The Potential for Compromised Interpretations When Based on Open Borehole Geophysical Data in Fractured Rock.

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It has long been recognized that open boreholes in rock can have substantial vertical flow from one fracture to another. This flow (vertical short circuiting) can influence geophysical logs, particularly fluid resistivity and temperature. Yet the hydraulic cross-connection is relied on by borehole flow meters (i.e. heat pulse, EM and impellers) to locate the zones of highest apparent transmissivity. These results are often used to plan other forms of testing such as straddle packers, design multilevel monitoring systems and support a conceptual model of the groundwater flow.

A literature review and our own logging data in fractured sedimentary rock indicate that rarely are more than 3 or 4 primary flow zones identified in open boreholes. Pehme et al (2007) present a comparison of high resolution (0.001ºC) temperature logging measured in an open borehole and in the same borehole with a FLUTe liners installed to prevent cross-connection and maintain that the logs collected within these liners represent the thermal stratification of the surrounding rock uncompromised by artificial vertical flow along the borehole, and reflect the natural ambient groundwater flow in the fractures.

Here we discuss the assumptions underlying these claims are and examine potential compromises of the interpretation from convection. We find that the results from these lined borehole temperature log interpretations are more consistent with complementary data (such as rock core contamination analysis, packer testing and geologic logging) than their open hole counterparts. A comparison of temperature logs collected in open and lined boreholes show that the vertical water movement can mask flow zones critical to the understanding of the hydraulically active fracture network and in some cases the key zones identified from open-hole logging (temperature and flow metering) are not the most hydraulically active fractures in the aquifer under natural conditions. In these cases open-hole characterization has not only created the potential redistribution of geochemistry and contamination but also resulted in erroneous interpretations of the flow distribution in the natural system.

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It is generally accepted that a borehole drilled through fractured rock will provide a short circuit to facilitate direct flow between fractures or hydrostratigraphic zones that in many cases would be hydraulically isolated under natural (ambient) conditions. Borehole flow is used to advantage when measurements with flowmeters (heat pulse, impeller, etc.) are made to identify the hydraulic contributions of various fractures (Paillett 1999). In some cases, when the flow is not adequate to characterize fractures, the system is pumped to enhance water movement. For other hydrophysical techniques such as FEC logging (Tsang et al. 1990), horizontal flow meters (Williams 2002) and for geophysical logging techniques such as temperature (Drogue, 1985), the cross-connected flow through the borehole can compromise the interpretation of the data.

Pehme et al, (2007) compare high resolution (<0.001 C°), high density (5-10mm) temperature logging data collected in and out of liners at four fractured rock study sites (Santa Suzana, California; Madison, Wisconsin; Cambridge and Guelph, Ontario). They show that the vertical flow in open boreholes can overshadow the response from hydraulically significant fractures and that temperature logs measured within a FLUTe lined (a removable borehole sleeve) borehole reflect ambient temperatures within the formation, allowing a direct comparison with open-hole temperature logs made with the sleeve removed. We present the underlying concept of how the ambient temperature is measured, the key factors in it's success and potential pitfalls to the interpretation.

The most striking of several examples Pehme et al. present comes from borehole UW1, a 150 meter deep borehole drilled a through dolostone in Cambridge Ontario (Johnson et. al. 1992). In Figure 1, temperature logs (two collected approximately a month apart) measured in the open borehole and heat-pulse flowmeter data are compared with rock core analysis, packer test results and geologic/structural logging of core (Parker et al. 2007, Burns 2002). The TCE contamination is from off site and rock core analysis represents migration along regional pathways, while the metalochlor could only have arrived from a source near the borehole and therefore indicates localized fracture flow.

Figure 1 highlights a recurring observation in the over 25 boreholes distributed between the four sites investigated with these techniques. There is a level of detailed complexity and variability in the rock core analysis and geologic/structural logging of core as well as in the packer testing that is generally absent in the open hole temperature logs and heat-pulse data. In this case the temperature logs are dominated by a near-uniform, linearly varying thermal gradient between 280 and 230 masl. For example, note the absence of any significant signature in the open hole temperature logs from the hydraulically active and contaminated zones at both 270 and 254 masl.

Heat-pulse flowmeter testing, conducted each meter up the borehole provides a similar response to the open temperature logs. No interpretable results were collected above 239 metres, either the traces were flat or too irregular to distinguish a pulse. Below 239 metres the downward flow decreases in each progressively deeper test. There exist a number of distinct declines in flow that coincide with some of the zones of elevated hydraulic conductivity and/or elevated rock core contaminant levels.

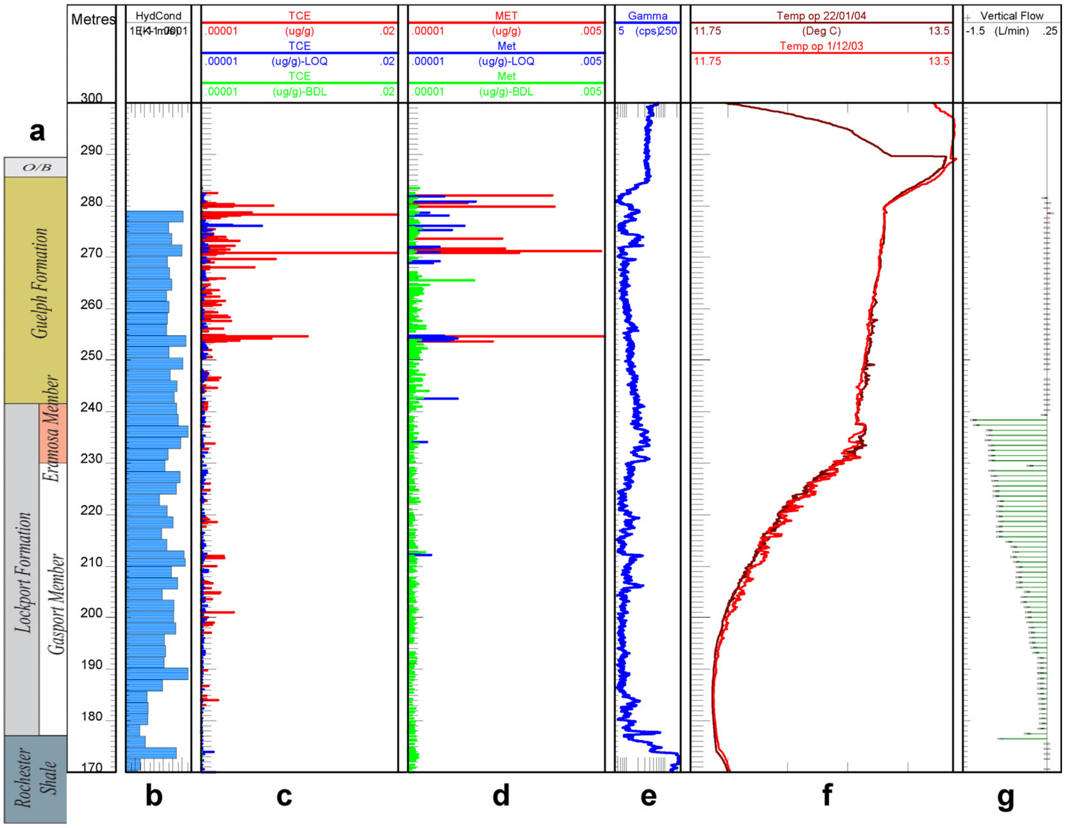

Figure 1: UW1 open hole data showing **(a)** the stratigraphic column, **(b)** hydraulic conductivity from packer testing, **(c&d)** TCE and Metalclor rock core analysis (red – quantifiable, blue low order quantification and green-below detection limit), **(e)** gamma log, **(f)** (open boreholes on 1/12/2003 and 22/01/2004, **(g)** heat pulse flow meter (note no pulse differentiated above 238 masl.) (columns a, b, c and d from Burns 2002), (adapted from Pehme et al. 2007)

The borehole was subsequently lined with a FLUTe liner, a thin, water inflated polyurethane coated nylon sleeve designed to avoid cross-contamination by way of vertical flow along the borehole. Pehme et al.(2007) show that temperature logs collected within a liner typically display a much more complex thermal pattern than in the open hole. The lined hole data correlates much better with the individual zones of increased contamination in the rock core, the patterns of hydraulic conductivity in the packer testing, and the overall complexity observed in these other forms of data. The interpretation of the temperature data is considerably enhanced when several logs are collected over a period of weeks or months and the temporal variations are used to interpret change over time.

Figure 2 (adapted from Pehme et. al, 2007) compares temperature data collected within a liner at UW1 to the data shown in Figure 1. The zone of linearly varying temperature described in the open hole data has included the most dynamic zone (253-260 masl) intersected by the borehole which is also a zone of high hydraulic conductivity that has highly elevated levels of rock core contamination. Note that two zones of high hydraulic conductivity identified by packer tests at 254 and 236 masl are marked by

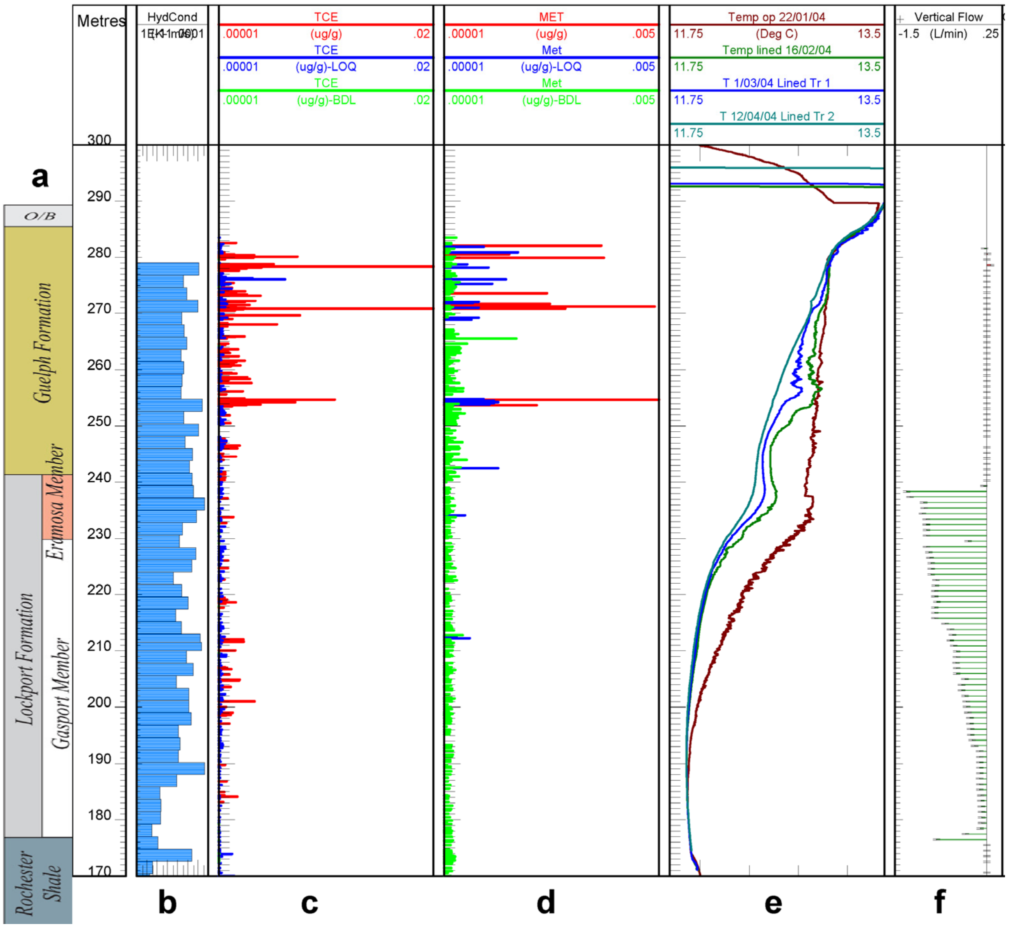

Figure 2: UW1 Data with the addition of temperature data in lined borehole. Columns as in Figure 1, with **e)** showing passive temperature logs collected in the lined hole from left to right 12/04/04, 1/03/04, 16/02/04 and the open borehole on 22/01/2004. (also adapted from Pehme et al., 2007)

strong positive temperature anomalies on the lined hole logs, and that these anomalies change amplitude with time. This convincing evidence for horizontal flow in these zones is not present on the open hole records. A shallower zone of contamination (270masl) also manifests as a distinct perturbation in the lined hole temperature logs.

Pehme et al. conclude that the temperature logs and heat-pulse data collected in open holes are compromised by the vertical flow that masks the ambient thermal stratification apparent in the data collected within the liner. Interpretation of the open hole data tends to lead towards an over simplified model and the correlation of the broader data sets are much more consistent when using the temperature logs collected in the liner.

Figure 3a is a schematic representation of a fractured rock sequence where two geologic layers of relatively high permeability are hydraulically separated by a less permeable unit. It does not matter whether the porosity and permeability is primary (matrix) or results from secondary (fractures or dissolution) effects. In the case of a fractured dolomite, there might exist within the upper and lower unit several fractures of varying

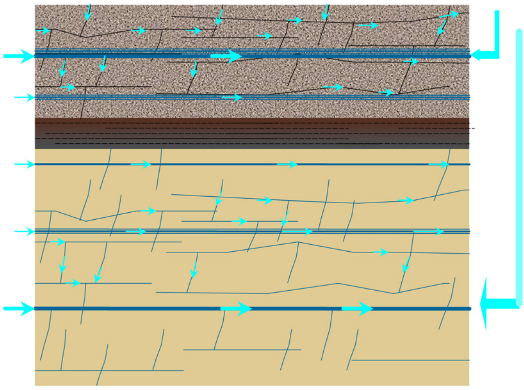

Figure 3a A schematic geologic sequence without borehole

hydraulic conductivities facilitating groundwater flow according to their size, but with the shallow fractures hydraulically isolated from the deeper ones by the impermeable layer.

Drilling a borehole through the sequence connects the upper and lower layers, violating the unit that provides the hydraulic isolation, facilitating downward water flow through the annulus of the borehole in this example. The sources and sinks for this local flow system will be either the matrix or the fractures, each contributing according to their head and effective permeability.

If the near surface temperature was warmer than that occurring at the bottom of the borehole a temperature log such as shown in Figure 3b would be expected. The temperature of the water moving down the open borehole from the upper large fracture would dominate the thermal profile. The water would lose thermal energy to the formation at a rate proportional to the thermal conductivity of the formation and the temperature gradient. The downward flow would replenish the borehole with warm water from above. The linear portion of the temperature will continue to the deepest significant fracture. Only minor variations in the steady trend occur at fractures between the upper and lower fractures, having amplitudes often unrelated to their contribution to ambient flow.

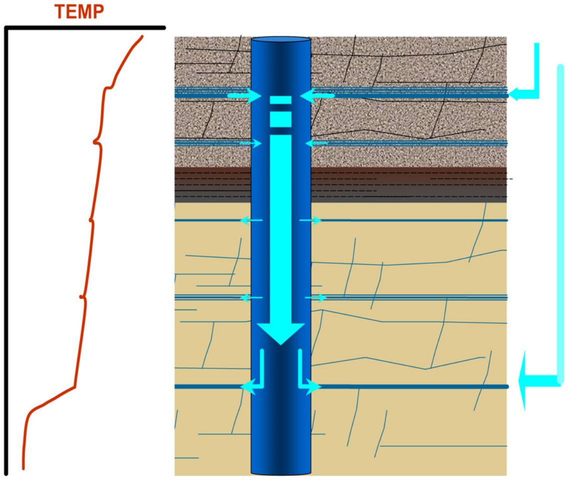

Figure 3b: Schematic of geologic sequence with borehole and anticipated temperature log. Arrows indicate water low into down and out of the borehole.

Figure 3c adds a liner system to seal the borehole. The water flowing in the fractures is forced to flow around the liner and none is allowed down the borehole annulus. Since there is no head difference within the liner, the water inside is stagnant. The water within the liner thermally equilibrates with the surrounding formation a few days after installation. Overall the temperature profile would be essentially that occurring "naturally" in the rock as if the borehole didn't exist. At each fracture we expect to measure a temperature very similar to that within the fracture adjacent to the borehole, for example the green trace in Figure 3c.

A subtle but important ramification of this model is that an interpretation of the depth of active flow and the significance of fractures made from temperature logs in an open hole can depend on the depth of that borehole. For example, if the borehole were not drilled as deep a fracture higher in the formation would become the dominant sink, or alternatively if the hole extended slightly deeper than a another major exit point for the vertical flow could be intersected and the currently dominant fracture appear insignificant. In either case very different interpretations might result. This would not be the case in a lined borehole.

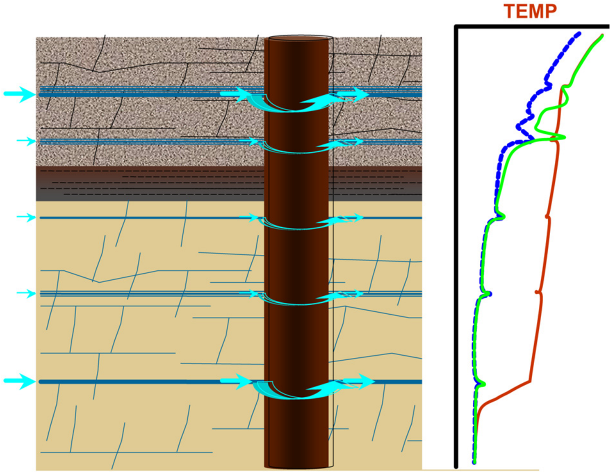

Figure 3c: Expected temperature profile in the open (red) and FLUTe lined borehole (green) and subsequent variability (blue dashed).

As Figure 2 shows, temperature logs can vary with time. Daily and seasonal changes in atmospheric temperature create a zone of thermal variability in the upper 10 to 15 metres of the earth (i.e. the near surface). The short-term daily cycles have a shallow influence and longer term (winter – summer) changes a deeper effect. Other factors that control either the surface temperature or the thermal conductivity of the subsurface contribute to the degree of this variability. For example we have observed that boreholes drilled through asphalt parking lots tend to be warmer near the surface than those in a grassed area, presumably due to preferentially solar warming of the blacktop and boreholes close to buildings warmer than those further away.

The premise that water movement through fractures can be detected by way of temperature log variations with time relies on changes in temperature of the moving water. More hydraulically active fractures can be expected to move more water, and changing water temperatures will be reflected in the surrounding rock.
If water flow along the borehole annulus is eliminated with a liner, repeated temperature logging over periods of days or weeks would be expected to show changes where the rock is thermally variable and, by inference, hydraulically dynamic. An example of the type of change anticipated is shown schematically as the difference between the green and blue temperature logs in Figure 3c.

The depth to which this variability affects the rock depends to a great degree on the overburden thickness. The natural buffer created by overburden is often compromised to some extent by the presence of steel casing used to seal off the overburden. The steel can act as thermal conduit or heat sink, cooling or heating both the borehole and surrounding earth materials. In many cases the upper surface of the rock is either weathered and/or particularly fractured, hence the common (and now often legislated) practice of drilling the surface casing into the upper portion of the bedrock. When the zone of variability extends from the overburden into the bedrock its depth limit can be influenced by the nature (amount and orientation) of shallow bedrock fractures.

Basic to the implementation of this technique are the requirements of instrument resolution of small thermal variations and the creation of an adequate seal with a nylon liner. Cherry et al (2006) provide a detailed discussion supporting the assumption that liners create a good seal. Although liners can occasionally lose integrity and leak, the condition can be identified by the inability to increase the water level in the liner. Pehme et al.(2007) address the issue of leaking liners and it's impact on temperature data, providing evidence that in a downward hydraulic gradient the impact can be minimal below the breach. Greenhouse and Pehme (2000) demonstrate the sensitivity to changes in temperature and the repeatability of variations of a few thousandths of a degree over months and years.

Having restricted vertical flow with the liner the only other potential driving mechanism to place the borehole in disequilibrium with the formation is convection when cool water overlies warm water. Sammel (1968) addressed the prospect of convection within an open borehole and showed that we should anticipate critical convection to begin at gradients of approximately 0.0035 to 0.0065 °C/m for a 4 inch diameter hole.

Sammel uses data collected in two piezometer nests within shallow alluvial sediments deposits, each with a shallow (3m) and a deep (12-15m) well. He used differences in the temperature profiles in adjacent wells as evidence for convection and based on temporal thermal variations. He concluded that "in northern temperate latitudes water columns within 9 to 12 m of land surface in many wells will be thermally unstable during much of the year", and "temperature in thermally unstable water-filled holes may depart significantly from temperatures in the surrounding rock". His field data did not "clearly define the relationship between critical thermal gradients and theoretical critical gradients, but they suggest that the theoretical critical values are close to an probably higher than the actual ones".

We note that although Sammel's equipment was capable of measurements within 0.001°C it had a time constant of approximately 3 minutes which hampered his ability to measure temporal variations. Much of his and Gretener's (1967) work in larger diameter wells rely on the temperature variations over time as evidence for convection and neither gave any consideration to thermal variations being caused by water moving past the borehole.

Figure 4a shows nine temperature logs measured over a 1 month period in 2001 in borehole UW13 at the Cambridge site. A broad temperature high, centered at 78m, is observed around a zone of significant fracturing that dominates the local flow (Plett, 2006). Neither the core logs (Plett, 2006) nor a video log of the borehole indicate the rock above 78 meters to be significantly more fractured than that below. However, the upper surface of the temperature bulge (from 35 to 75 metres), where temperature gradients reach 0.015 °C/m, is considerably more variable than the lower side of the bulge (75 to 140 metres). Also shown as Figure 4 (b and c) are the "change logs" for eight of the temperature logs. The change logs are calculated based on an adaptation of the process described by Pehme et al. (2007) where the first data set (July14th) is used as a base, smoothed over a 5 metres window, and then subtracted from subsequent temperature logs. Each data set represents the temporal variation in temperature with the geothermal gradient suppressed. Data in column b represents the change logs over the 5 day period from July 15th to 20th, 2001 while column c provides the change logs later in July and into mid August.

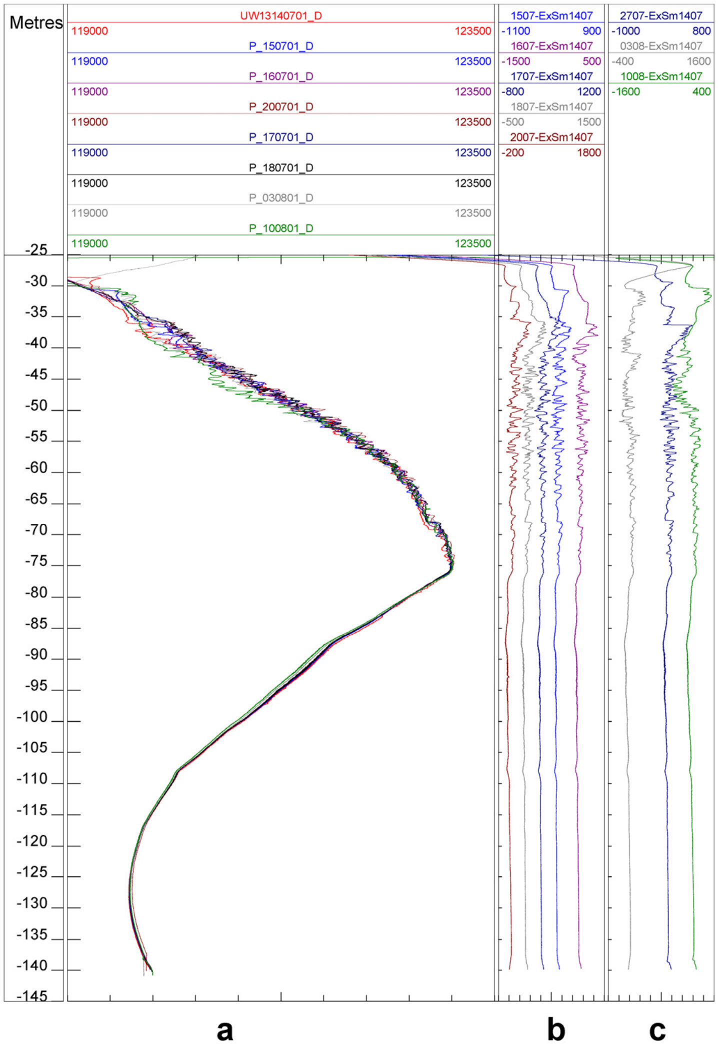

Figure 4: UW13 (Cambridge site) lined temperature data a) Nine temperature logs collected in a FLUTe lined borehole over a period of 1 month. Note the large bulge in the data and the variability in the data above 75 metres relative to that below. (Temperature is in ten thousandths of a degree Celsius) **b & c)** Change logs of temperature data in a) using July 14th data as base, b) July 15th-20th c) July27th-Aug 10th .

Figure 5 plots the range of the change log values at each depth (6mm intervals) from Figure 4 (column b), against the gradient (determined by calculating the slope of successive 1 metre long intervals along the base data set). Data over the limited (five day) span was used to observe short term variability while minimizing the impact of fracture flow. Below a gradient of 0.003 ºC/m the readings vary by less than one hundredth of a degree Celsius over the five day period. The variability increases with thermal gradient to what is a maximum range of approximately .035 ºC above a gradient of .008ºC/m.

If we assume, as did Sammel, that all the variability results from convection, the threshold for variability (convection) is near the low end of the gradient predicted for a

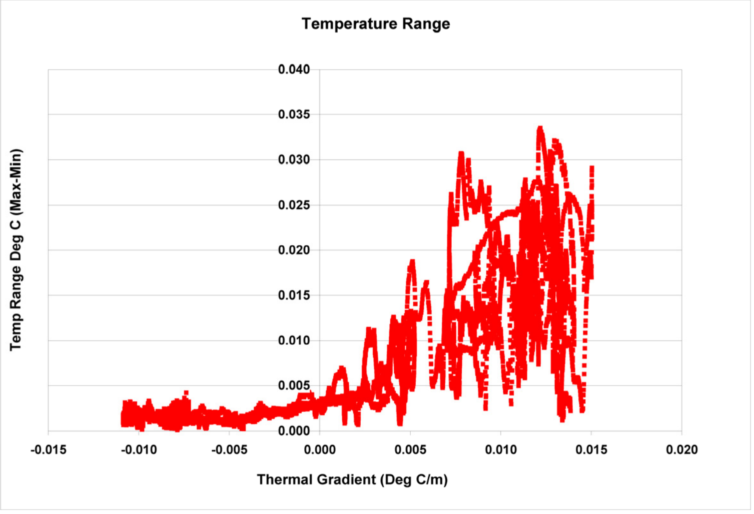

Figure 5 – The range of variability in five temperature logs collected over the period July 15th-20th, 2001 against the thermal gradient (over a 1 metre interval) at each depth interval (6mm).

4 inch diameter well. Note, however, that although we eliminated cross-connected flow within the borehole annulus, included within the "range of thermal variability" is still likely some variation that occurs due to groundwater movement in fractures. Multi level installations in the area have reported weekly fluctuations due variable pumping to meet cyclic water demand (Parker et al. 2007). This representation will therefore tend to overestimate the range of variability for a given temperature gradient.

Convection within the borehole remains a problematic phenomena for temperature logs measured within a liner. It can create irregularities within the temperature data that makes identification of flowing fractures difficult. Fortunately our experience has been that in the vast majority of cases, borehole have temperature gradients below that at which convection becomes a significant factor.

Many of the persistent features in multiple lined hole temperature logs are a few hundredths of a degree above or below background temperatures, and span less than 10 cm. Resolving these thermal aberrations with any confidence requires high resolution thermistors, slow logging speeds and sub-centimeter sampling. Yet experience has shown that, with appropriate instrumentation, patient logging techniques and the elimination of vertical flow in the borehole a consistent and highly detailed representation of the thermal stratification in a borehole can be achieved.

There is an increasing recognition of the complexity of the fractured rock environment. With that recognition comes more requirement for, and utilization of, expensive packer and hydrophysical testing, multi level installations and ultimately numerical modeling. Much of the cost of thermal logging in a lined borehole can be offset by improving the focus of these other, much more expensive techniques. The liner also has the added benefit of reducing cross-contamination. The relative expense of collecting the additional data is low compared to the other investigative and predictive tools being employed.

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John P. Greenhouse earned both his bachelor and masters degrees from the University of British Columbia and his Ph.D. from the University of California. He is an Adjunct Professor and past Chair of the Earth Science department at the University of Waterloo. Dr. Greenhouse has over 35 years of experience as a leader in the research and practice of environmental geophysical techniques. He has developed a number of data processing and field techniques for geophysical monitoring of groundwater contamination. He has experience across North, Central and South America, China, India and the former Soviet Union. He is a member of the American Geophysical Union, the Society of Exploration Geophysicists and has served as Chair of the Board of Directors of the Environmental and Engineering Geophysical Society.