheric variability influence the resolution and repeatability of ambient temperature profiles in the shallow subsurface at or near a groundwater-surface water interface in fractured dolostone rock?**

2. **How can spatiotemporal ambient temperature data improve conceptualization of the shallow subsurface flow system at this interface?**

3. **What attributes of a borehole monitoring network and temperature data acquisition strategy are most important for successful identification and quantification of groundwater flow features in space and time?**
2.0 – Background

2.1 – Groundwater Heat Flow

Heat flow in groundwater is controlled by convection (advection) and conduction (diffusion) processes. It can be described in three-dimensions using the following heat transport equation for flow in water-saturated porous media (Domenico and Schwartz 1998):

\[
\frac{\kappa}{\rho c} \nabla^2 T - \frac{\rho_w c_w}{\rho c} \nabla \cdot (T q) = \frac{\partial T}{\partial t},
\]

[1]

where \( T \) is temperature, \( t \) is time, \( \rho_w \) and \( c_w \) represent density and the specific heat capacity of water, \( \rho \) and \( c \) are the density and specific heat capacity of the rock-water matrix, \( q \) is the groundwater seepage velocity, and \( k_e \) represents the effective thermal conductivity of the rock-water matrix. Equation [1] is analogous to the advection-dispersion equation that describes the movement of solutes in water across a concentration gradient. The one-dimensional form of this equation is as follows (Freeze and Cherry 1979; Fetter 1994):

\[
D_L \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t},
\]

[2]

where \( D_L \) is the coefficient of longitudinal hydrodynamic dispersion, \( C \) is the solute concentration, \( v_x \) is the average linear groundwater velocity, and \( t \) is the elapsed time since solute release. The first term in Equation [1] describes the transport of heat by conduction and thermal dispersion; these two processes are analogous to the transport of solutes by molecular diffusion and mechanical dispersion shown in Equation [2]. The second term in Equation [1] represents the transport of heat by groundwater convection or advection, which are synonymous terms that represent the movement of solute or heat by bulk fluid movement and are used interchangeably in the literature (Anderson 2005). Density-driven transfer of heat is referred to as free convection, whereas forced convection describes heat transfer by other mechanisms (e.g., hydraulic gradients). A rigorous discussion of Equation [1] with references describing its derivation can be found in Anderson (2005).

2.1.1 – Flow through Porous Fractured Media

Many of the principles of heat and solute transport in porous media are applied to densely fractured rock. Fractured sedimentary bedrock is typically considered a dual porosity system where groundwater advection will be dominated by groundwater flow in many discrete, well-connected fractures forming fracture networks. Although sedimentary rock matrix porosity
may be orders of magnitude higher than that of the fracture porosity, the rock matrix pore geometry is generally smaller and more resistive to fluid flow and permeability is typically very low and often can be considered a negligible component in the advective transport of solutes. However, molecular diffusion between the fractures and the porous matrix has been shown to be a very important mechanism in the transport of solute mass over time (Freeze and Cherry 1979).

Given the higher permeability of an interconnected fracture network relative to the rock matrix, the bulk hydraulic conductivity of the formation will be dominated by the fractures; therefore, fractures are considered the important advective pathways. This duality in the groundwater flow regime results in a preferential migration of solute mass in the fractures, enabling the formation of large concentration gradients across the fracture-matrix interface and resultant mass transfer by diffusion (Schwartz and Zhang 2003). Analogously, thermal gradients can form between the convective fractures and conduction-dominated rock matrix, potentially creating marked thermal contrasts within the formation helping to support the identification of hydraulically active features by contrasts in temperature (or solute concentration) gradients in the system (Parker et al. 2012).

Thermal conduction is governed by groundwater advection within the fracture networks, which can lead to uneven distributions of heat at the meso-scale, as groundwater with differing temperatures preferentially moves through the groundwater flow system. The spatially variable distribution of temperature in a heterogeneous and anisotropic rock can be an effective tracer for preferential groundwater flow pathways (Anderson 2005). In principle, temperature within a fractured sedimentary rock will be more stable and evenly distributed within the matrix with increasing thermal deviations or contrasts observed in proximity to neighbouring hydraulically active fracture zones (Ge 1998).

2.1.2 – Thermal Profiles along Open Boreholes

Early studies involving the collection of temperature profiles in open boreholes focused on monitoring ambient temperatures (Trainer 1968; Drury 1984; Drury et al. 1984; Drogue 1985; Bidaux and Drogue 1993; Robinson et al. 1993; Barton et al. 1995; Ge 1998; Greenhouse and Pehme 2002; Genthon et al. 2005; Klepikova et al. 2011, 2014). Trainer 1968 was the first to use temperature as an analog for groundwater flow in a fractured bedrock system. By collecting temperature profiles with a thermistor at various depths along open boreholes and then correlating inflections within the profile with the depths of bedding plane fractures that had
previously been identified, he was able to infer the location of hydraulically active fracture sets within the system. This method was further refined by analytically estimating flow rates based on the difference in temperature of water flowing into a borehole at one fracture set and exiting at another (Drury 1984; Drury et al. 1984), relying on vertical flow in the open borehole.

Ambient temperature profiles from multiple boreholes can aid in understanding complex three-dimensional flow system (Silliman and Robinson 1989). Examining the magnitude of inflections during pumping tests has shown to be useful in assessing fracture connectivity and can help determine which hydraulically active features control flow within fractured bedrock system (Silliman and Robinson 1989). Even under ambient flow conditions, the magnitude of inflections along a temperature profile can effectively identify highly conductive fractures that serve as preferential pathways, a concept verified using contaminant concentrations by Malard & Chapuis (1995). More recent advancements have used ambient temperature profiles to estimate connectivity and the hydraulic properties of fractures within a bedrock system through a tomographic approach (i.e., sequential borehole profiling) (Paillet et al. 1987; Klepikova et al. 2011, 2014).

Interpretations of ambient temperature profiles from long open boreholes will be limited by two major factors: atmospheric temporal variation and vertical flow along the borehole. The first is that they are only effective at determining ambient flow to the depth at which atmospheric temporal variations exist (Taniguchi 1993; Pehme et al. 2010). Figure 1 shows the temperature profile of the earth with depth where the heterothermic zone represents the interval influenced by atmospheric temperatures as well as recharge and discharge patterns. In dual permeability and porosity systems, this heterothermic system will also create differences at the boundaries between these higher and lower permeability zones (different scale). This condition supports the existence of a thermal contrast between the more mobile water in fractures and less-mobile water contained in the matrix. The homothermic zone temperature is equal to the ambient geothermal gradient, where groundwater temperatures in the fractures have equilibrated to the ambient temperature of the fluid-rock matrix. At this depth the presence of thermal inflections along a vertical temperature profile will not exist (Drogue 1985). The vertical extent of the heterothermic zone will depend on the geology, weather conditions, physical properties of the rock and fluid and hydrogeologic conditions, and vary seasonally in temperate climates as the boundary condition at surface flips from hot to cold extremes. Equipment and sensor measurement capabilities can also play an important role in the delineation of heterothermic zones, particularly near the transition into the homothermic zone. For instance, the resolution of a temperature probe and rate or style in which the sensor is deployed can influence the
detection of thermal deviations along a borehole (Pehme et al. 2007b). The second factor that limits interpretation of ambient temperature profiles is that vertical flow along the borehole can dilute the temperature signatures of hydraulically active zones that play a major role in controlling the flow system (Robinson et al. 1993). Furthermore, the fractures dominating the ambient temperature profile along the borehole are not necessarily vertically connected in the absence of an open borehole (Pehme et al. 2007a, 2010). This is referred to as forced convection, in which vertical flow along the borehole is controlled by differences in hydraulic head at different depths intersected by a vertical borehole creating improved connectivity of these zones.

Free convection (flow induced by fluid density gradients) also has the potential to cause vertical flow within a borehole, open or sealed. When air temperatures are colder than the homothermic zone, colder and denser water accumulates above warm, less dense water and, if a critical thermal gradient is reached, the water column can become unstable and mix (Sammel 1968). This value of the critical gradient is largely controlled by the borehole diameter and the onset of free convection occurs at lower thermal gradients in larger diameter holes. Free convection occurs in what are known as “convection cells” where warmer water moves up one side of the borehole wall while colder water moves down the opposite, and whose heights have been measured up to half a meter in a standard groundwater monitoring well (Sammel 1968). This vertical mixing can be restricted to individual cells given strong horizontal boundaries, but thermal instabilities near the boundary layer can cause a thermal oscillatory regime to form between two cells, essentially combining them into a single cell with an irregular flow pattern (Cermak et al. 2008a, 2008b). Their occurrence is well known, but how to discern these conditions within boreholes is problematic when trying to characterize natural or ambient system flow conditions with expected temperature variability. Free convection results in thermal oscillations along a borehole profile that are not representative of the discrete temperature conditions of the surrounding formation (Cermak et al. 2008b; Eppelbaum and Kutashov 2011). These oscillations can distort the signatures of groundwater flow and make interpreting the zones of hydraulic activity difficult when downward warming conditions, where temperatures are higher at depth, are present at a local scale and throughout the borehole. Smaller diameter boreholes can be used to combat the formation of convection cells as they have larger frictional forces to overcome and, as such, require a larger thermal gradient to initiate free convection (Borner and Berthold 2009).
2.1.3 – Thermal Profiles along Sealed Boreholes

The vertical flow due to cross-connection can be eliminated through installation of a flexible polyurethane liner (FLUTe™). This impermeable membrane acts as a temporary seal and effectively eliminates the hydraulic cross-connection created by the borehole (Cherry et al. 2007), while preserving thermal deviations associated with preferential flow paths within the discrete fracture network. A static water column within the liner creates an outward (positive) pressure on the liner and pushes this liner against the borehole wall. Thermal equilibration across the liner into the static water column can mimic the thermal profile of the formation (Figure 2a). The thermal stratification within the static water column can be measured using wireline or fixed sensors. Therefore, inflections along an ambient temperature profile collected in this static water column will possibly denote hydraulically active fractures. Accurate and reliable detection of subtle temperature changes with depth is greatly improved with the use of the FLUTe™ liner, constructed of nylon fabric and coated with a polyurethane to be impermeable to water (Pehme et al. 2010). They have also been used to estimate volumetric groundwater flow under ambient flow conditions using active DTS (Coleman et al. 2015; Maldaner 2017). However, polyurethane-coated nylon fabric liners do not remove the potential for vertical flow due to free convection inside the static water column within the liner, as shown in laboratory studies of static water columns (Sammel 1968). Here, critical thermal gradients can still result in internal mixing due to free convection during downward warming conditions (Figure 2b) and have been observed in previous field studies (Pehme et al. 2013; Pehme et al. 2014).

2.2 – Wireline Temperature Trolling

The most common method of monitoring temperature distribution along a borehole is by using a thermistor probe attached to a cable that is moved up or down a borehole (i.e. trolling). The probe generates a temperature- depth profile that provides a snapshot of the borehole’s temperature stratification (i.e. variability with depth or length of borehole depending on borehole orientation). While it is meant to represent a single snapshot of downhole temperature in time, the trolling method can take hours to complete, depending upon the borehole’s depth and data acquisition rate. This may result in a temporal lag along the vertical profile that may be important in highly dynamic or forced-gradient environments. In contrast, high probe speeds can cause turbulent mixing of the water column as water is displaced by the sensor, resulting in eddy currents around the thermistor, and ultimately reduce the depth-resolving capability of the
sensor (Mansure and Reiter 1979). Hence, the goal is to troll as slowly as practical to maximize vertical spatial resolution, minimize disturbance and eddy currents, and limit the overall time lag from top and bottom of profile measurement.

While a temporal lag cannot be extricated from the wireline temperature log, technological advancements have allowed the technique to move from point measurements at widely spaced discrete intervals along a borehole to continuous temperature-depth profiles with centimeter to sub-centimeter sampling intervals (Anderson 2005). These higher resolution datasets have, in turn, been used with geophysical and hydraulic data (Stonestrom and Blasch 2003) to better identify individual hydraulically active fractures and fracture sets in lined boreholes (Pehme et al. 2010). Thermal datasets can be further refined to enhance small-scale variations, which in turn have been used to isolate specific hydraulically active fractures (Pehme et al. 2010).

2.3 – Active Line Source Temperature Profiling

The detection of hydraulically active fractures can be extended into the homothermic zone by using an Active Line Source (ALS) technique, whereby the unlined borehole’s water column is heated and followed by a series of time-lapse temperature profiles to capture spatial variations in heat dissipation (Greenhouse and Pehme 2002). Variations in the temperature profile will occur due to the difference in the density and the specific heat capacity of water and rock, their respective thermal conductivities, and the spatial variations in the mobility of the water phase. The technique has also been applied in a FLUTE™ lined fractured rock borehole with marked improvements in the resolution of temperature deviations associated with hydraulically active fractures, both above and within the homothermic zone (Pehme et al. 2007; Pehme and Parker 2012; Pehme et al. 2014). The ALS method typically requires heating of a single borehole for 4-6 hours followed by 2-3 snapshots of the temperature-depth profile over the course of a 3-4 day period.

While the ALS method does improve detection of subtle temperature changes, it suppresses seasonal fluctuations associated with the heterothermic zone and modifies the relative magnitudes of thermal deviations along the profile. Monitoring seasonal trends in the temperature profile has been shown to improve conceptual understanding of hydraulic transience within alluvial systems (Taniguchi 1993); equivalent applications in fractured bedrock groundwater environments for purpose of characterizing dynamic hydrologic processes in the
shallow subsurface at or near the surface water interface has not yet been reported in the literature.
3.0 – Study Site

3.1 – Regional Setting

The study site is located along the Eramosa River in Guelph, Ontario, which is a major tributary of the Speed River within the Grand River Watershed. The site is 3.9 km up gradient from the Eramosa –Speed River confluence, 23 km from the Speed –Grand River confluence, and 92 km from the river’s mouth at Lake Erie. The region is located in a humid continental climate zone, with air temperatures commonly ranging from 30°C to -20°C throughout the year, and a mean annual temperature of 9°C. The watershed receives an average annual precipitation of 946 mm/year with 15% accumulating as snow during the winter months of January through March.

The Silurian bedrock underlying the region has been eroded through pre-glacial and glacial and glaciofluvial erosion during the Pleistocene creating complex networks of bedrock valleys (Karrow et al. 1979; Eyles et al. 1997; Gao 2011). While many of these bedrock valleys have been infilled with Quaternary-aged glacial and interglacial sediment (Barnett 1992), some have remained exposed and become part of the modern surface water drainage network. The Eramosa River within the City of Guelph flows along sections of an exposed paleo-bedrock valley (Cole et al. 2009; Steelman et al. 2017a).

The entire Silurian dolostone sequence serves as a regional supply aquifer and is the primary drinking water source for the City of Guelph, supporting over 130,000 people (City of Guelph 2006; Statistics Canada 2016). The lithostratigraphic units that comprise this Silurian dolostone aquifer are often well-connected to surface and to the overlying Quaternary units due to the presence of thousands of open residential domestic wells and municipal water supply wells (City of Guelph 2006), as well as due to the discontinuous nature of the Eramosa formation, a lithostratigraphic unit that functions as an aquitard. As such, understanding the interactions between individual units and surface water is important to the long-term security of the region’s drinking water supply.

3.2 – Geologic and Hydrogeologic Environment

The Eramosa River cuts through the Eramosa Formation with minimal sediment along its reach, leaving extensive sections of exposed bedrock along the riverbed and shorelines (Steelman et al. 2015a, 2015b). Figure 3 provides a summary of the regional lithostratigraphic
units and their key characteristics that were studied in detail at two local field research sites in Guelph and summarized in two University of Guelph MSc theses (Munn 2012; Fomenko 2015). A more in-depth description of the local conditions can be found in these theses and the regional lithostratigraphy context can be found within (Brunton et al. 2009, 2013) and the study site fracture network characterization by Kennedy (2017). Below the water table and buried below the Silurian aged Guelph Formation and unconformable Pleistocene-aged glacial sediments outside of the river channel, the shaley dolostone Eramosa Formation is considered to be a regionally discontinuous aquitard (Cole et al. 2009); it is also heavily weathered with horizontal and vertical fractures, which results in variable vertical connectivity at the regional scale. The Eramosa overlies the cherty nodule-rich Ancaster Member of the Goat Island formation, whose contact is identified by a distinct colour change from dark grey to pale brown. The rest of the Goat Island formation consists of the underlying Niagara Falls Member, which is relatively thin at the site, only 2 to 4 m thick, but resembles the Gasport formation in colour. The contact between Ancaster and Niagara Falls members can be mistaken as that of the Goat Island and Gasport (Munn 2012). The Gasport formation has many dissolution-enhanced features and large vugs that make it more transmissive and an ideal water supply aquifer (Kunert et al. 1998); however, municipal supply wells are not exclusively completed in this unit. Its characteristic reef mounds also cause the depth of the contact between Goat Island and Gasport formations to be highly variable, even at the local scale (10s of meters).

Regionally, the groundwater flow direction varies based upon geologic unit and can be influenced by municipal pumping (Unonius 2012). Locally, groundwater in the Eramosa and Goat Island formations flow south-west, while flow is predominantly westward in the Gasport (Unonius 2012). The close proximity of the study site to the Arkell Springs well field ~3.5 km north of the City of Guelph likely controls the vertical gradient and predominant groundwater flow directions; however, the full extent of this potential influence to the shallow subsurface is unknown.

### 3.3 – Bedrock River Research Station

The study area consists of a 200 m reach of the Eramosa River that includes an exposed bedrock floodplain to the south (Figure 4). Vegetation in the form of grass, shrubs and trees can be found along the shorelines. The grounds south of the river are maintained by Scouts Canada. During the winter months the Eramosa River is liable to freeze and can exhibit substantial anchor ice along the exposed bedrock riverbed (Steelman et al. 2017b).
Bedrock River Research Station is instrumented with an extensive network of bedrock riverbed seepage meters, shallow piezometers and still wells located within the Eramosa River (Kennedy 2017; Steelman et al. 2017b). Locally, the water table resides between 1.5 and 2 m bgs based on water levels collected in neighboring multi-level monitoring wells. The Eramosa River experiences high-flow rates during spring melt events (>12 m$^3$/day), when air temperature first rises above 0°C, and low-flow during the hot, dry summer months (<0.70 m$^3$/day). River stage within the immediate study area ranges seasonally with maximum water levels ~1 m during high-flow and <0.1 m during low-flow. A summary of river flow rate and precipitation data during the study period is provided in Figure 5.

Six continuously cored boreholes were drilled along the south shoreline between Apr-2015 and May-2015 to the top of the Gasport formation reaching vertical depths of 24-32 m bgs. These boreholes were completed at three stations each consisting of a vertical and angled borehole pair (Figure 4). Each borehole was drilled using Hydracore Prospector (Hydracore Drills, Delta B.C.) equipped with an NQ core tube that results in a 75.7 mm borehole diameter and 47.6 mm core diameter. Steel surface casings were cemented into the bedrock to a depth of 0.2 m using a concrete drill prior to bedrock NQ coring. A continuous core was obtained from each borehole using a double barrel core sampler system. Vertical boreholes include SCV1, SCV2, and SCV3 while the angled boreholes are denoted as SCA1, SCA2, and SCA3. Each angled borehole plunges at 60° from horizontal and are orientated at 50°, 185° and 340° from true north, orthogonal to the principle fracture orientation mapped regional fracture network (Munn 2012) (Table 1). SCA1 and SCA2 plunge beneath the Eramosa River, while SCA3 extends south-southeast under the floodplain. Steelman et al. (2017b) provided a report on surface geophysical characterization of riverbed architecture and hydrogeologic flow system dynamics beneath the riverbed in response to seasonal changes in temperature and groundwater-surface water interaction and found evidence of a vertical fracture network that may readily connect surface water to groundwater.
4.0 - Methodology

A series of vertical thermal profiles were collected within each of the paired vertical (SCV1, SCV2, SCV3) and angled (SCA1, SCA2, SCA3) boreholes located along the southern shoreline of the Eramosa River (Figure 4). Temperature measurements were collected on 1-4 week intervals with more frequent sampling during seasonal transitional periods in an attempt to capture the more rapid evolution of thermal transients. This resulted in a variable distribution of sampling events throughout the annual cycle with respect to seasonal variability in ambient air temperatures (Figure 5 and 6); however, each of the four seasons (i.e., spring, summer, fall, and winter) was sampled at least once.

Characterization of the physical properties of the bedrock through collection of continuous core with lithology and feature logging, borehole geophysical logging, and depth-discrete hydraulic testing provided information about the fixed or static properties of the subsurface flow system, thus enabling a more process-based evaluation of the thermal signatures observed along the borehole. A suite of borehole characterization techniques based on the Discrete Fracture Network – Matrix (DFN-M) framework (recently modified from Parker et al. 2012) were applied on the six boreholes, which included lithologic and feature logging, geophysical logging (i.e., natural gamma, acoustic and optical televiewer), short-interval hydraulic packer testing, and FLUTe™ transmissivity profiling.

A suite of statistical techniques were applied to the thermal profile datasets to quantitatively evaluate the stationary and transient signatures observed along the borehole over a 1 year monitoring period. The approach enabled assessment of thermal data quality and its utility for the detection and delineation of active groundwater flow zones based on the existence of discrete flow features. Specifically, cross-correlation and Fourier spectra analysis was applied to the thermal profiles collected over a complete annual cycle. This approach was designed to improve identification of seasonal trends within the thermal profiles and establish a more quantitative framework for determining the optimal period and conditions to collect temperature profiles in a lined borehole. The approach described herein builds upon the temperature logging technique described by Pehme et al. 2010 and Pehme et al. 2015, in which downhole temperature profiles were collected in FLUTe lined boreholes and used to identify hydraulically active zones in FLUTe lined boreholes, by working in smaller diameter boreholes with a commercially available thermistor with new sensitivity, in a groundwater discharge area proximal to the surface water interface where the flow system dynamics are expected to be
variable due to specific recharge events, and seasonal temperature variability driven from recharge and/or discharge zone dynamics.

4.1 – Core and Borehole Characterization

4.1.1 – CoreDFN

A detailed feature and lithologic logging procedure (Parker 2007; Parker et al. 2011, 2012) was applied to each of the six cored boreholes (SCV1, SCV2, SCV3, SCA1, SCA2, SCA3). The CoreDFN procedure was applied using three standardized logging sheets:

1. **Run Log** – top and bottom depth of the logged interval, drilling start and end times, and Rock Quality Designation (RQD) and percent recovery (i.e., length recovered over length of cored interval);

2. **Feature Log** – feature type, start and end depth, continuity, dip angle, quality of fit, degree of roughness, styolite presence, sediment infilling, mineral precipitation, oxidization, and whether or not it was a mechanical (due to drilling) or natural fracture;

3. **Lithology Log** – primary and secondary Munsell rock colour (Munsell 1907), rock type, crystal grainsize, roundness vs. angularity (sphericity), crystallinity, cementation/hardness, fossil type and abundance, pore geometry, vug size and intensity, and sedimentary bedding structure.

A graphical logging methodology, standardized for the local geology conditions – based on closed-ended questionnaire forms – reduces human error and bias, aides with the data transfer to a digital database format, and increases the rate at which core can be logged. The logging was also accompanied by high-resolution photography of each run and numerous other borehole logging data sets, including geophysics described further below (Parker et al. 2012).

4.1.2 – Natural Gamma

Natural gamma logs were collected using the QL40-GR probe (Advanced Logic Technology, Mount Sopris Instruments, Denver, CO). The probe detects naturally occurring gamma radiation (K, U, Th) from the surrounding formation and therefore detects the presence or absence of shale (clay content) (In Butler 2005, Chp. 12). The most significant gamma-emitting radioisotopes are potassium-40 and the daughter products of uranium and thorium (Keys 1990). These measurements are often used to identify lithologic contacts. Bedrock
formations can exhibit unique gamma profiles, which can aid in lithologic correlation at local and regional scales (Aigner et al. 1995). Data were recorded upward at a rate of 1 m/min with a sampling interval of 0.0026 m; these data are averaged to produce a discrete measurement based on counts per second (cps) unit for each 0.01 m depth interval.

4.1.3 – Acoustic Televiewer

Boreholes were imaged using an acoustic televiewer (ATV) probe QL40ABI probe (Advanced Logic Technology, Mount Sopris Instruments, Denver, CO). The ATV probe provided a measure of the borehole diameter by measuring the two-way travel time of an acoustical pulse reflected off the borehole wall. The amplitude of the reflected pulse is recorded and used as a measure of the acoustical impedance of the rock material, which can be used to assess relative variations in fracture frequency or rock vugginess (i.e., porosity) (Kennel et al. 2009). At fractures, the acoustic wave will have a low amplitude and high travel time. ATV logs were used to create a virtual caliper log and determine the position, orientation and frequency of fractures and vugs. Data was recorded as the probe was raised up the open borehole at a rate of 2.0 m/min, resulting in a vertical resolution of 0.0025 m.

4.1.4 – Optical Televiewer

Optical televiewer logs (OTV) were collected using a QL40OBI probe (Advanced Logic Technology, Mount Sopris Instruments, Denver, CO). An OTV probe is essentially a high-resolution borehole camera that produces a panoramic 360° image of the borehole wall. Magnetometers, inclinometers, and accelerometers keep the probe aligned with magnetic north to ensure image alignment. It is also used in conjunction with ATV to provide borehole deviation from vertical and fracture orientations, azimuths, and apertures (Williams and Johnson 2004). Lastly, OTV logs were used to identify fractures and verify the position of lithologic contacts based on colour changes. Data were recorded as the probe was lowered down the open borehole at a rate of 1 m/min resulting in an oriented 720p image with a horizontal and vertical resolution 0.002 m.
4.2 – Hydrogeologic Characterization

4.2.1 – Packer Testing

A straddle packer testing apparatus was used to conduct a falling head slug test at regularly defined intervals in each borehole. Nitrogen gas was used to inflate two 1.5 m long packers, isolating a 1.5 m interval. Physical water slugs ranging from 0.50-2.0 L were added through 0.051 m diameter standpipe connected to the open interval. Each water slug was poured into the top of the standpipe to approximate an instantaneous injection. Hydraulic pressure responses were recorded using a Schlumberger 50 m Micro-Diver pressure transducer (accuracy 0.05 mH2O, resolution 0.01 mH2O) (Schlumberger Water Services, Kitchener ON, Canada) within, above, and below the packered off test interval recording at 1 second intervals. Each test was repeated 2-3 times with 0.50, 1.0, and 2.0 L slugs, equating to initial head displacements of 0.24, 0.49, and 0.98 m, respectively. Multiple sized slugs were used based upon the observed vs. expected head change within the interval to ensure viable results within each interval. Formation transmissivity was calculated using Hvorslev’s slug test solution for radial flow geometry (Hvorslev 1951):

\[ T = \frac{m(A_{xz})}{2\pi} \ln \left( \frac{r_o}{r_w} \right), \]  

where \( T \) is transmissivity (\( K_b \times \text{Length of test interval} \)), \( m \) is slope of the change in head, \( A \) is cross sectional area of riser pipe, \( r_o \) is radial zone of influence, and \( r_w \) is the radius of the well. The slope of the change in head was taken using early time-series data, which has been shown to provide more accurate estimates of transmissivity in similar dolostone bedrock environments (Quinn et al. 2012). Pressures were monitored above and below the upper and lower packers, respectively, to identify evidence for vertical flow (i.e. ‘short circuiting’) during the slug tests. If short-circuiting was detected the lowest calculated transmissivity value for that interval was used as ‘short-circuiting’ or vertical flow would result in an over estimation of \( T \) (Quinn et al. 2012). The bulk hydraulic conductivity (\( K_o \)) of the test interval can be determined by dividing by the test interval length, which was consistently 1.5 m.

4.2.2 – FLUTe™ Transmissivity Profiling and Borehole Sealing

Polyurethane coated nylon fabric (FLUTe™, Alcalde, NM) liners were installed in each borehole to obtain a continuous transmissivity profile of the bedrock (Keller et al. 2014). Once installed, the liners were also used to eliminate vertical cross-connection along the open
borehole channel (Cherry et al. 2007). As a liner descends and everts, the process forces water into the unlined portion of the formation (below the base of the liner). The liner’s rate of descent under an assumed constant and large hydraulic gradient is measured against associated forces. As the everting liner seals the open borehole, changes in the liner descent velocity indicate the position of permeable features. Total open borehole transmissivity and depth-discrete transmissivities were calculated using the Thiem equation based on the assumption of steady radial flow (Keller et al. 2014).

4.2.3 – Temporary Deployments

Temporary deployments refer to the installation of pressure transducers or other sensors behind a flexible impermeable liner (Chapman et al. 2014; Pehme et al. 2014). Here, RBRsolo pressure and temperature transducers (RBR Ltd., Ottawa ON, Canada) were positioned at targeted depth intervals within each borehole informed by core and geological logs, then subsequently sealed using a FLUTe™ liner (Figure 7). The series of transducers (2-8) were hung within each borehole using aircraft cable affixed to the top of the borehole casing. Each pressure-temperature sensor pair represented a single sampling interval of 0.5 m. This combination of transducers and FLUTe liner effectively created a temporary multi-level monitoring installation (Pehme et al. 2014) used to assess vertical components of the hydraulic gradients and delineate changes in vertical hydraulic conductivity (Meyer et al. 2014). Transducers recorded formation pressure from May 27th to June 9th, 2014, with a sampling interval of 0.5 seconds. A calibration methodology was used to determine the accuracy of each transducer to be able to calculate hydraulic head differences (vertical components of gradient). A correction factor was calculated for each pressure transducer using the correction methodology and underlying assumptions of the procedure provided in Appendix A.

4.3 – Borehole Thermal Profiling

4.3.1 – Wireline Temperature Trolling

Ambient temperature-depth profiles were recorded using a wireline temperature trolling technique (Figure 7). A profile was collected in each borehole (SCV1, SCV2, SCV3, SCA1, SCA2, and SCA3) every 1-4 weeks over a 12 month period between June 2014 and May 2015. However, vertical boreholes (SCV1, SCV2, and SCV3) were not profiled during the winter
months (January through April) due to the formation of a layer of ice at the top of the water column.

Temperature profiles were collected using a probe constructed of an RBRsolo™ pressure transducer (SN77917, 50 m depth range) and an RBRsolo temperature transducer (SN75730) (Figure 7). The transducers were synced to record at 0.5 second intervals and the assembly was manually lowered down a FLUTe™ lined borehole at an approximate rate of 0.5 ±0.1 m/min. Each discretely sampled temperature-time series was re-sampled and converted to a uniformly sampled temperature-depth series (i.e., 0.01 m vertical sampling interval) based on the coincidently collected pressure transducer data.

4.3.2 – Rayleigh Number

It is widely accepted that large thermal gradients that increase with depth within a borehole lead to turbulent mixing of the standing water column and is a function of borehole diameter. The threshold at which this mixing initiates is defined by the critical Rayleigh number and critical thermal gradient along the water column. The critical Rayleigh number, a numeric representation of the point at which destabilizing forces outweigh stabilizing forces, was calculated for both the vertical and angled wells using the following equation from Gershuni and Zhukhovitskii (1976):

\[
Ra_{c\text{ column}} = \frac{96}{5(1 + 7\lambda)} \left[3(33 + 103\lambda) - \sqrt{3(2567 + 14794\lambda + 26927\lambda^2)}\right],
\]

where \(Ra_{c\text{ column}}\) is the critical Rayleigh number of a vertical column and \(\lambda\) is the ratio of thermal conductivities of fluid and the surrounding material (i.e., the formation). A formation thermal conductivity of 4 W/mK was used for calculating \(\lambda\), an average of the site-specific thermal conductivities values measured for each formation (Maldaner 2017).

The critical thermal gradient, the point at which density driven mixing within a water column will occur, was also calculated for both the vertical and angled holes using the following equation from Hales (1937):

\[
A_{cr} = \frac{g\beta T}{c_p} + C \frac{va}{g\beta r_0^4},
\]

where \(A_{cr}\) is the critical thermal gradient, \(g\) is acceleration due to gravity, \(\beta\) is the coefficient of thermal volumetric expansion, \(T\) is the temperature in degrees Kelvin, \(c_p\) is the specific heat capacity of fluid at constant pressure, \(C\) is a constant equal to 216, \(v\) is kinematic viscosity, and \(r_0\) is the inside radius of the borehole. Here, the critical thermal gradient is defined over a 1 m interval and will occur when dense cold water overlies less dense warm water; this condition will
result in density-driven mixing along the water column. The critical thermal gradient is also dependent on the effective diameter of the borehole perpendicular to the gravitational vector. Therefore, the effective diameter of a borehole will increase with vertical deviation, as can be seen in Figure 8, and the largest value of the ellipses was be used.

4.3.3 – Thermal Deviations

A temperature deviation log, sometimes referred to as a variability log (Pehme et al. 2010), was calculated for each temperature-depth profile at each borehole using the following equation:

\[ T_{\text{deviation}} = T_{\text{raw}} - T_{\text{smoothed}} \quad [6] \]

where \( T_{\text{deviation}} \) is the instantaneous temperature deviation, \( T_{\text{raw}} \) is the corresponding temperature profile, while \( T_{\text{smoothed}} \) is the temperature profile after applying a low-pass filter. Here, a 1 m running average was applied to each temperature-depth profile to reduce small-scale variations resulting in a smoothed base temperature log \( (T_{\text{smoothed}}) \). The resulting smoothed log captures the effects of longer term seasonal temperature variations and the geothermal gradient. High-frequency thermal deviations along the borehole can be accentuated by subtracting the smoothed log from the raw base log. These so-called deviation logs provide the position and relative magnitude of temperature perturbations at the centimetre scale, allowing for the identification of thermal perturbations caused by individual or groups of hydraulically active fractures. A summary of the raw temperature profile and resulting thermal deviation log is provided in Figure 9. A 1 m window size was selected based on a qualitative comparison of different window sizes for a range of seasonal conditions (Figure 10). The window size was visually optimized in an attempt to remove the seasonal geothermal gradient while minimizing the effects on signal frequency and amplitude. The optimum (selected) window size will depend on site conditions and signal attributes of the thermal deviation log.

4.3.4 – Signal Cross-correlation

Correlation is the statistical measure of dependence between two random variables, regardless of causality (Samuels and Witmer 1999). A correlation coefficient, ranging from -1 to +1, is the most common measure of this dependence and represents the linearity of the relationship between two points as described by the following equation:
\[ r_{xy} = \frac{n(\sum x_i y_i) - (\sum x_i)(\sum y_i)}{\sqrt{n\sum x_i^2 - (\sum x_i)^2][n\sum y_i^2 - (\sum y_i)^2]} \]  

where \( r_{xy} \) is the correlation coefficient between two data sets \( x \) and \( y \), containing \( n \) values. Here, a coefficient of +1 indicates that both variables increase at the same time and -1 indicates that one variable increases while the other decreases, whereas a value of 0 indicates that there is no statistical relationship. The correlation coefficient also accounts for noise, as noisier data will move the coefficient towards 0.

Correlation coefficients were calculated between deviation logs within each of the six boreholes over the full 12 month period. Correlations were calculated across each lithologic unit (i.e., Vinemount Member, Ancaster Member, Niagara Falls Member, and Gasport formation) to assess signal stationarity over the annual period. The statistical procedure was coded and applied in R! (R Core Team 2013). Complete scripts are provided in Appendix B(I).

### 4.3.5 – Frequency Analysis

Any discretely sampled series (time or space) can be described by an infinite number of sinusoidal waves of varying frequency and amplitude (Telford et al. 1976). A Fourier transform decomposes a signal into the frequencies of which it is composed. The strength of a particular wave present in a signal is reflected by its relative amplitude in a spectral density plot; the stronger the wave, the higher its amplitude. Local peaks in the frequency spectrum (i.e., high signal amplitude) represent the dominant signals within the sampled series. A frequency spectrum may have one or more peak frequencies that describe its primary attributes. Fourier analysis enables a comparison of the frequency spectra from different boreholes or from different sampling events. This approach enables a more quantitative comparison of thermal deviation logs. Here, peak frequencies associated with discrete fractures are expected to have a unique frequency spectrum separate from those associated with dynamic processes or thermal noise.

The spatial distribution of hydraulically active fractures will depend on the static fracture network. Therefore, Fourier transforms corresponding to a series of time-lapse temperature deviation logs should exhibit the same diagnostic peaks, assuming the active fractures remain stationary over time (i.e., the peaks occur at the same frequencies). If the position of the hydraulically active fractures changes over time or there is a major change in the magnitude of flow within a particular fracture set, the frequency distribution associated with that borehole may change. Signal noise associated with instrument precision will manifest as a low-amplitude,
high-frequency signal in the frequency-amplitude spectrum, thereby providing a basis for distinguishing active fractures from noise.

Deviation logs from each sampling event for all six boreholes underwent a Fourier transform in R! (R Core Team 2013) based on the discrete Fourier transform:

\[ X(k) = \sum_{n=0}^{N-1} x(n) \cdot e^{-i \frac{2\pi}{N} kn} , \]  

where \( X(k) \) is the discrete Fourier transform of the 'time' series \( x(n) \), \( N \) is the period of the signal, \( k \) and \( n \) are integers and \( i = \sqrt{-1} \). For the case of a thermal deviation log, \( x(n) \) represents the change in temperature at depth position \( n \). A Fourier transform was performed on each log in its entirety (full borehole) and across the individual lithologic units. The highest frequency represented in a spectrum is determined by the maximum sampling rate:

\[ f_{\text{max}} = \frac{1}{2 \cdot \Delta d} , \]  

where \( f_{\text{max}} \) represents the Nyquest frequency or the highest resolvable frequency in the spectrum, and \( \Delta d \) is the spatial sampling interval. Here, each thermal profile was resampled using a uniform sampling rate of 0.01 m; therefore, the highest frequency sampled is 50 m\(^{-1}\). For comparison, amplitudes of the resultant Fourier spectrums were normalized based on the maximum amplitude within each spectrum.
5.0 – Results

5.1 – Rock Core Analysis and Open Borehole Testing

5.1.1 – Lithologic and Feature Descriptions

Regional lithologic contacts were identified in vertical and angled boreholes and included the Vinemount-Ancaster, Ancaster-Niagara Falls, and Niagara Falls-Gasport (Figures 11 and 12; Table 1). Both pyrite and calcite deposits, which are indicators of groundwater flow, were observed throughout each core, with pyrite deposits occurring predominantly within the Eramosa Member (302-312 masl) and calcite deposits occurring predominantly within the Niagara Falls Member and Gasport formation (281-300 masl). All depths herein refer to true vertical depth (TVD), the vertical distance from the well at ground surface. The Niagara Falls and Gasport also contained vugs of varying sizes (3-60 cm), some of which were filled with calcite crystals. The vertical extent and relative weathering of these dissolution features are denoted in Figure 11 and 12. A major dissolution enhanced horizontal conduit of approximately 20 mm was observed in SCA1, SCA3, and SCV3 near the base of the boreholes at an approximate elevation of 282 masl in SCA2 and SCV3, and at approximately 285 masl in SCA3. The contact between the Eramosa and Ancaster Members occurred at approximately 303 masl in all six wells, while the Ancaster-Niagara Falls and Niagara Falls-Gasport contacts were variable in elevation.

Cumulative fracture plots show variability in fracture distribution with depth across the site (Figures 11 and 12). Major inflections (i.e changes in fracture frequency) occur within the Eramosa and Ancaster Members, while none were observed within the Niagara Falls Member and Gasport Formation. Eramosa and Goat Island formations were characterized by the highest fracture frequency (vertical boreholes: 7.5 fractures/m; angled boreholes: 8.3 fractures/m) and dominated by horizontal (bedding parallel) fractures with dips <10° (refer to Table 2 for complete fracture summary). Vertical and sub-vertical fractures within these formations were less frequent (vertical boreholes: 2.4 fractures/m; angled boreholes: 4.0 fractures/m). Fracturing within the lowermost Gasport formation was much less frequent (1 fracture/m) and were almost always associated with horizontal bedding planes dipping <10°.
5.1.2 – Wireline Geophysical Logging

Natural gamma logs indicate higher rates of radioactivity within Vinemount and Ancaster Members (i.e., lower-Eramosa and upper-Goat Island formations) most often associated with higher clay mineral content due to potassium. Gamma signals sharply decline to near zero counts per second (cps) at the transition into the upper Niagara Falls Member (lower-Goat Island), with variable short-period peaks occurring between 16-31 m bgs within the Gasport Formation (Figure 11 and 12).

ATV logs show high frequency fracturing within the Vinemount (8.3-4.9 fx/m) and Ancaster (7.5.0-3.0 fx/m) Members (Table 2), while core logs showed even higher frequencies of fracturing within the Vinemount (20-12.7 fx/m) and Ancaster (8.5-4.6 fx/m). Fracture frequency was lower within the Niagara Falls and Gasport for both ATV (2.8-0.4 and 1.9-0.6 fx/m, respectively) and core logs (4.3-1.2 and 4.7-0.8 fx/m, respectively) than the two uppermost Members. ATV fracture analysis indicate fracture spacing of >1 m within the Gasport formation. Vugs or vuggy intervals were detected in each borehole, along with the most abundant presence of dissolution enhanced fracture features, between 20-31 m bgs within the Gasport formation. Corresponding OTV logs were used in combination with other geophysical logs to identify the depth of the lithologic contacts.

Fracture and dissolution feature type (complete fracture, incomplete fracture, broken zone, aligned voids and isolated voids) was identified using ATV and supported by core logs, photos, and OTV (Figure 11 and 12). A number of laterally continuous fractures and dissolution enhanced features were observed at the lithostratigraphic unit contacts at each borehole location. A zone of broken or highly-fractured rock was observed in all six boreholes at approximately 10 m bgs, at the Eramosa-Ancaster Member contact. A large void of approximately 24 mm diameter was detected near the Ancaster-Niagara Falls contact within the Goat Island at an elevation of approximately 300 masl in SCV1, SCV2, SCV3 and SCA2. A single complete fracture was observed at the Niagara Falls-Gasport contact in all six boreholes, occurring at 295-299 masl. Laterally continuous bedding plane fractures were observed within the Gasport at 296 and 282 masl in all six boreholes. Hydraulic characteristics associated with these fractures and boreholes in the next section.
5.1.3 – Packer Testing

Packer-derived transmissivity measurements across the site for 1.5 m intervals ranged from $10^{-4}$ to $10^{-8}$ m$^2$/s (Figure 11 and 12). Intervals of high transmissivity were observed at similar elevations and included peak transmissivities of $10^{-4}$ m$^2$/s at 302-303 masl corresponding to the Vinemount-Ancaster Member contact (Figure 11 and 12). Additional zones of high transmissivity were observed between 299-301 masl in the vertical boreholes, which corresponds to the Ancaster-Niagara Falls contact and at 294-296 masl corresponding to the Niagara Falls-Gasport contact. Similar peak transmissivity values were observed at consistent depths along each of the six boreholes.

5.1.4 – Transmissivity Profiling

FLUTe transmissivity profiling identified the position of the most transmissive features based on the position of inflections in the liner descent rate. Abrupt and gradual changes in the transmissivity profile were observed corresponding to discrete and distributed flow features, respectively. SCV1, SCV2, SCA1, and SCA2 are characterized by sharper inflections and these generally correspond with the position of peak transmissivities obtained from the packer testing, as both tests are conducted under forced gradient conditions. More gradual or less pronounced inflections were observed for SCV3 and SCA3 and show less consistency with corresponding packer derived transmissivities. The SCV3 and SCA3 cored holes also demonstrated a full order of magnitude higher transmissivity for the borehole reducing the depth resolution of the transmissivity compared to the SCA1/2 and SCV1/2 boreholes.

The most abrupt changes in transmissivity for SCV1, SCV2, and SCA2 occurred between 300-303 masl and coincide with the Vinemount-Ancaster and Ancaster-Niagara Falls contacts. The transmissivity profiles of the three deepest boreholes (SCV3, SCA1, and SCA3) were dominated by a single fracture near the base of the borehole within the Gasport formation. This fracture feature is located at 282 masl in SCA2 and SCV3, and at 284 masl in SCA3, which corresponds to the positions of a dissolution-enhanced conduit observed in the core photos, ATV and OTV logs shown in Figures 11 and 12.

5.1.5 – Vertical Hydraulic Gradients

Vertical head gradients are an integral component of understanding a flow system in fractured rock as the identification of contrasts in vertical conductivity ($K_v$) be used in the
delineation of hydrogeologic units (HGUs), hydraulically distinct units within the system (Meyer et al. 2008, 2014). Hydraulic head measurements from the temporary deployment installation from May-27 to Jun-9 2014 are largely characterized by downward “negative” gradients ranging from -0.005 to -0.067 m/m. Two snapshots of vertical hydraulic gradient are provided in Figure 13 from 12:00 AM on June 1st and June 4th, 2014. These two snapshots capture conditions prior to, and after a major precipitation event on Jun-3 where 13 mm accumulated over a 12 hour period (Figure 5). The precipitation event resulted in a negligible change in gradient, <0.005 m/m. Therefore, these snapshots are a fair representation of the vertical gradient during the two week monitoring period. Gradients were consistently downward at each borehole aside from a slightly upward (positive) gradient observed between the Vinemount-Ancaster Member contact in SCA3 (3.1-10.0 mbgs).

Vertical hydraulic head profiles reveal relative changes in the materials resistance to vertical groundwater flow (i.e., vertical hydraulic conductivity, \( K_v \)) (Meyer et al. 2008). Although these data show a systematic reduction in hydraulic head throughout the profile, relatively larger changes in vertical gradient were observed across the Ancaster Member of the Eramosa Formation and within the Gasport formation (e.g., SCV1 and SCA1) indicating flow may be more restricted across these boundaries. Here, the magnitude of the vertical gradient across these zones indicates that \( K_v \) is relatively lower than the overlying and underlying formation. The temporally consistent nature of the vertical gradients before and after the recharge event on Jun-3 indicates that these changes in gradient (i.e., \( K_v \)) are due to physical and stationary features in the rock (Meyer et al. 2014).

5.2 – Borehole Temperature Profiling

5.2.1 – Seasonal Thermal Gradients

The thermal gradient was calculated along 1 m segments of the raw temperature profiles (Figure 9). Here, a positive gradient indicates a warming water column with depth (downward warming), while a negative gradient indicates a cooling water column with depth (downward cooling). Water column temperatures ranged from 5°C to 25°C over the annual cycle within the heterothermic zone and converged to approximately 8.8°C at varying depths throughout the year; this position represents the top of the homothermic zone.

Thermal gradients in September and October show a strong downward cooling trend extending 10-12 m bgs. Although profiles from May and June show similar downward cooling
trends, the vertical extent of these transients are restricted to the upper 4.0 and 6.0 m, respectively; after which, these gradients reverse and begin to warm toward the geothermal gradient. Thermal profiles from November and December exhibit a warming downward gradient that extends to an approximate depth of 5.0 and 7.0 m, respectively, before reversing and cooling toward the 8.8 °C top of the homothermic zone before following the geothermal gradient.

The transition to frozen winter conditions resulted in a water column freeze-up in each of the vertical boreholes from Jan-9 to Mar-31 (Figure 14), preventing temperature logging in these holes, however, the corresponding angled borehole water columns (Figure 15) remained unfrozen during this period. Temperature profiles along the angled boreholes during the winter period reveal multiple thermal inflections where gradients oscillate between downward warming and downward cooling over relatively short distances (1-2 m), identified by white triangles in Figure 14 and 15. During these periods, shallow borehole temperatures were well-below the geothermal gradient, approaching 4°C within the upper 2.0 m, before gradually increasing in temperature to a depth of 15 m bgs.

These winter thermal profiles were accompanied by more frequent high-amplitude high-frequency variations along the thermal profiles. While the location of these oscillations in temperature gradient are not spatially consistent between sampling events, the gradients persist farther into the subsurface than those of sampling events where gradients were more unidirectional (i.e. June – December and April-June).

5.2.2 – Thermal Deviations

Thermal deviation logs calculated from the raw temperature profiles in Figures 14 and 15 based on Equation [6] reveal small-scale perturbations with depth. The majority of these occurred within the uppermost 10 m. However, smaller scaled deviations were detected up to 14 m bgs during the September to October period, 16 m bgs during November and December, and 20 m from May to June up to a maximum depth of 26 m bgs from January to April. Figures 14 and 15 show the thermal deviation logs of SCV1 and SCA1, respectively, and were chosen as they were representative of the other vertical or angled boreholes at the site. The thermal deviation logs for SCV2, SCV3, SCA2, and SCA3 can be found in Appendix C.

Thermal deviation logs exhibit a systematic seasonal evolution in their signal attributes (i.e., frequency and amplitude). For instance, logs collected during the warmer summer period
were mutually consistent, characterized by a strong negative thermal gradient with high-amplitude deviations near surface that progressively weakened with depth. The transition into cooler fall period was accompanied by a reduction in signal amplitudes near surface and more uniform thermal gradients. A marked increase in signal amplitude and frequency content was observed during frozen winter period as well as the occurrence of multiple reversals in thermal gradient along the vertical profile.

The highest frequency and largest magnitude deviations observed during the 12 month data collection period occurred in the upper 10 m during the winter, January to March, monitoring period (Figure 15). The winter period also exhibited systematic trends, such as lower frequency and lower amplitude deviations between 306 and 308 masl, relative to the higher frequency and amplitudes observed elsewhere along the vertical profile. Deviations during the winter period were also observed at the base of the angled boreholes in the Gasport formation.

Each borehole exhibited strong thermal deviations within intervals demarcated by moderate to high-vugginess (Figures 11 and 12). For example, relatively high deviations were observed at 292 masl in SCA1, 294 masl in SCA2, 295 masl in SCA3, and 297 masl in SCV1, 2, and 3 (Figure 14 and 15; Appendix C). These dissolution-enhanced features correspond to the Goat Island (Ancaster and Niagara Falls Members) and Gasport formations.

5.2.3 – Cross-Correlation of Thermal Deviation Logs

Cross-correlation was used to assess the temporal consistency of thermal deviation logs over an annual cycle in each borehole. Positive cross-correlations were generally observed amongst datasets collected during consistent seasonal temperatures, but did not persist for many consecutive events and varied by lithostratigraphic unit and/or depth. Strong positive cross-correlation was observed in each borehole between Sept-4 to Oct-3 within the uppermost Vinemount and Ancaster Members (Figure 16, 17, and 18). Similar intra-seasonal positive correlations were observed during the February to April period in the deeper Niagara Falls Member and Gasport formation, particularly in the angled boreholes. However, the winter period was marked by a more variable distribution of weakly positive or negative correlations; these largely warming downward profiles, demarcated by numerous inflections in the thermal gradient, exhibited variable degrees of correlation between adjacent datasets separated by relatively short periods of time (i.e., 1 to 2 weeks). Conversely, strong negative inter-seasonal correlations were observed between the spring (Mar-June) and fall (Sept-Dec) transitional
periods within the Ancaster Member of SCA1 (Figure 16) and Niagara Falls Member of SCA2 (Figure 17) and Niagara Falls-Gasport formation of SCA3 (Figure 18).

5.2.4 – Thermal Deviation Frequency Spectra

Frequency spectra of Fourier transformed thermal deviation logs from intra-seasonal groups exhibiting a strong positive cross-correlation coefficient are characterized by similar peak frequencies and bandwidths. Between Sept-4 and Oct-3 within the uppermost Vinemount Member (Figure 19), coherent signals that represent hydraulically active fractures were detected below 10 m$^{-1}$; similar peak frequency characteristics were observed in each borehole with primary peaks and those with the highest amplitude always occurred below 3 m$^{-1}$. Frequency spectra from the vertical boreholes were unimodal (i.e., a singular peak) (Figure 19a), exhibiting one major peak with minimal higher-frequency content (i.e., less noise); the angled boreholes exhibited similar peak frequencies with additional higher-order modes above the peak frequency (i.e., multiple high amplitude peaks) (Figure 19b). Of the three sampling events, Oct-3 showed the broadest frequency range with additional higher frequency peaks that were not readily evident in the Sept-4 or Sept-18 spectra (e.g., SCV2, SCV3, and SCA3).

Temporal variations in peak frequency within a given seasonal period (i.e., intra-seasonal grouping) were dependent on the geologic formation (Figure 20). For the Feb-27, Mar-11, Mar-24 winter period group, Fourier spectra of the Vinemount Member showed multiple peaks extending to maximum resolvable frequency of 50 m$^{-1}$. Although primary peak frequencies below 5 m$^{-1}$ remained stationary (i.e., the frequency at which the highest amplitude peak occurred did not change), secondary peaks of higher frequency were less consistent during the three sampling events. Signal behaviour in the Ancaster Member was similar to the overlying Vinemount aside from a slight decrease in the bandwidth. The lowermost Gasport formation had three major peaks below 7 m$^{-1}$, which were shared between all three spectra with no discernable high-frequency peaks above 10 m$^{-1}$.

A comparison of inter-seasonal thermal deviation frequency spectra from Sept-4, Nov-27, and Mar-24 is presented in Figure 21. Although the spectra of the Vinemount and Ancaster Members are characterized by a stationary peak frequency below 5 m$^{-1}$, where the frequency at which the peak occurs has minimal change between sampling events, these data also show an increase in the high-frequency signals during the cooler seasonal periods (i.e., Nov-27 and Mar-24) that is accompanied by an increase in the number and amplitude of the secondary peaks above 5 m$^{-1}$. However, these secondary peaks were not as stationary as the primary signal.
The primary peaks of the Niagara Falls and Gasport did not exhibit the same stationarity as the uppermost Members. Overall, the frequency spectra was more variable in the shallowest Vinemount Member, progressively becoming more stable in the Ancaster and Niagara Falls Members before returning to more temporal variability in lowermost Gasport formation.
6.0 – Discussion

6.1 – Delineating Groundwater Flow in Fractured Rock

The hydrogeologic flow system was characterized through multiple high-resolution fracture and hydraulic property measurements within each borehole. Following Meyer et al. (2008) and Meyer et al. (2014), delineation of hydrogeologic units was achieved by detailed interpretation of vertical hydraulic gradient profiles, packer transmissivity measurements, continuous core logs, and geophysical logs. Five hydrogeologic units were delineated: two in the Vinemount Member, one in the Ancaster Member, one in the Niagara Falls Member, and one in the Gasport formation. The transmissivity of the upper 7 m of the Vinemount Member ranged from $10^{-7}$ to $10^{6}$ m$^2$/s and was accompanied by minimal head loss along the vertical profile. A high degree of horizontal and vertical fracturing (i.e., horizontal $<10^\circ$: 4.9 – 8.3 fractures/m; vertical $>10^\circ$: 1.2 – 5.1 high-angle fractures/m) (Table 2) was observed in this section of the Vinemount. These attributes suggest a well-connected vertical zone with the potential for moderate to high horizontal flow.

The lowermost 2 m of the Vinemount and Vinemount-Ancaster Member contact (Figure 11 and 12) exhibited relatively high transmissivity values in each borehole (i.e., $10^{-5}$ to $10^{-4}$ m$^2$/s), and yet was accompanied by higher head loss relative to the upper zone. Head loss across an interval indicates the presence of a low-permeability feature that impedes vertical groundwater flow or lack of vertical fracture connectivity; if these zones are accompanied by high transmissivity, ambient groundwater flow will predominantly be horizontal.

The Ancaster Member (9 to 14 m bgs) and the Ancaster-Niagara Falls Member contact (Figure 11 and 12) exhibited similarly high transmissivity values (i.e., $10^{-5}$ to $10^{-4}$ m$^2$/s), also accompanied by more fractures (i.e., 4.6 – 7.5 fractures/m), and a marked head loss (Figure 13). These attributes support the dominance of horizontal groundwater flow. Conversely, the underlying Niagara Falls Member (14 to 17 m bgs) and the Niagara Falls-Gasport contact (Figure 11 and 12) is characterized by much lower fracture frequency (i.e., 0.5 – 2.6 fractures/m) and lower transmissivity (i.e., $10^{-6}$ m$^2$/s), with the exception of the interval spanning the lithologic contact (i.e., $10^{-5}$ to $10^{-4}$ m$^2$/s). This indicates that the Niagara Falls Member possesses a relatively lower vertical component of flow, and thus, acts as local hydraulic barrier between the more transmissive zones above and below.
The Gasport formation (>17 m bgs) is characterized by low fracture frequency (i.e., ≤10⁰: 0.6 – 1.9 total fractures/m; >10⁰: 0.3 – 0.9 fractures/m) and high vertical head loss. Packer testing predominantly showed low horizontal T (10⁻⁸ to 10⁻⁷ m²/s), with the exception of a few intervals (i.e., 10⁻⁵ to 10⁻⁴ m²/s). More transmissive zones were accompanied by large dissolution enhanced conduits observed between 27 – 30 m bgs, which also dominated the FLUTe transmissivity profiles in SCV3, SCA2, and SCA3 (Figure 11 and 12).

Thermal deviation logs provided evidence of hydraulic activity along distinct fracture features intersecting the borehole. The upper 7 m of each thermal deviation log exhibited multiple low-amplitude deviations that are consistent with the presence of highly fractured, well-connected rock. Relatively large thermal deviations were observed between 8 and 10 m bgs (Figure 14 and 15), which coincides with the zones of higher transmissivity and a large vertical head loss (i.e., dominated by horizontal flow). Thermal dynamics are also much higher, particularly during the June through October period, at these depths. Here, thermal deviations are consistent with fracture and hydraulic measurements indicating the presence of a hydraulically active zone dominated by one or more horizontal flow paths.

Thermal profiles within the Ancaster Member exhibited multiple and occasionally high-amplitude deviations relative to the overlying and underlying units. These large deviations were most prevalent in June and the period between February and April. Considering this geologic unit is characterized by high horizontal transmissivity, high fracture frequency, with low vertical connectivity, these observations indicate a hydrogeologic unit characterized by multiple horizontal, highly active hydraulic features. The thermal deviations observed across the Niagara Falls Member were relatively low amplitude and less-frequent than the overlying Vinemount and Ancaster units; this suggests that these transmissive features are not a strong component of the total groundwater flow field. This is evident in the February to April period, which shows high-frequency high-amplitude thermal deviations along much of the profile, with the sole exception of this Niagara Falls depth range (Figure 15). The absence of strong thermal deviations indicative of groundwater flow along the Niagara Falls Member is consistent with the lower observed fracture frequency and transmissivity as well as the prior assessment that the unit acts as a less-transmissive hydrogeologic interval (Brunton et al. 2009). It should be noted that the attenuation of the influence of atmospheric conditions with depth likely dampened thermal deviations within the Niagara Falls Member, but the larger magnitude deviations observed in the underlying Gasport Formation, where the dampening effects should be greater, support the conceptualization of a less-transmissive unit.
The more variable thermal deviations measured within the Gasport formation are consistent with the more heterogeneous distribution of transmissive fracture features, but is encumbered by the dampening of signals from the surface due to depth. Therefore, full characterization of the Gasport formation is hampered, but nevertheless some activity was observed. Here, thermal deviations reveal infrequent deviations that are correlated between boreholes at roughly the same depths and are further corroborated by fractures identified in the core and geophysical logs. Marked thermal deviations between Feb-27 and Mar-31 were observed at 19 and 20 m bgs in SCA1, 22 m bgs in SCA2, and 18, 19, and 20 m bgs in SCA3 (Figure 15; Appendix C). These deviations coincide with discrete fractures identified at similar depths in Figure 12. These observations are consistent with previous studies (Pehme et al. 2010, 2013; Coleman et al. 2015) who found consistencies between thermal deviations from ambient temperature profiles and discrete flow features detected in lined borehole.

6.2 – Intra-Seasonal Temperature Fluctuations: Signal Stationarity

Thermal deviation logs generally exhibited similar patterns along the borehole water column during periods of seasonal temperature stability (i.e., intra-seasonal conditions). These intra-seasonal periods included the warm summer (June-Oct) and cold winter (Feb-Mar) months, where frequencies at which high amplitude peaks were observed in the Fourier spectra remained stationary between sampling events. Thermal deviations during the spring and fall periods were more transitional or non-stationary in nature, and were generally characterized by a combination of transient and stationary signal attributes. The cooling downward profiles during the warmer summer months were typically characterized by lower amplitude and longer period deviations predominantly within the upper 6-8 m bgs. Seasonal atmospheric cooling near the surface with the onset of fall resulted in a systematic shift from a downward cooling to downward warming profile (i.e., reversal in thermal gradient). This fall transitional period was accompanied by a reduction in the thermal deviation amplitudes near-surface, and an increase in the depth of resolvable deviations in the borehole. A full reversal in the thermal gradient was achieved by January. The cooler winter period was characterized by a marked increase in the amplitude, signal frequency, and the vertical extent of thermal deviations detected in each borehole.

Relatively stationary thermal deviation profiles were observed during downward cooling periods (Jun-23 through Oct-3). This is evident in the high positive cross-correlation observed between adjacent profiles (Figure 16, 17, and 18) particularly within the uppermost Vinemount
Member. Here, stationary signals were predominantly observed below a frequency $5 \text{ m}^{-1}$ (Figure 19). The lack of higher-frequency peaks suggest these signals, collected during downward cooling conditions, were less-susceptible to measurement noise.

Stationarity was not readily observed between thermal deviation logs within the colder winter months (i.e., November through April). This seasonal period, accompanied by a strong systematic downward warming in the vertical temperature profile, was characterized by higher amplitude and higher frequency deviations compared to downward cooling conditions in the summer. Results presented in figures 16, 17, and 18 confirm that these changes in the borehole temperature gradient resulted in a significant reduction in the cross-correlation of thermal deviation logs between sampling events. A comparison of the peak signal frequencies observed within the Vinemount and Ancaster between Feb-27, Mar-11 and Mar-24 (Figure 20) further confirms that these deviations are unrelated, with all logs exhibiting multiple mutually inconsistent low-frequency peaks ($<7 \text{ m}^{-1}$). This inconsistency in frequency content suggests that a portion of these signals are attributed to measurement noise.

Signal stationarity was only observed during downward warming conditions along the Niagara Falls Member and Gasport formation within the angled wells (Figure 15). Converse to that observed in the Vinemount Member, the Fourier spectra for the Gasport formation (Figure 20) shows three shared peaks below $7 \text{ m}^{-1}$, with no discernible peaks at higher frequencies. This implies that while the depth of thermal detection may increase during the cooler downward warming periods, these periods will be accompanied by higher amplitude noise predominantly contained within shallower portions of the borehole.

6.3 – Implications of Free Convection to Thermal Deviation Logs

The temporal characteristics of a borehole thermal profile were strongly dependent on seasonal temperature conditions. Field observations revealed a $20^\circ\text{C}$ temperature swing in the uppermost formation as the borehole water column transitioned from downward cooling in the summer to downward warming in the winter. The magnitude of vertical temperature gradients along the lined water column during downward warming periods far exceeded the threshold required to induce free-convection in a water column and was especially strong in the shallower portions of the borehole. Here, density-driven convection during the cooler winter period induced a thermal disequilibrium between the water column and adjacent formation water within the homothermic zone. Although thermal deviations were more readily detected due to an
increase in signal amplitude and frequency during these periods and also increased the
detection of deviations deeper in the profile, these signals were less stable than those observed
during the warmer summer periods. Elevated thermal deviations near surface are most likely
attributed to varyingly scaled convection cells (Sammel 1968; Borner and Berthold 2009) that
formed as the borehole water column temperatures approach 4°C. Therefore, inter-seasonal
datasets can be distinguished in terms of their non-stationary signal attributes. Time-series and
frequency analysis during these periods show that the formation of free convection cells will
ultimately limit the utility of a thermal deviation log in the near surface, yet increase the
maximum depth of detectable thermal deviations assuming temperature gradients no longer
exceed the critical Rayleigh number.

Free convection cells likely formed before Nov-13, when the thermal gradient exceeded
the critical value of 0.0042 °C/m (Figure 8). This coincides with a period of inconsistent cross-
correlations within the Vinemount Member. The occurrence of positive cross-correlation
amongst Nov-13, Nov-27, and Dec-12 datasets within the Ancaster Member indicates that
thermal gradients had not yet exceeded the critical thermal gradient threshold necessary to
initiate free convection at that depth. As seasonal temperatures decreased near surface, the
effects of free convection cells became more evident in the upper 10-12 m bgs. A marked
decrease in the cross-correlation within the Vinemount and Ancaster Members was observed
between January and April (Figure 15) as free convention began to interfere with signals
associated with ambient groundwater flow along fractures. These effects were also evident in
the intra-seasonal Fourier spectra comparison (Figure 21) that shows an increase in high-
frequency peaks during the colder winter months (i.e., January-March). Free convection
resulted in a marked increase in high-frequency noise, particularly near the surface in the
Vinemount unit.

Free convection cells increased the depth of detectable thermal deviations. While
obscuring the signals in shallower sections where thermal gradients exceed the critical value,
the disequilibrium induced by free convection cells deeper in the profile was more stationary.
The presence of mutually consistent frequency spectra within the lowermost Gasport relative to
the overlying Ancaster in Figure 20 indicates that thermal gradients in deeper sections did not
exceed the critical gradient. Instead, the induced disequilibrium deeper within the water column
was predominantly influenced by the contrast in borehole water column temperatures to
formation temperatures and varying hydraulic conditions that were previously undetected during
the warmer summer months. This interpretation is consistent with field observations by Cermak
et al. (2008a), who noted that temperature time-series collected in shallow monitoring wells have a propensity to exhibit intermittent, non-periodic oscillations that diminished with increasing depth. Subsequent numerical simulations by Cermak et al. (2008b) revealed that free convection cells could result in a thermally unstable water column and would be accompanied by complex thermal oscillations, confirming that the water column in a borehole can become unstable when the geothermal gradient exceeds the critical value. Ultimately this instability will result in the formation of cascading convection cells and a predominantly stochastic temperature signal.

Cermak et al. (2008b) identified the lack of strong horizontal thermal boundaries between convection cells as a cause for the cells’ mixing and the resultant non-periodic oscillating temperature signature, which means that mixing through free convection cells will likely be higher in the more densely vertical and horizontally fractured Vinemount and Ancaster Members, relative to the horizontally fractured Gasport formation. The lower frequency of high angle fractures (i.e., >10°) observed in the Gasport, in combination with the smaller thermal gradients, likely reduced the probability that hydraulic activity through these features would result in thermal boundaries across a non-horizontal plane within the water column. This is evidence that thermal deviation logs of geologic units with predominantly horizontal hydraulic activity during downward warming periods may exhibit more consistent thermal deviations in the presence of free convection cells, which may improve their utility for characterization.

The formation of free convection cells can both limit and enhance the interpretation of ambient temperature profiling in a lined borehole. Comparison of Fourier spectra with increasing depth during downward warming conditions (Figure 20) reveals the nature of non-stationary components of the temperature signals. This is most evident in the Vinemount and Ancaster Member, where large vertical temperature gradients and subsequent convection cells manifest in the form of a complex and chaotic spatiotemporal temperature response. These density-driven thermal signatures become superimposed over the ambient thermal gradient-driven response associated with the presence and movement of water along discrete fractures. However, deeper in the profiles where free-convection can only induce a slight to moderate thermal disequilibrium between the borehole fluid and formation due to the less variable temperatures and the attenuation of atmospheric conditions, the signals become more stable reflecting the static features of the flow system. Combined interpretation of stationary cooling downward and non-stationary warming downward profiles improves interpretability of thermal deviation logs. However, the filtration of free-convection noise from any single downward
warming log to reveal the ambient flow system response may be challenging given the similar frequency bands. Yet, ambient temperature profiling during these oscillatory periods may be the only way to characterize the deeper flow system that would otherwise be undetected during stationary downward cooling conditions.

6.4 – Identification of Hydraulically Active Zones Using Thermal Deviations

Given the relationship between intra-seasonal stability and the depth of detection, multiple thermal deviation logs from different seasons were used to identify hydraulically active zones along the entire borehole. Thermal deviation logs from September 4th, 18th, and October 3rd were used to characterize the Vinemount and Ancaster Members, while logs from February 27th, March 11th, and 31st were used for the Niagara Falls Member and Gasport formation (Figure 22). The fall thermal deviation logs were chosen for having multiple closely spaced sampling events showing repeatability or reproducibility of measurements, which improved confidence in the thermal deviations identified as resulting from hydraulic activity; however, there is evidence that the thermal deviation logs from summer had an increased depth of detection when compared to the fall. Based upon Figure 6, it would appear that closely spaced sampling events within a two week period following the warmest and coldest weeks of a year would provide the most complete data set for identifying hydraulic activity using ambient temperature trolling.

As an example data set, hydraulically active zones were identified in SCA3 (Figure 22). The upper 7 m of the Vinemount Member is differentiated into 3 contiguous hydraulically active zones. Within the uppermost 4 m, there is a single high amplitude deviation between 3 and 4 m bgs. This deviation coincides with two closely spaced fractures identified in both the core and ATV logs, which are likely hydraulically active. From 4 to 6 m bgs there are a series of small amplitude thermal deviations, relative to those in the rest of the log, that are indicative of multiple active fractures and align with ATV fractures that are near horizontal. It is also a zone of high fracture frequency. Due to the potential effects of superposition and the large number of identified fractures within this zone, it is difficult to associate individual thermal deviations with specific fractures; however, it is reasonable to assume that there multiple hydraulically active fractures with similar and lower magnitudes of flow. Lastly, there are two distinct peaks between 6 to 7 m bgs that correspond with the depths of two broken zones at 305 and 306 masl that are likely associated with hydraulic activity.
Within the lowermost 3 m of the Vinemount there is one identifiable peak in the thermal deviation log. Between 8 to 9 m bgs there is a wide peak of larger amplitude than those of the zone above it, likely indicating a more hydraulically active zone. Given the width of the peak and the number of fractures in the ATV and core logs at that depth, the hydraulic activity can most likely be attributed to multiple fractures with this 1 m zone.

There are three thermal deviations within the Ancaster Member, with the first occurring at approximately 10 m bgs just below the Vinemount-Ancaster contact. Due to the multiple fractures identified within this zone it is difficult to attribute the deviation to an individual fracture, but the short depth range does correspond with a zone of significant horizontal groundwater flow identified between 302 and 304 masl and discussed in Section 6.1. The other two deviations, located at 13 and 14 m bgs, both correspond with individual fractures detected within the ATV and core logs, and represent likely locations of groundwater flow.

Within the winter thermal deviation logs used for characterization of the Niagara Falls Member and the Gasport formation, there is a single deviation located at the Ancaster-Niagara Falls contact at approximately 14 m bgs which corresponds to a fracture within the ATV and core logs. However, other than that single deviation, there is little repeatability between logs within the Niagara Falls Member. Potentially a result of free-convection as discussed in Section 6.3, this lack of repeatability means that these thermal deviations cannot conclusively provide evidence of hydraulic activity within this Member.

The Gasport contains four distinct zones of hydraulic activity. One long, heavily fractured, and highly vuggy zone between 16 to 18 m bgs exhibits multiple low amplitude thermal deviations, indicative a multiple hydraulically active features along its reach that are too closely spaced to be individually identified. Between 20 to 21 m bgs there are three distinct peaks in thermal deviation that align with three fractures in the ATV log, indicating that each are likely hydraulically active. Another such peak indicative of an active feature is located at 22 m bgs. Lastly, at 24 m bgs there is a distinct thermal deviation peak that corresponds to an incomplete fracture that core logs identified as intact. Given that the zone is also moderately vuggy and the thermal deviations are consistent across all three logs used, there is strong evidence that there is groundwater flow occurring at this zone despite the lack of an open visual fracture.

Overall, thermal deviations from logs shown to be statistically similar proved an effective method of identifying zones of formation hydraulic activity. However, the limited depth
resolution inherent with temperature methods (~10 cm) and close spacing of features resulted in the inability to identify exact features in certain cases, in which only a zone of hydraulic activity could be determined.

6.5 – Bedrock Groundwater Flow System Conceptualization

Groundwater flow in fractured sedimentary rock can be highly heterogeneous depending on fracture orientations, frequencies, and apertures. Therefore, interpretation of thermal deviations logs collected in shallow environments over a wide range of conditions can provide additional insights in the dynamic and transient behaviour of groundwater flow systems. Quantitative evaluation of the attributes of a vertical thermal profile along a lined borehole can aid in the conceptualization of the depth-distribution of ambient flow paths, particularly in shallow environments where groundwater temperatures are more susceptible to atmospheric transients in temperature …. enhanced by evapotranspiration driven into the subsurface by thermal transport or facilitated by precipitation driven recharge to groundwater, surface water, and groundwater interaction due to hydraulic transients

The information gained from any single borehole will be dependent on its positioning and orientation with respect to the local fracture network. The Fourier spectra for each borehole during stable intra-seasonal periods (i.e., summer) show distinct peak frequencies for each lithostratigraphic defined geologic unit (i.e., no two boreholes displayed the same peak frequencies for a given geologic unit). This suggests that the position of a flow zone within a geologic unit varies between adjacent boreholes spaced 10s of metres apart. Figure 21 shows the inter-seasonal transients in peak frequency within the same geologic unit. Here, shifts in the peak frequency and the arrival of additional higher frequency modes were observed during the transition to cooler seasonal conditions. While high-frequency noise increased during the colder months due to the formation of free convection cells, the fact that low-frequency peaks in the deeper geologic units show fewer similarities suggests that hydraulically active zones are likely to vary depending on the seasonal conditions and predominant driving mechanism (i.e., seasonal recharge/discharge patterns).

The relatively more transient behaviour of thermal deviation within the angled boreholes suggests a stronger vertical component across the system compared to the nearby or adjacent vertical borehole profiles. Further, the absence of an ice layer within the water columns of the angled boreholes, yet its presence in all the vertical boreholes despite similar vertical depths, supports a substantive difference in the intersected or sampled hydrogeologic flow regime. The
angled boreholes also have a larger effective diameter (relative to the gravitational vector), which lowers the critical thermal gradient, and thus, makes them slightly more susceptible to the formation of free convection cells, mitigating the formation of an ice layer at the top of the water column. However, the difference in critical thermal gradient is relatively small (i.e., 0.0032 °C/m) (refer to Figure 8) and is likely a second order effect compared to the intersection of a higher number of vertical fractures facilitating vertical water movement across this high thermal gradient zone (Table 2).

Table 2 shows a higher frequency of high-angle fractures within the Vinemount and Ancaster Members along the angled boreholes, supporting the likelihood of intersecting additional hydraulically active vertical and sub-vertical fractures, and thus, increasing the effective thermal capacity of the water column. If groundwater flow were predominantly horizontal, the angled boreholes would have most likely frozen as did their vertical counterparts as the thermal stratigraphy of the water columns would have been the same. Therefore, the absence of borehole freezing in the angled borehole, all of which intersected vertical and sub-vertical fractures, supports the conceptualization that vertical groundwater flow represents a significant component of the 3D flow system. Figure 23 illustrates two potential interpretations of the ambient flow field based upon thermal deviation from a vertical and an angled well collected over a complete annual cycle.
Conclusions

The utility of time-lapse ambient groundwater temperature profiles, collected across a network of vertical and angled boreholes sealed with FLUTE™ liners for characterization of shallow groundwater flow systems in seasonally dynamic environments, was evaluated through an analysis of time-lapse thermal deviation logs. A combination of time-series and frequency spectra analyses was used to assess changes in thermal deviation signals over a complete annual cycle.

Although a portion of the thermal deviation logs were variably impacted by the formation of free-convection cells within the borehole water column depending on the magnitude of the seasonal thermal gradient, stable thermal deviations were generally consistent across 2-3 profiling events with the position of discrete flow based on the lithological, geophysical, and hydraulic information collected within each borehole. Seasonal transience observed in thermal deviations logs were largely attributed to density-driven mixing of the borehole water column, which led to short-period thermal disequilibrium between the fluids in the water column and the ambient groundwater temperatures. Although this temporarily limited interpretability of thermal deviations close to surface, it enabled detection of flow features within the deepened heterothermic zone. As a result, a combination of logs taken within the two weeks following the hottest and coldest weeks of the year were the most effective as characterizing an entire borehole.

The statistical analysis of time-lapse thermal deviation logs proved useful for the discrimination of fracture and atmospherically induced thermal deviations, providing a diagnostic measure for the analysis of time-lapse data, and qualitatively describing the inter- and intra-seasonal impacts of the shallow flow system on the temperature measurements. Ambient temperature profiles proved effective at identifying ambient groundwater flow locations in fractured sedimentary rock during periods of intra-seasonal stability. Combined with geophysical and core logs, thermal deviation logs aided in the identification of pertinent flow features and assessment of relative changes in hydraulic activity, including areas of medium to high vugginess without the added contribution of borehole cross-connection or violation of natural flow system conditions. There was also strong evidence of a significant vertical groundwater flow component within the upper 8 m of the angled boreholes that is consistent with the presence of a dynamic groundwater-surface water system adjacent to the borehole network.
Free convection with the liner water column was commonly associated with periods of non-stationarity and poses a major limitation to ambient temperature methodologies. However, the statistical framework employed here effectively defined the lateral extent and enabled a lithologic classification of thermal transients associated with groundwater flow features. When applied to an integrated network of boreholes of varying depths and orientations with respect to the regional fracture network, cross-correlation and frequency analysis of time-lapse thermal profiles proved to be an effective diagnostic tool that increased confidence in the interpretation of thermal deviation logs under both periods of stability and transience.

Though the utility of ambient temperature profiling in sealed boreholes is promising, several improvements to the methodological and analytical techniques presented herein would increase the interpretability and ultimately the utility of a temperature log in any hydraulically and thermally dynamic environment. Identification of high-frequency noise arising from free convection within the water column and subsequent removal of this signal based on a comparison with more stationary periods might improve interpretation of gradient-driven thermal signals associated with discrete fracture networks. This could further increase the utility of ambient temperature profiling methods in lined boreholes using wireline methods, stationary depth-discrete sensors, or continuous DTS cables. Regardless of the method used to characterize the groundwater flow system, the statistical analysis of high-resolution time-lapse temperature data sets enables detection and quantification of flow system transients deeper in the system and the varying effects of free-convection along the water column. More frequent sampling over the course of a calendar year would also improve the method’s ability to differentiate between single isolated events (i.e., major recharge events) and seasonal trends within the shallow subsurface. Such data would aid in the conceptualization of groundwater-surface water interactions as they vary throughout the seasons and better assess the impacts of changes in atmospheric conditions have on shallow groundwater thermal transients.
Table 1: Borehole summary at Barber Scout Camp, Guelph ON.

<table>
<thead>
<tr>
<th>Well ID #</th>
<th>Azimuth</th>
<th>Diameter (m)</th>
<th>Length (m)</th>
<th>TVD (mbgs)</th>
<th>Contacts (masl)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vinemount - Ancaster</td>
</tr>
<tr>
<td>SCV1</td>
<td>vertical</td>
<td>0.0757</td>
<td>24.5</td>
<td>24.5</td>
<td>303.3</td>
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<tr>
<td>SCV2</td>
<td>vertical</td>
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<td>24.4</td>
<td>303.2</td>
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<tr>
<td>SCV3</td>
<td>vertical</td>
<td>0.0757</td>
<td>32.3</td>
<td>32.3</td>
<td>302.9</td>
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<tr>
<td>SCA1</td>
<td>340°</td>
<td>0.0757</td>
<td>36.8</td>
<td>31.9</td>
<td>302.4</td>
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<tr>
<td>SCA2</td>
<td>50°</td>
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<td>27.4</td>
<td>23.8</td>
<td>301.5</td>
</tr>
<tr>
<td>SCA3</td>
<td>185°</td>
<td>0.0757</td>
<td>36.7</td>
<td>31.8</td>
<td>302.3</td>
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</table>
Table 2: Fracture summary of each borehole based on core and ATV logs.

<table>
<thead>
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<th>ATV</th>
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<td></td>
<td>Count</td>
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<td>2</td>
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<tr>
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<td>6</td>
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<td>49</td>
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<tr>
<td>Ancaster</td>
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<td>9</td>
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<tr>
<td>Niagara Falls</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>Gasport</td>
<td>10</td>
<td>31</td>
</tr>
</tbody>
</table>
Figure 1: Vertical temperature profile showing seasonal variations with respect to geothermal gradient. Cooling downward will occur in warmer summer months when temperatures at depth remain cool and shallower temperature warm in response to atmospheric conditions, while warming downward will occur in colder winter months, where shallower temperatures are affected by colder atmospheric conditions. Surface warming and cooling cycles create oscillations in the thermal profile which define the vertical extent of the heterothermic zone. The homothermic zone is equal to the geothermal gradient and is not influence by seasonal dynamics. The transition from heterothermic to homothermic conditions may vary depending on the season and site conditions. In shallow groundwater, the homothermic zone will be demarcated by a uniform temperature equal to the average annual temperature, while deeper groundwater will exhibit a gradual temperature increase with depth.
Figure 2: Schematic diagrams of an ambient groundwater flow field and associated thermal deviation signatures along a sealed borehole a) without the presence of free-convection and b) with free convection due to a strong vertical temperature gradient (modified from Borner & Berthold 2009). Hydraulic head is denoted by ‘p’, while temperature is denoted by ‘t’.
Figure 3: Proposed stratigraphy of the Region of Guelph in Ontario. The Vinemont Mbr of the Eramosa Formation, Goat Island and Gasport formations were observed in the rock core obtained from SCV and SCA boreholes (modified from Brunton et al. 2009).
Figure 4: Bedrock River Research Station located in Guelph, Ontario, Canada, along the Eramosa River, showing the location of six continuously cored boreholes.
Figure 5: Summary of precipitation, air temperature, river flow, and temperature trolling sampling events at the Bedrock River Research Station. Wireline temperature trolling included vertical (circles) and angled (triangles) wells. Vertical boreholes (SCV1, SCV2, and SCV3) were not profiled during the winter months (January through April) due to the formation of a layer of ice at the top of the water column.
Figure 6: Summary of the distribution of wireline ambient temperature trolling events within each season (i.e., spring, summer, fall, and winter) and the weekly average temperature. Sampling events in bold were used for identification of hydraulically active features.
Figure 7: Schematic representation of 1) temperature trolling and 2) a temporary deployment installation using FLUTe™ liner with monitoring intervals at depths i, ii, iii, & iv. Trolling and temporary deployments were applied to both angled (1) and vertical (2) boreholes. Figure not to scale.
Figure 8: The critical Rayleigh number for dolostone given geologic conditions is 171 based on site-specific thermal conductivity measurements. The critical gradients for vertical and angled wells are 0.0074 and 0.0042 °C/m, respectively.
Figure 9: Raw temperature profile with corresponding deviation log collected from SCA1 on September 18, 2014. High-frequency variations are enhanced by removing the low-frequency seasonal and geothermal gradient.
Figure 10: Effects of varying window size (low-pass filter) on the deviation log. A 1 m window size was selected based on its enhancement of high-frequency signals and removal of low-frequency noise.
Figure 11: Core logs, geophysical logs, and transmissivity profiles for vertical boreholes SCV2, SCV1, and SCV3. Note: an OTV log was not collected for SCV3. Laterally continuous zones of high transmissivity are located at contacts between 1) the Vinemount (V) and Ancaster (A) Members, 2) the Ancaster (A) and Niagara Fall (NF) Members, 3) the Niagara Falls (NF) and Gasport (G), and 4) at a dissolution enhanced feature. Feature log, ATV, and OTV features are differentiated by colour with orange representing complete fractures, blue for incomplete fractures, pink for a broken zone, purple for aligned voids, and grey for large isolated voids. ‘Fx Count’ is the cumulative fracture count, ‘FLUTe Cum. T’ is the continuous FLUTe transmissivity profile, and ‘FLUTe T’ is the FLUTe derived transmissivity for specific intervals.
**Figure 12:** Core logs, geophysical logs, and transmissivity profiles for angled boreholes SCA2, SCA1, & SCA3. Depths are in true vertical depth (TVD), the vertical distance from the wellhead. Note: an OTV log was not collected for SCV3. Laterally continuous zones of high transmissivity are located at the contacts between 1) the Vinemount (V) and Ancaster (A) Members, 2) the Ancaster (A) and Niagara Fall (NF) Members, 3) the Niagara Falls (NF) and Gasport (G), and 4) at a dissolution enhanced feature. Feature log, ATV, and OTV features are differentiated by colour with orange representing complete fractures, blue for incomplete fractures, pink for a broken zone, purple for aligned voids, and grey for large isolated voids. ‘Fx Count’ is the cumulative fracture count, ‘FLUTe Cum. T’ is the continuous FLUTe transmissivity profile, and ‘FLUTe T’ is the FLUTe derived transmissivity for specific intervals.
Figure 13: Vertical head profiles collected across the vertical and angled borehole network on June 1st, 2014 (0:00) in red. Data from June 4th, 2014 (0:00) are not visible, as June 1st data overlaps. Depths are in true vertical depth (TVD), the vertical distance from the wellhead.
Figure 14: Raw temperature profiles with corresponding thermal deviation logs from SCV1. The shaded region superimposed behind the deviation logs represents the seasonal thermal gradient associated with the raw temperature profile, i.e., cooling (negative) versus warming (positive) downward. (△) indicates a point of thermal inflection (reversal in thermal gradient) with those pointing down representing a transition from a positive to a negative gradient and those pointing upward representing a transition from a negative to a positive gradient. (−) indicates the maximum depth of detected thermal deviations.
Figure 15: Raw temperature profiles with corresponding thermal deviation logs from SCA1. Depths are in true vertical depth (TVD), the vertical distance from the wellhead. The shaded region superimposed behind the deviation logs represents the seasonal thermal gradient associated with the raw temperature profile, i.e., cooling (negative) verses warming (positive) downward. (Δ) indicate a point of thermal inflection (reversal in thermal gradient) with those pointing down representing a transition from a positive to a negative gradient and those pointing upward representing a transition from a negative to a positive gradient. (—) indicates the maximum depth of detected thermal deviations.
Figure 16: Comparisons of cross-correlation between thermal deviation logs in SCV1 and SCA1 for each lithologic unit. Blue squares indicate positive correlation, red squares indicate negative correlation, while white regions indicate no statistically significant correlation (\(p > 0.01\)). Grey regions indicate data was not collected at that time.
**Figure 17:** Comparisons of cross-correlation between thermal deviation logs in SCV2 and SCA2 for each lithologic unit. Blue squares indicate positive correlation, red squares indicate negative correlation, while white regions indicate no statistically significant correlation (p > 0.01). Grey regions indicate data was not collected at that time.
**Figure 18:** Comparisons of cross-correlation between thermal deviation logs in SCV3 and SCA3 for each lithologic unit. Blue squares indicate positive correlation, red squares indicate negative correlation, while white regions indicate no statistically significant correlation ($p > 0.01$), and grey indicates data was not available from that specific sampling event.
Figure 19: Comparison of thermal deviation frequency spectrums from a) vertical and b) angled boreholes within the uppermost Vinemount Member on Sep-4, Sep-18, and Oct-3 2014. Similar peak frequencies were identified at each location during this one month period with slightly more variable spectra observed within the vertical boreholes. No significant frequency peaks occurred between 20 and 50 1/m.
Figure 20: Lithologic comparison of thermal deviation frequency spectrums from SCA3 on Feb-27, Mar-11, and Mar-24, 2015. Each lithologic unit exhibits a distinct frequency distribution during the one month period. Frequency spectrums were relatively more variable in the uppermost Vinemount and Ancaster units. No significant frequency peaks occurred between 20 and 50 1/m.
Figure 21: Inter-seasonal comparison of thermal deviation frequency spectrums on Sep-4, Nov-27, and Mar-24 across each lithologic unit in SCA3. Spectrums reveal seasonal variability in the number, range, and amplitude of peak frequencies dependent on lithologic type. No significant frequency peaks occurred between 20 and 50 1/m.
Figure 22: Core logs, geophysical logs, transmissivity profiles, and thermal deviation logs for hydraulically active feature delineation for SCA3. Depths are in true vertical depth (TVD). Feature logs and ATV features are differentiated by colour with orange representing complete fractures, blue for incomplete fractures, pink for a broken zone, purple for aligned voids, and grey for large isolated voids. ‘Fx Count’ is the cumulative fracture count, ‘Fx Freq.’ is the fracture frequency per meter, ‘FLUTe Cum. T’ is the continuous FLUTe transmissivity profile, and ‘FLUTe T’ is the FLUTe derived transmissivity for specific intervals. Thermal deviation logs from September 4th, 18th, and October 3rd are used for delineation of hydraulic activity in the Vinemount and Ancaster Members. Thermal deviation logs from February 27th, March 11th and 24th from cross-correlation are used for delineation of hydraulic activity in the Niagara Falls Member and Gasport formation using Fourier analysis. These hydraulically active zones are identified by the black bars on the far right.
Figure 23: Comparison of groundwater flow field conceptualization based on interpretation of thermal deviation logs within a lined borehole of vertical and angled orientation. Angled boreholes intersect a higher numbers of high-angle fractures, which improves detection of both static (fracture) and dynamic (flow) elements. Seasonal effects upon thermal deviation logs are also depicted, with the depth of detection increasing during seasons with higher atmospheric-groundwater temperature contrasts and resolution decreasing with the presence of free convection in the winter months. The numbers identify individual hydraulically active zones and how their respective thermal deviation logs would vary seasonally: 1) depicting the increased noise due to free convection in the winter months, 2) remaining stable throughout the year, 3) a deviation only observed during the summer and winter months when the atmospheric and average groundwater temperatures have the highest contrast, and 4) where a thermal deviation is observed only when free convection increases the depth of detection during the winter months. Fracture networks are based upon core and geophysical logging for the Vinemount Member (V), Ancaster Member (A), Niagara Falls Member (NF), and the Gasport formation (G).
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9.0 – Appendices

Appendix A: Pressure Transducer Normalization

1.0 Major Assumptions

1.0.1 A transducer is measuring the change in pressure accurately, but the comparison of transducers is uncertain due to possible offsets.
1.0.2 The correction factor calculated for an RBR does not change in response to varying pressure or temperature.
1.0.3 No drift is occurring over the time of the RBR’s deployment.

1.1 Normalization Procedure

1. Prior to deployment, leave all the RBRs recording at one second intervals in the same location such as the lab. Isolate them and avoid direct sunlight or other factors that may influence the pressure of an individual RBR relative to the rest of the group.
2. Leave the RBRs undisturbed for an entire day. Record the start and end time.
3. After the data has been downloaded from the RBRs, use the start and end times previously recorded to isolate the desired interval for normalization.
4. Plot the pressure data from each individual RBR on the same graph.
   4.1 This plot should serve as a visual validation of Major Assumption 1.2.1; where all transducers follow the same changes in barometric pressure, but their absolute pressure readings differ.
5. Calculate an arithmetic mean of all the RBRs as well as the standard deviation for said mean.
6. Determine if any RBR falls outside of one standard deviation of the mean. If any are, recalculate the arithmetic mean without the data from these RBRs.
7. To minimize the noise in the arithmetic mean value, calculate a 5-point sliding average.
8. Subtract the 5-point sliding average of the mean from an individual RBR. This will give the difference between what the individual RBR and the mean RBR values were for every recording interval within the isolated window.
9. Take the average of this difference from the mean to obtain a single value, the correction factor.
10. Repeat the above two steps for each individual RBR, including any that were removed from the arithmetic mean calculation.

11. Apply the correction factor to the entire data set of an individual RBR to ensure that any comparisons made between RBRs are normalized relative to one another.
   11.1 To ensure this had been conducted properly, apply the correction factor to its respective RBR for the isolated time interval over which it was calculated. The correction factor should cause all the data to converge to a single value. The small scale variability can be attributed to the noise.

12. For quality assurance, the procedure should be conducted after RBR deployment has finished as well. Once the RBRs have been removed, prior to stopping recording, the RBRs should again be isolated in a lab and left undisturbed for an entire day.
   12.1 The sampling rate may be different than the one second intervals used to calculate the first correction factors. In cases of larger interval spacing, isolating the RBRs for more than a day is preferable.

13. Calculate the correction factors for each RBR using this period and compare the results to the correction factors calculated prior to deployment.
   13.1 Differences between calibration factors are possible indicators of Major Assumptions 1.2.2 and 1.2.3 being violated.
Appendix B: R Code for Statistical Analyses

(I) Correlation Analyses

#Select directory
setwd("C:/Users/Donovan/Google Drive/Scout Camp Thesis/R/SCA1")

#Select name of file and headers
df <- read.csv("SCA1TP.csv", header = TRUE)
Jun23 <- df[,2]
Jun25 <- df[,3]
Sep4 <- df[,4]
Sep18 <- df[,5]
Oct3 <- df[,6]
Oct17 <- df[,7]
Nov13 <- df[,8]
Nov27 <- df[,9]
Dec12 <- df[,10]
Jan9 <- df[,11]
Mar11 <- df[,12]
Mar24 <- df[,13]
Mar31 <- df[,14]
Apr14 <- df[,15]
May22 <- df[,16]
whole <-
data.frame(Jun23,Jun25,Sep4,Sep18,Oct3,Oct17,Nov13,Nov27,Dec12,Jan9,Mar11,Mar24,Mar31,Apr14,May22)

#Open library containing correlation plot data visualization functions
library("corrplot")
library("Hmisc")

#Vinemount Member
a <- whole[1:721,]

#Vinemount Correlation Plot
cor3 <- rcorr(as.matrix(a))
corrplot(cor3$r, mar=c(1,1,2,1), type="upper", order="original", tl.col="black", tl.srt=45,
p.mat=cor2$p, sig.level=0.01, insig=c("blank"))

#Ancaster Member
b <- whole[722:1091,]

#Ancaster Correlation Plot
cor4 <- rcorr(as.matrix(b))
corrplot(cor4$r, mar=c(1,1,2,1), type="upper", order="original", tl.col="black", tl.srt=45,
p.mat=cor2$p, sig.level=0.01, insig=c("blank"))

#Niagara Falls Member
c <- whole[1092:1411,]
# Niagara Falls Correlation Plot
cor5<-rcorr(as.matrix(c))
corrplot(cor5$r, mar=c(1,1,2,1), type="upper", order="original", tl.col="black", tl.srt=45,
p.mat=cor2$p, sig.level=0.01, insig=c("blank"))

# Gasport Formation
d <- whole[1412:1802,]

# Gasport Correlation Plot
cor6<-rcorr(as.matrix(d))
corrplot(cor6$r, mar=c(1,1,2,1), type="upper", order="original", tl.col="black", tl.srt=45,
p.mat=cor2$p, sig.level=0.01, insig=c("blank"))

(II) Fourier Transforms

# Select directory
setwd("C:/Users/Donovan/Google Drive/Scout Camp Thesis/R/SCV1")

# Select file to read in
df <- read.csv("SCV1TP.csv", header = TRUE)

# Name each thermal deviation log
Jun23 <- df[,2]
Jun25 <- df[,3]
Sep4 <- df[,4]
Sep18 <- df[,5]
Oct3 <- df[,6]
Oct17 <- df[,7]
Nov13 <- df[,8]
Nov27 <- df[,9]
Dec12 <- df[,10]
Jan9 <- df[,11]
Feb27 <- df[,12]
Mar11 <- df[,13]
Mar24 <- df[,14]
Mar31 <- df[,15]
Apr14 <- df[,16]
May22 <- df[,17]

# Gets the frequencies returned by the FFT function
getFFTFreqs <- function(Nyq.Freq, data)
{
  if ((length(data) %% 2) == 1) # Odd number of samples
  {
    FFTFreqs <- c(seq(0, Nyq.Freq, length.out=(length(data)+1)/2),
                 seq(-Nyq.Freq, 0, length.out=(length(data)-1)/2))
  }
  else # Even number
  {
  


FTTFreqs <- c(seq(0, Nyq.Freq, length.out=length(data)/2),
    seq(-Nyq.Freq, 0, length.out=length(data)/2))

return (FTTFreqs)

#Pads deviation log with trailing zeroes
pad <- function(X){
  N = length(X)
  append(X,rep(0,910-N),after=N)
}

#Normalize amplitude and plots FFT
library(zoo)
plot.fft.ma <- function(X,Y,Z){
  padX <- pad(X)
  testX <- fft(padX)
  rX <- Mod(testX)
  mX <- rollmean(rX,5)
  mXn <- mX/max(mX)

  padY <- pad(Y)
  testY <- fft(padY)
  rY <- Mod(testY)
  mY <- rollmean(rY,5)
  mYn <- mY/max(mY)

  padZ <- pad(Z)
  testZ <- fft(padZ)
  rZ <- Mod(testZ)
  mZ <- rollmean(rZ,5)
  mZn <- mZ/max(mZ)

  Nyq.Freq <- 50
  FFTFreqs <- getFFTFreqs(Nyq.Freq, mXn)

  plot(FFTFreqs[1:906/2],mXn[1:906/2], xlim=c(0,20),ylim=c(0,1),type="l", xlab="Frequency (1/m)",ylab="Normalized Amplitude",col="red",xaxs="i",yaxs="i")
  lines(FFTFreqs[1:906/2],mYn[1:906/2],col="blue")
  lines(FFTFreqs[1:906/2],mZn[1:906/2],col="forestgreen")
  abline(h=0.1,col="black",lty=2)
  legend(12,0.9,c("Sep4","Sep18","Oct3"),lty=c(1,1,1),col=c("red","blue","forestgreen"))
}

#Export FFT Figure
png(filename="Figure 19 - SCV1.png",width=5,height=5,units="in",res=1152,type = c("windows",
"cairo", "cairo-png"),antialias="cleartype")
plot.fft.ma(Sep4[1:720],Sep18[1:720],Oct3[1:720])
dev.off()
Appendix C: Temperature Profiles and Thermal Deviations Logs (SCV2, SCV3, SCA2, and SCA3)