Combining High Resolution Vertical Gradients and Sequence Stratigraphy to Delineate Hydrogeologic
Units for a Contaminated Sedimentary Rock Aquifer System

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Abstract

Hydrogeologic units (HGU), representing subsurface contrasts in hydraulic conductivity, form the basis for all conceptual and numerical models of groundwater flow. However, conventionally, delineation of these units relies heavily on data sets indirect with respect to hydraulic properties. Here, we use the spatial and temporal characteristics of the vertical component of hydraulic gradient (i.e., vertical gradient) as the primary line of evidence for delineating HGUs for Cambrian-Ordovician sedimentary rocks at a site in Dane County, Wisconsin. The site includes a 16 km² area encompassing a 3 km long mixed organic contaminants plume. The vertical gradients are derived from hydraulic head profiles obtained using high resolution Westbay multilevel systems installed at 7 locations along two, orthogonal 4 km long cross-sections and monitoring to depths between 90 and 146 m with an average of 3-4 monitoring zones per 10 m. These vertical gradient cross-sections reveal 11 laterally extensive HGUs with contrasting vertical hydraulic conductivity (K_v). The position and thickness of the K_v contrasts are consistently associated with sequence stratigraphic features (maximum flooding intervals and sequence boundaries) distinguished at the site using cores and borehole geophysical logs. The same sequence stratigraphic features are also traceable across much of the Cambrian-Ordovician aquifer system of the Midwest US. The vertical gradients and sequence stratigraphy were arrived at independently and when combined provide a hydraulically calibrated sequence stratigraphic framework for the site. This framework provides increased confidence in the precise delineation and description of the nature of HGU contacts in each borehole, reduced uncertainty in interpolation of the HGUs between boreholes, and some capability to predict HGU boundaries and thickness in offsite areas where high resolution hydraulic data sets are not available. Consequently, this HGU conceptual model will serve as a better basis for numerical simulations of groundwater flow and contaminant transport needed for continued risk assessment and to evaluate potential remedial technologies for the site. More broadly, the association between K_v contrasts and sequence stratigraphy demonstrated at this site provides valuable insight into the relationship between geology and hydraulic contrasts that can be transferred to other areas of the upper Midwest US and

63 perhaps elsewhere to strata deposited in similar settings.

1. Introduction

The geometries and spatial distributions of hydraulic conductivity contrasts are often conceptualized as three-dimensional units (3D), referred to here as hydrogeologic units (HGUs). HGUs form the framework for conceptual and numerical models of groundwater flow and contaminant transport. Furthermore, because HGUs are the basis for conceptual models, they also guide the installation of monitoring wells used to collect hydraulic and geochemical data needed to parameterize, calibrate, and validate these models. Consequently, developing robust methods for delineating HGUs is critical to evaluating and reducing uncertainty in these models.

Delineating HGUs commonly involves relating hydraulic contrasts to a geologic framework. Traditionally, practitioners have relied heavily on lumped or split versions of lithostratigraphy to delineate HGUs. A reliance on lithostratigraphy likely stems from early definitions of “aquifer”, that equate these layers with a formation, group of formations, or part of a formation (Meinzer, 1923; Lohman et al., 1972) because of the general relationship between lithology and hydraulic conductivity. In addition, because lithostratigraphic descriptions are readily available for most study areas, it is a relatively convenient geologic framework on which to base HGUs.

As focus shifted toward contaminant transport issues, a number of theoretical studies (e.g., Freeze, 1975; Smith and Schwartz, 1980; Smith and Schwartz, 1981; Degan, 1982; Gelhar and Axness, 1983) combined with several key natural gradient field tracer tests (e.g., Mackay et al., 1986; LeBlanc et al., 1991; Boggs et al., 1992) showed the profound impact of small scale geologic/hydraulic heterogeneities on the paths and transport rates of contaminants. As a result, researchers began to look for higher resolution geologic characterization methods that focus on describing the geometry and spatial arrangement of depositional units to improve the delineation of HGUs beyond the traditional reliance on lithostratigraphy.

Several early studies demonstrated the use of lithofacies models to improve delineation of HGUs for heterogeneous sediments deposited in fluvial, glacial, and glaciofluvial environments (e.g., Anderson,

1989; Poeter and Gaylord, 1990). Delineation of HGUs was improved in these environments because lithofacies models provided some ability to predict spatial trends in hydraulic conductivity based on sparsely distributed site specific geologic and hydraulic data. Similarly, Fogg (1986) used a large database of geologic information to qualitatively map the geometry and distribution of sand bodies deposited by meandering to sinuous streams in order to predict the distribution of hydraulic conductivity from much more sparsely distributed hydraulic data. The results of the study showed that accurate representation of the sand body interconnectivity was key to accurate representation of groundwater flow patterns.

More recently, researchers have begun using sequence stratigraphic techniques to guide HGU delineation (e.g., Macfarlane et al., 1994; Ehman and Cramer, 1996; Sugarman and Miller, 1997; Weissmann and Fogg, 1999; Brunton, 2008; Velasco et al., 2012). Sequence stratigraphy focuses on identifying relatively conformable successions of genetically related strata providing a geometric characterization of depositional elements across various scales. Consequently, sequence stratigraphy can provide a better depiction of the 3D geometry of material units, which commonly have different hydraulic properties, than a traditional lithostratigraphic approach alone.

Most of these studies focused on improving the geologic characterization of unconsolidated sediments in order to improve the delineation of HGUs. These HGUs were then parameterized with hydraulic data that was typically less resolved and more sparsely distributed than the geologic data. This approach is successful partly because the relationship between grain size/lithology and hydraulic conductivity is strong in unconsolidated sediments, thus supporting prediction of hydraulic properties on the basis of geologic data.

Delineating HGUs in fractured sedimentary rocks involves added complexity because the lengths, apertures, and distribution/connectivity of fractures dominate the bulk hydraulic properties of units and these characteristics are not necessarily predictable from lithofacies or lithostratigraphy. Examples of this complexity are found in both the rock mechanics and hydrogeological literature. For example, outcrop studies of sedimentary rocks in the Midwest United States show complex relationships between stratigraphic horizons and mechanical interfaces (Underwood et al., 2003; Cooke et al., 2006; Anderson et

al., 2011; Runkel et al., 2014). This has important implications for fluid flow because vertical fractures terminate at mechanical interfaces, likely reducing vertical hydraulic connectivity (Underwood et al., 2003; Meyer et al., 2008), and the spacing of mechanical interfaces controls the density of vertical fractures within the unit, which influences the bulk hydraulic conductivity of the unit. Hydrogeological studies of sedimentary rocks have found that the position and thickness of hydraulic contrasts are not predicted by lithostratigraphy or detailed lithologic data (Runkel et al., 2006; Tipping et al., 2006; Meyer et al., 2014).

These complexities of fractured rock suggest the need for an HGU delineation approach that, in contrast with the current standard of practice, focuses first on direct hydraulic data that is not dependent on stratigraphic or lithofacies conceptual models. Meyer et al. (2008) and Meyer et al. (2014) proposed such an approach built on the premise that in a steady state flow system a change in hydraulic conductivity will be accompanied by a change in the hydraulic gradient, as was demonstrated numerically by Freeze and Witherspoon (1967). The magnitude of the change in gradient will depend on the magnitude of the hydraulic conductivity contrast and the position of the borehole in the flow system. Numerous depth-discrete and minimally blended (i.e., high resolution) measurements of hydraulic head are collected in vertical profile from a borehole using a multilevel system (MLS). The high resolution head profiles are then used to identify changes in the vertical component of the hydraulic gradient (i.e., vertical gradient) that in turn, indicate the position and thickness of units with contrasting vertical hydraulic conductivities (K_v) (Meyer et al., 2014). Meyer et al. (2008) provided the initial indication that high resolution head profiles could identify hydraulic contrasts in sedimentary rocks independent from existing geologic and hydrogeologic conceptual models and Meyer et al. (2014) demonstrated the reliability of the method in several different sedimentary rock and flow system settings.

The current study builds on these previous studies by applying the high resolution head profile method to a contaminated sedimentary rock site in order to delineate HGUs. The objective of this experiment was to determine if the spatial and temporal characteristics of vertical gradients can be used as the primary line of evidence for the delineation of HGUs. The data collected at 7 locations across a 16

km² area address two primary questions: (1) are vertical gradients identified in individual head profiles from multiple locations along two orthogonal two-dimensional (2D) sections laterally correlatable, indicating laterally extensive contrasts in K_v , and (2) what geologic framework best describes the distribution of these K_v contrasts in vertical cross sections? The analysis and interpretation of these data along multiple 2D sections then provides a basis for interpretation of 3D HGUs.

1.1. Study Area and Geologic Setting

The study area, located about 20 km east of Madison, Wisconsin, is the site of groundwater contamination caused by a mixture of organic chemicals released into the subsurface prior to 1970 (Fig. 1). These releases resulted in the accumulation of mixed organics dense non-aqueous phase liquids (DNAPLs) in Cambrian sandstone in the upper Tunnel City Group between 45 and 56 m bgs (see observed DNAPL source area (Fig. 1). Groundwater flow has created a dissolved phase plume extending 2.8 km downgradient at its maximum observed extent in 2003 (Fig. 1). The site encompasses an area of roughly 25 km² with low to moderate topographic relief defined by drumlins. The main surface water bodies at the site are a man-made pond constructed in 1994, primary north-south and east-west drainage ditches, wetland areas, and Koshkonong Creek. The local groundwater flow direction in the unconsolidated deposits and shallow bedrock is predominantly east toward Koshkonong Creek and the groundwater flow direction in the deep bedrock is more southerly (Bradbury et al., 1999).

The bedrock hydrogeologic system monitored at the research site includes Upper Cambrian through Middle Ordovician fractured sandstone, siltstone, dolostone, and shale. These units are part of a laterally extensive package of strata deposited in an inland sea on a broad shallow shelf referred to as the Upper Mississippi Valley epeiric ramp (Runkel et al., 2007). These bedrock units extend across much of southern Wisconsin, south-eastern Minnesota, Iowa, northern Missouri, and Illinois forming the Cambrian-Ordovician aquifer system (Young and Siegel, 1992). The Cambrian-Ordovician aquifer system is relied upon heavily for municipal, industrial, and agricultural water supplies (Maupin and Barber, 2005) and more recently, the lowermost formation, the Mt. Simon Sandstone, is being evaluated

as a reservoir for carbon sequestration in the Illinois Basin (Leetaru and McBride, 2009; Zhou et al., 2010). Historically, the bedrock underlying the study area has been described using lithostratigraphic nomenclature presented by Ostrom (1968) and later updated by the Wisconsin Geological and Natural History Survey (WGNHS, 2006) (Fig. 2). Site specific lithologic descriptions of the units are provided by Meyer et al. (2008). Four well documented regional unconformities, one in the Wonewoc Sandstone (Sauk II-III) (Runkel et al., 1998), one underlying the Prairie du Chien Group (Cambrian-Ordovician) (Runkel, 1994), one underlying the St. Peter Sandstone (Sauk-Tippecanoe) (Sloss, 1963), and one between the Paleozoic bedrock and Pleistocene unconsolidated deposits, have been identified in the study area (Fig. 2). A regionally extensive unconformity within the Prairie du Chien Group (Smith et al., 1993) may also be present but was not identified at the site.

Runkel et al. (2007) developed a high resolution sequence stratigraphic framework for the lower Paleozoic bedrock deposited on the Upper Mississippi Valley epeiric ramp. Their approach used facies-scale stacking patterns at dozens of individual outcrop and core locations, hundreds of borehole geophysical logs, and high resolution biozones to recognize and regionally trace key sequence stratigraphic features such as parasequences, maximum flooding intervals, and subaerial unconformities or their associated correlative conformities. Maximum flooding intervals are formed when relative sea level is high and the shoreline is at its maximum landward extent. Conversely, subaerial unconformities are formed when relative sea level is low and the shoreline is at its maximum seaward extent. These features were traced regionally, and used to define sequences and systems tracts across the Upper Mississippi Valley area (Fig. 3).

Lower Paleozoic strata in this region are part of the northernmost extent of rocks of this age in the relatively stable interior of the North American central craton. The strata across most of the region are subhorizontal, and relatively undeformed, aside from localized gentle folds and high angle faults. Opening-mode fractures are the most widespread and, characteristic structural feature in the region (Underwood et al., 2003). The earliest development of these vertical systematic fractures is attributed to far-field stress transmission during the late Paleozoic Alleghanian Orogeny, resulting in a predominantly

northwest trending fracture set (Craddock et al., 1993; Apotria et al., 1994; McGarry, 2000). The origin of systematic fracture sets with different trends, commonly nearly orthogonal to the northwest set, is less certain, but also generally believed to be related to regional- to continental-scale stresses. Although most intensively studied in carbonate bedrock, these vertical systematic fractures are pervasive in all sedimentary bedrock of the region, including friable sandstone and shale. They have long been observed in numerous surface exposures, in mines (Heyl et al., 1959) and, rarely, in deep (several tens to hundreds of meters) boreholes (Haimson and Doe, 1983; Runkel et al., 2003).

Secondary porosity features such as fractures are commonly observed throughout the Cambrian-Ordovician bedrock in continuous cores and boreholes both at the site and regionally (e.g., Runkel et al., 2006; Swanson et al., 2006; Swanson, 2007; Meyer et al., 2008; Gellasch et al., 2012). In addition, enlargement of pores by dissolution is extensive enough in the Prairie du Chien Group, both at the site and regionally, that it is best classified as karstic (Palmquist, 1969; Smith and Simo, 1997; Meyer et al., 2008).

2. Methods

2.1. Borehole Characterization

The study area has been the focus of intensive groundwater contamination investigations since 1982 (Hydro-Search Inc., 1989; HSI GeoTrans, 1998; HSI GeoTrans, 1999; GeoTrans Inc., 2003). Due to the complexity of the site, research was initiated in 2003 where conventional and novel, high resolution characterization methods were tested in order to advance understanding of the processes controlling groundwater flow and contaminant transport. Between 2003 and 2008 twelve research boreholes (Fig. 1) were drilled to depths between 53 and 152 m bgs and comprehensively characterized using the Discrete Fracture Network (DFN) approach (Parker et al., 2012). Four of the boreholes, MP-6, MP-16, MP-17, and MP-18, were deliberately located outside the upper Tunnel City Group dissolved phase plume to allow more time for open borehole characterization without the risk of cross-connecting the plume zone with

units above or below. The remaining eight boreholes (MP-7, MP-19S, MP-19D, MP-5, MP-15, MP-21S, MP-21D, MP-8) were located along a west-east longsect of the plume from the source zone to the plume front. The MP-19 and MP-21 locations both included two, one shallow (S) and one deep (D), boreholes located within ~20 m of one another and are presented as a single borehole location/head profile in figures. This study relies on geologic and geophysical data collected from all of the research cores/coreholes and primarily on data collected from high resolution MLSs at seven locations across the site forming west-east and north-south cross-sections.

The boreholes were continuously cored using a rotary rig and the HQ3 wireline coring technique, which produces a 6.1 cm (2.4 in) diameter core and 9.6 cm (3.8 in) diameter borehole. A total of 1,014 m of core was collected between 2003 and 2008 for this study. Cores were logged at a 5 cm scale for composition, Munsell color, grain size, sorting, rounding, ichnofabric index (Droser and Bottjer, 1986), cementation index (Aswasereelert, 2005), and sedimentary structures (Aswasereelert, 2005; Meyer, 2013). Over 100 samples were collected from the core for measurements of matrix porosity and hydraulic conductivity. Porosity was measured using a gravimetric method (Collins, 1961) and permeability was measured using a nitrogen gas permeameter (ASTM, 2004). The depths and approximate dip of all fractures (excluding mechanical breaks) observed in the cores were also recorded. Additional qualitative data regarding the fractures were collected from the MP-16, MP-17, MP-18, MP-19S, MP-19D, MP-21S, and MP-21D cores. These data included whether the fracture was oriented parallel to bedding, if the fracture was associated with a lithologic change, whether the core was still in-tact, and if not, descriptions of the fracture plane roughness, how well the fracture planes fit back together, and any material filling the fracture plane or any mineral precipitation on the surface.

A wide variety of downhole datasets were collected from all coreholes with the exception of MP-15. A subset of these data are utilized and presented here. Natural gamma and formation resistivity and/or induction conductivity logs were used to interpret grain size, bulk mineralogical composition, and stratigraphic changes/contacts in each of the research boreholes. Acoustic and/or optical televiewer logs were collected in all of the research boreholes and used to characterize fracture intensity and orientation.

In addition, straddle packer hydraulic conductivity testing was performed in several key open boreholes. Slug tests were performed in the MP-6 borehole using a modified version of the method presented by Muldoon (1999) and constant head step tests were performed in the MP-16, MP-17, and MP-18 boreholes (Quinn et al., 2012). These tests provided values for the horizontal component of hydraulic conductivity (K_h) that add to the existing site database of K_h values derived from a wide variety of test and analysis methods (HSI GeoTrans, 1998; Austin, 2005; Meyer, 2005).

The borehole and core data sets were used in several ways. All borehole and core data sets were utilized to design the high resolution MLSs as described in section 2.2. Detailed core logs, high resolution core photos, and natural gamma logs from our study area were used to characterize the sequence stratigraphic attributes of the site. Features such as facies successions, parasequence stacking patterns, evidence for starved sedimentation, and surfaces of erosion provided the information necessary to discriminate multiple sequence stratigraphic units.

2.2. Multilevel Design, Installation, and Data Acquisition

Collection of depth discrete measurements from boreholes requires minimization of the bias caused by cross-connective flow in long open holes/well screens (e.g., Lerner and Teutsch, 1995). Dedicated MLSs provide a reliable and readily available way to obtain depth discrete data from boreholes. This study focuses on data collected from high resolution MLSs installed at seven locations along two orthogonal cross-sections (Fig. 1; purple triangles). Cherry et al. (2015) provide a recent comprehensive description of the attributes of the four MLSs commercially available in North America. The Westbay MP® MLS was chosen here because it accommodates the largest number of monitoring zones within the borehole dimensions typical of this study (Meyer et al., 2014) and it has been successfully applied in fractured rock settings for over three decades.

In order to use high resolution head profiles to delineate HGUs, the head data must be independent from existing conceptualizations of the HGUs. In a standard monitoring approach, the available data would be use to infer HGU boundaries and then the MLS would be designed with a single monitoring

zone, often long screened, for each suspected HGU. This approach makes the data collected from the MLS dependent on the conceptual model of the HGUs used to design the MLS. For this study, the MLSs were deliberately designed as characterization tools independent from an existing conceptual model. The design approach included 5 basic components described by Meyer et al. (2014) and summarized here. (1) The raw geologic, geophysical, and hydraulic data sets collected from the cores and coreholes were used to infer **potential** HGU boundaries and important flowpathways. (2) Ideally, at least 3 monitoring zones were included within each potential HGU and monitoring zones were positioned on both sides of potential boundaries. (3) The lengths of the monitoring zones were minimized. (4) The total number of monitoring zones was maximized in order to resolve changes in head across short depth intervals. (5) All intervals of the borehole that were not being monitored were sealed.

Many profiles of shut-in, absolute formation fluid pressure were collected from all of the MLSs throughout various seasons each year for between six and eleven years. The same Westbay MOSDAX downhole tool equipped with a pressure transducer was used to measure pressures for each profile which were then converted to hydraulic head using the average field measured atmospheric pressure at the time of the profile and the depth of each port (Meyer et al., 2014). The relative uncertainty of hydraulic heads collected from closely spaced monitoring intervals is ± 0.01 m (Meyer et al., 2008; Meyer et al., 2014). Vertical gradients were subsequently calculated for each head profile between every pair of adjacent monitoring zones by dividing the difference in hydraulic head between the two zones by the length of the packer seal (Meyer et al., 2014). Given the uncertainty in the hydraulic heads, vertical gradients with absolute values ≤ 0.02 m are not resolvable (Meyer et al., 2014).

Each high resolution MLS includes between 16 and 45 adjacent monitoring intervals allowing for the calculation of 227 high resolution vertical gradients for each round of head profile snap shots. Consequently, collection of head profiles over multi-year periods resulted in a large database of vertical gradients (4,569) available for temporal and spatial analysis. The first step in using the vertical gradients for delineation of HGUs is determining which vertical gradients represent contrasts in K_v rather than transience in the flow system. This determination is made by evaluating the temporal behavior of the

vertical gradients using vertical gradient time series plots (Fig. 4, Meyer et al. (2014)). Each vertical gradient is assigned to one of three categories based on its temporal behavior as summarized below.

- Resolvable (green bars in Fig. 4 and Fig. 5) – are resolvable in all head profile snap shots, generally maintain the same direction and similar magnitude through time, and indicate an interval of rock with low K_v relative to intervals with unresolvable vertical gradients
- Unresolvable (grey bars in Fig. 4 and Fig. 5) – are not resolvable in any of the head profile snap shots, indicate an interval of rock with high K_v relative to intervals with resolvable vertical gradients
- Sometimes resolvable (yellow bars in Fig. 4 and Fig. 5) – are sometimes resolvable in head profile snap shots, are typically small in magnitude, have magnitudes and directions that vary through time, likely represent flow system transience due to short term changes in the water table position or pumping or a minor K_v contrast

Based on this categorization of gradients, Meyer et al. (2014) showed that the majority of vertical gradients at three different sedimentary bedrock sites in North America were either resolvable or unresolvable making them a highly reliable data sets for delineating contrasts in K_v . The current study is focused on using vertical gradients for HGU delineation: spatial evaluation of the temporally categorized vertical gradients and identification of a geologic framework that describes their 3D distribution.

3. Results and Discussion

3.1. 3-D Vertical Gradient Characteristics and Intervals of Contrasting K_v

The categorized vertical gradient profiles along the west-east (Fig. 4) and north-south (Fig. 5) cross-sections show excellent temporal and spatial consistency. Temporal analysis of each of the 227 vertical gradients showed that 33% of the vertical gradients were resolvable, 51% were unresolvable, and 16% were sometimes resolvable (Table 1). Spatially, the deeper bedrock units tend to be dominated by unresolvable vertical gradients (grey categorization) and the Tunnel City Group bedrock by resolvable

vertical gradients (green categorization) whereas the shallow bedrock has a higher number of sometimes resolvable (yellow categorization) vertical gradients (Fig. 4 and Fig. 5).

Spatial evaluation of the cross-sections revealed eleven laterally extensive zones of distinct vertical gradient indicating 11 corresponding intervals of fractured rock with contrasting K_v (Fig. 4 and Fig. 5). For example, the downward vertical gradients observed at ~ 186 m above mean sea level (AMSL), in the middle of the Wonewoc Sandstone, were always resolved and of the same direction and similar magnitude for a minimum of 18 head profile measurements over a 6 year period at all 7 locations (Fig. 4 and Fig. 5). Similarly, vertical gradients between adjacent monitoring zones for the portions of the Wonewoc above and below the distinct gradient at ~ 186 m AMSL (Fig. 4 and Fig. 5; zones 3 and 5) were consistently unresolvable.

The insights gained from site specific data (this study and Meyer et al. (2014)) can be used to construct a conceptual model of head and vertical gradient profiles for a *generic* flow system in layered, fractured, sedimentary rocks (Fig. 6). First, the consistency observed in the vertical gradient data suggest that K_v contrasts in sedimentary rocks are associated with distinct intervals of rock with relatively uniform bulk hydraulic properties at the scale of the MLS monitoring intervals. The bulk hydraulic conductivity of fractured rocks is controlled by the relative contributions of the fractures and the lithified rock matrix. The hydraulic conductivity of the rock matrix is commonly 1 or more orders of magnitude lower than the bulk hydraulic conductivity. Consequently, the contrasts in K_v are thought to be controlled by the properties of, and contrasts between, relatively dense and interconnected fracture networks associated with each unit (Fig. 6a). This is in contrast to conceptual models for fractured rock systems where groundwater flow is controlled by very few, large aperture fractures, which in turn, would be expected to result in erratic head and vertical gradient profiles, poor spatial correlation, and measurable vertical gradients throughout the profiles. In a steady state or quasi steady state flow system, contrasts in K_v refract flow and equipotential lines (Fig. 6a) resulting in persistent inflections in the head profiles with consistent vertical positions and thickness (Fig. 6b). These inflections can be examined as vertical gradients. The magnitude and direction of individual vertical gradients is controlled by the position of the

profile in the flow system (Fig. 6c). This generic conceptual model is presented here to help guide future studies of high resolution head and vertical gradient profiles at sites where similar dense and interconnected fracture networks exist.

The eleven vertical gradient zones can be grouped into three broad domains based on their characteristics: deep bedrock, Tunnel City Group bedrock, and shallow bedrock. The following sections describe the specific characteristics of each vertical gradient zone and examine the association between intervals of contrasting K_v and the stratigraphic framework.

3.1.1 Deep Bedrock

Vertical gradients in the deep bedrock (Mt. Simon, Eau Claire, and Wonewoc formations; Fig. 2) share common characteristics. First, all of the resolvable vertical gradients are directed downward, which is in keeping with groundwater withdrawal by three municipal pumping wells located near the site and screened across the Mt. Simon, Eau Claire, and Wonewoc formations (wells 2, 3, 4; Fig. 1). The second characteristic of the vertical gradients in the deep bedrock is the prevalence of unresolvable vertical gradients. Of the 104 vertical gradients monitored in the deep bedrock between 2003 and 2014, 73% are unresolvable, 18% are resolvable, and only 9% are sometimes resolvable (Table 1).

There are five distinct zones of vertical gradient in the deep bedrock traceable across the study area: 3 zones of unresolvable vertical gradients and 2 zones of resolvable vertical gradients (zones 1-5; Fig. 4 and Fig. 5). The zones of unresolvable vertical gradients in the deep bedrock include zones 1, 3, and 5 (Fig. 4 and Fig. 5). The lack of resolvable vertical gradients between adjacent monitoring intervals in these zones over the long monitoring periods suggests the bedrock associated with these three zones has higher K_v relative to the adjacent zones (zone 2, 4, and 6; Fig. 4 and Fig. 5) with resolvable vertical gradients.

The zone 2 vertical gradients provide the most reliable indication of the presence and position of the Eau Claire aquitard, regionally described as a shale rich portion of the Eau Claire Formation (Bradbury et al., 1999; Aswasereelert et al., 2008). At the site, this lithostratigraphic unit differs from its

regional character in being dominated by fine-medium grained sandstone, with only subordinate, thin intervals of very-fine sandstone, siltstone, and/or shale (Fig. 7). However, the zone 2 vertical gradients that are downward at all locations with average magnitudes varying between -1.4 and -0.04 m/m clearly indicate a thin interval of decreased K_v within the Eau Claire Formation (Fig. 4 and Fig. 5). A resolvable vertical gradient is also observed near the top of the Eau Claire Formation at MP-6 and MP-15 but does not appear to be laterally consistent across either cross-section. The Eau Claire Formation is often delineated based on gamma log response and ranges in thickness at the site between 8 and 14 m, whereas the vertical gradient occurs across an interval less than about 1 m in thickness. This finding has important implications with respect to the integrity of this regionally important aquitard unit.

Vertical gradient zone 4 occurs in the middle of the Wonewoc Sandstone separating the unresolvable vertical gradients of zones 3 and 5 (Fig. 4 and Fig. 5). All zone 4 vertical gradients are downward and the average magnitude observed at each location varies between -0.50 and -0.08 m/m. The zone 4 vertical gradients appear to occur across the contact between zones 3 and 5 rather than across a very thin lower K_v layer.

3.1.2 Tunnel City Group Bedrock

In contrast to the deep bedrock, where the majority of vertical gradients are unresolvable, 63% of the Tunnel City Group bedrock vertical gradients are resolvable (Table 1). In addition, unlike the vertical gradients in the deep bedrock, vertical gradients in the Tunnel City Group bedrock are both upward and downward in direction. There are 3 zones of resolvable vertical gradients in the Tunnel City Group bedrock (zones 6, 8, 9) and 1 zone of unresolvable vertical gradients (zone 7) (Fig. 4 and Fig. 5).

Vertical gradient zone 6 occurs near, but not everywhere coincident with, the Wonewoc/Tunnel City Group contact and gradients associated with this zone are downward at all locations except the MP-18 location where the gradient is generally upward (Fig. 4 and Fig. 5). The prevalence of downward vertical gradients in zone 6 is likely the combined result of the drawdown of the municipal wells (Fig. 1) and position in the flow system. The upward gradient observed for zone 6 at MP-18 suggests the location

is not substantially influenced by the drawdown of the municipal pumping wells and may be located more distant from primary recharge areas. The average magnitude of the downward vertical gradients in zone 6 varies between -0.56 and -0.07 m/m and the average magnitude of the upward vertical gradients at the MP-18 location is 0.06 m/m.

The unresolvable zone 7 vertical gradients occur near the middle of the Tunnel City Group bedrock and separate the resolvable vertical gradients of zone 6 and 8. The zone 6 and 8 resolvable vertical gradients indicate intervals of bedrock with relatively low K_v separated by the relatively higher K_v bedrock of zone 7.

The upper half of the Tunnel City Group bedrock includes two zones of resolvable vertical gradients, zones 8 and 9, distinguished by their directions and magnitudes rather than being separated by a zone of unresolvable vertical gradient as observed throughout the rest of the section (Fig. 4 and Fig. 5). The zone 8 vertical gradients are generally downward at all locations except for the MP-18 location where the vertical gradient is generally upward. The average magnitude of the zone 8 downward vertical gradients varies between -0.54 and -0.06 m/m whereas the average upward gradient at MP-18 is 0.08 m/m. Zone 9 represents a thin zone of resolvable vertical gradients in the uppermost Tunnel City Group (Fig. 4 and Fig. 5). In contrast to zone 8, Zone 9 resolvable vertical gradients are generally upward at the MP-19S/D, MP-21S/D, MP-17, and MP-18 locations and downward only at the MP-6 and MP-16 locations. The average magnitude of the zone 9 upward and downward vertical gradients varies between 0.13 and 0.19 m/m and -0.53 and -0.32 m/m respectively.

Distinct vertical gradients associated with the contact between the Tunnel City Group and the St. Lawrence Formation are observed at the MP-6, MP-16, MP-19S/D, and MP-21S/D locations (zone 10; Fig. 4 and Fig. 5). The zone 10 vertical gradients are downward at MP-6 and MP-16 with average magnitudes varying between -2.33 and -1.74 m/m and upward at MP-19S/D and MP-21S/D with average magnitudes varying between 0.09 and 0.38 m/m. The zone 10 vertical gradients, like the zone 4 vertical gradients, may be representative of the K_v contrast at the contact between zone 9 and the shallow bedrock or they may be associated with a very thin unit with relatively low K_v near the Tunnel City Group/St.

Lawrence Formation contact. The resolution of the MLSs (spacing and length of monitoring zones) combined with the relatively large and resolvable vertical gradient in zone 9 make it difficult to reliably distinguish a possible zone 10 vertical gradient from those associated with zone 9. However, the contact between zone 9 and the shallow bedrock is an important geologic contrast at the site because it marks the shift from siliciclastic to carbonate dominated deposition and an important hydraulic contrast marking the shift from the large and resolvable vertical gradients in the upper Tunnel City Group to the sometimes resolvable and spatially variable vertical gradients of the shallow bedrock.

3.1.3 Shallow Bedrock

The vertical gradients in the shallow bedrock (including the St. Lawrence Formation, Prairie du Chien Group, and St. Peter Sandstone; Fig. 2) are distinct from both the Tunnel City Group bedrock and the deep bedrock units for two reasons. First, there are no laterally extensive zones of resolvable vertical gradient in the shallow bedrock (Fig. 4 and Fig. 5). This indicates a lack of K_v contrasts at the scale of the plume in the shallow bedrock. Second, a larger percentage of the vertical gradients in the shallow bedrock are sometimes resolvable (27%) compared to the Tunnel City Group bedrock (18%) and deep bedrock (9%) (Table 1). The occurrence of sometimes resolvable vertical gradients generally decreases with depth at the field site, which likely represents the natural dampening of shallow flow system transience with depth and the strong and relatively steady hydraulic influence of the deep municipal water supply wells. The vertical gradients suggest the shallow bedrock has relatively high K_v and flow is slightly more transient than in the deeper units.

3.2. *Characteristics of Sequence Stratigraphic Units*

The high resolution vertical gradient profiles provide direct hydraulic evidence for the position and thickness of K_v contrasts. The lateral correlation of these K_v contrasts between coreholes suggests a layered system of HGUs. However, the vertical gradient profiles do not provide direct information regarding the 3D geometry of these HGUs between the boreholes or in areas where high resolution head

profiles are not available. Consequently, a 3D geologic framework at the site scale (16 km²), and ultimately at the scale of a numerical groundwater flow model centered on the site and constrained by physically based boundary conditions (275 km²), is necessary to depict the 3D geometries of the HGUs and confidently inform the lengths/trajectories and groundwater residence times of flow paths, as illustrated hypothetically by Freeze and Witherspoon (1967).

Comparison of the 11 vertical gradient zones discussed in section 3.1 with the lithostratigraphic delineation for the site shows that the position and thickness of the vertical gradient zones, and thus contrasts in K_v , are not reliably predicted by traditional lithostratigraphic subdivision of the bedrock on site. For example, zones 6, 8, and 9 are associated with resolvable vertical gradients and zone 7 is associated with unresolvable vertical gradients, and all are within the Tunnel City Group (Fig. 4 and Fig. 5). Zone 2 in the Eau Claire Formation is much thinner than the formation, and the two thick zones of unresolvable vertical gradient in the deep bedrock, zones 1 and 3, each incorporate parts of at least two formations (Fig. 4 and Fig. 5). This lack of association suggests that the geologic characteristics responsible for the contrasts in K_v are not being adequately captured by the lithostratigraphic delineation.

The poor correspondence between lithostratigraphic boundaries as well as more highly stratigraphically resolved measures of petrophysical properties (Meyer, 2013; Meyer et al., 2014) led us to examine whether an alternative geologic framework better captures the contrasts in K_v for the site. In this context, the detailed lithologic data, core photos, and geophysical logs from the research coreholes were used to delineate key sequence stratigraphic features such as maximum flooding intervals (MFI) and unconformities or their associated correlative conformities (purple shading and thick pink lines respectively; Fig. 4 and Fig. 5), at each of the on-site borehole locations. Four upper Cambrian and lower Ordovician sequences were delineated at the site. Each sequence is bound by unconformities or their correlative conformities and includes one maximum flooding interval. Specific characteristics of the maximum flooding intervals and sequence boundaries that separate the strata into depositional sequences and systems tracts at the site are presented below.

3.2.1 Maximum Flooding Intervals

Maximum flooding intervals within successions that accumulated on texturally graded shelves, such as the Upper Mississippi Valley epeiric ramp, characteristically are composed of the finest-grained siliciclastic material because they were deposited when the shoreline was at its maximum landward position within a given sequence (Runkel et al., 2007). In the Cambrian/Ordovician siliciclastic bedrock at the site, the finest grained intervals are composed of feldspathic, very-fine grained sandstone and subordinate siltstone and shale deposited in relatively distal positions on the offshore shelf. Such intervals are identifiable in natural gamma logs by relatively high signatures Fig. 7. Stratification is generally poor in most MFI's due to pervasive bioturbation as well as soft sediment deformation.

Stacking patterns reflected on natural gamma logs signatures are also used to recognize MFIs, showing a staggered signature characteristic of retrogradationally and progradationally stacked parasequences below and above, respectively, the MFIs (Fig. 7). Features in the core indicative of condensed (siliciclastic starved) sedimentation are also common attributes of MFI's (Posamentier et al., 1988), and at the site, include intraclasts, glauconite, carbonate, and iron precipitates, and, more rarely, carbonate microbiolites that formed in areas where siliciclastic input was especially limited (Runkel et al., 2007).

There are four MFIs identified on site: in the lower Eau Claire Formation, in the lower Tunnel City Group, in the upper Tunnel City Group, and in the lower-most St. Lawrence Formation. The MFI in the Eau Claire Formation varies between 1.0 and 1.3 m thick at the site and is composed of very fine to fine grained sandstone (Fig. 7) with one very thin (< 0.5 m) bed of siltstone or shale present in the MP-17 and MP-18 cores (Fig. 8). The Eau Claire Formation is between 8 and 13.5 m thick here and generally includes between 1 and 3 prominent peaks in the gamma log with the MFI generally corresponding to the stratigraphically lowest peak (Fig. 7).

The MFIs in Tunnel City Group bedrock are composed of very-fine to fine-grained silty sandstone (Fig. 7). These MFIs are also rich in intraclasts and glauconite (Fig. 8) and are typically poorly stratified,

which is reflected by increases in the disrupted sediment index (Fig. 7). The Tunnel City Group varies in thickness between 22 and 25 m whereas the lower and upper MFIs within the unit vary between 2.9 and 3.1 m thick and between 5.7 and 6.2 m thick respectively (Fig. 7). The MFI in the lowermost St. Lawrence Formation is associated with a pronounced peak in the gamma log near the Tunnel City Group and St. Lawrence Formation contact (Fig. 7), corresponding to a thin interval of dolostone, rich in thrombolites and glauconite (Fig. 8).

3.2.2 Unconformities

Five sequence bounding unconformities/correlative conformities have also been identified at the field study area, one within the Wonewoc Sandstone, two within the Tunnel City Group, one underlying the Prairie du Chien Group, and one underlying the Readstown Member of the St. Peter Sandstone (Fig. 4 and Fig. 5). An unconformity also separates the Paleozoic bedrock from Pleistocene sediments (Fig. 4 and Fig. 5).

The unconformity in the Wonewoc Sandstone was identified at all borehole locations and corresponds to a sharp contact between a highstand systems tract (HST) composed in its uppermost part of terrestrial and marine shoreface facies and an overlying transgressive systems tract (TST) dominated by nearshore, tidally influenced facies. The latter contains substantially more very fine grained sandstone, siltstone, and shale, reflected by a small and sustained increase in the gamma logs (Fig. 7 and Fig. 8). This contact corresponds to the interregional Sauk II-Sauk III sequence boundary (Palmer, 1981), in the upper Mississippi Valley represented by a regionally extensive subaerial erosion surface in the Wonewoc Sandstone (Fig. 3) (Runkel et al., 1998; Runkel et al., 2007).

Sequence boundaries are also present between the MFIs in the Tunnel City Group, in each place marking the contact between a high stand system tract (HST) and an overlying transgressive system tract (TST). As such, their approximate position on gamma logs is marked by a relatively thin interval that separates a progradational signature of parasequence stacks below from a retrogradational signature above

(Fig. 7). A more precise position of sequence boundaries in the Tunnel City Group, corresponding to individual surfaces, is problematic, in part because they are physically cryptic, especially at the scale of individual cores, and also because they may be correlative conformities at this paleodepositional position.

Cores and open borehole geophysics indicate that the Ordovician Prairie du Chien Group directly overlies the Cambrian St Lawrence Formation across much of the site Fig. 4 and Fig. 5. The apparent absence of the Jordan Sandstone, widely present as an intervening unit elsewhere in the region, indicates the presence of a subaerial unconformity between the Prairie du Chien Group and St Lawrence Formation. Removal of the Jordan Sandstone prior to deposition of the Prairie du Chien Group at the site is consistent with stratigraphic relationships noted by Runkel et al. (2007) in the nearby Madison Wisconsin area, near the Wisconsin arch.

The most physically prominent unconformity within the bedrock succession at the site underlies the St Peter Sandstone. Evidence for the unconformity has been observed in the source area and at the MP-16 location where the St. Peter Sandstone variably overlies strata ranging from the upper Tunnel City Group to the Prairie du Chien Group as a result of subaerial erosion (Fig. 5). The unconformity underlying the St. Peter Sandstone is an interregional unconformity known as the Sauk-Tippecanoe unconformity (Sloss, 1963). The contact between Cambrian/Ordovician bedrock and overlying unconsolidated Pleistocene sediment also is a high relief unconformity.

3.3. Comparison of Vertical Gradient Zones to Sequence Stratigraphic Features

Fig. 4 and Fig. 5 show that the sequence stratigraphic features at the Cottage Grove site closely correspond in position to the independently derived 11 vertical gradient zones. The most consistent correspondence appears to be in the correlation between low K_v intervals and MFI's. The three MFIs associated with the Eau Claire and Tunnel City Group are associated with resolvable, and often large, vertical gradients that mark relatively low K_v intervals. Furthermore, the sequence boundary within the

Wonewoc Sandstone also corresponds to a low K_v boundary or surface. In contrast, systems tracts and sequences between these MFIs and sequence boundaries are associated with unresolvable vertical gradients delineating units with relatively high K_v .

Application of sequence stratigraphy thus provides a 3-dimensional geologic framework for predicting K_v contrasts on site. An even greater understanding of the flow system, and correlation off-site to other areas, requires insight into the specific rock attributes of sequence stratigraphic features that create the K_v contrasts: i.e., understanding the cause and effect relationship that explains the strong correlation between sequence stratigraphic features and K_v contrasts. Meyer (2013) and Meyer et al. (2014) showed that the detailed lithologic data and bulk horizontal hydraulic conductivity data derived from straddle packer hydraulic testing in the boreholes did not consistently correspond with the vertical gradient zones. Changes in the measured values for the rock matrix porosity and matrix hydraulic conductivity do not correspond to the vertical gradient zones either. The poor correspondence is likely because the vertical gradients respond to changes in bulk K_v and those changes are controlled by changes in the characteristics of vertical or near vertical fractures. As the data above do not provide direct insight into the characteristics of vertical or near vertical fractures, fracture stratigraphy needs to be considered.

3.4. Fracture and Mechanical Stratigraphy of Regional Lower Paleozoic Rocks

In fractured rocks, the hydraulic conductivity of the matrix is typically several orders of magnitude less than that of the bulk hydraulic conductivity of the rock due to an interconnected fracture network. Consequently, the characterization of fractures in the context of stratigraphy, “fracture stratigraphy” (e.g., Laubach et al., 2009) has potential to provide insights into the 3D geometry of HGUs defined by hydraulic conductivity contrasts.

The extent of fractures in a direction perpendicular to bedding is particularly relevant as a potential control on vertical gradients and K_v . However, independent physical evidence for such preferential termination horizons is difficult to acquire in subsurface investigations reliant on vertical or slightly inclined boreholes. Over 3,340 fractures interpreted as natural were observed in the rock cores

collected at the site and 1,286 fractures were identified in acoustic or optical televiewer image logs collected in the boreholes. Of fractures observed, 80% had dip angles ≤ 30 degrees and only 13% had dip angles > 60 degrees. An example of the rare occurrences of high angle fractures in these data sets is illustrated visually in the core photos where there are numerous bedding parallel or low angle fractures and nearly no high angle or vertical fractures (Fig.8). The small percentage of high angle fractures is at least partly due to the sampling bias associated with using vertical boreholes (Terzaghi, 1965). As a result, vertical borehole fracture data sets are not adequate to characterize the vertical or high angle fractures that are key to understanding the K_v contrasts inferred from the vertical gradient profiles. Therefore, improved understanding of the fracture stratigraphy must rely on fracture characterization studies of off-site outcrop analogues.

A number of outcrop studies of the relatively undeformed lower Paleozoic bedrock of the central midcontinent region have provided fracture and mechanical stratigraphic context relevant to interpreting the vertical gradient profiles at the Wisconsin site. Underwood et al. (2003) and Cooke et al. (2006) showed that vertical fractures in a Silurian dolostone in northeast Wisconsin preferentially terminate at thin, cycle bounding organic horizons, and with lesser probability within thin mudstone interbeds (Fig. 9a). These mechanical interfaces separate units of strata as thick as about four meters in which fractures more commonly cross multiple beds, some fully penetrating the entire unit. Runkel et al. (2014) identified preferential fracture terminations in the Cambrian Jordan Sandstone in southeastern Minnesota at the contacts between 0.5-1 m thick sandstone beds in three outcrop areas, at a consistent stratigraphic position. Vertical fractures above and below these interfaces commonly extend several meters across multiple beds. Observable features that might account for terminations at the key bed contacts include thin (<2 cm), bioturbated and ductilely deformed shale-rich sandstone seams, and at one outcrop a bed parallel void network (Fig. 9a). Anderson et al. (2011) mapped fractures in outcrops of the Mifflin, Hidden Falls, and Magnolia members (in ascending order) of the Ordovician mixed siliciclastic Platteville Formation in south-eastern Minnesota. Fractures in the ~ 4 meter thick Magnolia and Mifflin members, many of which cross the full extent of the members, preferentially terminate within discrete, thinly

bedded intervals of about a half meter that represent the transitional contacts with the shale and silt-rich dolomudstone Hidden Falls Member (Fig. 9b). Runkel et al. (2014) also examined poorer exposures of St Lawrence-Tunnel City Group contact strata, and noted that prominent vertical fractures in well-cemented lower St. Lawrence Formation most commonly terminate at, or within 2 meters below, the contact with underlying much more poorly cemented, sandy and shaley Tunnel City Group (Fig. 9c).

Some hydrologic characteristics of the Platteville and Jordan formations appear to reflect the subsurface hydraulic expression of the outcrop fracture patterns. For example, the interval of preferential fracture terminations at the top of the Hidden Falls member of the Platteville Formation corresponds to a well-documented preferential position of perched springs, as well as perched subsurface water table aquifers, in the Twin Cities Metro area (Anderson et al., 2011). Hydraulic head data from nested monitor wells and packer tests similarly indicate significant resistance to vertical flow across this termination horizon (Anderson et al., 2011). Stratigraphically discrete measures of the hydraulic properties of the Jordan Sandstone are much more limited. However, Runkel et al. (2014), noted that a large vertical gradient measured using a high resolution MLS is constrained to within a relatively narrow stratigraphic interval consistent with the position of key fracture termination interfaces identified in outcrop 15 miles away.

Distinct fracture patterns associated with shallow bedrock have also been observed regionally in outcrop and borehole studies for the lower Paleozoic rocks. In a study of the Cambrian strata near Minneapolis and St. Paul, Minnesota, Runkel et al. (2006) described nonsystematic fractures as “irregular, curved, to straight fractures that commonly intersect bedding at a lower angle than systematic fractures, appear more randomly distributed, are more variable in shape, and generally have apertures less than 1 cm”. They also observed that nonsystematic fractures were more densely distributed in shallow bedrock (< 15 m from top of rock) conditions, and that systematic fractures have larger apertures than in conditions of deeper burial. These contrasts between shallow and deep conditions of burial result in distinct differences in hydraulic properties whereby bedrock in shallow conditions of burial has greater bulk hydraulic conductivity and decreased aquitard integrity compared to the same material under

conditions of deeper burial (Runkel et al., 2006; Green et al., 2012; Runkel et al., 2014). An increased density of non-systematic fractures and larger apertures of systematic fractures associated with the shallow bedrock interval at the Wisconsin site may explain, in part, the lack of resolvable vertical gradients observed in the shallow rock.

Although all of the fracture stratigraphic characterizations summarized above are based on outcrops many tens of kilometers from the Wisconsin Site, the results provide some useful context to the interpretation of the vertical gradients at the site. Collectively, they show that the fracture patterns in both siliciclastic and carbonate bedrock in the central midcontinent, ranging in age from Cambrian to Silurian, appear to share the following general characteristics:

- thick intervals with fractures that have propagated through multiple beds over vertical extents of a few to several meters
- terminations of fractures can be preferentially located along much thinner intervals that separate these thicker units
- terminations can be preferentially along a single, discrete surface, or dispersed in a more transitional manner
- termination horizons can occur at predictable (correlatable) stratigraphic positions
- Fractures are more extensively developed (greater density of nonsystematic fractures and larger apertures of systematic fractures) in conditions of shallow burial of bedrock
- The fracture characteristics documented in outcrops can correspond to observable and measureable subsurface hydraulic properties

3.5. Association Between Sequence Stratigraphic Intervals and Fracture Network

Characteristics

Understanding of the processes that dictate the characteristics of a fracture network has been a longstanding challenge, and recent research indicates the need to collectively evaluate the roles of

existing mechanical properties, tectonic and burial histories, and the evolution of material properties during diagenesis (Laubach et al., 2009). Such an investigation is beyond the scope of our current research. Here, we draw on previous studies (Helgeson and Aydin, 1991; Renshaw and Pollard, 1995; Rijken and Cooke, 2001; Underwood et al., 2003; Shackleton et al., 2005; Cooke et al., 2006) that have specifically assessed preferential termination horizons in relatively undeformed sedimentary rocks to consider how the materials associated with the sequence stratigraphic features at the study site may have provided the contrasts in rheologic properties and/or weak mechanical interfaces that hindered propagation of vertical fractures across those features.

A number of physical characteristics associated with MFI's and some sequence boundaries at the Wisconsin site are more conducive to terminating the propagation of fractures in comparison to the physical properties of intervening stratigraphic packages. For example, transgressive or highstand systems tracts consist of stacked facies that gradually change in physical properties such as grain size (fining or coarsening upward) and mineralogy over meters of stratigraphic section. The changes in physical properties that might hinder the propagation of vertical fractures across these intervals are subtle and similarly transitional, leading to a greater likelihood that individual fractures with large heights will propagate across multiple beds. Most of the traditional lithostratigraphic boundaries in the Cambrian strata of this region are positioned within such systems tracts, which could account for the lack of correspondence between head deflections and these lithostratigraphic contacts.

In contrast, MFI's are characterized by a number of features more conducive to terminating the propagation of fractures. Perhaps most importantly, natural gamma logs and cores show that the MFIs in the Tunnel City Group and Eau Claire Formation contain a higher percentage of shale and siltstone than strata above and below, as a matrix in coarser material and in discrete, contorted beds. Relatively ductile, very fine-grained siliciclastics are well known to cause fracture tip termination via distribution of stresses (Cooke et al., 2006). The MFIs are internally a much more heterolithic assemblage of material compared to other parts of the section. They consist of an amalgamation of the distal (seaward) parts of parasequences, with a dense vertical spacing of multiple erosional discontinuities separating thin,

irregular beds that vary widely in composition, grain size, and cementation (Runkel et al., 2007). Intervals of thinly bedded strata with contrasting material properties (e.g. rigidity contrasts) and weak interfaces would inhibit propagation of vertical fractures from the thicker, more homogenous, adjacent units (Helgeson and Aydin, 1991; Renshaw and Pollard, 1995; Shackleton et al., 2005). Fractures of layer-limited height within the thinly bedded MFI's may also have relatively narrow apertures compared to the taller fractures in adjacent units (Odonne et al., 2007). These characteristics would likely result in layers with relatively low K_v .

Another possible control on preferential termination of vertical fractures in MFIs, and thus on reduced K_v associated with these intervals, is the presence of bed parallel "fractures" that could serve as weak mechanical interfaces. Vertical fractures are known to preferentially terminate at bed-parallel "fractures" in outcrops of lower Paleozoic carbonate and siliciclastic strata elsewhere in the region (Anderson et al., 2011; Runkel et al., 2014). There are some hydrogeologic indications that such bed parallel fractures are more densely clustered within MFI's compared to other parts of the stratigraphic section. MFIs corresponding to vertical gradient zone 6 and vertical gradient zone 10 are known to correspond to preferential development of high hydraulic conductivity bedding parallel fractures in southeastern Minnesota, within intervals that in a vertical direction serve as low K_v units (Runkel et al., 2003; Runkel et al., 2006; Luhmann et al., 2011; Green et al., 2012; Runkel et al., 2014). Swanson et al. (2006) and Meyer et al. (2008) noted a correspondence between what we now know are parasequence boundaries, and the preferential presence of bedding plane fractures in the Tunnel City Group, HGU8 and HGU6, of southwestern Wisconsin. Because parasequence boundaries downlap into MFIs where they are densely clustered, bedding plane fractures may logically also be more densely clustered.

The MFI in the lowermost St. Lawrence Formation at the Wisconsin site differs from underlying MFIs in being particularly uniformly well-cemented carbonate rock. It therefore may internally lack the weak interfaces characteristic of underlying MFIs. Presumably this would promote development of through-going vertical fractures across the lower St Lawrence. The distinct zone 10 vertical gradients across the St Lawrence-Tunnel City contact strata in some of the MLSs at the site may reflect preferential

693 termination of lower St Lawrence through-going fractures at or just below the contact within the
694 underlying more poorly cemented shale and sandstone of the Tunnel City Group, in a manner similar to
695 that displayed in outcrops of the contact between these formations (Runkel et al., 2014).

696 The zone 4 vertical gradient within the Wonewoc Sandstone is the most difficult to relate to
697 apparent contrasts in material properties or interfaces that might account for corresponding fracture
698 attributes. If the vertical gradient occurs across a surface rather than a thin interval, it could be explained
699 by fracture terminations at sandstone bed contacts similar to those documented within the Jordan
700 Sandstone by Runkel et al. (2014). However, unlike the Jordan Sandstone termination interfaces, the
701 cores and borehole geophysical logs at the Wisconsin Site do not reveal the presence of discontinuities
702 (e.g. bedding plane “fractures”) or shale at the sequence boundary. Instead, like most sequence boundaries
703 within sandstones of this region, the unconformity is cryptic, within a succession dominated by medium-
704 to coarse-grained sandstone (Runkel et al., 1998; Runkel et al., 2007). Even though the sequence
705 boundary appears physically cryptic, on a larger scale it does separate Wonewoc sandstone facies that
706 subtly differ from one another in grain size, bedding, and texture. This contrast may have been sufficient
707 to cause the upper and lower Wonewoc to independently behave as discrete mechanical units, with
708 limited fracture connection between them across the sequence bounding unconformity. This mechanism
709 of poor hydraulic connection was proposed conceptually by Underwood et al. (2003). Meyer et al. (2008)
710 presented evidence of the hydraulic effect with a measured head profile, which was then simulated
711 stylistically using a discrete fracture network model. The high resolution vertical gradients associated
712 with HGU4 and the new understanding of their association with a sequence bounding unconformity adds
713 support for this type of vertical hydraulic discontinuity in fractured rocks.

714 The vertical gradient data indicate the shallow bedrock can be treated as a single HGU at the
715 scale of the plume. However, the shallow bedrock is not represented by a single sequence stratigraphic
716 unit and the site data indicate smaller scale lithologic and possibly hydraulic heterogeneities within the
717 shallow bedrock unit due to the influence of three overlapping unconformities within this interval
718 (Cambrian-Ordovician, Sauk-Tippecanoe, Paleozoic-Pleistocene). The presence of these unconformities

limits the lateral continuity of stratigraphic units in the shallow bedrock. In addition, the subaerial weathering, erosion, and re-deposition of materials associated with the three overlapping unconformities have the potential to change secondary porosities thus affecting the 3D distribution of K_v . For example, the frequency of non-systematic, high angle fractures observed in cores and borehole image logs is much higher in the shallow rock units than in the deeper units. This may, in part, explain the lack of resolvable vertical gradients traceable across the plume in the shallow bedrock. In addition, karstic conditions have been observed in the Prairie du Chien Group in the region and at the field site (e.g., Palmquist, 1969; Smith and Simo, 1997; Tipping et al., 2006; Meyer et al., 2008) and younger sediment is commonly observed in these karst channels (Smith and Simo, 1997; Tipping, 2002). These geologic heterogeneities may result in smaller scale heterogeneities in physical properties and hydraulic characteristics and further detailed characterization of these heterogeneities is a topic of future research.

The relationship between sequence stratigraphy and laterally extensive contrasts in K_v presented here provides confidence in interpolation of the HGU's at the plume scale (16 km²). The correspondence between HGU's and sequence stratigraphic units also demonstrates potential for predicting the position of intervals with possible contrasts in K_v (such as important aquitards) beyond the area of the research site, because the same sequence stratigraphic units can be traced regionally across the Upper Mississippi Valley area (Runkel et al., 2007). Recently collected data from a high resolution MLS in Cambrian strata in Minnesota, 400 km from the Wisconsin study area, shows similar relationships, such as an abrupt change in vertical gradient corresponding to a maximum flooding interval in the lower St Lawrence Formation (Runkel et al., 2014).

Wider application of sequence stratigraphy to predict hydraulic properties will require a better understanding of the physical properties (i.e., the mechanical stratigraphy) that together with tectonics, burial history, and other factors, dictate fracture patterns. For example, the physical properties of sequence stratigraphic features such as MFI's and unconformities can be variable even within the deposits of an individual depositional basin, such as the Cambrian strata in this part of the cratonic interior (Runkel et al., 2007), and therefore their impact on fracture patterns could likewise be variable. Toward this goal,

we will continue to explore the relationships between hydraulic properties, fracture patterns, and mechanical properties at the Wisconsin Site, and more regionally in our future research.

4. Hydraulically Calibrated Sequence Stratigraphy for Delineation of Hydrogeologic Units

In summary, comparison of the position and thickness of the K_v contrasts indicated by the vertical gradient zones to the sequence stratigraphic units shows a very strong spatial association between the two (Fig. 4 and Fig. 5). These two data sets were arrived at independently and when combined provide a hydraulically calibrated sequence stratigraphic framework for the site. This framework provides increased confidence in the precise delineation and description of the nature of HGU contacts in each borehole and interpolation of the HGUs between boreholes at the site scale. In addition, because sequence stratigraphic units are closely constrained with respect to time and depositional environments the hydraulically calibrated sequence stratigraphy developed for the site provides some capability to predict HGUs offsite in areas where high resolution hydraulic data sets are not available.

Integration of vertical gradient zones and sequence stratigraphy allows for robust delineation of 11 (1-10 and the shallow bedrock) HGUs corresponding to the 11 vertical gradient zones (Fig. 10). The name 'shallow bedrock' is retained for the eleventh HGU because the basis for its delineation is slightly different than for the other 10 units. The attributes of the sequence stratigraphic units and regional information regarding vertical fracture terminations provide additional information to describe the HGUs.

HGUs 1, 3, 5, and 7 are composed of relatively thick sections of unresolvable vertical gradients associated with coarser grained, highstand and transgressive system tracts deposits between MFIs (Fig. 4 and Fig. 5). The lack of vertical gradient between adjacent monitoring intervals within these four HGUs suggests relatively high K_v potentially due to well-connected, through-going, vertical fractures, as have been observed regionally in outcrops (Fig. 10).

HGU9 is also associated with highstand and transgressive system tract deposits between MFIs. However, HGU9 is characterized by relatively large vertical gradients indicative of lower K_v (Fig. 4 and

Fig. 5). The strata associated with HGU9 are finer grained, finely laminated, and thinner than the strata associated with HGUs 1, 3, 5, and 7, which might account for their distinct hydraulic behavior.

HGUs 2, 6, and 8 are characterized by resolvable vertical gradients associated with maximum flooding intervals (Fig. 4 and Fig. 5). The vertical gradients associated with these units indicate relatively low K_v compared to the adjacent units. The relatively low K_v may be attributed to fracture terminations within these units resulting in limited vertical fracture length and poor fracture connectivity within each unit (Fig. 10).

Both HGU 4 and HGU 10 are conceptualized as surfaces (i.e., negligible thickness) where vertical fractures may terminate resulting in poor vertical hydraulic connectivity between the units above and below the surface (Fig. 10). HGU 4 is characterized by a resolvable vertical gradient associated with the sequence bounding unconformity in the middle of the Wonewoc Sandstone (Fig. 4 and Fig. 5). The HGU 4 vertical gradients likely indicate poor vertical hydraulic communication between fracture networks across the unconformity separating HGU3 and 5. Similarly, the HGU 10 vertical gradients likely represent poor hydraulic communication between the fracture networks of the shallow bedrock and that of HGU9 in the upper Tunnel City Group (Fig. 10). The lateral continuity of these ‘surfaces based’ HGUs indicates they play an important hydraulic role in the flow system. Although important, they are extremely subtle and only evident due to the MLS design approach used here, which maximized the vertical resolution and specifically designed the position and lengths of seals and monitoring zones to minimize blending.

The vertical gradient data support delineation of the shallow rock as a single HGU because there were no laterally correlatable zones of resolvable vertical gradient observed in the shallow rock. Rather, the shallow rock is characterized by unresolvable vertical gradients and an increased frequency of sometimes resolvable vertical gradients compared to the other units (Fig. 10). The lack of laterally correlatable resolvable vertical gradients is an important result because it indicates a lack of laterally extensive contrasts in K_v most likely due to the high frequency of non-systematic fractures in the shallow bedrock units and the poor lateral continuity of stratigraphic units due to the presence of three overlapping

unconformities. The multiple, overlapping unconformities in the shallow bedrock system result in the presence/absence of distinct lithostratigraphic units on a lateral scale much smaller than the plume or study site scale. Further characterization of these heterogeneities within the shallow bedrock HGU is a focus of future research. The increased frequency of sometimes resolvable vertical gradients in the shallow rock is consistent with the conceptual model for this flow system where transience in hydraulic head diminishes with distance from the water table due to decreased influence of recharge and due to the relatively steady hydraulic gradient applied to the deeper units by nearby municipal pumping wells.

5. Conclusions and Implications

The objective of this experiment was to determine if the spatial and temporal characteristics of depth discrete measurements of the vertical component of hydraulic gradient (i.e., vertical gradient) can be used as the primary line of evidence for the delineation of hydrogeologic units (HGUs). To that end, multilevel systems with numerous, depth-discrete, minimally blended monitoring zones (high resolution) were installed at seven locations along two orthogonal cross-sections spanning a 16 km² area which encompasses a mixed organic contaminants plume in fractured sedimentary rocks (i.e., at the ‘plume scale’). The results showed that the high resolution vertical gradients were highly reproducible over multiyear periods and reliably identified the position and thickness of intervals of rock with contrasting vertical hydraulic conductivity (K_v) in each hole. The position and thickness of these K_v contrasts occurred at the same stratigraphic position across the 16 km² area but, most notably, they did not correlate with the thickness/boundaries of lithostratigraphic units indicating an alternative geologic model was needed to adequately represent the hydraulic contrasts. The high resolution geologic information collected from continuous cores and geophysical logging was further used to delineate sequence stratigraphy for the site. We observed that the contrasts in K_v were strongly associated with key sequence stratigraphic units (i.e., maximum flooding intervals and unconformities). The vertical gradients and sequence stratigraphy were arrived at independently and when combined supported robust delineation of 3-D HGUs for the site.

These sequence stratigraphic units are distinguishable throughout the Cambrian-Ordovician aquifer system of the Midwest US suggesting a potential ability to predict K_v contrasts in areas where high resolution head profiles are not available.

These findings are important for several reasons. Consistency of the K_v contrasts over a 16 km² area strengthens the high resolution head profile method for delineating HGUUs (Meyer et al., 2014). The 11 HGUUs delineated here refine the previous HGU conceptual model for the site (Meyer et al., 2008) and improve the lithostratigraphically based HGUUs previously documented for this area of Dane County, Wisconsin (Bradbury et al., 1999; Krohelski et al., 2000). In a broader context, this paper clearly shows how high resolution hydraulic head data can be used to identify the key geologic features responsible for K_v contrasts. The HGU framework delineated using this approach essentially represent a ‘hydraulically calibrated geologic framework’. This is a distinctly different approach to the traditional reliance on a geologic framework first without independent hydraulic confirmation which, in sedimentary rock, often leads to cross-connection between distinct units resulting in blended measurements with unknown biases in hydraulic and geochemical data and possible redistribution of natural solutes and contaminants. A hydraulically calibrated geologic framework, serves as an improved basis for predictions of groundwater and solute travel paths and times by numerical models, which are increasingly important for analysis of environmental and health risks. The refined hydrogeologic unit framework also provides a means to consistently interpret historical hydraulic and geochemical data sets from existing cross-connecting monitoring wells on site. This will in turn also guide the placement of monitoring well/multilevel system screens used to collect new, minimally blended data that can be used for calibration of numerical models and evaluation of remediation system performance.

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1090 **Tables**

1091

1092 Table 1. Summary of vertical gradient characteristics

Broad Domain	Total # Gradients ¹	Resolvable			Unresolvable	Sometimes Resolvable
		Total %	Up %	Down %	Total %	Total %
All	227	33	20	80	51	16
Deep Bedrock	104	18	0	100	73	9
Tunnel City Group Bedrock	71	63	29	71	18	18
Shallow Bedrock	52	23	17	83	50	27

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1094 ¹ The values presented in this table are derived from all of the head profiles measured for each MLS

1095 between their installation date (2003-2008) through December 2014. Head profiles were measured several

1096 times per year throughout the various seasons for between 6 and 11 years.

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Figure Captions

Fig. 1. Maps showing the site location, source area, plume extent, and distribution of coreholes and different types of wells on site. 3.05 (10 ft) contour interval shows distribution of drumlins on site. Municipal well #4 is off the map 1.4 km to the north.

Fig. 2. Generalized site lithostratigraphic column showing the average thickness of each unit and the general stratigraphic position of major unconformities and correlative conformities identified at the site (updated from Meyer et al. (2008)). (*) The unit is not always present at the site. (**) Site data do not provide clear evidence for the Jordan Formation. Trempealeau is abbreviated as 'Trempe.'.

Fig. 3. (a) Map showing the regional extent of the Cambrian-Ordovician aquifer system found on site. (b) Sequence stratigraphic cross-section through part of the Cambrian-Ordovician aquifer system (location shown in (a)) providing a regional sequence stratigraphic context for the rocks at the site. Note that maximum flooding intervals and unconformities are traceable throughout the depositional basin spanning from central Wisconsin to eastern Nebraska.

Fig. 4. Lithostratigraphy, sequence stratigraphy, and high resolution head and vertical gradient profiles for 5 locations along a west-east cross-section. The stratigraphic positions of the vertical gradients are consistent along the cross-section and strongly associated with the independently derived sequence stratigraphic units. Combination of the two data sets results in delineation of 11 HGUs.

Fig. 5. Lithostratigraphy, sequence stratigraphy, and high resolution head and vertical gradient profiles for 3 locations along a north-south cross-section. The stratigraphic positions of the vertical gradients are consistent along the cross-section and strongly associated with the independently derived sequence stratigraphic units. Combination of the two data sets results in delineation of 11 HGUs.

Fig. 6. A conceptual model illustrating the characteristics of head and vertical gradient profiles at different positions in a generic steady state flow system with layers of contrasting K_v . The head profiles inflect across contrasts in K_v resulting in contrasts in vertical gradient occurring at the same stratigraphic position across the flow system. The magnitude and direction of the vertical gradients in a given profile are determined by the position within the flow system.

Fig. 7. The stratigraphic positions and thicknesses of MFIs were delineated in each hole based on the shift from retrograding to prograding facies indicated by peaks in the gamma log combined with core data indicating finer grained sandstones and/or siltstone/shale, poorly stratified sediment (high SDI), and other indications of sediment starved conditions. The gamma log shows a small, consistent increase in the middle of the Wonewoc Sandstone separating the nearshore, tidally influenced facies above the unconformity from terrestrial and marine shoreface facies below. The MP-6 lithostratigraphy applies to all other boreholes except MP-16.

Fig. 8. Core photos showing examples of the physical attributes of the maximum flooding intervals (green boxes), the unconformity (sequence boundary, black box) in the Wonewoc Sandstone, and the strata adjacent to these sequence stratigraphic units. The MFIs in the Tunnel City Group and Eau Claire Formation are characterized by an increased density of features typical of sediment starved conditions such as: (1 and 2) intraclasts (arrows) in glauconite rich matrix, (3 and 4) poorly stratified sediment with some well-preserved burrows (arrows), and (5) intraclasts (arrow) and a thin glauconite rich lamination (box).

Fig. 9. Schematic summary of vertical fracture terminations reported for the Cambrian-Ordovician sedimentary rocks in the upper Mississippi Valley (Underwood et al., 2003; Cooke et al., 2006; Anderson et al., 2011; Runkel et al., 2014). (a) Terminations at a surface, weak interface at bed contact or bed

parallel “fracture”, or within very thin (cm) shale. (b) Terminations staggered across an interval that could include relatively ductile shale, multiple weak interfaces, and/or bed parallel “fractures”. (c) Terminations of the most extensively through-going fractures in uniformly well cemented unit above are staggered, tapered across an interval that could include relatively ductile shale or poorly cemented sandstone.

Fig. 10. Schematic summarizing the geologic, vertical gradient, and inferred K_v characteristics of the hydrogeologic units delineated for the site. HGUs 2, 6, and 8 are MFIs characterized by resolvable vertical gradients indicating relatively low K_v . HGU 9 is a thin interval of finer grained, finely laminated sandstones also characterized by resolvable vertical gradients indicating relatively low K_v . HGUs 1, 3, 5, and 7 are relatively thick packages of coarser grained, highstand and transgressive system tract deposits characterized by unresolvable vertical gradients indicating relatively high K_v . HGUs 4 and 10 are conceptualized as surfaces where vertical fractures may terminate resulting in poor vertical hydraulic connectivity between the units above and below the surface.

Fig. 1

Time	Lithostrat			Major Lith	Avg Thickness (m)
Pleistocene	Horicon Member				17
Ordovician	Ancel Group	St. Peter Sandstone (Fm)	Tonti Member		11*
			Readstown Member		15*
	Prairie du Chien Group				17*
Cambrian	Trempealeau Group	Jordan Sandstone (formation)			0**
		St. Lawrence Formation			9*
	Tunnel City Group	Lone Rock Formation			24
		Mazomanie Formation
		Lone Rock Formation
	Wonewoc Sandstone (formation)				30
	Eau Claire Formation				10
	Mt. Simon Sandstone (formation)				>80
<div><div> Till consisting of gravelly, clayey, silty, sand with minor stratified sediments (unconsolidated)</div><div> Interbedded sandstone, clay, and conglomeratic mixture of shale, chert, sandstone, and/or dolostone fragments in fine to coarse sand or clay</div><div> Sandstone</div></div> <div><div> Silty sandstone, sandstone with thin interbeds of siltstone and/or shale</div><div> Dolostone</div><div> Sandy dolostone, dolostone with intervals of sandstone</div></div> <div> Unconformity Correlative Conformity</div>					

Fig. 2

Fig. 3

MP-18 (A')

MP-15 MP-21S/D

MP-19S/D

MP-6 (A)

Fig. 4

Fig. 6

Fig. 7

Fig. 8

Fig. 10