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Distributed thermal response test to analyze thermal properties in heterogeneous lithology

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ABSTRACT

A fiber optic distributed thermal response test (DTRT) conducted in well-documented heterogeneous geology is combined with laboratory thermophysical measurements of cores and novel data analysis techniques to provide a detailed description of variability in subsurface heat transfer. The results of this study show that appreciable variation in subsurface heat flow exists and can be quantified in a lithological context, which may aid in the optimization of future geothermal borefield design. District-scale borefields that are expected to contend with imbalanced loads and potential overheating may find additional value from knowledge of which geologic units to utilize and which to avoid.

1. Introduction

Worldwide, the installed energy capacity of Ground Source Heat Pumps (GSHPs) has increased from 85 PJ in 2005 to 325 PJ in 2015 (Lund and Boyd, 2015), which is equivalent to ten 1000-MW nuclear or coal power plants. Further gains in energy efficiency can be made by optimizing the design and layout of new geothermal borefields, which is the most expensive and variable capital component of a GSHP system. These systems must be carefully designed to provide the capacity for estimated heating and cooling loads while minimizing the capital cost of installation. However, life-cycle heating and cooling performance has proven difficult to predict and many systems have deviated from expected design performance, leading to poor environmental and economic outcomes (Magraner et al., 2010; Knudson, 2013). Economic viability and payback periods are highly sensitive to energy extraction and rejection rates that deviate from design parameters (Garber et al., 2013). The importance of accurate load prediction and appropriate sizing of GSHP systems has led to the development of many predictive models (Nagano et al., 2006; Sayyaadi et al., 2009; Puttagunta et al., 2010). These models are predominately built from well-developed thermoeconomic optimization principals (Bejan et al., 1996) that maximize the performance of mechanical component heat transfer, while minimizing capital operation and fuel costs. The long-term performance of the ground heat exchange is traditionally secondary, if considered at all. However, considering the subsurface as an infinite heat source or sink (at a constant temperature) has led to difficulties and oversimplification, especially in operating district-scale systems.

Thermal Response Tests (TRT) are used to quantify *in situ* ground heat exchanger (GHX) thermal performance. A conventional TRT quantifies heat transfer in a pilot GHX by supplying a known heating load and measuring the exchanger flow rate and change in water temperature, ΔT ($T_{in} - T_{out}$), from the GHX inlet to outlet. Single values of *in situ* heat exchange capacity and effective borehole thermal conductivity are then used to supplement and refine design model inputs. Typical analysis (Puttagunta et al., 2010; Luo et al., 2015) of these results relies on a line-source heat model (Zeng et al., 2002) that assumes radial heat flow, homogeneity, and negligible advective heat transfer by groundwater. Heterogeneous geology, variable thermophysical properties, and ground water flow are realities that will affect the performance of the vast majority of GSHP installations in ways that are difficult to quantify with the above assumptions. Quantification of variable subsurface thermophysical properties to decrease uncertainty in GSHP performance can be accomplished by drill core collection and geologic mapping (Stumpf and Dey, 2012), laboratory testing of the geologic materials (Meyer, 2013), and distributed analytical solutions (Walker et al., 2015). Numerical modeling can incorporate these

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physical properties and groundwater flow patterns to more accurately predict *in situ* three-dimensional heat flow (Raymond and Lamarche, 2013; Özdoğan-Dölçek, 2015). To complement these methods, in-hole distributed temperature data profiles are needed to validate model results and refine future application of these analytical and numerical methods.

Fiber-optic distributed temperature sensing (DTS) has been used to characterize the vertical distribution of thermophysical properties during a TRT (Fujii et al., 2009; Beier et al., 2012; Acuña and Palm, 2013). DTS is a technique that uses the interaction of laser light with the silica core of a fiber optic cable and time-domain reflectometry principles to calculate the temperature of the cable at discrete sections of the fiber. Recently, the scientific community has taken advantage of improvements in DTS technology that have provided finer temporal, spatial, and temperature resolutions in environmental and infrastructure applications (Selker et al., 2006).

A distributed thermal response test (DTRT, Acuña and Palm, 2013) uses a fiber optic temperature probe within a GHX during a TRT to observe differential subsurface heat transfer. Freifeld et al. (2008) pioneered this concept by using a resistance heater in a borehole to create a thermal perturbation and monitor the subsequent temperature decay with DTS. Inverted temperature data and a radial heat flow model were used to create a profile of thermal conductivities with depth. Fujii et al. (2009) enhanced the DTRT with fiber optics in both the supply and return side of the GHX, during heat injection and decay in a mostly homogenous volcanic bedrock. The DTRT was expanded even further by placing fiber within both a coaxial and standard u-tube GHX configuration (Acuña and Palm, 2013) to study the effects of pipe configuration on heat transfer. Sellwood et al. (2015) investigated the limitations of using DTS and a resistance heater in an open borehole. Recently, a DTRT was performed on a GHX within an overheated geothermal field as a diagnostic tool to analyze differential heat decay with depth (Herrera, 2016).

This work combines a conventional TRT and a DTRT in a borehole surrounded by well-documented heterogeneous and layered lithology to study the extent to which a DTRT can provide *in situ* distributed thermal properties. A novel approach is used for DTRT data analysis that applies hydrogeological pumping test concepts (Raymond et al., 2011), and statistically minimized model error to achieve an effective borehole thermal conductivity, λ_{ss}, of 2.0 W m^{-1} K^{-1}. This effective conductivity is used as the basis of a distributed subsurface thermal conductivity analysis based on an analogy to the Molz et al. (1989) impeller meter pumping test for distributed hydraulic conductivity.

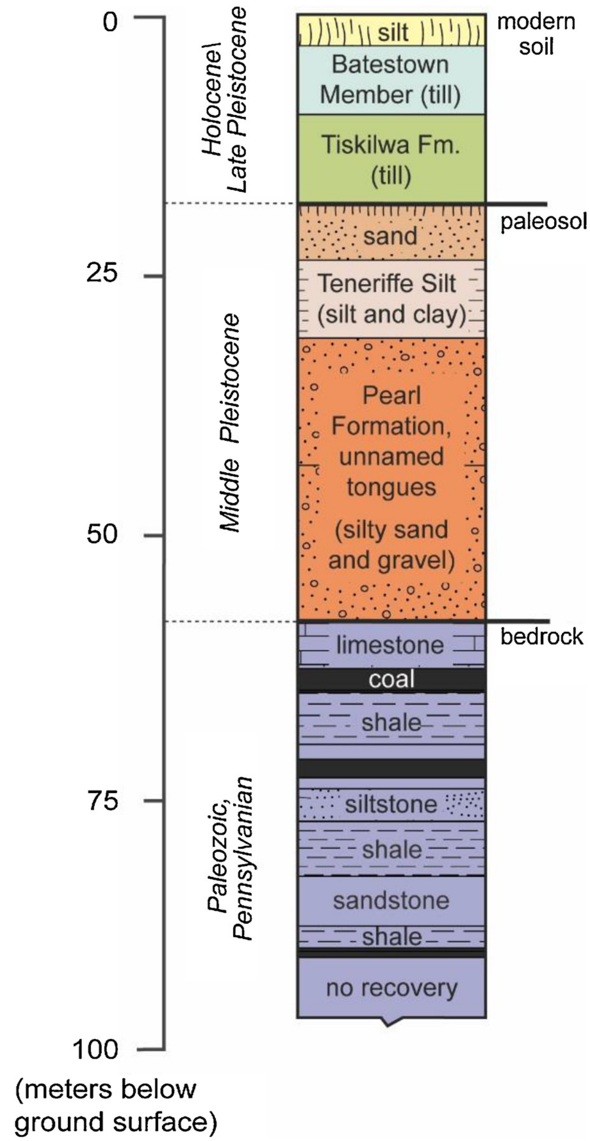

Fig. 1. DTRT Borehole Log.

2. Materials and methods

2.1. Site geology

The TRT was conducted in a borehole completed at the University of Illinois at Urbana-Champaign (UIUC) Energy Farm located in Champaign County in east-central Illinois (site coordinates N40.066202°, W88.207597°). The geology in the borehole represents multiple cycles of deposition and erosion occurring over the past ~310 million years. Glacial and proglacial deposits of at least two glacial cycles (the Middle to Late Pleistocene glaciations; Curry et al., 2011) overlie an irregular bedrock surface formed by Pennsylvanian-age mixed marine and terrestrial coal-bearing sedimentary strata (*i.e.*, cyclothems) that outcrop within the Illinois Basin (Rosenau et al., 2013). An approximately 60-m-thick sequence of unconsolidated glacial and postglacial sediments, including glacial till, outwash, and glacial lake sediment (Fig. 1) overlie a bedrock upland adjacent to the Mahomet Bedrock Valley; (Stumpf and Dey, 2012). Within the proglacial sequence, the lowermost horizons of a truncated interglacial soil marks the boundary between the two glacial cycles. The upper 3 m of the sequence includes fine-grained windblown sediment (loess), which overlies reworked sand, silt and gravel (colluvium), and outwash that was deposited along a postglacial river draining a recessional moraine north of the site. An erosional unconformity separates the glacial sequence from the bedrock, a limestone bench or platform classified to the Shelburn Formation (Rosenau et al., 2013). The heterogeneous geology encountered at the site provides an excellent field laboratory to test the application of a DTRT to differentiate varying subsurface thermophysical properties vertically in the subsurface.

2.2. Thermal response test

A 16.5-cm-diameter borehole was advanced to a depth of 97.5 m below ground surface (bgs). The borehole was cased from 0.75 m to 2.9 m bgs to prevent caving of the surface material. Continuous core was extracted from the borehole by the mud-rotary drilling method. The core was sampled in the field and subsamples retained for later thermal conductivity, density, and moisture content measurements. The samples (25 in total shown in Table 1) were taken at regular depth intervals, immediately sealed in airtight bags and refrigerated to maintain *in situ* moisture content and prevent oxidation.

All subsurface fiber optic cables were first threaded through 6-mm-diameter plastic tubing for protection against pinching, pressure head, and repeated impacts caused by flow. One continuous fiber optic cable