# HYDROGEOLOGIC PROPERTIES OF THE ST. LAWRENCE AQUITARD, SOUTHEASTERN MINNESOTA

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# EXECUTIVE SUMMARY

The deep Paleozoic bedrock aquifers in southeastern Minnesota (Figs 1-3) are in most places not yet significantly impacted by pollution and presumed to be protected by low permeability overlying geologic layers, called aquitards. Even though aquitards are an important control on recharge and contaminant transport, their hydrologic characteristics are poorly understood compared to aquifers, particularly in fractured rock such as the Paleozoic bedrock of southeastern Minnesota.

To better understand the properties of bedrock aquitards, we initiated a project that utilizes widely ranging methods to gain insights into the properties of the St Lawrence Formation and adjacent strata of the upper Tunnel City Group (Mazomanie and Lone Rock Formations) and lower Jordan Sandstone. The St Lawrence Formation has been traditionally regarded as an aquitard in the Paleozoic bedrock hydrogeologic system. The research was funded through the Environment and Natural Resources Trust Fund (ENRTF), per the recommendation of the Legislative and Citizens Committee on Minnesota Resources (LCCMR). Our investigation addresses hydraulic properties at site-specific as well as sub-regional (square miles) scales. Specific activities included drilling, testing and instrumentation of a borehole in the eastern Twin Cities Metro area (TCMA), the Afton multilevel system (MLS) hole, that has provided us with detailed multi-level measurements of hydraulic characteristics above, below and within the St Lawrence Formation. We also analyzed the distribution of fractures in bedrock outcrops, in an effort to understand the controls these fractures might have on borehole hydraulic conditions. Borehole and outcrop scale data are augmented with ground-water tracer experiments (Green et al., 2008, 2012) that provide horizontal and vertical travel times at the sub-regional scale. Compilation of existing published and unpublished hydraulic and water chemistry data provide additional insights into the properties of the St Lawrence Formation and adjacent units across a wider extent of southeastern Minnesota. Our results are synthesized into a conceptual model of flow through the lower Jordan Sandstone, St Lawrence Formation, and upper Tunnel City Group in variable geologic conditions. This provides a better understanding of the "aquitard integrity" of these and other bedrock units inferred to protect deeper groundwater in southeastern Minnesota.

Discrete interval hydraulic head data from 14 ports in Afton MLS hole show the presence of thin, key barriers to vertical flow. The hydraulic head data reveal that the head difference of approximately 50 ft between the top and bottom of the open hole is mostly expressed as distinct, large deflections across four thin (<10ft) intervals in the lower Jordan Sandstone and St Lawrence Formations. There also appears to be a two-fold division into upper and lower flow systems that internally show similar magnitude and direction of changing hydraulic head with time, but differ from one another. A number of chemical parameters show variability between units delineated by hydraulic head characteristics. The most distinct change in water chemistry appears to be present in the upper part of the St Lawrence Formation, across a 9 ft interval approximating the position of the largest head deflection (18-20ft) between any of the monitored ports, and to the boundary between the upper and lower flow systems. Evaluation of the water chemistry is ongoing, but the variability in water chemistry might be explained by differences in the relative amount of groundwater contributed to each monitoring zone by the fractures versus the rock matrix and/or differences in the length/residence times of flow paths sampled by each of the monitoring zones. Vertical connectivity can be a key control on physical flow paths and also produce conditions whereby chemical reactions cause changes in the concentrations of non-conservative constituents.

Our evaluation of fracture characteristics in exposures of lower Jordan Sandstone through upper Tunnel City Group indicates that certain bed contacts serve as mechanical interfaces at which vertical fractures preferentially terminate compared to other bed contacts in the stratigraphic section. Such mechanical interfaces are likely the cause of the abrupt hydraulic head deflections in the Afton MLS hole, as well as discrete deflections documented at other sites in the region (Meyer et al., 2008, 2014; Anderson et al., 2011). They are an important factor in determining aquitard integrity by serving as low permeability barriers to vertical flow in saturated subsurface conditions.

The new and existing information we have compiled and analyzed indicates that where the St Lawrence Formation is relatively deeply buried by younger bedrock it is properly classified as an aquitard, as it has been traditionally treated. Vertical hydraulic conductivity in the St Lawrence under these conditions is sufficiently low to maintain pronounced vertical hydraulic head differences across the formation. Importantly, however, we have shown that aquitard boundaries do not correspond precisely to the boundaries of the St Lawrence Formation. Fine clastic-dominated strata of the lower Jordan Sandstone are also properly classified as an aquitard, and grouped together with the underlying St Lawrence Formation. Estimates of bulk vertical conductivity of about $10^{-4}$ to $10^{-5}$ ft/day at a site in the central TCMA are reasonable for deep bedrock conditions, assuming leakage through narrow, generally poorly connected vertical fractures accounts for a conductivity orders of magnitude greater than matrix vertical conductivity. Stratification of water chemistry across the lower Jordan Sandstone-upper Tunnel Group in a different way also imply relatively high aquitard integrity in deep bedrock settings. Where the lower Jordan and St Lawrence is the uppermost bedrock aquitard that is relatively deeply buried (>50 ft) beneath younger bedrock, it sufficiently limits vertical recharge to produce groundwater bodies that are stratified in age across extensive, mappable areas. Uppermost bedrock groundwater is dominantly recent in age, and commonly contains anthropogenic constituents such as chloride and nitrate not present below the lower Jordan-St Lawrence aquitard. However, protection of lower aquifers by overlying aquitards can be variable, even in deep bedrock settings, due to a number of factors, including hydraulic head gradients, faults, and multiaquifer wells.

Although the lower-Jordan-St Lawrence aquitard has a low bulk vertical conductivity in deep bedrock settings, bulk horizontal conductivity is high, resulting in pronounced anisotropy. The anisotropy is the result of low matrix permeability and poor connectivity of fractures in a vertical direction, but with the ubiquitous presence of high conductivity bedding-plane parallel macropore networks in a horizontal direction. This has implications for contaminant transport in the aquitard. Even if vertical transport is inhibited, lateral transport across the aquitard in a direction parallel to bedding could be significantly rapid.

The vertical integrity of the lower Jordan-St Lawrence aquitard in shallow bedrock conditions must be viewed as at least locally very poor, and likely highly variable. Characterizing aquitard integrity in shallow bedrock conditions is especially difficult because fractures are more greatly developed compared to deeper conditions of burial. Dye trace results have consistently shown that the ability of the St. Lawrence to impede vertical flow, that is, its aquitard integrity, is apparently quite limited in these subcrop settings. Groundwater chemistry profiles in several counties in southeastern Minnesota reflect the same phenomenon: Relatively rapid recharge of recent water to deeper aquifers locally occurs in areas where the lower Jordan-St Lawrence aquitard loses its vertical integrity. This includes where it is cut by erosional windows such as in buried bedrock valleys, is displaced by faults, and anywhere it is breached by well-connected vertical fractures that are developed in shallow bedrock conditions. Underlying aquifers in these settings, and the aquitard itself, are more susceptible to contamination than in deeply buried settings. This has a number of environmental implications, including water quality management of the many coldwater trout streams that are tributaries to the Mississippi River system in southeastern Minnesota, and protection of drinking water in underlying aquifers.

Our research will continue at least until June of 2015 with additional monitoring and sampling at the Afton MLS hole, funded by the Minnesota Department of Natural Resources. Our ongoing research may provide additional insights into vertical conductivity across the lower Jordan through upper Tunnel City interval. This informal report will be modified and disseminated as one or more formal publications after June, 2015.

# INTRODUCTION

The deep Paleozoic bedrock aquifers in southeastern Minnesota (Figs 1-3) are in most places not yet significantly impacted by pollution and presumed to be protected by low permeability overlying geologic layers, called aquitards. Even though aquitards are an important control on recharge and contaminant transport, their hydrologic characteristics are poorly understood compared to aquifers, particularly in fractured rock such as the Paleozoic bedrock of southeastern Minnesota. Specific unanswered questions associated with aquitards include:

- What are the pathways for water and contaminants to move into deeper aquifers?
- How long does it take water to move through these pathways?
- What are the estimates of long-term sustainability of lower aquifers?

The St. Lawrence Formation is a relatively fine-grained, mixed siliciclastic and carbonate layer that is widely considered to function as an aquitard in the Paleozoic bedrock aquifer system of southeastern Minnesota (e.g. Kanivetsky, 1978; Runkel et al., 2003). Despite recognition by regulators of the potential importance of the St. Lawrence Formation as an aquitard, its hydrologic properties are poorly known. Furthermore, the traditional view that it has uniformly low permeability that protects underlying aquifers across its extent appears to be inconsistent with a number of hydrogeologic observations. For example, several studies have shown that across large areas of southeastern Minnesota recent water impacted by human activity is separated from older, less impacted water at depths that approximate the position of the St. Lawrence Formation (Berg, 2003; Peterson, 2005; Tipping, 2012). Yet in other areas, there is recent, contaminated water below the St. Lawrence. Furthermore, the formation is widely used as a source of water for domestic use across southeastern Minnesota, with yields comparable to those of the traditional aquifers (Runkel et al., 2006a). Recently, dye traces through the St. Lawrence Formation in areas where it subcrops have revealed flow speeds from hundreds to over a thousand feet per day (Green et al., 2008, 2012). These observations are seemingly inconsistent with the characterization of the formation as a low-permeability, isotropic aquitard.

Identification of which parts, if any, of the St. Lawrence Formation serve as barriers to vertical flow has yet to occur, in part because closely-spaced hydraulic head measurements have not been collected across the formation. Low permeability beds in the overlying Jordan

Sandstone and underlying Tunnel City Group may by themselves serve as aquitards, providing some of the vertical protection assumed to be derived from the St. Lawrence (Runkel et al., 2003, 2006a). Thus the aquitard boundaries may not correspond precisely to the top and bottom of the formation, and there may be multiple barriers with intervening aquifer layers within this sequence. Meyer et al. (2008, 2014) collected discrete interval hydraulic head profiles in sedimentary rocks at three sites in North America, including Paleozoic bedrock of south-central Wisconsin, and recognized that thin (<6.5 ft.) intervals may be the key barriers to vertical flow. Meyer et al. (2008) suggested that traditional aquitard and aquifer definitions may not be applicable to the Paleozoic bedrock of this region.

To better understand the properties of bedrock aquitards, we initiated a project that utilizes widely ranging methods to gain insights into the water-bearing properties of the St. Lawrence Formation and adjacent strata of the upper Tunnel City Group and lower Jordan Sandstone. The research was funded by the Environment and Natural Resource Trust Fund (ENRTF) as recommended by the Legislative and Citizens Commission on Minnesota Resources (LCCMR) as a subproject entitled "Investigation of the hydrologic properties of the St. Lawrence Formation", within a broader project called "Minnesota Geological Survey County Geologic Atlases and Related Hydrogeologic Research" (Project M.L. 2010, Chp. 362, Sec. 2, Subd. 3a). Our investigation addresses hydraulic properties at site-specific, as well as sub-regional (a few square miles) scales. Specific activities include drilling, testing, and instrumentation of a borehole in the eastern Twin Cities Metropolitan Area (TCMA), referred to in this report as the Afton MLS hole (Fig. 1), which has provided us with detailed multi-level measurements of hydraulic characteristics above, below, and within the St. Lawrence Formation. We have also analyzed the distribution of fractures in bedrock outcrops, in an effort to understand the influence these fractures might have on borehole hydraulic conditions. Borehole and outcrop scale data are augmented with ground-water tracer experiments (Green et al., 2008, 2012) that provide horizontal and vertical travel times at the sub-regional scale. We have also compiled existing published and unpublished hydraulic and water chemistry data that provide additional insights into the properties of the St. Lawrence Formation and adjacent units across a wider extent of southeastern Minnesota.

This informal report is a contract deliverable to the LCCMR. It summarizes the results of our investigation to date, synthesizing the results into a conceptual model of flow through the lower Jordan Sandstone, St. Lawrence Formation, and upper Tunnel City Group in variable geologic conditions. This provides a better understanding of the "aquitard integrity" of these and other bedrock units inferred to protect deeper groundwater in southeastern Minnesota. Our research will continue at least until June of 2015 with additional monitoring and sampling at the Afton MLS hole, funded by the Minnesota Department of Natural Resources. Thus, data collection and interpretation is ongoing, and this informal report will be modified and disseminated as one or more formal publications after June of 2015.

## GEOLOGIC CONTEXT AND LITHOLOGIC PROPERTIES OF UPPER TUNNEL CITY GROUP THROUGH LOWER JORDAN SANDSTONE

The regional geologic setting for southeastern Minnesota is characterized by Paleozoic sedimentary bedrock (Figs. 1-3) overlain by a greatly variable thickness of unconsolidated sediment related mostly to glacial processes. The bedrock in southeastern Minnesota, described in detail by Mossler (2008), is Cambrian to Devonian in age (~505 to 350 million years old). Most individual formations are layers of sedimentary rock from 50 to 200 feet thick that are dominated by either fine- to coarse-grained, quartz-rich sandstone; very fine-grained sandstone, siltstone, and shale; or carbonate rock (limestone and dolostone). The lower part of this stack of layers, Cambrian in age, is dominated by siliciclastic material (sandstone, siltstone and shale) whereas the upper part of the stack, Ordovician and Devonian in age, is dominated by carbonate rock and shale (Figs. 1-3).

The bedrock formations across most of the region are nearly flat-lying, with shallow dips of less than two degrees. Along the St. Croix and Mississippi Rivers (Fig 1) and their tributaries bedrock dips generally west and southwest as part of the eastern margin of a subtle structural depression called the Hollandale embayment. Along the western side of preserved Paleozoic bedrock, for example along the Minnesota River and its tributaries, the bedrock dips gently to the east. Faults are locally common, especially in areas where underlying Proterozoic bedrock contains faults related to the Midcontinent Rift System (Mossler, 2008).

Paleozoic bedrock has been dissected by pre-glacial, inter-glacial, and to a lesser extent, recent erosion. Older strata are uppermost bedrock on the uplifted western and eastern limbs of the Hollandale Embayment (Fig 1) with progressively younger bedrock preserved toward the center. Across most of southeastern Minnesota, Paleozoic bedrock is buried beneath unconsolidated, Quaternary glacial sediments and Holocene alluvium as much as a few hundred feet thick. Bedrock exposures are limited to scattered, small outcrops along St Croix, Mississippi, and Minnesota Rivers and their tributaries. Subcrop patterns are heavily influenced by the presence of valleys eroded into the bedrock and subsequently filled with sediment, which are separated by plateaus of more resistant rocks such as formations dominated by limestone and dolostone.

The St. Lawrence Formation is a thin, heterolithic sedimentary rock unit that occupies a position near the middle of the Paleozoic bedrock sequence across most of southeastern Minnesota (e.g. Fig. 2). Along its easternmost extent in Minnesota, the mapped subcrop of the St. Lawrence is characterized by a thin, convoluted polygon that follows present-day and buried valleys of the St. Croix and Mississippi Rivers and their tributaries (Fig. 1). Along the western and northern edges of Paleozoic bedrock, the St. Lawrence Formation also subcrops across wider areas that represent buried mesas overlying the Tunnel City Group (Fig. 1).

The St. Lawrence Formation is composed of interbedded very fine-grained feldspathic sandstone, siltstone, shale, and sandy dolostone (Runkel et al., 2006a) (Fig. 4). It is moderately to well-indurated by pervasive dolomitic and feldspathic pore-filling cements. Dolostone is more abundant in the lower one-half of the formation than in the upper one-half. The formation ranges from about 25 to 90 ft. thick. It is thinnest in the northeastern TCMA, and thickens to the south and west. Along the western margin of the Hollandale embayment and south of the TCMA it is typically greater than 60 ft. thick.

The Jordan Sandstone is composed of two intercalated facies: quartzose, friable, fine- to coarse-grained sandstone, and more tightly cemented (feldspar and dolomite), very fine-grained, feldspathic sandstone, siltstone and shale (Runkel, 1994). The contact between the Jordan Sandstone and underlying St Lawrence Formation (Fig. 4) is conformable and gradational. The lower 5 to 30 feet of Jordan Sandstone is composed largely of very fine to fine-grained, feldspathic sandstone which overlies interbeds of feldspathic, very fine-grained sandstone, siltstone and shale in the upper St. Lawrence. Selecting a precise contact between these formations in a consistent fashion from site to site can therefore be problematic. For example, the contact between these formations occurs on natural gamma logs along a gradual shift from relatively high to relatively low gamma counts up-section (Fig. 4). The contact on such logs is typically chosen within the lowermost approximately five feet of this shift. Driller's descriptions on water-well records generally indicate a downward change from relatively soft sandstone to harder, and finer-grained (siltstone, shale, or dolostone) rock across the Jordan Sandstone-St. Lawrence contact interval. Drill records commonly also indicate a color change, typically from white or light gray for the Jordan Sandstone, to green, pink or red for the St. Lawrence Formation (Runkel et al., 2006a).

The Tunnel City Group includes two formations (Fig. 4) (Mossler, 2008). The Mazomanie Formation is dominated by poorly to moderately cemented (dolomite) fine- to coarse-grained quartzose sandstone. The Lone Rock Formation consists mostly of better cemented (feldspar and dolomite) very fine-grained, glauconitic, sandstone, siltstone, and shale. The Mazomanie Formation is present only in the TCMA, thinning in a general northeast to southwest direction. The contact between the Tunnel City Group and the overlying St. Lawrence Formation is lithologically variable. The contact in the northern part of the TCMA (Anoka, Chisago, and northern Washington and Hennepin counties) is characterized by siltstone and silty dolostone in the lower St. Lawrence overlying fine- to medium-grained sandstone of the Mazomanie Formation. Driller's logs from this area typically include a description of this lithic change, and natural gamma log curves show a distinct deflection from high gamma counts in the feldspathic siltstone of the St. Lawrence to low gamma counts in the quartzose sandstone of the Mazomanie (Fig. 4). To the south and west, the St. Lawrence Formation commonly overlies glauconitic and feldspathic very fine grained sandstone of the Lone Rock Formation. The natural gamma log signatures for the two formations are similar to one another, and the precise contact may be hard to ascertain without well cuttings. It is particularly difficult to interpret geophysical logs from holes when there is only a very short interval of bedrock penetrated. Additionally, the two formations interfinger, with the lower St. Lawrence Formation containing interbeds of glauconitic sandstone that are similar to the Lone Rock Formation. The contact between the two formations in such areas is picked at the base of the lowest dolostone-rich beds, which have gamma radiation intensities lower than underlying sandstone of the Lone Rock. This contact interval on driller's logs is typically expressed as a change from hard, gray or pink St. Lawrence

Formation to softer, green sandstone of the Lone Rock, but the stratigraphic position of such a change is commonly inconsistent from record to record.

## OVERVIEW OF REGIONAL HYDROSTRATIGRAPHIC CONTEXT

Previous work has led to a hydrostratigraphic characterization generally applicable to all Paleozoic bedrock of southeastern Minnesota (e.g. Runkel et al., 2003, 2006b; Tipping et al., 2006; Anderson et al., 2011). Evidence to support this characterization comes from multiple kinds of hydrogeologic data. In addition to traditional data such as laboratory measures of plug permeability, aquifer tests, discrete-interval packer tests, and potentiometric data, over the past 15 years we have employed relatively new techniques of borehole geophysical and video logging to describe and measure hydrogeologic properties. We also draw heavily upon borehole video, core, and outcrop descriptions of secondary pores. A summary of the hydrostratigraphic properties of the Paleozoic bedrock, presented below, provides regional context to our research focusing on the St. Lawrence Formation and adjacent strata.

### *Rock matrix (Primary Porosity)*

Matrix characteristics of bedrock are of particular importance because the greatest volume of water (and also typically the greatest mass of contaminants) stored is within the small pore spaces of matrix blocks. The Paleozoic strata of southeastern Minnesota can be generally divided into three distinct hydrostratigraphic components based entirely on matrix characteristics (Runkel et al., 2003, 2006b). The components are: 1) fine clastic, 2) coarse clastic, 3) carbonate rock (e.g. Figs. 2, 3, 4). The mineralogy, texture, and cementation are well-known in these components from decades of stratigraphic and sedimentologic studies (e.g., Berg, 1951; Odom, 1975). The values for matrix porosity and permeability of these three components where they occur in settings with relatively minor development of secondary pores have been determined at the smallest scale through laboratory testing of plug-samples (Runkel et al., 2003).

The fine clastic component consists of feldspathic, variably glauconitic, very fine-grained sandstone, siltstone, and shale in thin to thick beds. Fine clastic strata are strongly to moderately cemented by authigenic feldspar overgrowths and by pore-filling carbonate cement. Bulk porosity typically ranges from 5-30 % and permeability is low to very low, several orders of magnitude less than that of the coarse clastic component described below. Plug tests indicate a hydraulic conductivity that typically ranges from $10^{-6}$ to $10^{-10}$ ft/day (original values reported as millidarcies and converted to hydraulic conductivity using 1 millidarcy = $2.7 \times 10^{-3}$ ft/day at $20^{o}$C). Horizontal permeability commonly is about two orders of magnitude greater than vertical.

The coarse clastic component is poorly cemented, moderately to well-sorted, fine- to coarse-grained sandstone composed of about 98 % quartz. Plug sample tests conducted on this sandstone indicate a bulk porosity of about 15 to 30% and a high vertical hydraulic conductivity of $10^{-1}$ to as high as 100 ft/day due to relatively large, well-connected intergranular pore spaces. Horizontal permeability typically is roughly equal to, or as much as an order of magnitude greater than vertical permeability.

The carbonate rock component consists of very fine to fine grained dolostone and limestone with variable amounts of silt, sand and shale as interbeds or admixed in the carbonate matrix. Rock matrix bulk porosity and vertical permeability values are typically less than 20 % and $10^{-5}$ ft/day respectively. Limited tests of horizontal permeability indicate that it is commonly about two orders of magnitude greater than vertical permeability where the carbonate rock is horizontally laminated.

### *Macropores (Secondary Porosity)*

The largest amount of and most rapid groundwater movement in the bedrock occurs through secondary pores that are larger than intergranular spaces in matrix blocks, collectively referred to herein as macropores. Figures 2 and 3 schematically show in cross-sectional view regional-scale depictions of the distribution of macropores in Paleozoic bedrock of southeastern Minnesota. Examples of various kinds of macropores in the lower Jordan Sandstone, St. Lawrence Formation, and upper Tunnel City Group, from outcrop and borehole photographs, are shown in Figures 5 and 6.  The illustrations highlight two fundamental kinds of macropore networks based on orientation relative to bedding: 1) macropores aligned with bedding and, 2) macropores intersecting bedding. Openings that preferentially align congruent to bedding are referred to as bedding-parallel macropores. Outcrop and large diameter borehole observations indicate that bedding-parallel macropores are part of an anastomosing network of such elongate apertures developed along discrete stratigraphic intervals (Runkel et al., 2003, 2006b). Other macropores intersect bedding at a relatively high angle and include vertical to subvertical macropores such as systematic joints that commonly penetrate several feet to tens of feet, as well as nonsystematic, irregular fractures that are less linearly extensive. Systematic joints occur in sets with a preferred orientation that intersect one another to create an orthogonal network in plan view.

Both bedding parallel and vertical macropores are now known to be common in all Paleozoic bedrock formations regionally across southeastern Minnesota and southern Wisconsin, and to play a major role in the groundwater flow system (e.g. Muldoon et al., 2001; Runkel et al., 2003, 2006a, 2006b; Tipping et al., 2006; Swanson et al., 2006; Meyer et al., 2008; Anderson et al., 2011). Averaged across thick (tens of feet) intervals, bulk hydraulic conductivities of Paleozoic bedrock commonly range from several tens to hundreds of feet per day, significantly greater than intergranular permeability alone would accommodate (Runkel et al., 2003). Individual macropores intersected by boreholes have conductivities measured as high as tens of thousands of feet per day (Table 1). Dye traces demonstrate that macropore networks commonly accommodate flow speeds measured in tens of feet to miles per day (e.g. Alexander and Lively, 1995; Runkel et al., 2003; Green et al., 2012).

An important outcome of research on Paleozoic bedrock hydrostratigraphy over the past 15 years is documentation of stratigraphic distribution of macropores (e.g. Muldoon et al., 2001; Tipping et al., 2006; Runkel et al., 2006b; Swanson et al., 2006; Anderson et al., 2011). This research provides a degree of understanding of preferential flow paths through high conductivity macropore networks. For example, bedding parallel macropore networks are densely clustered along specific stratigraphic intervals. Conversely, specific stratigraphic intervals have been shown to be resistant to the through-going development of vertical macropores (e.g. Anderson et al., 2011), and these intervals hinder groundwater flow in a vertical direction. Such intervals serve as key aquitards in the Paleozoic bedrock hydrogeologic system.

The degree to which macropores are developed in bedrock varies in a predictable fashion whereby density and connectivity decrease with increasing depth below the bedrock surface (Runkel et al., 2003), shown schematically in Figures 2 and 3. In conditions of relatively deep burial by younger bedrock (50 feet or greater), macropores are typically limited to discrete intervals with abundant, bedding-plane parallel openings and subvertical macropores, such as systematic joints. These macropores have relatively narrow apertures compared to shallow conditions of burial. In conditions of shallow burial by younger bedrock (less than 50 ft), macropores are more abundant, better-connected, and have larger apertures compared to conditions of deeper burial. The term "shallow bedrock conditions" in this report refers to the upper 50 ft of Paleozoic bedrock regardless of the thickness and composition of overlying unconsolidated materials. This 50 foot boundary is somewhat arbitrary in the sense that the change from shallow bedrock conditions to deep bedrock conditions is transitional, and will vary in depth from place to place.

In addition to depth of burial beneath younger bedrock, the composition of the bedrock also has an impact on the development of macropore networks. Macropores in siliciclastic-dominated units (coarse clastic and fine clastic strata) generally have relatively small apertures, and limited trace lengths of vertical macropores, based on outcrop observations. Apertures of individual bedding parallel macropores in siliciclastic bedrock are rarely greater than a few inches (Runkel et al., 2006a, 2006b). In contrast, apertures in carbonate rock range upward to markedly larger sizes, including cave networks, and commonly have vertical macropores with wide apertures that extend continuously for over 100 feet perpendicular to bedding (Runkel et al., 2013). Much of the aperture development in the carbonate bedrock is the result of solution enhancement, and as such is consistent with the traditional definition of a karst system: an integrated mass-transfer system in soluble rocks with a permeability structure dominated by conduits dissolved from the rock and organized to facilitate the circulation of fluid (Klimchouk and Ford, 2000). Our hydrogeologic framework therefore delineates a number of major karst systems (e.g. Fig. 3) in carbonate-dominated Ordovician and Devonian bedrock of southeastern Minnesota (Runkel et al., 2003), based largely on the work of Alexander and Lively (1995), Alexander et al. (1996), and Green et al. (1997, 2002). Although siliciclastic-dominated bedrock such as the St. Lawrence Formation contains volumetrically minor dolostone, and is known to have abundant macropores, it is herein not considered karst because the origin of secondary porosity is unlikely to have been derived chiefly from dissolution (Stewart et al., 2012).

| Formation/facies | Laboratory tests, plug samples | Discrete interval tests | Individual macropores | Bulk well tests (28) |
|---|---|---|---|---|
| Jordan Ss Coarse clastic | Kv ~10 to 100 (1)<br>Kv >8.0 (2) | Kh 10 to 100 (11)<br>Kh~9 (12) | | Shallow<br>Kh avg 184.2<br>Kh med 31.8<br>Deep<br>Kh avg 49.0<br>Kh med 10.7 |
| Jordan Ss fine clastic | Kv avg $3.5*10^{-4}$ med $2..3*10^{-6}$ ; Kh x39Kv (3)<br>$7.9*10^{-2}$(4)<br>$9.3*10^{-5}$ (5) | | Kh $1.4*10^{4}$ (22) | |
| St Lawrence Fm Fine clastic, minor carbonate | Kv <$2.7*10^{-6}$, Kh $8.7*10^{-4}$(6)<br>Kv avg $2.7*10^{-4}$; med $5.5*10^{-6}$ ; Kh=Kv, to Kh x37 Kv(7) | Kh ~$10^{-3}$ to $10^{-4}$ (13)<br>Kh <$10^{-3}$, 6.7 (14)<br>Kh 2.0, 4.0, 22.0 (15) | Kh 85 (23)<br>Kh 145 (24)<br>Kh ~30, ~110 (25) | Shallow<br>Kh avg 112.7<br>Kh med 17.3<br>Deep<br>Kh avg 39.6<br>Kh med 8.5<br>Kv $10^{-4}$- $10^{-5(29)}$ |
| Tunnel City Gp Mazomanie Coarse clastic | Kv <$2.6*10^{-4}$ to 1.9; Kh 0.9 to 1.6 (8) | Kh ~2.0 (16)<br>Kh 1.5 to 7.7 (17)<br>Kh 1.8 (18)<br>Kh 25.5 to 56.7 (19)<br>Kh~31(20) | Kh 145 to $1.4*10^{4}$, avg $5.6*10^{3}$ (26)<br>$1.4*10^{4}$ (27) | Shallow<br>Kh avg 74.0<br>Kh med 11.3<br>Deep<br>Kh avg 27.2<br>Kh med 5.1 |
| Tunnel City Gp Lone Rock fine clastic | Kv $2.7*10^{-6}$ to $7.2*10^{-3}$; Kh $1.6*10^{-5}$ to $1.3*10^{-2}$ (9)<br>Kh=Kv to Kh x100Kv (9)<br>Kv avg $2.7*10^{-3}$; med $3.5*10^{-5}$ (10) | Kh <$5.5*10^{-2}$ to $4.5*10^{-1}$ (21) | | |

**Table 1**. Hydraulic conductivity measurements for the Jordan Sandstone, St Lawrence Formation, and Tunnel City Group. All values in feet per day. Kv=vertical conductivity, Kh=horizontal conductivity. See text for additional explanation. (1) Estimate based on tests of similar material in other formations Runkel et al, (2003; 2006b). (2) Setterholm et al. (1991), one sample chosen as representative of the volumetrically largest coarse clastic component, friable sandstone, but with sufficient cement to allow plug extraction and lab testing;). (3) MUGSP (1980), 26 samples; comparison of Kv to Kh based on single sample. (4) Setterholm et al (1991), one sample, selected as representative of higher end of range of permeability for fine clastic material. (5) Setterholm et al (1991), one sample selected as representative of lower end of range of permeability. (6)Walton et al., (1991), single sample. (7) MUGSP (1980), 422 samples; comparison of Kv to Kh based on five samples. (8) Walton et al. (1991), 3 samples. (9) Walton et al. (1991), 5 samples. (10)MUGSP (1980), 539 samples. (11) estimate based on packer tests of similar material in other formations Runkel et al., (2003; 2006b). (12)10 ft interval, Afton MLS hole, this report. Tested interval includes fine clastic and coarse clastic interbeds. See text for discussion. (13) estimate based on pulse tests of three two-foot intervals (Ports 7,8,10) in Afton MLS hole (preliminary interpretation; this report). (14) Miller and Delin (1993), ~20 ft intervals tested. Lower value represents estimate based on packer test of ~20 ft interval that yielded no discharge after 5 minutes pumping. (15) Three 10 ft intervals tested by USGS on Afton MLS hole, this report (4.0 value is average of 2 tests). (16) ~10 ft interval, flowmeter injection log, DNR Obwell 82012 at site of Afton MLS hole. (17) Miller and Delin, (1993), two ~20 ft intervals. (18) Runkel et al. (2008) ~15 ft interval, flowmeter injection log (well unique number 674487). (19) three intervals of ~3 ft in Afton MLS hole based on flexible liner insertion rate (this report). See text for discussion of uncertainties. (20) 10 ft interval, Afton MLS hole, this report. Tested interval includes fine clastic and coarse clastic interbeds. See text for discussion (21) (Miller and Delin, 1993), five ~20 ft intervals and one ~35 ft interval tested. (22) Unpublished MGS flowmeter injection logging in stratigraphic test hole near City of Webster, Minnesota. Bed parallel macropore aperture estimated at 0.2 ft based on video and caliper log. (23) Runkel et al. (2008) Flowmeter injection logging. Bed parallel macropore aperture estimated at 0.2 ft. (unique number 658174). (24) Runkel et al. (2008) Flowmeter injection logging,. Bed parallel macropore aperture estimated at 0.2 ft.(unique number 658157). (25) Estimate based on USGS packer tests of Afton MLS hole, for two intervals with known bedding parallel macropores, under assumption of negligible yield from matrix, and macropore aperture of 0.2 ft. (this report). Additional tests planned. (26) Runkel et al (2008). Flowmeter injection logging of five holes, yielding conductivity values for 12 bedding parallel macropores. Macropore apertures estimated at 0.2 ft. (27) Afton MLS hole based on flexible liner insertion rate (this report) . Macropore aperture estimated at 0.2 ft. See text for discussion of uncertainties. (28)based on specific capacity data for wells in County Well Index (CWI) for all of southeastern Minnesota. Converted to hydraulic conductivity using method of Bradbury and Rothschild (1985). The high average values of conductivity in the specific capacity derived dataset reflect the inclusion of a small percentage of wells where no drawdown was reported and a value of 1 ft of drawdown was assigned to calculate hydraulic conductivity. See Figure 10 for additional information. (29) Aquifer tests by Walton et al., 1991, described in text. Miller and Delin (1993), and Walton et al., (1991) data are from cores at ATES site in TCMA; MUGSP samples from cores in south-central Minnesota (Fig 1). Setterholm et al. (1991) samples from outcrops in eastern Twin Cities Metro area (City of Stillwater, Washington County). Runkel et al (2008) tests are all within TCMA.

## TUNNEL CITY GROUP, ST. LAWRENCE FORMATION, JORDAN SANDSTONE HYDRAULIC CONDUCTIVITY

As part of this project we compiled hydraulic conductivity measurements of Tunnel City Group, St. Lawrence Formation, and Jordan Sandstone strata from several sites across southeastern Minnesota. The data are summarized in Table 1. Much of the data was originally compiled in Runkel et al. (2003) but is now supplemented with results of hydraulic tests reported in Runkel et al. (2006a, 2008), and our tests of hydraulic conductivity at the Afton MLS hole as part of this project. The data are presented here from smallest scale tests that are presumably the best measure of intergranular rock matrix permeability, to larger scale tests that are more representative of a measure of contribution through macropores. We also provide estimates of hydraulic conductivity of individual bedding parallel macropores.

### Plug-scale permeability tests

Our database of the smallest-scale measurements of hydraulic conductivity is dominated by laboratory tests of vertical permeability through inch-scale plugs extracted from bedrock cores in southeastern Minnesota. A much smaller number of plugs were tested for horizontal permeability. The cores were collected from three sites (Fig. 1). Most of the conductivity values are from tests of plug samples from two of these sites, and compiled from unpublished reports by the Minnesota Gas Company (Minnegasco), who in the 1970’s conducted a subsurface study to assess the feasibility of underground natural gas storage in Paleozoic bedrock of southeastern Minnesota (Fig. 1). The raw data collected as part of that work is stored at the Minnesota Geological Survey (MGS) and cited as “Minnegasco Underground Gas Storage Project” (MUGSP, 1980). The third site is in the central part of the TCMA, where a 1980’s project evaluated the potential for storage of heated water in Cambrian bedrock aquifers. This project is referred to as the Aquifer Thermal Energy Storage Project (ATES) (Walton et al., 1991; Miller and Delin, 1993). A small number of plug samples tested for permeability are from outcrops of the Jordan Sandstone near Stillwater, Minnesota, in the eastern TCMA, reported by Setterholm et al. (1991).

### *Fine Clastic and Carbonate Matrix*

Our compilation of conductivity values representative of lower permeability matrix of the lower Jordan , St. Lawrence and Lone Rock formations includes values derived from tests of fine clastic material that dominates these strata, as well as sandy dolostone that is present as a minor constituent. The matrix hydraulic conductivity across the lower Jordan-St. Lawrence-Lone Rock stratigraphic interval is consistent through the three formations in having average values of $10^{-3}$ to $10^{-4}$ ft/day and median values of $10^{-5}$ to $10^{-6}$ ft/day (Table 1, Fig. 7). The slightly higher average and median values are from samples of the Lone Rock and Jordan Formations. A smaller number of tests of vertical permeability from the TCMA mostly fall within this range of values for the three formations (Table 1, Figure 8). The similarly low matrix conductivity across the three formations led Runkel et al. (2003) to suggest that the lower Jordan and upper Lone Rock, which are dominated by this material, may potentially serve as aquitards together with the intervening St Lawrence Formation. For example, figure 9 graphically shows for a single core how vertical hydraulic conductivity of matrix in the lower Jordan Sandstone is not substantially different from that in the St. Lawrence Formation.

Horizontal permeability measurements are scarce. Lab measurements of a total of 12 samples of fine clastic and sandy dolostone from the three formations indicate that the horizontal conductivity ranges from being approximately equal to vertical conductivity, to as much as two orders of magnitude greater than vertical conductivity (Table 1).

### *Coarse clastic matrix*

There are few tests of coarse clastic material sampled from the Jordan Sandstone and Tunnel City Group (Mazomanie Formation). This material is dominantly friable, leading to poor core recovery, and is most commonly insufficiently competent to yield a coherent plug suitable for laboratory testing. As a result, the samples that have been tested, such as those of the Mazomanie Formation (Table 1, Fig. 8), are atypically well-cemented, and thus representative of the lower end of the range in permeability, and of a volumetrically subordinate component, of the coarse clastic facies in these formations. An outcrop sample of fine- to medium-grained sandstone with just enough calcite and iron oxide, grain-coating cement to withstand plug extraction and testing, had a vertical hydraulic conductivity greater than the upper limit of testing capacity of 3,000 md

(>8ft/day) (Setterholm et al., 1991). Other samples of slightly better cemented coarse clastic material in the Wonewoc and Mt. Simon sandstones range from a few to several tens of feet per day in vertical conductivity (MUGSP, 1980). On this basis, a reasonable estimate for plug-scale vertical conductivity for the dominantly friable coarse clastic material in the Jordan Sandstone and Mazomanie Formations would be between 10 and 100 ft/day.

## Discrete-interval borehole tests

Discrete interval measurements of hydraulic conductivity in boreholes includes: (1) tests of intervals between inflated packers, (2) results from flowmeter logging during injection or pumping (procedure described in Paillet et al., 2000 and Runkel et al., 2006b), and (3) a conductivity profile interpreted from the insertion of a FLUTe (Keller et al., 2014) flexible liner in the Afton MLS hole. Collectively the measurements are similar to those of plug-scale measures in showing the distinction between the high conductivity coarse clastic and low conductivity fine clastic material. However, the measured conductivity of both of these materials is commonly significantly greater than that of plug-scale values. This likely reflects the larger scale of the tests (measuring across a few feet to a few tens of feet of borehole) which increases the likelihood of contribution from macropores that are not present in the small plugs selected for laboratory testing.

### *Fine Clastic and Carbonate*

Packer testing of five 20 to 35 foot intervals of fine clastic (and minor sandy dolostone) strata of the Lone Rock Formation at the ATES site in the TCMA yielded horizontal conductivity values ranging from less than 5.5 x$10^{-2}$ to 4.5 x$10^{-1}$ ft/day (Table 1, Fig. 8) (Miller and Delin, 1993). Packer tests of more dolomite-rich fine clastic strata in the lower St. Lawrence Formation in two boreholes at the same site yielded two very different conductivity values. In one hole (BC-1) an approximately 20 foot packed interval yielded no water after five minutes of pumping, indicating a conductivity at least as low as $10^{-3}$ ft/day. The conductivity of the lower St. Lawrence in a second hole at  site (AC-1) was measured at 6.7 ft/day. Contribution to yield through bedding parallel macropores, known to be common in the St. Lawrence Formation (e.g. Runkel et al., 2006a, and this report) likely explains the high conductivity value in the latter hole, given the known low matrix conductivity of the St. Lawrence, and close proximity (0.17 miles) of the 2 holes at this site.

Horizontal conductivity has also been measured across the St. Lawrence Formation using two methods at the Afton MLS hole constructed as part of this project (Table 1). These tests are described in greater detail in the next section of this report. The smallest scale tests, measuring two foot intervals of the St. Lawrence, yielded the lowest values, of about $10^{-3}$ to $10^{-4}$ ft/day. Macropores were not recognized on video and geophysical logs across these intervals, and therefore these values may be representative of matrix conductivity. They are consistent with horizontal conductivity values estimated from plug-scale tests. Packer tests of three longer intervals (10feet) of St. Lawrence Formation at the Afton MLS hole yielded values ranging from 2.0 to 22 ft/day. Video and geophysical logs indicate that all three of the tested intervals include bedding parallel macropores or vugs, which likely account for conductivity values orders of magnitude higher than known for the matrix of the St. Lawrence Formation.

### *Coarse clastic*

Few discrete interval borehole measurements of hydraulic conductivity of the coarse clastic strata in the Jordan Sandstone and Mazomanie Formations exist. We are unaware of any such tests for the Jordan Sandstone, and infer a conductivity for material without significant secondary pores that likely ranges from about ten to several tens of feet/day, based on discrete interval flowmeter and packer tests of generally similar material in other Paleozoic formations (e.g. Miller and Delin, 1993; Runkel et al., 2006b, 2011) and on the high matrix conductivity measured in plug-scale laboratory tests, described earlier. The highest packer-tested interval in the Afton MLS hole includes coarse clastic matrix interbedded with fine clastic layers, and the measured hydraulic conductivity of about 9 ft/day (Table 1) may largely reflect matrix contribution from these coarser-grained beds. Tests of coarse clastic material in the Mazomanie Formation are limited to sites where the tested interval is interbedded with finer-grained Lone Rock Formation, or where the Mazomanie is atypically fine grained and cemented. Two 20 foot interval packer tests and two boreholes tested with flowmeter logging, all in the TCMA, yielded values within a narrow range of 1.5-7.7 ft/day.

Upper Tunnel City strata in the Afton MLS hole consist of interbedded Mazomanie Formation, and finer-grained Lone Rock Formation. Packer tests yielding a hydraulic conductivity value of about 31 ft/day could reflect contribution largely via coarse-clastic beds of the Mazomanie Formation, although the tested interval included the lowermost four feet of St. Lawrence Formation that could have yielded water through vugs noted on video logs. Higher conductivity values for discrete intervals in the upper Tunnel City Group interpreted from data collected during the monitored insertion of a FLUTe liner at the Afton MLS hole may also be representative of individual friable, coarse clastic beds of Mazomanie Formation. These intervals ranged in hydraulic conductivity from about 26 to 57 ft/day. However, problems associated with the FLUTe insertion test (described later in this report) renders the values suspect. These tests are also described in greater detail in the next section of this report.

## Individual macropore tests

Video and flow logs collected from boreholes over the past 15 years have shown that bedding parallel macropores with apertures typically from a fraction of an inch to about 2 inches are ubiquitous in the Paleozoic bedrock of southeastern Minnesota (e.g. Runkel et al., 2003, 2006a, 2007). They are common in all matrix components in the upper Tunnel City Group, St. Lawrence Formation, and lower Jordan Sandstone (e.g. Figs 5, 6), even in friable, coarse clastic material. These features commonly accommodate ambient flow rates into or out of the borehole of liters per minute (Runkel et al., 2006a). At the land surface the same kind of bedding parallel macropores are also common in this stratigraphic interval, and are the source of springs along valleys of the St. Croix and Mississippi rivers and their tributaries.

We have obtained hydraulic conductivity values for individual bedding parallel macropores in a number of boreholes through flowmeter logging under stressed conditions of pumping or injection (methods are described in Paillet et al., 2000, and Runkel et al., 2006b). Conductivity values for individual fractures in the upper Tunnel City through lower Jordan Sandstone range from about 85 ft/day to about 14,000 ft/day (Table 1). The values were determined based on an aquifer thickness of 0.2 feet, assigned on the basis of video and geophysical logs of boreholes, as well as outcrop observations that bedding parallel macropore aperture rarely exceeds that thickness.

## Bulk productivity tests

Large databases of hydraulic conductivity calculated from specific capacity tests of water wells in southeastern Minnesota can provide some useful hydrogeologic insights, even though detailed understanding of the properties of the open-hole intervals in the individual wells is unknown. As part of this project we extracted specific capacity data from the Minnesota County Well Index (CWI) water well database and calculated hydraulic conductivity values (Bradbury and Rothschild, 1985) for 13,076 wells open to the Wonewoc, Tunnel City, St. Lawrence, or Jordan formations (Fig 10).

The compiled hydraulic conductivity values reveal relationships consistent with our understanding of the hydrostratigraphic properties described above. For example, the lack of a substantial difference in median conductivity values for Jordan, St. Lawrence and Tunnel City wells drawing water from deep bedrock conditions (Fig. 10) likely reflects the significant role of bedding parallel macropores in providing well yield. If, instead, matrix conductivity was the primary control on well yield, the fine-clastic dominated St Lawrence Formation would be expected to have orders of magnitude lower conductivity than the Jordan and Wonewoc Sandstones, which consist mostly of coarse clastic material.

The increase in development of secondary pores with decreasing depth of burial beneath younger bedrock is reflected by variability in hydraulic conductivity (Fig. 10). Enhanced development of secondary pores in shallow bedrock conditions corresponds to a measurable increase in hydraulic conductivity in all four formations, and an increase in the variability in hydraulic conductivity. Water wells open to Tunnel City Group, St. Lawrence Formation, and Jordan Sandstone in conditions of shallow burial (less than 50 feet of overlying bedrock) have average and median hydraulic conductivity values two to three times greater than do wells open to the same formations in conditions of deep burial.

In the TCMA, approximately three-fourths of known St. Lawrence Formation wells are constructed in shallow bedrock settings, over half where the formation is uppermost bedrock. This includes a large number of wells that are constructed to draw water from a buried plateau composed of St. Lawrence Formation in southern Scott County. These wells commonly penetrate less than 20 feet of St. Lawrence, likely drawing water from well-developed fracture networks similar to those exhibited in the video logs of the formation in boreholes open across subcrop conditions (Fig 5).

### Bulk vertical hydraulic conductivity

Measuring vertical hydraulic conductivity at a relatively large, “field” scale is a longstanding problem in hydrogeology (Bradbury et al., 2006; Cherry et al., 2006). Vertical conductivity of matrix plug samples can be viewed as a minimum potential field scale value, but will be significantly lower than actual conditions in rock that we know contains vertical fractures, such as the Paleozoic bedrock of southeastern Minnesota. We are aware of only one calculation of bulk vertical conductivity across any part of the lower Jordan Sandstone through upper Tunnel City Group interval, based on testing at the ATES site in the central TCMA (Fig. 9). Walton et al. (1991) used a number of methods to estimate a vertical conductivity for the St. Lawrence Formation at the site. Among these methods were eight-hour pumping tests during which hydraulic head levels within the St. Lawrence were monitored and compared against hydraulic head changes in the overlying Jordan Sandstone or underlying Tunnel City Group. Analysis using the Terzaghi solution yielded a vertical conductivity of $10^{-5}$ ft/day, and the Neuman-Witherspoon method yielded a value of $10^{-4}$ ft/day. While these values are reasonable estimates based on known matrix conductivity, all of the analyses invoke assumptions that limit confidence in the calculation, as do most tests of vertical hydraulic conductivity.

Aside from the tests described in Walton et al. (1991) vertical conductivity of the St. Lawrence Formation at field scale has only been qualitatively characterized as being sufficiently low enough to be classified as an aquitard. The basis for this is the traditional method of identifying relatively pronounced differences in hydraulic head above and below a potential aquitard, compared to lesser head differences within the units considered aquifers in the same larger-scale system. Prior to construction of the Afton MLS hole as part of this project, even these kinds of basic hydraulic head measurements have been documented at only a few site-specific locations. For example, the St. Lawrence Formation separates middle to upper Jordan from upper Tunnel City aquifer heads that differ by two to five feet at the ATES site in the central TCMA (Walton et al., 1991), and in the southern TCMA (USGS on-line data for well network CL4, 2006). Water level measurements in domestic wells within local areas of Winona and Washington counties appear to show vertical head differences of as much as tens of feet across the lower Jordan-upper Tunnel City interval (Minnesota County Well Index data). These latter measurements, however are not from closely paired wells, and are not synoptic. At best these potentiometric data suggest that at least some interval(s) in the lower Jordan through uppermost Tunnel City Group are of sufficiently low bulk vertical conductivity to maintain distinctly different hydraulic heads above and below.

Flowmeter, conductivity, temperature, and video logs provide additional support for the interpretation that parts of the lower Jordan through upper Tunnel City strata can serve as an aquitard in a vertical direction (e.g. Fig 11). Logs collected at a number of sites in southeastern Minnesota record ambient vertical flow in a borehole moving from one macropore to another (Runkel et al., 2003, 2006a,b, 2008). Such flow demonstrates that the intervening interval is of sufficiently low conductivity to maintain a hydraulic head differential that drives flow at rates of up to gallons per minute between the two macropores.

## AFTON MLS HOLE

The scarcity of information that can provide insights into vertical connectivity across the St. Lawrence Formation and adjacent units led to the decision to construct a borehole with a multilevel system (MLS) for monitoring and testing hydraulic characteristics across discrete stratigraphic intervals. Meyer et al. (2008) describes the use of a similar MLS, a Westbay MP system (Black et al., 1986), that they have installed in a number of boreholes in the Paleozoic bedrock at a site in south-central Wisconsin. These MLSs allow for accurate hydraulic head measurements, and water sampling for chemical analysis, in many depth-discrete intervals within a single borehole.

The MLS we constructed is located in Afton State Park in the eastern TCMA, near the St Croix River, Washington County (Figs. 1, 12, 13). Information from an extensive suite of borehole geophysical logs and packer tests guided construction of the MLS. The 14 ports for discrete interval fluid pressure measurements and water sampling, and six ports for higher capacity pumping were deliberately designed on the basis of the information gained from this borehole testing, as well as from knowledge of the broader regional geology and flow system, and hydrostratigraphic attributes from previous investigations. The selection of Afton State Park to construct the MLS system to monitor across the St Lawrence Formation was based on several factors. We limited our search to public property, and preferred the TCMA in part to reduce travel time from the MGS St. Paul office. In addition we preferred a site where vertical hydraulic head differences were known or suspected to be relatively large, and where natural or anthropogenic stresses on the system varied significantly. Afton State Park in the eastern TCMA was specifically chosen because CWI data indicated the possibility of vertical head differences of tens of feet across the St. Lawrence. In addition, its proximity to a major discharge area and incised bedrock valleys, with thin cover of unconsolidated sediment, as well as commercial, municipal, and domestic water use create stresses that should measurably impact hydraulic heads in the MLS hole. Anthropogenic activity in this mixed urban/agricultural area may also have measurable impact on groundwater chemistry. Finally, exposure of Jordan Sandstone through upper Tunnel City Group along the nearby St. Croix River allowed us to collect information on outcrop fracture characteristics that have relevance for interpreting hydraulic characteristics of the MLS hole.

The site has a relatively thin cover of unconsolidated glaciogenic sediment on top of an incised topography of Cambrian and Lower Ordovician bedrock (Figs. 12, 13). In this part of Washington County, groundwater generally moves from west to east, discharging to the nearby St. Croix River and its tributaries (Kanivetsky and Cleland, 1990). Springs that emerge from the Jordan Sandstone, St. Lawrence Formation and upper Tunnel City Group in the area are a land surface expression of this discharge. A larger component of discharge occurs as disseminated flow into unconsolidated sediment that fills bedrock valleys. Bedrock faults are common in this area, within the Cottage Grove and Hastings fault zones, and represent reactivation of Precambrian structures related to the Mesoproterozoic Midcontinent Rift.

Another important discharge from the system is via groundwater withdrawals. The most pronounced groundwater pumping center near the Afton MLS hole occurs about one mile to the south, at Afton Alps Ski area (Figs. 12,13). Three wells are used to pump water for snowmaking (Fig. 13, section B-B'). Hydrographs from Minnesota Department of Natural Resources (MDNR) observation wells in this area show a clear drawdown and recovery response to this pumping, including in an observation well open to the lower St. Lawrence Formation and upper Tunnel City Group less than 100 yards from the Afton MLS hole (MDNR obwell no. 82012). As part of our research at the Afton site, we are evaluating the potential impact of this pumping across the 14 monitored ports in the MLS hole.

The Afton borehole was drilled to a total depth of 345 feet in July and August of 2012 by Traut Drilling using reverse circulation/dual rotary methods. The borehole is cased with steel to a depth of 245 feet, with the annular space between the steel casing and borehole grouted. The open hole interval of about 100 feet below the bottom of the casing is 6 inches in diameter. The following geophysical logs were collected in the borehole and the nearby MDNR observation well by the US Geological Survey (USGS): 1) natural gamma, 2) electromagnetic induction, 3) optical televiewer, and 4) acoustic televiewer. In addition, electromagnetic (EM) flowmeter, fluid conductivity, and fluid temperature logs were conducted under ambient and stressed (pumped) conditions in the borehole, while heat-pulse flowmeter, fluid conductivity, and fluid temperature logs were collected under ambient and stressed (pumped) conditions in the observation well. The MGS also collected natural gamma, caliper, and electromagnetic flowmeter logs under ambient conditions. Following borehole logging, the USGS conducted packer tests to measure discrete interval static water levels, and slug tests were conducted in five isolated intervals in the borehole. Monitored insertion of a FLUTe flexible liner for the purpose of calculating hydraulic conductivity across the open hole took place on August 9, 2012. The MLS system was installed in the open hole interval from November 6 to November 8, 2012.

In addition to the results summarized below, individual reports by the USGS, and FLUTe Company detailing their testing and interpretations are included in this report as Appendices A and B.

### Borehole geologic and hydrologic characteristics

A thin cover of 23 ft of Quaternary unconsolidated sediment, 133 feet of Prairie du Chien Group and the upper approximately 90 feet of Jordan Sandstone are cased and grouted in the borehole (Fig. 13). The open hole prior to installation of the MLS was about 100 feet in length, exposing the lowermost 13 feet of Jordan Sandstone, all of the St. Lawrence Formation, and the upper 49 feet of the Tunnel City Group. Lithologic properties of these formations at the site, shown in Figure 14, are based on natural gamma logs, drill cuttings, and a borehole video collected by the Minnesota Department of Health. The Jordan Sandstone in the open hole interval transitions downward from fine- to medium-grained sandstone (coarse clastic facies) in the upper part of the hole, to dominantly very fine grained sandstone, siltstone, and shale (fine clastic facies) at the Jordan-St. Lawrence contact. Cuttings from the coarse clastic beds are dominated by disaggregated grains of well-rounded quartz with a brown to orange, "rust" color produced by oxidized, iron-rich grain coatings. Stronger cement (dolomite and feldspar) in the fine clastic intervals is expressed in the drill cuttings by the more common presence of rock chips in addition to disaggregated individual grains. Some fine clastic beds also differ from coarser grained sandstone in this lowermost part of the Jordan Sandstone by a gray to white color and by containing unoxidized sulfides (likely pyrite).

The St. Lawrence Formation is dominated by the fine clastic component, with subordinate thin beds of sandy dolostone (carbonate rock component). Relatively strong dolomitic and feldspathic cementation results in drill cuttings dominated by chips of very fine grained sandstone, siltstone, and shale, with only minor disaggregated grains. Unoxidized iron sulfide, likely pyrite, is common in the St. Lawrence. The gray color is likely due to finely disseminated pyrite, and larger crystal aggregates of pyrite are also common in cuttings from the borehole. Shale and siltstone are most abundant in the upper 20 feet of the formation. The St. Lawrence becomes more carbonate-rich and glauconitic down-section.

The lithologic properties of the Tunnel City Group exposed in the open hole interval are typical of this part of the section in southern Washington County, where its two formations, the Mazomanie and Lone Rock interfinger (Runkel et al., 2007). In such areas, thin to thick beds of coarse clastic Mazomanie sandstone are intercalated with finer-grained, more strongly cemented, and more highly feldspathic and glauconitic Lone Rock.

Several bedding parallel macropores were identified in the open hole interval, with the video and acoustic televiewer logs providing the most confident recognition of these features (Figs. 14, 15). Five bedding parallel macropores were recognized on both video and acoustic televiewer logs: two are closely spaced in in the upper part of the St. Lawrence Formation (~262-263 feet), one in the middle St. Lawrence Formation (~275 feet) and two in the upper Tunnel City Group (between 330-340 feet) (Fig. 15). The acoustic televiewer log also indicates the presence of a high angle fracture oblique to bedding at about 280 ft. Other possible macropores are also shown in Figure 14, based on observations of irregular, vuggy cavities on the video log.

Ambient flow conditions in the open hole prior to installation of the MLS were dominated by strong downflow (~60 gal/min), driven by a vertical hydraulic head difference of approximately 47 feet based on water levels measured during packer testing by the USGS shortly after flow logging. Flowmeter and video logs show that downflow entered the hole from the lower Jordan Sandstone in the uppermost part of the open hole, including some component of input from annular space above the bottom of the well casing. This downflow exited the borehole at the lowest identified bedding parallel macropore, at a depth of 338 feet, in the Tunnel City Group near the bottom of the open hole (Fig. 14). No measurable inflow or outflow was recorded in the intervening open hole, although minor loss or gain would be difficult to detect given the strong overall rate of ambient flow in the hole. Under slower flow rates, flowmeter logs collected from boreholes elsewhere in the TCMA across this stratigraphic interval commonly show water entering or exiting at multiple bedding parallel macropores in individual holes (Runkel et al., 2006a,b, 2008).

### Hydraulic conductivity

Measures of hydraulic conductivity in the Afton MLS hole are ongoing. Preliminary interpretation of our smallest scale tests yielded approximate values of $10^{-3}$ to $10^{-4}$ ft/day for three borehole intervals of two foot length each in the St. Lawrence Formation (Fig 14). These values are based on pressure-pulse tests of three of the fourteen monitored zones in the MLS hole. A pulse test is a short duration, small volume hydraulic conductivity slug test (Meyer, 2010). The pressure pulse caused by allowing a zone to temporarily equilibrate to overall multiport casing pressure, and then isolating it again by closing the valve connecting the zone to the casing. For low permeability formations, the recovery period can be measured and analyzed using standard slug test methods. (Cooper et al., 1967; Hvorslev,1951) Three of the 14 zones had a time lag recovery period of sufficient length to be analyzed using this approach. All three are open across intervals where macropores were not detected on video nor on geophysical logs. The relatively low hydraulic conductivity in these zones may be largely a measure of rock matrix horizontal conductivity, as it is consistent with estimates of horizontal conductivity for plug samples of the St Lawrence Formation collected from other boreholes in southeastern Minnesota described earlier in this report.

Hydraulic conductivity values based on larger scale tests (10 foot spacing between packers) were estimated by the USGS from water-level data collected during 8 slug tests of five intervals (Fig 14). Two estimates for a single 10 foot interval of the lower Jordan Sandstone were 7.2 and 10.9 ft/day, which is generally consistent with measures of matrix permeability across an interval that includes a substantial component of coarse clastic beds interbedded with fine clastic material. Unrecognized bedding parallel macropores could be potentially contributing to the conductivity as well, although commonly the presence of such features results in conductivity of tens of ft/day or more, based on our flowmeter tests of other holes open to the upper Tunnel City Group and lower Jordan Sandstone in southeastern Minnesota (Runkel et al., 2006b). Estimates for the St. Lawrence Formation ranged from 2.0 to 22 ft/day (Fig 14). The highest value corresponds to a ten foot packed interval in the approximate middle of the St. Lawrence, between 271 and 281 feet depth, which includes a well-developed bedding parallel macropore at 275' (Fig 15C), and a possible steeply dipping fracture at ~280 ft. Given the orders of magnitude lower matrix conductivity known for the St. Lawrence Formation, the value of 22 ft/day may largely reflect a high conductivity of tens to hundreds of feet per day for those individual macropores. Conductivities of 2.0 to 5.0 ft/day for the upper and lower St. Lawrence are also higher than what would be expected from matrix contribution alone, and similarly are likely to reflect contribution by flow through macropores. Estimates of hydraulic conductivity for the 10 foot interval that includes the lower 4 feet of the St. Lawrence Formation and upper 6 feet of the Tunnel City Formation were 30.0 and 32.1 ft/day (Fig.14). High conductivity across this interval could largely be the result of flow from vuggy, carbonate-rich lower St Lawrence Formation, as well as from coarse-clastic beds (Mazomanie Formation) in the upper Tunnel City Group.

As part of our borehole testing prior to the installation of the MLS, an attempt was made to collect a continuous hydraulic profile of the open hole through the insertion of a FLUTe flexible liner. An explanation of this technique is provided in Keller et al. (2014). The results are shown as a conductivity profile in Figure 14. A number of factors not typically encountered during such tests at other sites led to substantial uncertainties with the analysis of the results for the Afton MLS hole. These included the great depth to static water level (exceeding 200 ft), large vertical hydraulic head differences (approximately 50 ft), the 60 gal/minute inflow in the upper part of the open hole, and the hydraulic dominance of the high conductivity bedding parallel macropore where water exited near the bottom of the borehole (at 338 ft). Additionally, a tear near the bottom of the flexible liner was discovered after the conductivity test was completed, which may have occurred when the rapidly descending liner abruptly slowed after passing the highly permeable fracture near the bottom of the hole. Although these problems significantly reduce the confidence in the calculated values for hydraulic conductivity, the results do appear generally consistent with other measures of conductivity for these strata at this and other sites in southeastern Minnesota. At least some of the high conductivity intervals (tens of ft/day or greater) in the profile correspond in position to the presence of coarse-clastic beds and bedding parallel macropores, separated by thicker intervals that would be expected to be orders of magnitude lower in hydraulic conductivity. The highest permeability intervals are present in the uppermost part of the hole that includes coarse clastic Jordan Sandstone, and at a bedding parallel macropore in the Tunnel City Group near the bottom of the hole (338 ft). Three other relatively conductive intervals, estimated at tens of feet per day, in the upper Tunnel City Group may correspond to intervals dominated by coarse clastic material (Mazomanie Formation).

Additional horizontal hydraulic conductivity values for the MLS hole will be calculated by tests of the six monitoring zones that include pumping ports (Fig 14). These tests, scheduled for the summer of 2014, will more precisely quantify the hydraulic conductivity of intervals with bedding plane fractures and coarse clastic matrix.

### Hydraulic head

Manual hydraulic head measurements from all 14 ports have been collected 10 times since installation of the MLS in November, 2012. They are shown in Figure 14. In addition, transducers were installed in five of the ports in February 2014, and are scheduled to be removed in mid-June. The transducers recorded hourly from February 1 until May 29, in 15 minute intervals from May 29 to May 30, and in one minute intervals from May 30 until June 7.

The data reveal that a hydraulic head difference of approximately 50 ft between the top and bottom of the open hole is mostly expressed as distinct, large deflections across four thin (<10ft) intervals in the lower Jordan Sandstone and St. Lawrence Formations (Fig 14). About an 18 foot decrease in hydraulic head is present across two packed intervals in the lower 15 feet of the Jordan Sandstone. Another 18 to 20 foot decrease occurs about 10 feet below the top of the St. Lawrence Formation, and a 6-7 foot decrease in the lower few feet of the St. Lawrence. The remaining 6-7 feet of the approximately 50 feet of head difference between the top and bottom of the monitored interval of strata is expressed as smaller decreases from port to port in a downhole direction. Meyer et al. (2008, 2014) and Meyer (2013) documented similar stratigraphically abrupt deflections in hydraulic head in Paleozoic bedrock near Madison, Wisconsin, including parts of the St. Lawrence Formation and Tunnel City Group. They suggested such deflections represent limited vertical hydraulic connectivity across discrete intervals of strata compared to other parts of the aquifer system.

Figures 16 and 17 compare the hydraulic head data from the Afton MLS hole in a different manner, showing variability over time in the 14 monitored ports. This comparison appears to distinguish a two-fold division into upper and lower systems that internally show similar magnitude and direction of changing head with time, but differ from one another. Hydrographs for ports 1-10, across the upper Tunnel City Group to upper St. Lawrence Formation, are representative of the lower system (Fig 16). Hydrographs for ports 11-14, uppermost St. Lawrence Formation and lower Jordan Sandstone, represent the upper system. The graphs of hydraulic head through time for ports within each group are more similar to one another than to those in the other group. For example, all 10 hydrographs of the lower system show a steady increase in head elevation from January to approximately June, 2013, followed by a decline in hydraulic head in October to December. In contrast the hydrographs of the upper system show markedly less change in head, instead being relatively stable over the same period of time. More detailed hydrographs based on closely spaced sampling from the transducers installed in 5 ports in 2014 generally show the same relationship (Fig 17). Hydrographs from ports 1, 7 and 10, monitoring the lower system, closely match in direction and magnitude of change from early February through late May, but differ from the hydrographs from ports 11 and 13 across the upper system. These latter hydrographs of the upper system closely match one another.

Our evaluation of hydraulic head in the Afton MLS hole will continue at least until early 2015, and will likely add to our understanding of head variability through time. In particular, a better understanding of stresses that are driving the head changes will be gained by monitoring through another year of seasonal changes, and by comparison to hydrographs from nearby DNR observation wells in addition to pumping records for Afton Alps Ski area. Although assimilation of such data is at this time incomplete, the information at hand thus far indicates that the decreasing hydraulic head in ports 1-10 in the late fall and early winter of 2012 and 2013 appears to correspond in time to pumping of Tunnel City wells at nearby Afton Alps (Fig 16). Transducer data were collected until early mid-June, 2014, and manually collected head measurements from all 14 ports will be collected at least until early 2015. As we continue to monitor hydraulic heads in the Afton MLS ports, and collect information from nearby DNR Observation wells and pumping at Afton Alps, more insight is likely to be forthcoming.

## Water Chemistry

Water samples were collected from all 14 ports in the Afton MLS holes three times from February 2013 to January 2014. Standard cations and anions along with physical measurements of temperature, pH, and conductivity were analyzed for all three sampling events, stable isotopes (hydrogen and oxygen) for two sampling events, and tritium and $SF_6$ for one sampling event. Figure 18 summarizes the results of most of these analyses, compared against the stratigraphy in the monitored borehole, and hydraulic head profile. A number of chemical parameters show variability between units defined by head deflections. The most distinct change in water chemistry appears to be present in the upper part of the St. Lawrence Formation, across a 9 foot interval between ports 9 and 11. It is best expressed in concentration of chloride, sulfate, nitrate and manganese, as well as electrical conductivity. This interval approximates the position of the largest head deflection (18-20 feet) between any of the monitored ports, and to the boundary between the upper and lower flow systems defined on the basis of head variability over time described in the previous section. In addition to the change in chemistry across ports 9-11, the water chemistry from port 1, which is open to a highly conductive bedding fracture in the Tunnel City Group, is different in several parameters from the water sampled in Tunnel City ports that are not open to recognized high conductivity fractures.

Evaluation of the water chemistry is ongoing, but the variability in water chemistry might be explained by differences in the relative amount of groundwater contributed to each monitoring zone by the fractures versus the rock matrix and/or differences in the length/residence times of flow paths sampled by each of the monitoring zones. Vertical connectivity can be a key control on physical flow paths as well as chemical reactions that can change the levels of non-conservative constituents such as nitrate and sulfate. For example, a permeability barrier to vertical flow corresponding to the large hydraulic head deflection between ports 10 and 11 would physically inhibit flow, limiting the transport of nitrate-enriched water downward to deeper levels of the St. Lawrence Formation. Additionally, such low permeability barriers can also approximate the boundary at which chemical reactions cause changes in the concentrations of non-conservative constituents. A tentative interpretation of such reactions that might account for some of the changes in the chemistry profile across ports 9-11 at the Afton MLS site was offered by Tom Al of the University of New Brunswick in an informal discussion (personal communication to Meyer, 2013). He suggested a possible scenario whereby downward flowing oxygenated water in Jordan Sandstone oxidizes sulfide minerals (e.g. pyrite) in the upper St. Lawrence Formation. Such sulfide minerals are common in the cuttings samples of the St. Lawrence at the Afton site. The oxidation of pyrite and any other sulfide minerals consumes oxygen and produces sulfate, leading to increase in the concentration of that constituent. The oxidation process could also cause conditions to become more reduced lower in the system. These reducing conditions can lead to denitrification, decreasing the levels of nitrate. Changes in the concentration of other constituents may also be related to this process, for example, causing dissolution of manganese oxide minerals, which releases manganese and causing those concentrations to increase, as is seen in the chemistry profile of Figure 18.

Chloride concentrations show a pronounced increase from port 10 downward to port 9 (Fig. 18). This trend is opposite of what is typically expressed across the Twin Cities Metro area, where anthropogenic chloride diminishes in concentration deeper in the system. However, the ratio of chloride to bromide from the samples in the Afton MLS hole is indicative of naturally elevated chloride originating from relatively deep in the bedrock aquifer system (Tipping, 2012). Deep, natural sources of saline water have been documented at a number of local areas in southeastern Minnesota, including the TCMA, most commonly in proximity to faults related to the Proterozoic Midcontinent Rift (e.g. Lively et al., 1992). Our preliminary interpretation of relatively high chloride levels in the St. Lawrence and upper Tunnel City Group at the Afton MLS site is that nearby faults provide path(s) for relatively deep chloride-enriched water to rise to the shallower parts of the system locally. Lateral transport through units such as the St. Lawrence could be achieved predominantly through bedding parallel macropores.

## OUTCROP FRACTURE CHARACTERIZATION AND POSSIBLE RELEVANCE TO AFTON MLS HOLE HYDRAULIC HEADS

Inflections in vertical hydraulic head profile  across relatively thin stratigraphic intervals similar to those in the Afton MLS hole have been recognized elsewhere in the Paleozoic bedrock of the central midcontinent by Eaton et al. (2007), Meyer et al. (2008, 2014), and Meyer (2013). They suggested such inflections reflect poor vertical connectivity of fracture sets. Such poor connectivity has been documented in outcrops of Paleozoic bedrock within this region, specifically in Ordovician and Silurian carbonate dominated strata (Underwood et al., 2003, Anderson et al., 2011).  These studies used mechanical stratigraphic techniques to identify horizons where vertical fractures preferentially terminate.  For example, Underwood et al. (2003) recognized discrete intervals across which greater than 50 percent of vertical fractures terminate, and considered those to be important mechanical boundaries that could have hydraulic significance.

Although the interpretation that poor vertical fracture connectivity is responsible for discrete hydraulic head deflections is reasonable, it has proved to be difficult to support in a manner whereby hydraulic head profiles are linked to vertical fracture attributes.  A longstanding problem is the inability to characterize vertical fractures in the vertical boreholes where the deflections are documented. Conversely, outcrop-based characterization of fractures has been only rarely linked to nearby boreholes with hydraulic head profiles identifying discrete head deflections. One exception in this region was presented by Anderson et al. (2011) who showed that an abrupt change in hydraulic head across a discrete stratigraphic interval in an Ordovician carbonate-dominated formation (Platteville Formation) in the TCMA corresponded to a mechanical interface where vertical fractures preferentially terminate.

The hydraulic head deflections in the Afton MLS hole are best accounted for by the same conditions of poor vertical connectivity of fractures across specific discrete intervals, given that beds of sufficiently low vertical  matrix conductivity to provide hydraulic separation are common throughout the lower Jordan through upper Tunnel City Group stratigraphic interval. As part of our project we attempted to locate outcrops of Jordan Sandstone, St. Lawrence Formation and upper Tunnel City Group amenable for vertical fracture mapping that might provide insight to better understand the head deflections in the Afton MLS hole. Exposures adequate for this technique have been identified thus far only in the lower Jordan Sandstone and to a much more limited degree across St. Lawrence-Tunnel City contact strata. Herein we present our results on fracture tracing of lower Jordan Sandstone exposures near Stillwater Minnesota, and the potential relevance of the results to understanding the source of the head deflections across the lower Jordan Sandstone in the Afton MLS hole about 15 miles south of these outcrops.

Fracture tracing has been conducted at three exposures of the lower Jordan Sandstone in the Stillwater area: Lookout Point, Fairy Glen, and Oasis Café (Fig. 1). All three of these outcrops expose typical lower Jordan Sandstone facies: relatively friable, trough-cross stratified, fine- to coarse-grained sandstone (coarse clastic facies), intercalated with intervals dominated by very fine grained, feldspathic, and better cemented sandstone, siltstone, and minor shale (fine clastic facies) (Figs 19,20). The facies are arranged as typical coarsening-upward parasequences, readily recognizable on both borehole and outcrop natural gamma logs. Beds with traceable contacts across the extent of the outcrop are mostly thick to very thick (greater than about one foot).

Exposures at each of the three areas were photographed, and individual photos merged into mosaics onto which fractures and bedding contacts were traced digitally in the office. Figures 20 and 21 are examples from one of several outcrop faces at the Lookout Point locality. Photos of exposures and fracture traces for all evaluated outcrops are located in Appendix C. These traces were taken back into the field as a template onto which revisions to fracture identification and trace length were made. All three outcrop areas were visited multiple times by two or more geologists as part of this process. Additional visits to the sites will likely be made to further refine the tracing over the coming summer and fall.

Our analysis thus far evaluates percentage of fracture terminations in two ways. Adopting the general approach of Underwood et al. (2003), we calculated the percentage of fractures that terminate within 2 foot bins, corresponding to the minimum thickness of most beds that can be traced across the length of these outcrops. We also calculated the termination percentage of fractures that meet each of the traceable bedding planes at an outcrop. For both of these analyses we used only fractures with trace lengths exceeding 2 feet.

Our results for the three localities are summarized in Figures 22 to 24. At each outcrop, mechanical interfaces with high percentages of vertical fracture terminations are present in the lower Jordan Sandstone. Each of the three outcrop areas include one or two interfaces within the low matrix permeability fine clastic component of the lower Jordan Sandstone, and thus have the potential to serve as a key low vertical permeability barrier in saturated subsurface conditions. Exposures at Lookout Point along the St. Croix River in northern Stillwater exemplify our results at all three outcrop areas (Fig 22). Upper and lower contacts of a single approximately 3 foot thick bed (Fig. 22, bed contacts 4 and 5) have termination percentages of about 90% and 70%, respectively. Of the 40 traced vertical fractures that intersect the top or bottom of this bed, only 1 (2.5%) passes entirely through the bed.

A single continuous exposure of the lower Jordan Sandstone near an intermittent water fall in Fairy Glen, a tributary to the St. Croix River in northern Stillwater, also includes a single fine clastic bed with a high percentage of fracture terminations, particularly at its upper contact. Bed contact 2 (Fig 23) has a fracture termination percentage of about 75 percent, more than double the termination percentage of any other contact at this location. The lower contact of the same bed has a termination percentage of about 25%, and only 3 of 21 (14.3%) traced fractures that intersect the top or bottom of this bed pass entirely through it.

Another single exposure, at the parking lot for the Oasis Cafe along Minnesota State Highway 95 in southern Stillwater, includes an approximately one meter thick bed of fine clastic strata with an upper contact (contact 6, Figure 24) having a value of greater than 90% fracture terminations. The lower bounding contact of this bed (contact 5) has a termination percentage of about 30%. Only one of 33 (3%) traced fractures that intersect the top or bottom of this bed pass entirely through it. A second bed contact (contact 1, Fig 24) in the lowermost part of this exposure may also be a significant mechanical interface where vertical fractures preferentially terminate. However, an overall relatively lower density of fractures and limited lateral extent of exposure permit only 4 fractures to be traced to their intersection with this contact. Therefore, the statistical significance of the data at this contact is limited.

The key mechanical interfaces within fine clastic strata at the three outcrop areas appear to occupy a similar position to one another within lower Jordan Sandstone facies successions. At each area the interfaces are present within a distinctly coarsening upward succession, part of meter-scale parasequences (Runkel et al., 2007) (Fig 25). These parasequences are well-expressed on natural gamma logs and allow the relative position of the mechanical interfaces within parasequences to be compared from outcrop to outcrop, and to boreholes in which gamma logs have been collected. At each of the three areas, the key interfaces occur within the fine-clastic dominated part of a parasequence, at a position about half-way up the transition that ultimately is dominated by coarse-clastic strata.

Our identification of the presence of key mechanical interfaces that limit propagation of vertical fractures within fine clastic strata of the lower Jordan Sandstone has important implications for understanding the mechanisms responsible for the hydraulic head inflections documented in the Afton MLS well, about 15 miles to the south. The two significant decreases in head across relatively thin intervals of lower Jordan, fine clastic strata, are best explained by mechanical stratigraphic conditions at the site that are similar to what we have documented in outcrop. The subsurface fracture conditions corresponding to the large head differential between ports 13 and 14 in the Afton MLS hole may be most similar to what we have documented in the Stillwater area (Fig 25). Although the construction of the MLS hole does not allow for confident recognition of the precise position of a discrete stratigraphic interval where the large lower Jordan head inflection is located, it is constrained to within a relatively narrow stratigraphic interval consistent with the position of key mechanical interfaces identified in our outcrop evaluation. A thin interval of unoxidized, white to gray, fine clastic strata (~245-250 feet deep) between strata characterized by orange to brown sandstone with oxidized grain coatings and pore-filling cement in the lower Jordan Sandstone in the MLS hole (Fig 26) may correspond to a low permeability boundary caused by such a mechanical interface. Another unoxidized bed between oxidized strata lies in a similar position within a parasequence higher in the Jordan Sandstone, in the cased and grouted part of the Afton MLS hole, and may also correspond to a significant permeability contrast. Variability in the presence of visibly oxidized iron in sandstones is well-known to correspond to contrasts in permeability (e.g. Beitler et al., 2006).

Fracture tracing in other horizons in the lower Jordan Sandstone through upper Tunnel City Group stratigraphic section would be similarly useful to gain a better understanding of the controls on borehole hydraulic conditions. However, diligent searching across southeastern Minnesota, southwestern Wisconsin, and northeast Iowa has led to disappointing results in finding any suitable outcrops for fracture termination analysis. For example, lower Jordan Sandstone- upper St. Lawrence Formation contact strata in which the largest head deflection in the Afton MLS hole occurs (between ports 10 and 11) are very poorly exposed across southeastern Minnesota and western Wisconsin. The contact in the field most commonly corresponds to a break in slope downward to lower gradients, where the bedrock becomes covered by colluvium. This break in slope could very well reflect the presence of a mechanical boundary at which major vertical joints preferentially terminate.

St. Lawrence Formation-Tunnel City Group contact strata are exposed in a few, relatively small, scattered outcrops across southeastern Minnesota, northeast Iowa, and western Wisconsin, and some have potential for fracture tracing. For example, Figure 27 shows fractures across the St. Lawrence-Lone Rock contact along the Mississippi River near Lansing, Iowa. Prominent vertical fractures in well-cemented lower St. Lawrence Formation most commonly terminate at the contact between the two formations, or within the upper 6 feet of the underlying Lone Rock. Such terminations may reflect conditions responsible for hydraulic head inflections with stratigraphic positions that are at, or close to, the St. Lawrence Formation-Tunnel City Group contact in south-central Wisconsin (Meyer et al., 2008, 2014; Meyer, 2013) and at our Afton MLS site.

## DYE TRACING

The greater degree of development of macropores in the Paleozoic bedrock in shallow bedrock conditions compared to deeper conditions of burial beneath younger bedrock has important implications for aquitard integrity. Our previous research in this region has demonstrated that bulk hydraulic conductivity is enhanced in such conditions, and we have suggested that the greater density, trace length and aperture size of vertical fractures would diminish the ability of aquitards to protect underlying aquifers in shallow bedrock conditions (Runkel et al, 2003; 2006a). Water chemistry data locally provide support for this interpretation, showing the presence of recent, water impacted by anthropogenic activities beneath aquitards where they are close to the bedrock surface (e.g. Runkel et al., 2013).

Dye trace investigations over the past 6 years, led by Jeff Green from the Minnesota Department of Natural Resources, have provided important physical measures of flow through the St. Lawrence aquitard and adjacent units in shallow bedrock conditions. This research has been conducted as part of successive ENRTF funded projects, and in collaboration with E.C. Alexander Jr. of the University of Minnesota Department of Earth Sciences. Geologic context for the traces has been provided by the Minnesota Geological Survey authors of this report, funded through our grant to study the St. Lawrence aquitard. Results of the dye tracing research have been published in Green et al. (2008, 2012), and are summarized below, along with some information that postdates the 2012 publication. This dye-tracing research is ongoing.

Map-based and field investigations have led to the identification of a number of streams where water sinks underground at stratigraphic positions that correspond to the lowermost Jordan Sandstone and uppermost St. Lawrence Formation. These streams are in tributary valleys to the Mississippi River, in a bedrock-dominated landscape with only minimal unconsolidated glacial cover. The streams are flowing (discharge rates less than 0.5 $ft^3$/sec) through a series of riffles and pools, usually on gravel to cobble beds. The streams terminate in pools (which can be as large as 100 yards long by 10 yards wide) or, less commonly, discrete sinking points (Green et al., 2008, 2012) .

Site conditions at 15 sinking or losing streams have been judged suitable for dye trace investigations to date. The location of these sites at regional scale is shown in Figure 1, and a detailed illustration of tracing results at a southwest Winona County Site is depicted in Figure 28. The various dye traces show similar patterns of rapid breakthrough, rapid rise to a peak concentration, followed by very long, months to years, tails. In some cases, dye is still detectable in the springs 3 years after dye input, showing temporally extended recovery tails that likely reflect a component of storage and travel though intergranular matrix blocks and fracture networks with limited aperture size and connection to other fractures. Flow speed results were reported for six traces by Green et al. (2012) (Table 2). All were calculated as minimum-flow speeds based on assumed straight-line flow distances. The data are reported in ranges due to use of integrating passive charcoal detectors changed at week- to month-long intervals and in the variability in the sampling schedules. The velocity range for all sites is 35–600 m/day. The mean for all sites was 318 m/day and the average from all sites was 274 m/day. All of these times are for flow from sinking streams to springs.

Table 2 Dye trace sites and flow speeds (Green et al., 2012)

| Site | Flow speeds (meters/day) | Sample type |
|---|---|---|
| Ahrensfeld 1 | 150–300 | Charcoal detector |
| Ahrensfeld 2 | 400–600 | Direct water sample |
| Kiefer Valley | 260–580 | Charcoal detector |
| Daley Creek | 180–360 | Charcoal detector |
| Sullivan Creek | 35–240 | Charcoal detector |
| Borson Northeast | 75–110 | Charcoal detector |

Lateral travel times are much more rapid than would be expected for flow through low permeability matrix of the lower Jordan Sandstone and St Lawrence Formation, and clearly rely on flow through macropores.  Horizontal flow would be enhanced greatly by the ubiquitous presence of bedding parallel macropores in these formations. The springs with dye-detects at locations where the bedrock is exposed all show that water is emerging from such macropores. A laterally well-connected system of linearly extensive vertical fractures with large apertures would also permit rapid horizontal flow.

The dye traces document not only relatively rapid horizontal breakthrough velocities, but also vertical flow that passes through the entire stratigraphic extent of the formation in a matter of days to a few weeks. Vertical transport of the largest volumes of water at relatively rapid speeds through the lower Jordan and St. Lawrence Formation also is largely a function of macropores, specifically the vertical fractures. The dye trace results relative to stratigraphic context for each site shows a consistent pattern (Fig. 29) that provides some insight into vertical fractures and flow through them. The streams sink into the top of the St. Lawrence Formation and the lowermost part of the Jordan Sandstone. Dye exits at springs at the base of the St. Lawrence, and at three sites at  Tunnel City Group springs as well.

The cross section in Figure 30 interprets the results of the dye traces within the context of our understanding of the hydrostratigraphic attributes of the lower Jordan Sandstone through upper Tunnel City Group strata, drawing upon the recently acquired information from vertical fracture termination evaluations as well as borehole hydraulic insights from Afton MLS hole, and those in equivalent strata in south-central Wisconsin (Meyer et al., 2008, 2014; Meyer, 2013)  In relatively deep conditions of burial on the plateaus outside of the incised valleys the lower Jordan and St. Lawrence should be expected to have hydrogeologic properties similar to those documented at the Afton MLS site, i.e. strongly anisotropic with a moderate to high horizontal permeability but orders of magnitude lower in bulk vertical conductivity. Vertical fractures are compartmentalized to some degree, with discrete intervals where a high percentage of fractures terminate. Flow is partitioned stratigraphically, with poor vertical connectivity across such intervals. As the bedrock becomes more deeply incised down-valley, vertical fracture density, connectivity, trace lengths, and aperture size increase. Mechanical interfaces that created relatively effective vertical barriers to flow in deeper bedrock conditions are, in these shallower conditions of burial, breached by progressively more fractures down valley, and the aquitard loses vertical integrity. Stream loss occurs where lower Jordan and uppermost St. Lawrence fractures become sufficiently well connected vertically to allow substantial downward conduit flow.  Rapid subsurface transport to even deeper stratigraphic positions, to the bottom of the St Lawrence Formation and upper Tunnel City Group, likely occurs in a stair-step fashion as other low permeability boundaries to vertical flow are progressively breached down-valley.

## Discussion and Conclusions

The St. Lawrence Formation has traditionally been viewed as an aquitard ( or “confining unit” in other terminology) in Minnesota by both scientists and regulators. In settings where the formation is relatively deeply buried by younger bedrock the data we have compiled, including detailed hydraulic head profiles at the Afton MLS, are consistent with such a classification in that vertical hydraulic conductivity in the St. Lawrence under these conditions is sufficiently low to maintain pronounced vertical head differences.  Importantly, however, we have shown that aquitard boundaries do not correspond precisely to the boundaries of the St. Lawrence Formation. Fine clastic-dominated strata of the lower Jordan Sandstone are also properly classified as an aquitard, and should be grouped together with the underlying St. Lawrence Formation in delineating the upper  aquitard boundary. Upper Tunnel City Group strata, especially south of the TCMA where it is dominated by fine-clastic beds, can potentially also serve as an aquitard, although our understanding of the vertical hydraulic characteristics in that part of the stratigraphic section remains limited.

Quantifying aquitard integrity is a longstanding problem in hydrogeology (Bradbury et al., 2006; Cherry et al., 2006). The estimates of bulk vertical conductivity of  about $10^{-4}$ to $10^{-5}$ ft/day at the ATES site in the central TCMA (Walton et al., 1991) is reasonable for deep bedrock conditions, assuming leakage through narrow, generally poorly connected vertical fractures accounts for  a conductivity orders of a magnitude greater than matrix vertical conductivity. Hart et al. (2006) arrived at field-scale values of vertical conductivity for a more shale-rich, Ordovician bedrock aquitard in Wisconsin that were an order of magnitude less ($10^{-6}$ ft/day), using a model that included a very low matrix conductivity and with vertical fractures with apertures of 50 microns spaced 5 km apart. Our ongoing research at the Afton MLS hole may provide additional insights into vertical conductivity across the lower Jordan through upper Tunnel City interval. We are currently evaluating hydraulic responses in the various ports at the MLS hole to an injection test of a nearby observation well, and to pumping at the Afton Alps ski area.

Stratification of water chemistry across the lower Jordan Sandstone-upper Tunnel City Group in a different way also implies relatively high aquitard integrity in deep bedrock settings. Where the lower Jordan and St. Lawrence is the uppermost bedrock aquitard that is relatively deeply buried (>50 ft) beneath younger bedrock, it sufficiently limits vertical recharge to produce groundwater bodies that are stratified in age and chemical composition across extensive, mappable areas. A representative example across parts of Goodhue and Wabasha Counties is shown in cross section view in Figure 31.  Uppermost bedrock groundwater is predominantly recent in age, and commonly contains anthropogenic constituents such as chloride and nitrate because it is dominated by locally sourced recharge from the past few decades that moves rapidly through shallow, well-connected bedrock fractures. Where the lower Jordan-St Lawrence aquitard is deeply buried it separates this shallow bedrock water from less impacted water of measurably older age. In most places, the water beneath the aquitard in such settings is of mixed or vintage age and part of a flow system that is of more regional extent, containing a mixture of locally and regionally sourced water. In any given area, downward flow is retarded by the aquitard, which causes the largest volumes of recharged water to travel in a horizontal direction. In essence, water flows mostly across the top of the aquitard, rather than vertically through it. Tipping (2012) showed a similar relationship across large parts of the TCMA, where groundwater impacted by anthropogenic activity was found most often above the lower Jordan-St Lawrence aquitard.

Protection of lower aquifers by overlying aquitards can be variable, even in deep bedrock settings, due to a number of factors. Tipping (2012) showed that especially large vertical gradients created by local pumping centers in the TCMA apparently increase the rate of leakage across Paleozoic bedrock aquitards, leading to localized recharge of recent and more contaminated water to deeper aquifers. Multi-aquifer water wells constructed prior to modern regulatory codes can also provide direct vertical connection across aquitards, and these can be particularly common in urban areas. Additionally, faults with sufficient displacement can provide "windows" where ground water can pass through an aquitard and vertically. Enhanced development of fractures in close proximity to the faults may also provide vertical pathways with high conductivity, although such a phenomenon has not been documented in Paleozoic bedrock of this region.

Although the lower Jordan-St. Lawrence aquitard has a low bulk vertical hydraulic conductivity in deep bedrock settings, and apparently is of high integrity, bulk horizontal conductivity is high, comparable in magnitude to the traditionally defined aquifers in southeastern Minnesota. Such a highly anisotropic conditions have also been documented in Paleozoic bedrock at a number of others sites in the region (e.g. Swanson et al., 2006; Meyer et al., 2008;, Anderson et al., 2011). The strong anisotropy is the result of low matrix permeability and poor connectivity of fractures in a vertical direction, but with the ubiquitous presence of high conductivity bedding-plane parallel macropore networks in a horizontal direction. This type of groundwater-flow setting has implications for contaminant transport in the aquitard. Even if vertical transport is inhibited, lateral transport across the aquitard in a direction parallel to bedding could be significantly rapid. We have informally referred to units with these characteristics as "aquitardifers" to convey our understanding that they can have properties of both aquifers and aquitards, even at a single location, depending on whether they are viewed from a vertical or a horizontal perspective (e.g. Anderson et al., 2011).

Characterizing aquitard integrity in shallow bedrock conditions is especially difficult because fractures are more greatly developed compared to deeper conditions of burial. The depiction of dye trace results (Figs 28-30), and the regional cross section highlighting groundwater ages (Fig. 31), are illustrative of variability in aquitard integrity across the lower Jordan-St Lawrence aquitard in shallow conditions. Dye trace results have consistently shown that the ability of the

St. Lawrence to impede vertical flow, that is, its aquitard integrity, is apparently quite limited in these subcrop settings. Groundwater chemistry profiles in several southeastern Minnesota counties (e.g. Fig 31) reflect the same phenomenon.: Relatively rapid recharge of recent water to deeper aquifers locally occurs in areas where the lower Jordan-St Lawrence aquitard loses its vertical integrity. This includes where it is cut by erosional windows such as in buried bedrock valleys, is displaced by faults, and anywhere it is breached by well-connected vertical fractures that are developed in shallow bedrock conditions.

The vertical integrity of the lower Jordan-St. Lawrence aquitard in shallow bedrock conditions must be viewed as at least locally very poor, and likely highly variable. Underlying aquifers in these settings, and the aquitard itself, is more susceptible to contamination than in deeply buried settings. This conclusion has a number of environmental implications, including water quality management of the many cold water trout streams that are tributaries to the Mississippi River system in southeastern Minnesota (Green et al., 2008, 2012). Many of these stream reaches receive significant baseflow from St. Lawrence and Tunnel City springs and seeps. The relatively direct and rapidly flowing connection between surface water and these baseflow springs and seeps indicates that they are significantly more susceptible to degradation than previously thought (Green et al., 2008). Relatively shallow water wells in these hydrogeologic settings will also be less protected by the lower Jordan-St. Lawrence and other bedrock aquitards compared to where they are present in more deeply buried settings.

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## FIGURE CAPTIONS

**Figure 1** Regional geologic map of Paleozoic bedrock in southeastern Minnesota, with locations of principal sources of data described in this report. Highlights distribution of St. Lawrence Formation (red) where it has been mapped separately. St. Lawrence subcrop in Le Sueur, Watonwan, and Martin counties has not been mapped. In Goodhue, Wabasha and Fillmore counties it has been mapped together with underlying Tunnel City Group, shown as green polygon. Cross section lines for illustrations in Figures 2, 3, and 31 are also shown. Cross section line C-C' is offset because it represents location of individual sections for Wabasha (Peterson, 2005) and Goodhue counties (Berg, 2003), which are offset at the border between those counties. ATES= Aquifer Thermal Energy Storage Project (Miller and Delin, 1993). MUGSP=Minnegasco Underground Gas Storage Project (MUGSP, 1980). Afton MLS hole is the borehole multilevel monitoring system constructed as part of this project.

**Figure 2** Cross-section highlighting hydrogeologic properties of Paleozoic bedrock across the TCMA and outlying areas. Upper section shows typical distribution of hydrostratigraphic attributes including matrix components and fractures. Note higher density of fractures in the uppermost approximately 50 feet of bedrock and the preferential development of bedding parallel fractures along specific stratigraphic positions. Lower section shows regionally defined aquifers and aquitards. Cross-section location shown on Fig. 1. Afton MLS hole is the borehole multilevel monitoring system constructed as part of this project. Modified from Runkel et al. (2006b).

**Figure 3** Generalized, regional scale cross section from approximately central Mower County, east to the Mississippi River in southeastern Minnesota. (A) shows typical distribution of hydrostratigraphic attributes including matrix components and fractures. Note higher density of fractures in the uppermost approximately 50 feet of bedrock and the preferential development of bedding parallel fractures along specific stratigraphic positions. (B) shows regionally defined aquifers and aquitards. Location of cross section is shown in Figure 1. From Runkel et al. (2013).

**Figure 4.** Lithic properties and representative natural gamma log signatures of the St. Lawrence Formation and adjacent stratigraphic strata across the TCMA. Note that the St. Lawrence Formation thickens to the southwest, largely by virtue of more abundant and thicker beds of carbonate rock in its lower part. The upper and lower contacts of the St. Lawrence Formation with adjacent units are transitional, making precise, consistent identification problematic in some areas. See text for additional discussion.

**Figure 5**. Outcrop and borehole examples of macropores in the St. Lawrence Formation and lower Jordan Sandstone in shallow bedrock conditions (buried by less than 50 feet of younger bedrock). **A)** Vertical and subvertical fractures in outcrop. Green arrows point to a prominent systematic fracture ("vertical joint") with large aperture. Red arrows point to selected smaller-scale vertical fractures (hammer circled for scale). **B)** Prominent systematic fracture (green arrows), and bed-parallel macropores (black arrows). The latter has aperture walls with mineralization indicating former groundwater flow. **C)** Bedding parallel macropores (black arrows) in lower Jordan Sandstone. Aperture walls have mineralization indicating former groundwater flow. **D)** Spring with flow emerging from bedding parallel macropore. **E)** Down-hole view of systematic vertical fracture in borehole wall. **F)** Down-hole view of rubbly, heavily fractured borehole wall. **G)** Side-hole view of nonsystematic fractures in borehole wall. **H)** Side-hole view of bedding parallel macropore. **A), B)** near Red Wing, Minnesota. **C), D)** along St Croix River near Osceola, Wisconsin, and Stillwater, Minnesota respectively. **E)-H)** from borehole video of Montgomery City Well #2 (Le Sueur Co, unique number 218355) between 252.9 ft. and 269.9 ft. Borehole is about 12" diameter. **(C)** is lower Jordan Sandstone, all others are St. Lawrence Formation.

**Figure 6** Examples of bedding-plane parallel macropores in boreholes open to the Lower Jordan Sandstone, St. Lawrence Formation, and Upper Tunnel City Group in deep bedrock conditions**. A)-I)** are St. Lawrence Formation examples. **A)** Side-hole view at 339 ft in Montgomery City Well number 2 (218355) **B)** Side view in Victoria Creamery Well (256002) at 415 ft. **C)** Side view in Coon Rapids City Well number 11 (202965) at 191 ft. **D)** Down-hole view in Stillwater City Well number 7 (224467) at about 260 ft. **E)** Down-hole, and **F)** Side view of fracture at 297 ft. in Hugo test well 3 (645394). **G)** Side view in Hasting Railroad well (255768) at 218 ft. **H)** Side view in Inver Grove Parks well (257056) at 273 ft. **I)** Down-hole view in Chaska Test Well 2 (665714) at 355 ft. **J)** Side view in City of Webster stratigraphic test hole (699024). Lower Jordan Sandstone, ~432 ft. **K**) Side view in Afton MLS hole, ~338 ft, upper Tunnel City Group. The bedding-plane parallel pores in examples **D** through **K** actively emitted or accepted water under ambient conditions, based on observation of suspended particles in borehole video and/or geophysical flowmeter, temperature and conductivity logs. Conductivity of macropores in **J)** and **K)** estimated to be greater than 10,000 ft/day. Precise scale on photographs cannot be determined, but apertures in all examples likely range up to about 0.2 ft. Modified from Runkel et al. (2006a).

**Figure 7** Histograms showing vertical permeability (converted from millidarcies to ft/day) for plug samples of fine clastic and sandy dolostone extracted from cores collected at the MUGSP sites in southeastern Minnesota. Compares values of Jordan Sandstone, St. Lawrence Formation, and Tunnel City Group to one another. Average and median values for each formation are provided in Table 1 and discussed in text. MUGSP locations shown in Figure 1.

**Figure 8** Stratigraphic column showing lithic and hydrogeologic properties of Cambrian bedrock in the Twin Cities Metro area. This figure is based on observations and measurements of two cores and packer tests in two boreholes from the ATES (Aquifer Thermal Energy Storage) Project site in Ramsey County. The St. Lawrence Formation lithic properties and hydraulic tests of matrix are generally similar to those of aquitards in the lower Tunnel City Group and uppermost Eau Claire Formation. The St. Lawrence Formation is of low matrix permeability, and packer tests as well as analysis of bulk vertical conductivity show correspondingly low values. However, one packer test of an upper interval of the St. Lawrence Formation (borehole BC-1) has a relatively high hydraulic conductivity comparable to known Paleozoic bedrock aquifers, reflecting contribution through secondary pores. See text for additional discussion. Hydraulic testing is from Walton et al. (1991) and Miller and Delin (1993). L.R.=Lone Rock Formation. See Figure 1 for location of ATES site.

**Figure 9** Stratigraphic column, gamma log, and graphic representation of vertical matrix hydraulic conductivity measured from plug samples extracted from core of lower Jordan Sandstone, St. Lawrence Formation, and upper Lone Rock Formation. Core is Pratt-3 (212980), from MUGSP site in Waseca County. Fine clastic and sandy dolostone matrix vertical hydraulic conductivity is low in all three formations.

**Figure 10** Scatter and boxplots of hydraulic conductivity data for 13,076 wells open to Wonewoc Sandstone, Tunnel City Group, St. Lawrence Formation, and Jordan Sandstone in southeastern Minnesota. Scatter plots show relationship between depth of open hole interval below the bedrock surface to conductivity. Note trend of wells in shallower bedrock conditions having higher conductivity. Note also that conductivity of the St. Lawrence Formation is generally similar to that of the other units, which contain appreciable high permeability coarse clastic matrix. Yield to St. Lawrence Formation is therefore believed to be primarily through bed parallel macropores. Hydraulic conductivity values are calculated from specific capacity tests in the County Well Index database of the Minnesota Geological Survey and Minnesota Department of Health and converted to hydraulic conductivity using the methods of Bradbury and Rothschild (1985).

**Figure 11** Example of flowmeter logs collected to document borehole flow associated with the St. Lawrence Formation and adjacent strata. Example in **A)** shows water entering borehole between casing bottom and 350’ depth, and exiting at about 352 ft. and 410 ft. Entrances and exits are abrupt, through bedding parallel macropores. These flow patterns are common in boreholes intersecting these strata, as shown for other flowmeter logs in **B)**, and indicate the presence of an aquitard between entry and exit intervals in the boreholes. See Runkel et al. (2003, 2006a,b, 2008) for detailed information on flow-logging techniques, methods of interpretation and details of individual flow logs.

**Figure 12**. Bedrock geology at site of Afton MLS hole, eastern Washington County, TCMA. From in progress mapping of Washington County as part of Minnesota Geological Survey County Atlas Mapping program. See Figure 1 for location in regional context.

**Figure 13.** Cross sections across site of Afton MLS hole, eastern Washington county, TCMA. See Figure 12 for location of section lines.

**Figure 14.** Selected lithologic, borehole geophysical, and hydraulic test data from the Afton MLS hole. Natural gamma log, video log, and drill cuttings were used to depict matrix materials in the lower Jordan Sandstone through upper Tunnel City Group. ATV (Acoustic Televiewer), OTV (Optical Televiewer), and video logs were used to identify macropores and vugs along borehole walls of open-hole interval prior to installation of multiport monitoring system (MLS). Hydraulic conductivity was measured in ten foot intervals by the USGS. Three 2 ft. interval "pulse" tests were collected in monitoring ports using method described in text of this report. Conductivity profile calculated from monitored insertion of FLUTe liner based on techniques described in Keller et al., (2014). Three columns on far right show position of packers and monitored zones with pumping and measuring ports, and hydraulic head data collected since November, 2012. Colored lines for OTV log are tentative interpretation of where macropores may exist.

**Figure 15**. Side view of bed parallel macropores (A-F) and vugs (G-H) in open hole of Afton MLS well. From video log collected prior to installation of the MLS. Footages on recorded log shown in photos are one foot greater than depth below land surface.

**Figure 16.** Hydraulic head data collected from November, 2012 through late May, 2014, from 14 monitored ports in the Afton MLS hole. Note that hydrographs for ports 1-10 vary

similarly to one another in direction and magnitude of changing head. Graphs for ports 11-14 also vary similarly to one another, but differ from ports 1-10. These two groups of ports could be considered representative of a lower and upper flow system at the site. Lower part of illustration shows a hydrograph from DNR Observation well 82012 less than 100 yards from Afton MLS well. Decreasing hydraulic head in that well during fall and winter of 2012-2013 and 2013-2014 is due in part to pumping at Afton Alps Ski area about one mile south of the site. Slight decreases in heads in the lower ports of the MLS hole may also be responding to this pumping.

**Figure 17**. Hydrographs of hydraulic head data collected from transducers installed in ports 1,7,10,11 and 13 in the Afton MLS hole. Comparison of the hydrographs shows that ports 1, 7, and 10 vary similarly to one another in direction and magnitude of changing head. Graphs for ports 11 and 13 also vary similarly to one another, but differ from the graphs for the lower ports. See text for discussion.

**Figure 18**. Selected water chemistry from the 14 ports in the Afton MLS hole. Shows results from 3 sampling events. Evaluation of the water chemistry is ongoing, but initial results show variability between units defined by hydraulic head deflections.  For example, distinct changes in chloride, sulfate, nitrate and manganese concentrations, as well as electrical conductivity, approximate the position of the largest head deflection, in the upper St Lawrence Formation, that separates informally designated “lower” and “upper” flow systems.

**Figure 19** Measured section of Jordan Sandstone at Lookout Point, near Stillwater, eastern TCMA, and gamma log from water well about 0.3 miles from the outcrop. Intercalations of fine clastic and coarse clastic sandstone, representing stacked parasequences, are typical of lower Jordan and upper St. Lawrence strata regionally (Runkel et al.,~~,~~ 2007). See Figure 1 for location.

**Figure 20**. Lower Jordan Sandstone at Lookout Point that was evaluated for fracture characteristics. Outcrop gamma log collected in field according to methods described in Anderson et al. (2011).

**Figure 21**. Lookout Point outcrop of lower Jordan Sandstone, as shown in Figure 20, with traced bed contacts (numbered white lines) and fractures (red lines).

**Figure 22**. Compilation of traced fractures, relative to position of bed contacts, in lower Jordan Sandstone at Lookout Point locality. Four outcrop faces were photographed and traced for fractures. Bar graphs on the right depict calculated percentage of fractures that terminate within 2 foot bins, corresponding to the minimum thickness of most beds that can be traced across the length of these outcrops. We also calculated the termination percentage of fractures that meet each of the traceable bedding planes at an outcrop. For both of these analyses we used only fractures with trace lengths exceeding 2 ft. Note the high percentage of fracture terminations associated with contacts 4 and 5, which define an individual bed of about 3 ft. thick.

**Figure 23**. Compilation of traced fractures, relative to position of bed contacts, in lower Jordan Sandstone at Fairy Glen locality. Bar graphs on the right depict calculated percentage of fractures that terminate within 2 foot bins, corresponding to the minimum thickness of most beds that can be traced across the length of these outcrops. We also calculated the termination percentage of fractures that meet each of the traceable bedding planes at an outcrop. For both of these analyses we used only fractures with trace lengths exceeding 2 ft. Note the high percentage of fracture terminations associated with bed contact 2.

**Figure 24**. Compilation of traced fractures, relative to position of bed contacts, in lower Jordan Sandstone at Oasis Cafe locality. Bar graphs on the right depict calculated percentage of fractures that that terminate within 2 foot bins, corresponding to the minimum thickness of most beds that can be traced across the length of these outcrops. We also

calculated the termination percentage of fractures that meet each of the traceable bedding planes at an outcrop. For both of these analyses we used only fractures with trace lengths exceeding 2 ft. Note the high percentage of fracture terminations associated with bed contact 6. A second bed contact (contact 1) in the lowermost part of this exposure may also has a high percentage of terminations, although an overall relatively lower density of fractures and limited lateral extent of exposure permit only 4 fractures to be traced to their intersection with this contact.

**Figure 25**. Summary of fracture tracing results at three locations around Stillwater Minnesota (Fig 1) compared to hydraulic head data from Afton MLS hole. Note that the stratigraphic interval where a large lower Jordan head deflection is located is consistent with the position of key mechanical interfaces identified in our outcrop evaluation.

**Figure 26**. Natural gamma log and drill cuttings from Afton MLS hole for part of Jordan Sandstone and upper St. Lawrence Formation. Boundaries between white, unoxidized sediment, and brown to orange oxidized sediment may approximate vertical contrasts in permeability.

**Figure 27**. Traced fractures in lower St. Lawrence and upper Lone Rock strata along west side of Highway 26, in north end of City of Lansing, Iowa. Contact between the two formations shown as dashed yellow line. Vertical fractures shown by red lines. Note that many prominent vertical fractures in lower St. Lawrence Formation terminate at, or within two yards below, the top of the Lone Rock Formation.

**Figure 28**. Geologic map, southwestern Winona County (Ahrensfeld and Borson NE locations, Fig 1), showing results of dye traces through the lower Jordan Sandstone and St. Lawrence Formation. Dye inputs and vectors from Jeff Green, MDNR.

**Figure 29** Stratigraphic column showing dye entry and exit points for selected traces through the lower Jordan Sandstone and St Lawrence Formation in southeastern Minnesota. The numbers in parentheses indicate the number of springs where dye was recovered. From Green et al. (2012). At some locations, dye has now also been detected to emerge from springs in the Lone Rock Formation, lower in the stratigraphic section.

**Figure 30**. Cross section, southwestern Winona County, showing subsurface interpretation of dye flow path and distribution of bedrock macropores. The lower Jordan-St. Lawrence aquitard loses vertical integrity in shallow bedrock conditions, where density, trace length, aperture size and connectivity of vertical fractures are enhanced. Streams sink where key, discrete aquitards are breached, and rapid lateral (parallel to bedding) flow occurs along bed parallel macropore networks.

**Figure 31.** Cross section highlighting distribution of groundwater ages as determined by tritium concentration, across parts of Wabasha and Goodhue Counties. Note that there is a distinct stratification in age separating vintage from younger water corresponding to where the lower Jordan Sandstone and St. Lawrence Formations are largely continuously buried by younger bedrock (right side of cross section). In contrast, where bedrock is more deeply incised, and faulted, vertical aquitard integrity is diminished. See text for discussion. Modified from Berg (2003) and Petersen (2005).

**Apppendix A.** USGS summary of borehole geophysical logging and packer testing of Afton MLS hole.

**Appendix B**. Data from FLUTe Company summarizing results of liner insertion and conductivity profiling. (separate Excel File).

**Appendix C.** Outcrop photographs and fracture tracing from Lookout Point, Oasis Café and Fairy Glen locations.

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Walton, M., Eisenreich, S.J., Holm, N.L., Holm, T.R., Kanivetsky, R., Jirsa, M.A., Lee, H.C., Lauer, J.L., Miller, R.T., Norton, J.L., and Runke, H., 1991, The University of Minnesota aquifer Thermal Energy Storage (ATES) field test facility-system description , aquifer characterization, and results of short-term test cycles: Pacific Northwest Laboratory Report PNL-7220, UC-202, 295 p.

Zhang, H., and Kanivetsky, R., 1996, Bedrock Hydrogeology, Plate 6, in R.S. Lively and N.H. Balaban, eds., Geological Atlas of Fillmore County, Minnesota: Part B, County Atlas Series published by the Minnesota Department of Natural Resources, Division of Waters.

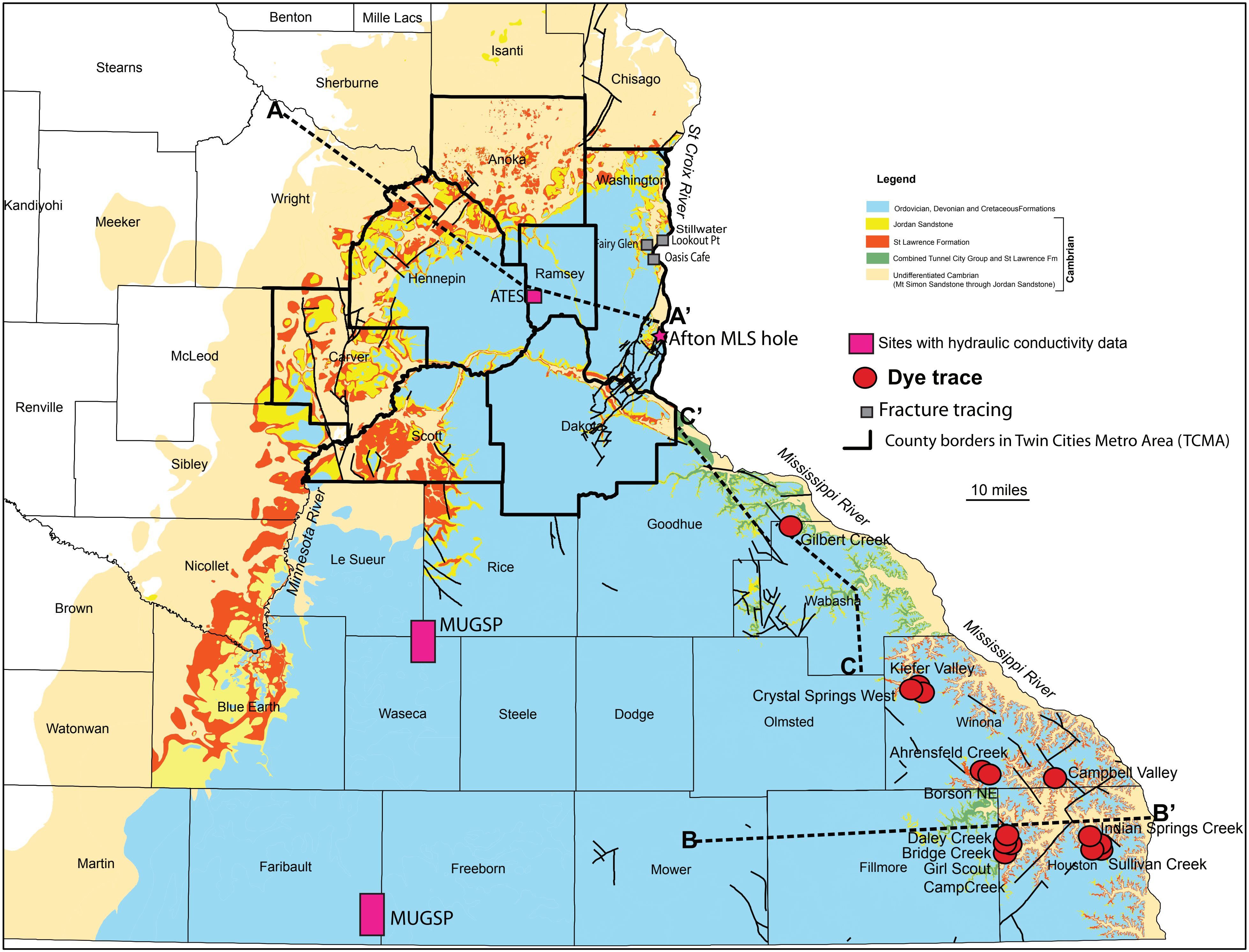

Benton
Mille Lacs
Stearns
Sherburne
Isanti
Chisago
A
Anoka
St Croix River
Washington
Kandiyohi
Meeker
Wright
Stillwater
Lookout Pt
Fairy Glen
Oasis Cafe
Hennepin
Ramsey
ATES
A'
Afton MLS hole
McLeod
Carver
Renville
C'
Dakota
Scott
Sibley
Mississippi River
Goodhue
Gilbert Creek
Nicollet
Minnesota River
Le Sueur
Rice
Brown
Wabasha
MUGSP
C
Kiefer Valley
Crystal Springs West
Blue Earth
Waseca
Steele
Dodge
Olmsted
Winona
Watonwan
Ahrensfeld Creek
Campbell Valley
Borson NE
B'
B
Indian Springs Creek
Daley Creek
Bridge Creek
Girl Scout
CampCreek
Martin
Faribault
Freeborn
Mower
Fillmore
Houston
Sullivan Creek
MUGSP
Legend
Ordovician, Devonian and CretaceousFormations
Jordan Sandstone
St Lawrence Formation
Combined Tunnel City Group and St Lawrence Fm
Undifferentiated Cambrian (Mt Simon Sandstone through Jordan Sandstone)
Cambrian
Sites with hydraulic conductivity data
Dye trace
Fracture tracing
County borders in Twin Cities Metro Area (TCMA)
10 miles

Fig 1

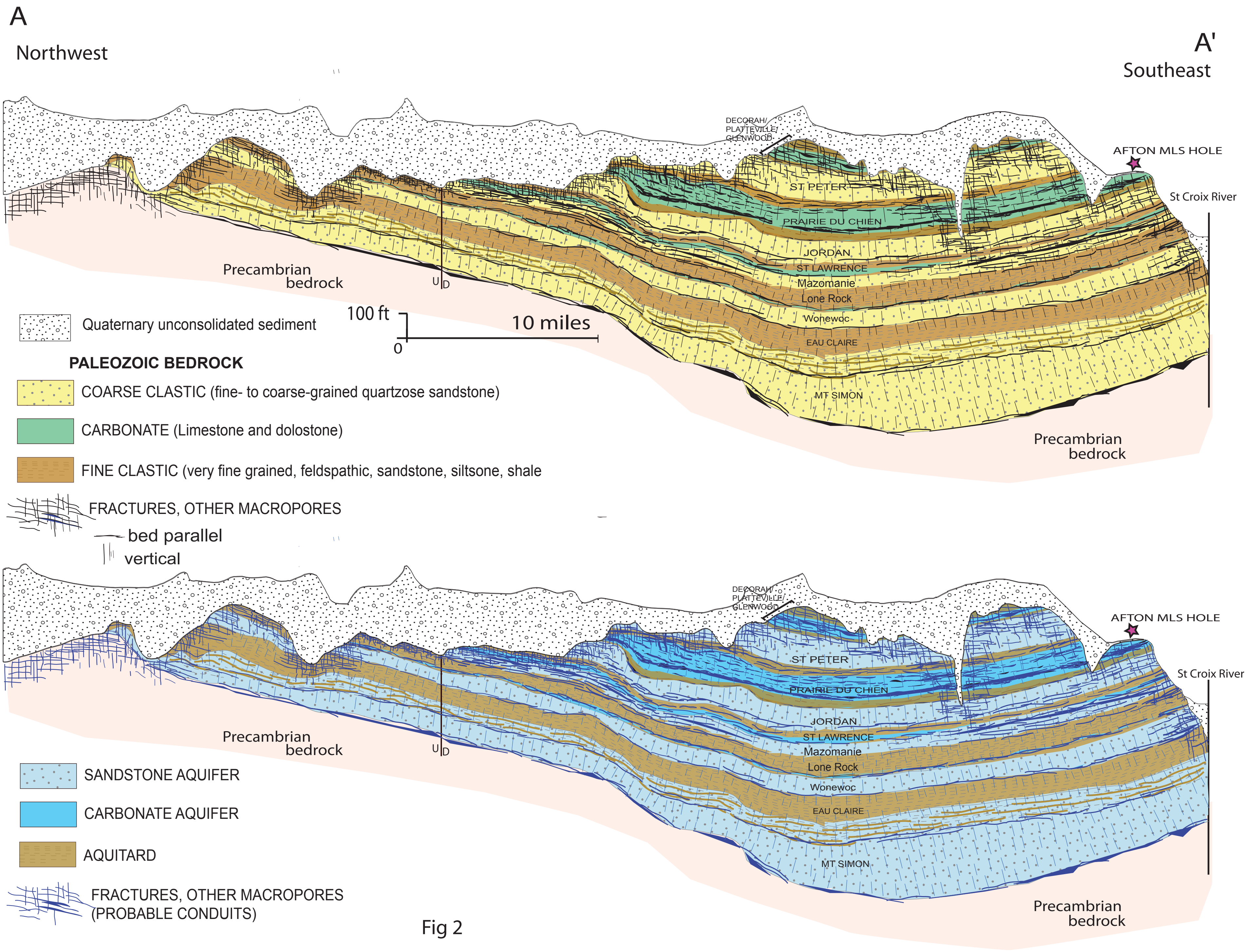

A
Northwest
A'
Southeast
DECORAH/
PLATTEVILLE/
GLENWOOD
AFTON MLS HOLE
St Croix River
ST PETER
PRAIRIE DU CHIEN
JORDAN
ST LAWRENCE
Mazomanie
Lone Rock
Wonewoc
EAU CLAIRE
MT SIMON
Precambrian bedrock
U
D
100 ft
0
10 miles
Quaternary unconsolidated sediment
PALEOZOIC BEDROCK
COARSE CLASTIC (fine- to coarse-grained quartzose sandstone)
CARBONATE (Limestone and dolostone)
FINE CLASTIC (very fine grained, feldspathic, sandstone, siltstone, shale
FRACTURES, OTHER MACROPORES
bed parallel
vertical
DECORAH/
PLATTEVILLE/
GLENWOOD
AFTON MLS HOLE
St Croix River
ST PETER
PRAIRIE DU CHIEN
JORDAN
ST LAWRENCE
Mazomanie
Lone Rock
Wonewoc
EAU CLAIRE
MT SIMON
Precambrian bedrock
U
D
SANDSTONE AQUIFER
CARBONATE AQUIFER
AQUITARD
FRACTURES, OTHER MACROPORES (PROBABLE CONDUITS)

Fig 2

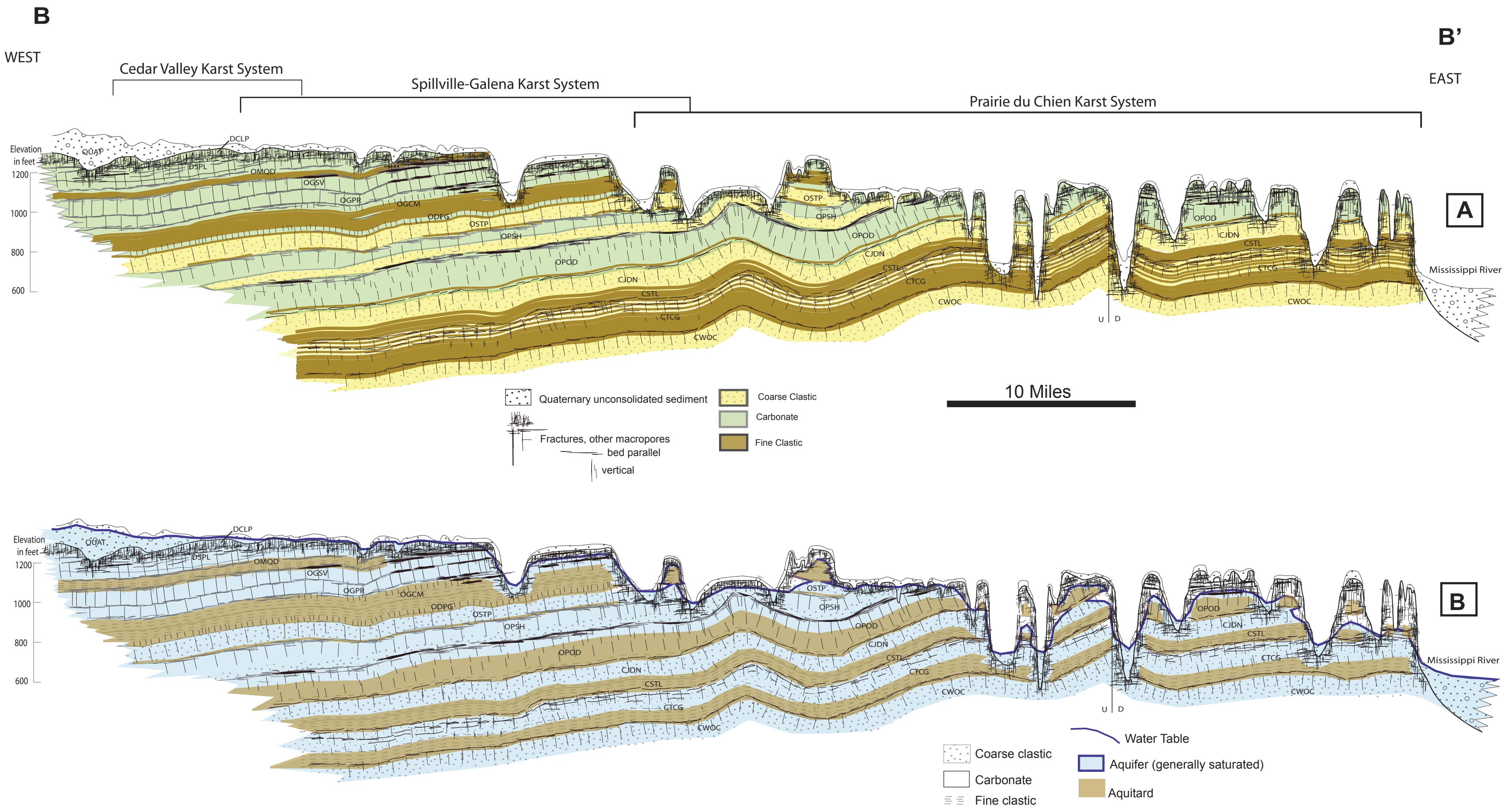

B
WEST
B'
EAST
Cedar Valley Karst System
Spillville-Galena Karst System
Prairie du Chien Karst System
Elevation in feet
1200
1000
800
600
QUAT
DCLP
DSPL
OMQD
OGSV
OGPR
OGCM
ODPG
OSTP
OPSH
OPOD
CJDN
CSTL
CTCG
CWOC
U
D
Mississippi River
A
Quaternary unconsolidated sediment
Fractures, other macropores
bed parallel
vertical
Coarse Clastic
Carbonate
Fine Clastic
10 Miles
B
Water Table
Coarse clastic
Carbonate
Fine clastic
Aquifer (generally saturated)
Aquitard

Fig 3

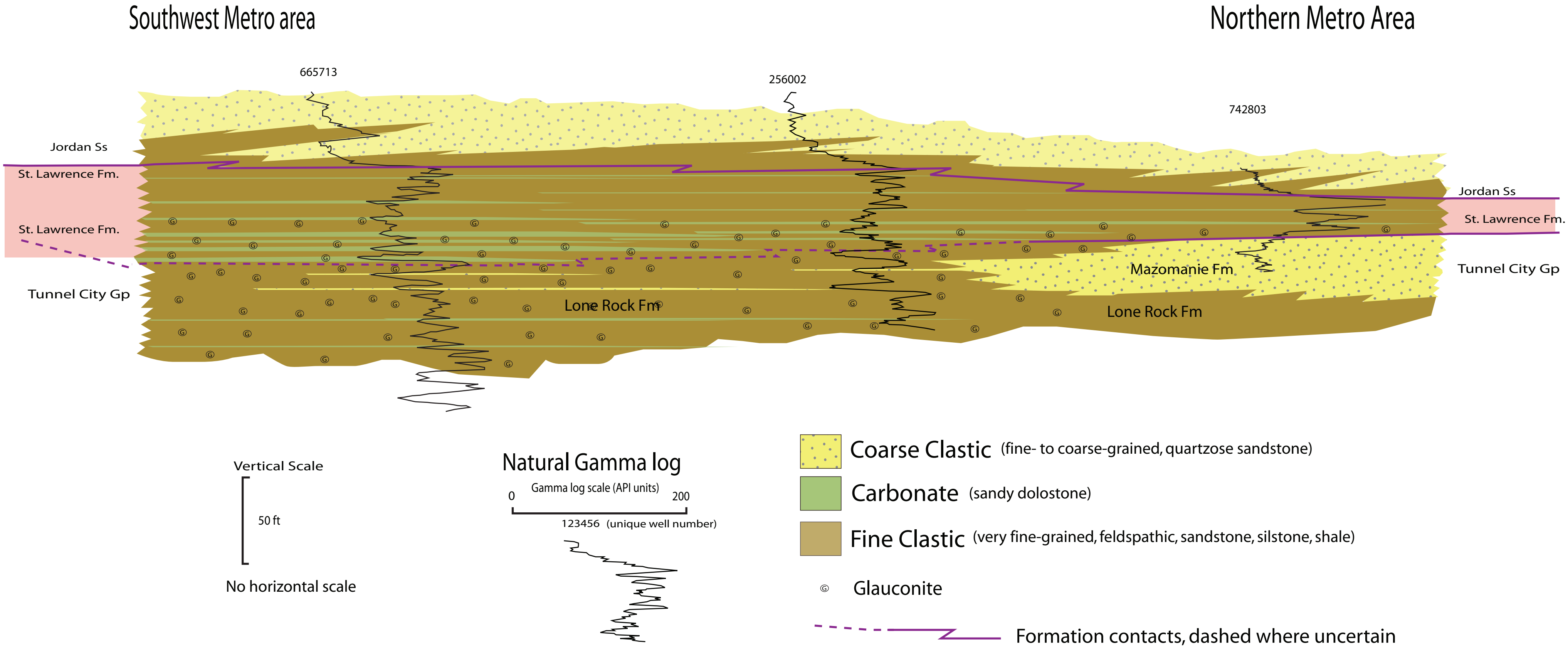

Southwest Metro area
Northern Metro Area
665713
256002
742803
Jordan Ss
St. Lawrence Fm.
St. Lawrence Fm.
Tunnel City Gp
Lone Rock Fm
Mazomanie Fm
Lone Rock Fm
Jordan Ss
St. Lawrence Fm.
Tunnel City Gp
Vertical Scale
50 ft
No horizontal scale
Natural Gamma log
Gamma log scale (API units)
0
200
123456 (unique well number)
Coarse Clastic (fine- to coarse-grained, quartzose sandstone)
Carbonate (sandy dolostone)
Fine Clastic (very fine-grained, feldspathic, sandstone, silstone, shale)
Glauconite
Formation contacts, dashed where uncertain

Fig 4

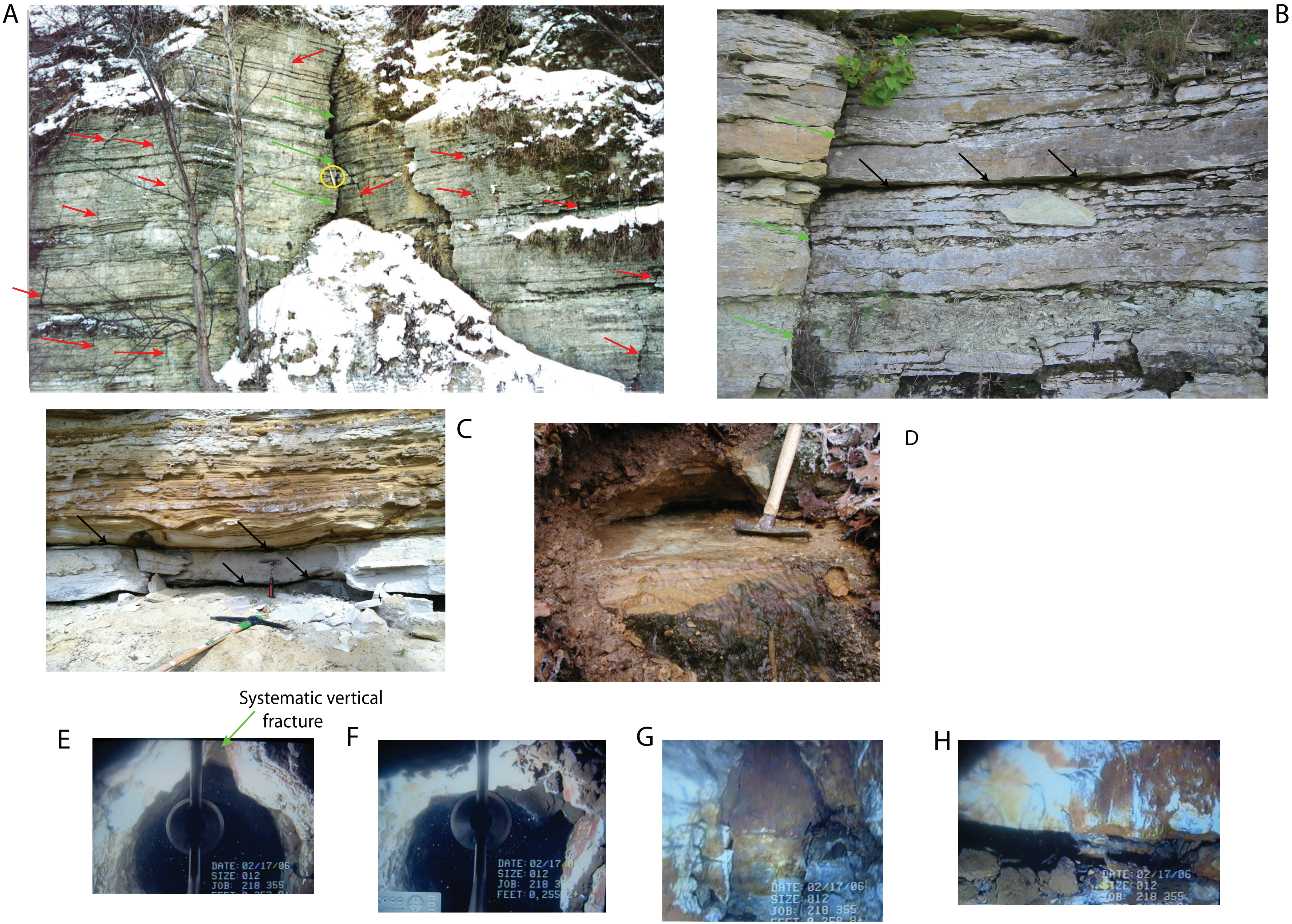

A
B
C
D
Systematic vertical fracture
E
DATE: 02/17/06
SIZE: 012
JOB: 218 355
F
DATE: 02/17/0
SIZE: 012
JOB: 218 3
FEET: 0,255
G
DATE: 02/17/06
SIZE: 012
JOB: 218 355
H
DATE: 02/17/06
SIZE: 012
JOB: 218 355

Fig 5

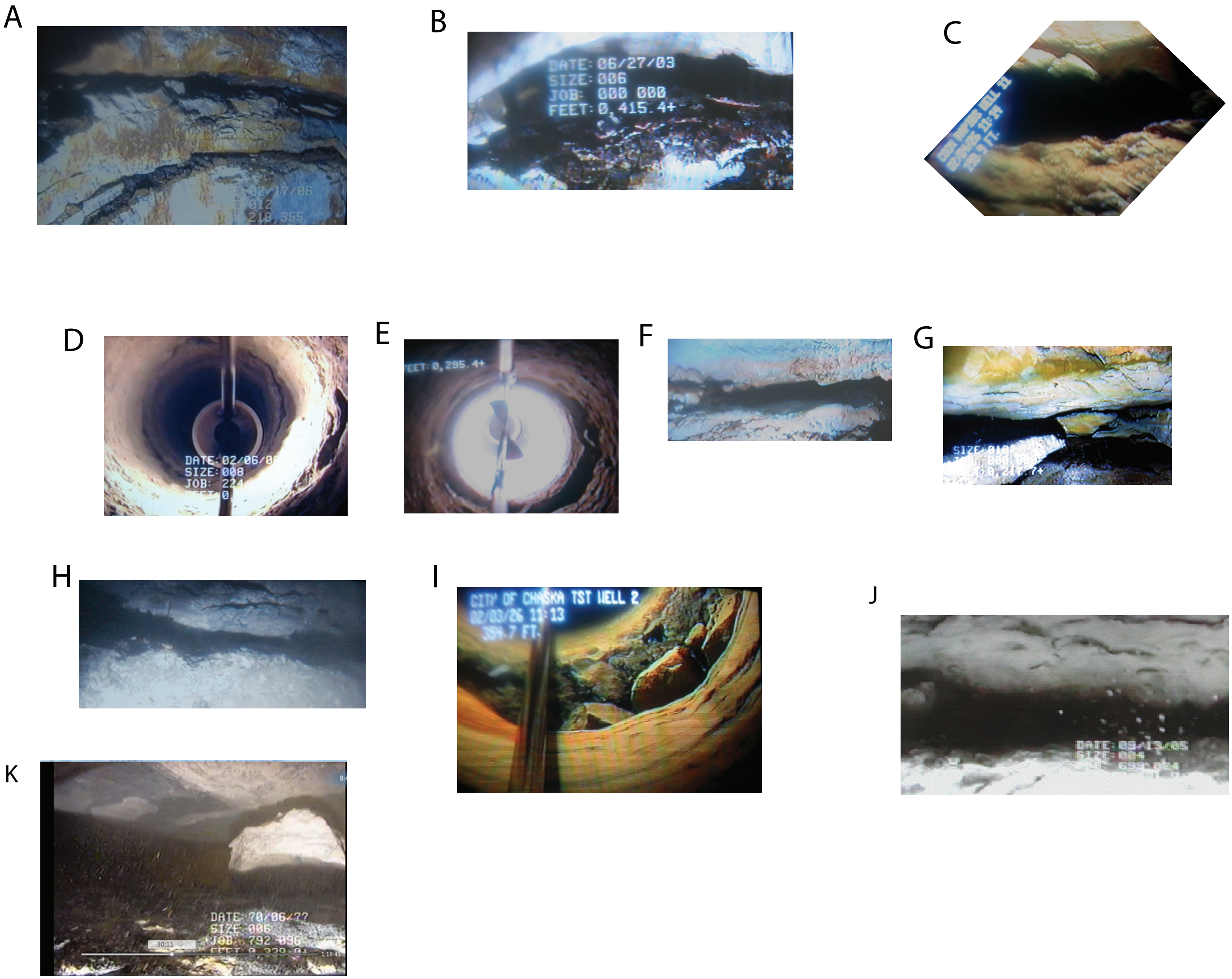

A
02/17/06
012
218.955
B
DATE: 06/27/03
SIZE: 006
JOB: 000 000
FEET: 0,415.4+
C
D
DATE: 02/06/0
SIZE: 008
JOB: 224
E
FEET: 0,295.4+
F
G
SIZE:
0,217.7+
H
I
CITY OF CHASKA TST WELL 2
02/03/26 11:13
354.7 FT.
J
DATE: 05/13/05
SIZE: 004
K
DATE: 70/06/77
SIZE: 006
JOB: 792 096
30:11
1:18:41

Fig 6

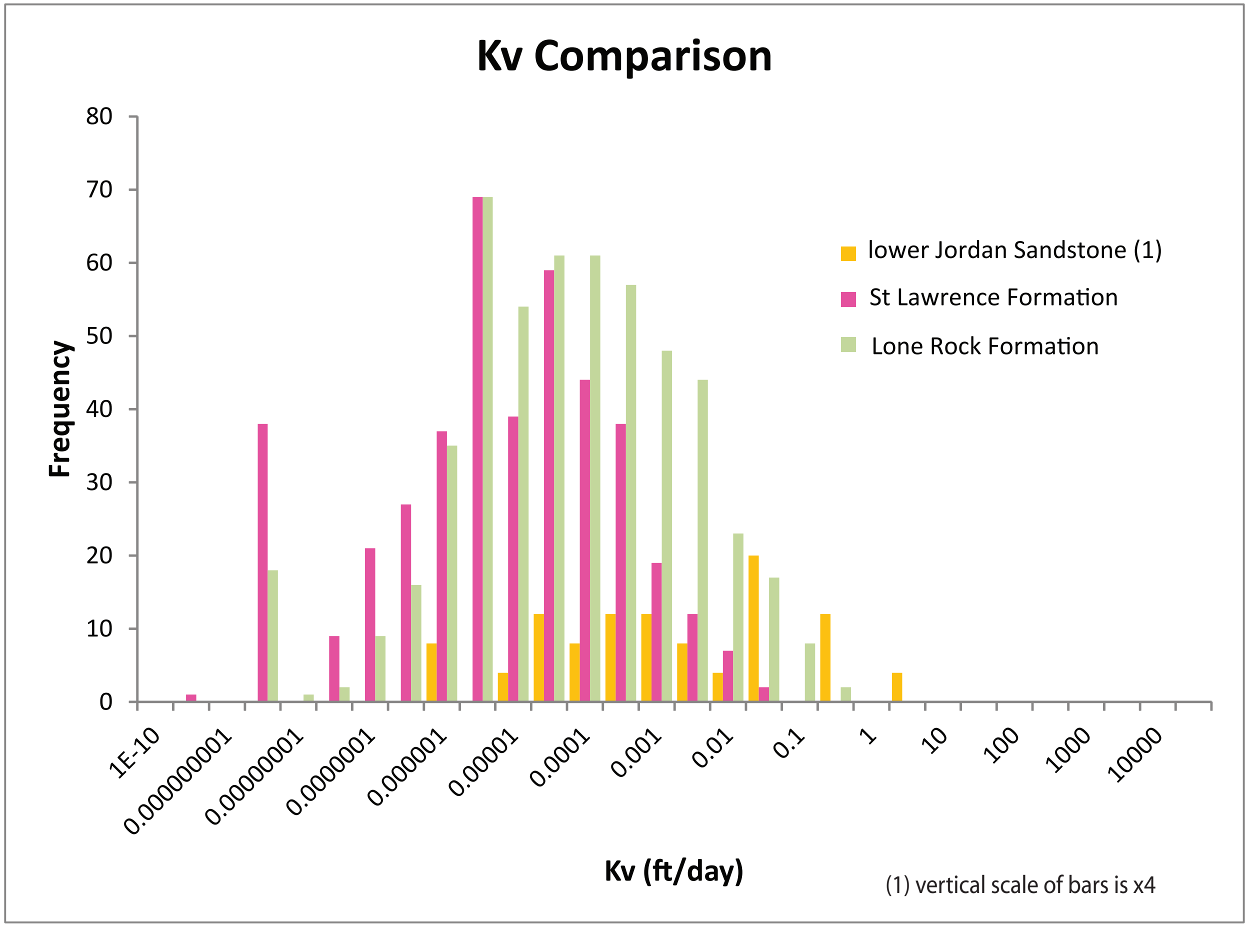

Kv Comparison
Frequency
80
70
60
50
40
30
20
10
0
1E-10
0.000000001
0.00000001
0.0000001
0.000001
0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
Kv (ft/day)
lower Jordan Sandstone (1)
St Lawrence Formation
Lone Rock Formation
(1) vertical scale of bars is x4

Fig 7

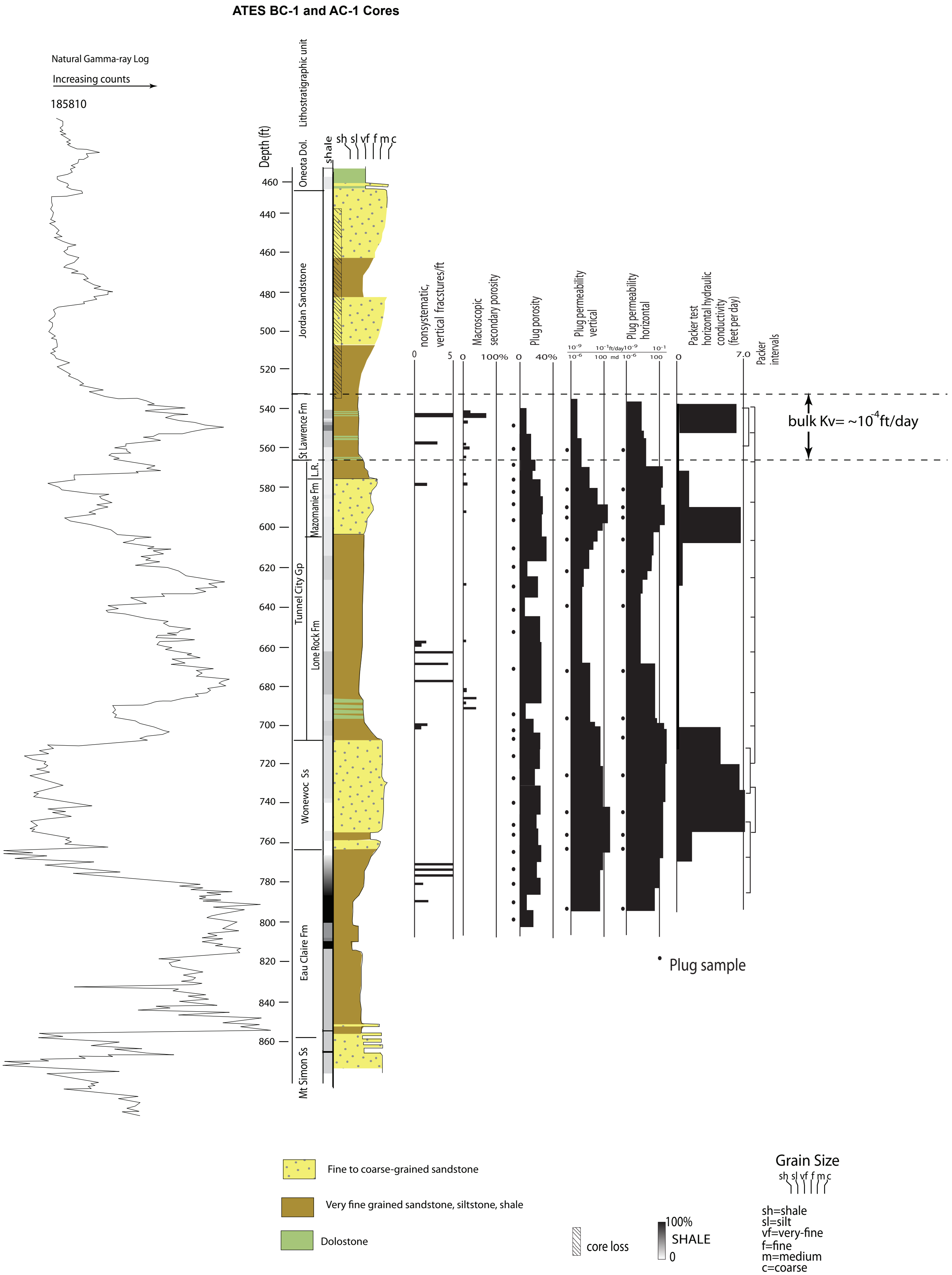

ATES BC-1 and AC-1 Cores
Natural Gamma-ray Log
Increasing counts
185810
Depth (ft)
Lithostratigraphic unit
shale
sh sl vf f m c
460
440
460
480
500
520
540
560
580
600
620
640
660
680
700
720
740
760
780
800
820
840
860
Oneota Dol.
Jordan Sandstone
St Lawrence Fm
L.R.
Mazomanie Fm
Tunnel City Gp
Lone Rock Fm
Wonewoc Ss
Eau Claire Fm
Mt Simon Ss
nonsystematic, vertical fracstures/ft
0
5
Macroscopic secondary porosity
0
100%
Plug porosity
0
40%
Plug permeability vertical
Plug permeability horizontal
10⁻⁹
10⁻¹ ft/day
10⁻⁹
10⁻¹
10⁻⁶
100
md
10⁻⁶
100
Packer test horizontal hydraulic conductivity (feet per day)
0
7.0
Packer intervals
bulk Kv= ~10⁻⁴ft/day
Plug sample
Fine to coarse-grained sandstone
Very fine grained sandstone, siltstone, shale
Dolostone
core loss
100%
SHALE
0
Grain Size
sh sl vf f m c
sh=shale
sl=silt
vf=very-fine
f=fine
m=medium
c=coarse

Fig 8

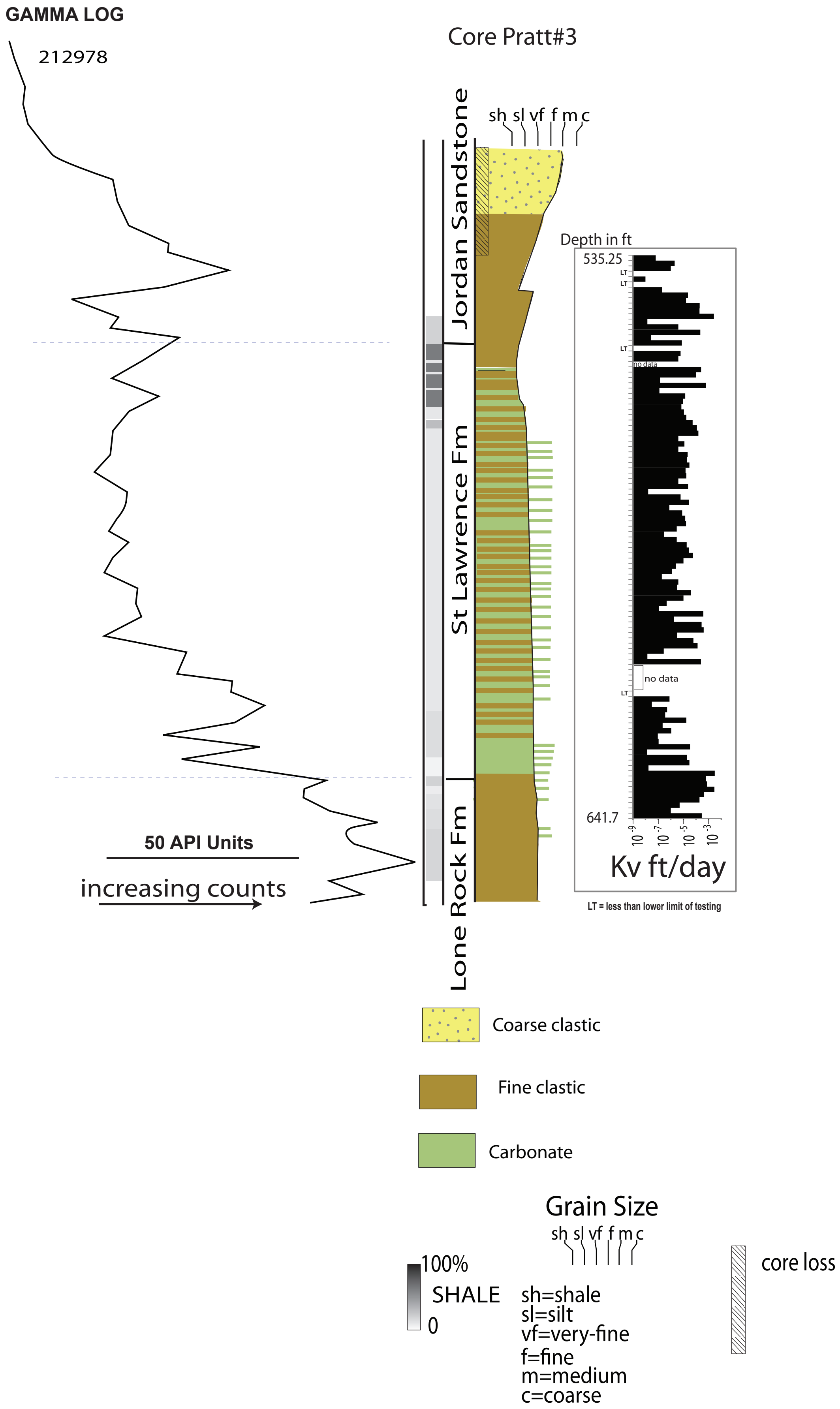
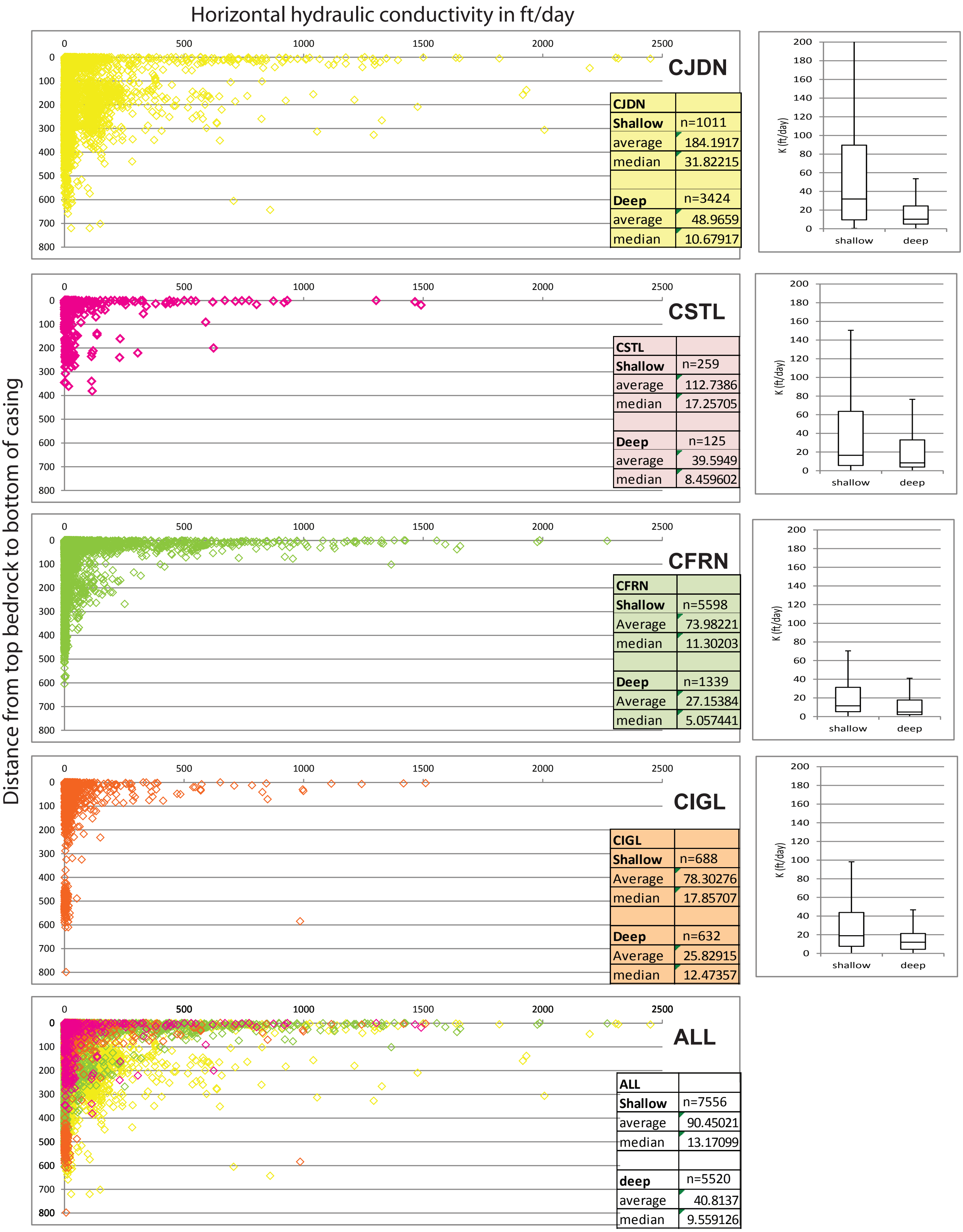

GAMMA LOG
212978
50 API Units
increasing counts
Core Pratt#3
sh sl vf f m c
Jordan Sandstone
St Lawrence Fm
Lone Rock Fm
Depth in ft
535.25
LT
LT
LT
no data
no data
LT
641.7
$10^{-9}$
$10^{-7}$
$10^{-5}$
$10^{-3}$
Kv ft/day
LT = less than lower limit of testing
Coarse clastic
Fine clastic
Carbonate
Grain Size
sh sl vf f m c
100%
SHALE
0
sh=shale
sl=silt
vf=very-fine
f=fine
m=medium
c=coarse
core loss

Fig 9


Horizontal hydraulic conductivity in ft/day

| CJDN | |
|---|---|
| Shallow | n=1011 |
| average | 184.1917 |
| median | 31.82215 |
| | |
| Deep | n=3424 |
| average | 48.9659 |
| median | 10.67917 |

| CSTL | |
|---|---|
| Shallow | n=259 |
| average | 112.7386 |
| median | 17.25705 |
| | |
| Deep | n=125 |
| average | 39.5949 |
| median | 8.459602 |

| CFRN | |
|---|---|
| Shallow | n=5598 |
| Average | 73.98221 |
| median | 11.30203 |
| | |
| Deep | n=1339 |
| Average | 27.15384 |
| median | 5.057441 |

| CIGL | |
|---|---|
| Shallow | n=688 |
| Average | 78.30276 |
| median | 17.85707 |
| | |
| Deep | n=632 |
| Average | 25.82915 |
| median | 12.47357 |

| ALL | |
|---|---|
| Shallow | n=7556 |
| average | 90.45021 |
| median | 13.17099 |
| | |
| deep | n=5520 |
| average | 40.8137 |
| median | 9.559126 |

Fig 10

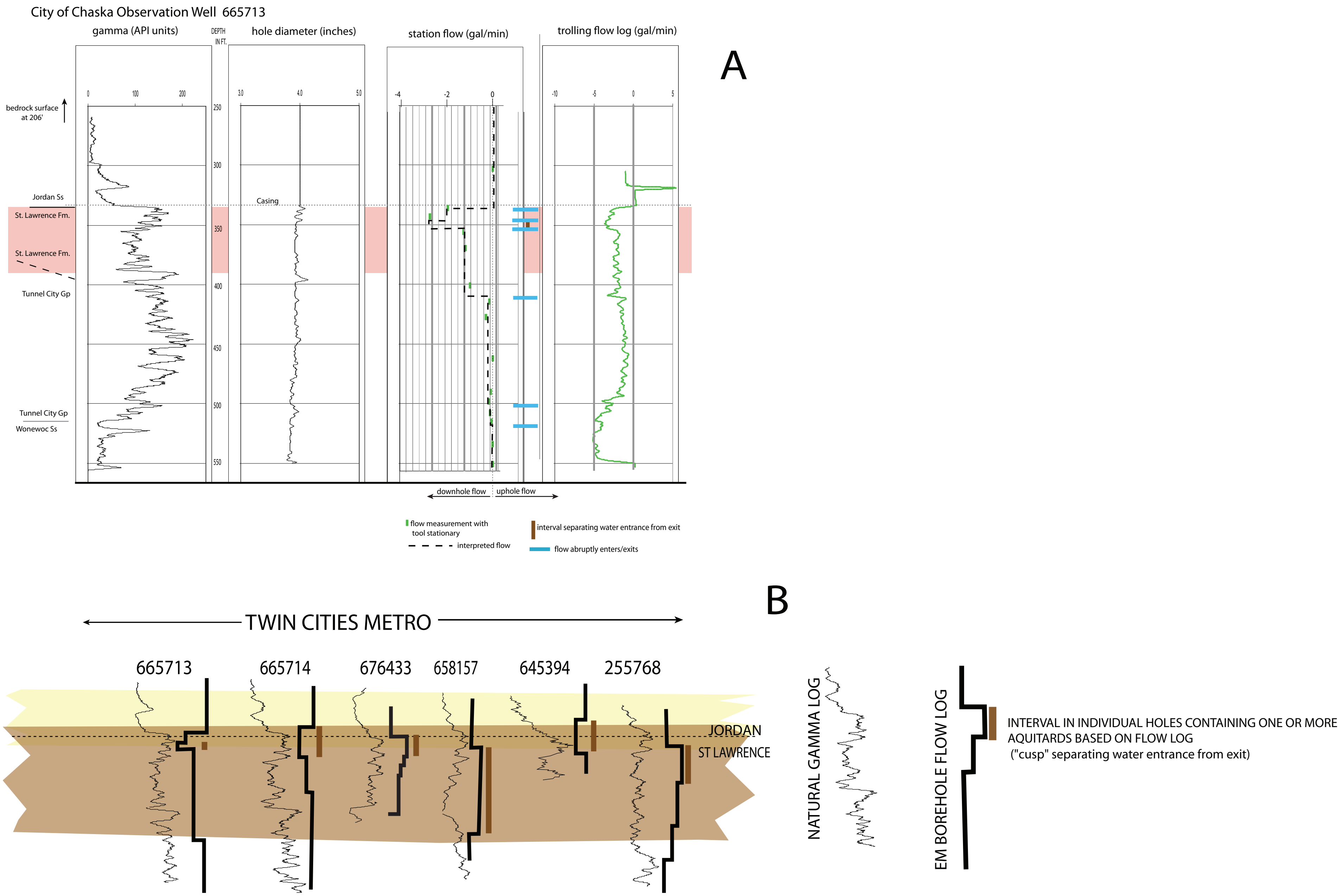

City of Chaska Observation Well 665713
gamma (API units)
DEPTH IN FT.
hole diameter (inches)
station flow (gal/min)
trolling flow log (gal/min)
A
0
100
200
3.0
4.0
5.0
-4
-2
0
-10
-5
0
5
bedrock surface at 206'
250
300
350
400
450
500
550
Jordan Ss
Casing
St. Lawrence Fm.
St. Lawrence Fm.
Tunnel City Gp
Tunnel City Gp
Wonewoc Ss
downhole flow
uphole flow
flow measurement with tool stationary
interpreted flow
interval separating water entrance from exit
flow abruptly enters/exits
B
TWIN CITIES METRO
665713
665714
676433
658157
645394
255768
JORDAN
ST LAWRENCE
NATURAL GAMMA LOG
EM BOREHOLE FLOW LOG
INTERVAL IN INDIVIDUAL HOLES CONTAINING ONE OR MORE AQUITARDS BASED ON FLOW LOG ("cusp" separating water entrance from exit)

Fig 11

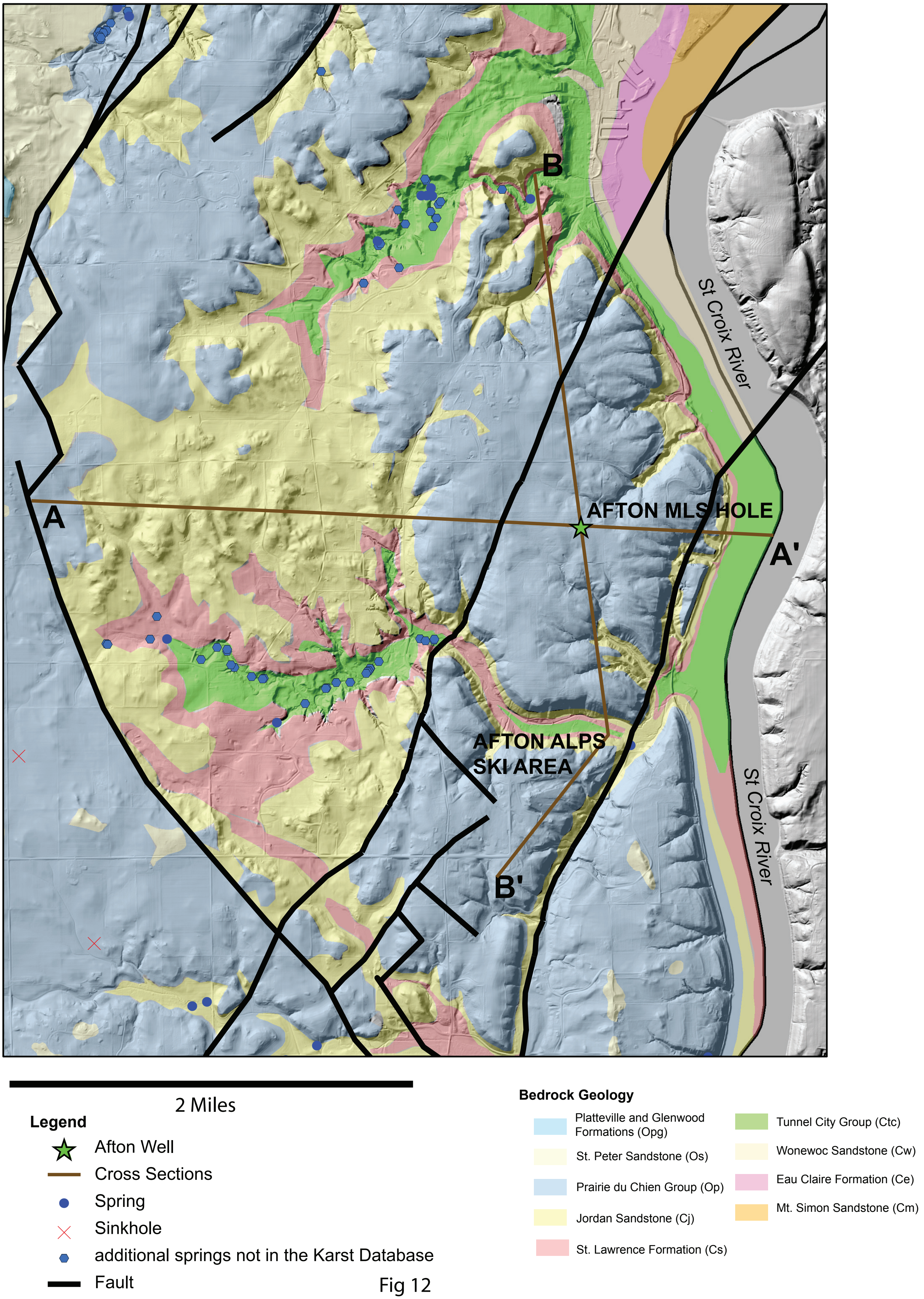

B
St Croix River
AFTON MLS HOLE
A
A'
AFTON ALPS
SKI AREA
B'
St Croix River
2 Miles
Legend
Afton Well
Cross Sections
Spring
Sinkhole
additional springs not in the Karst Database
Fault
Bedrock Geology
Platteville and Glenwood Formations (Opg)
St. Peter Sandstone (Os)
Prairie du Chien Group (Op)
Jordan Sandstone (Cj)
St. Lawrence Formation (Cs)
Tunnel City Group (Ctc)
Wonewoc Sandstone (Cw)
Eau Claire Formation (Ce)
Mt. Simon Sandstone (Cm)

Fig 12

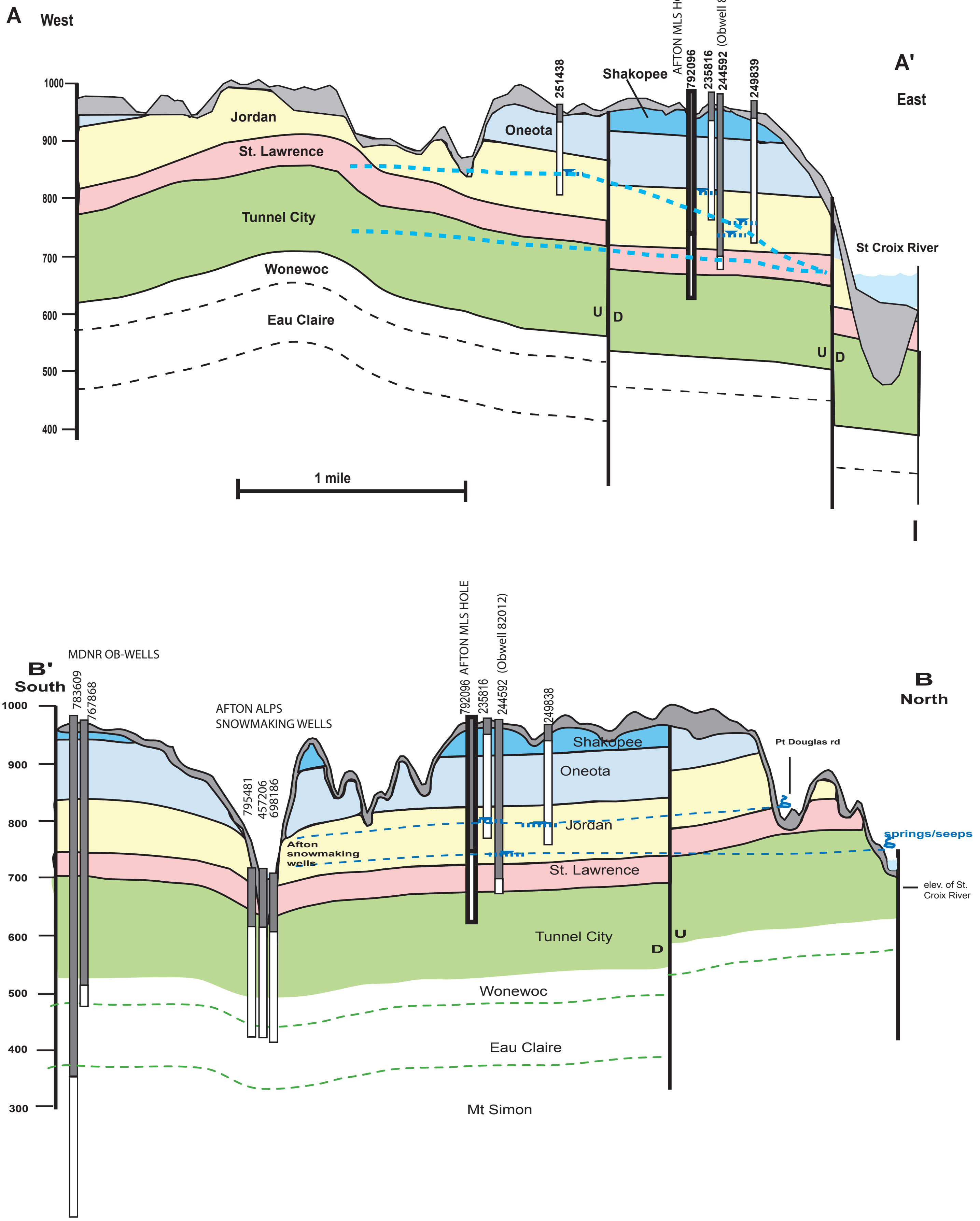

A
West
A'
East
1000
900
800
700
600
500
400
Jordan
St. Lawrence
Tunnel City
Wonewoc
Eau Claire
251438
Shakopee
AFTON MLS HOLE
792096
235816
244592 (Obwell 82012)
249839
Oneota
St Croix River
U
D
U
D
1 mile
MDNR OB-WELLS
B'
South
783609
767868
AFTON ALPS
SNOWMAKING WELLS
795481
457206
698186
Afton snowmaking wells
792096 AFTON MLS HOLE
235816
244592 (Obwell 82012)
249838
B
North
Shakopee
Oneota
Jordan
St. Lawrence
Tunnel City
Wonewoc
Eau Claire
Mt Simon
Pt Douglas rd
springs/seeps
elev. of St. Croix River
U
D
1000
900
800
700
600
500
400
300

Fig 13

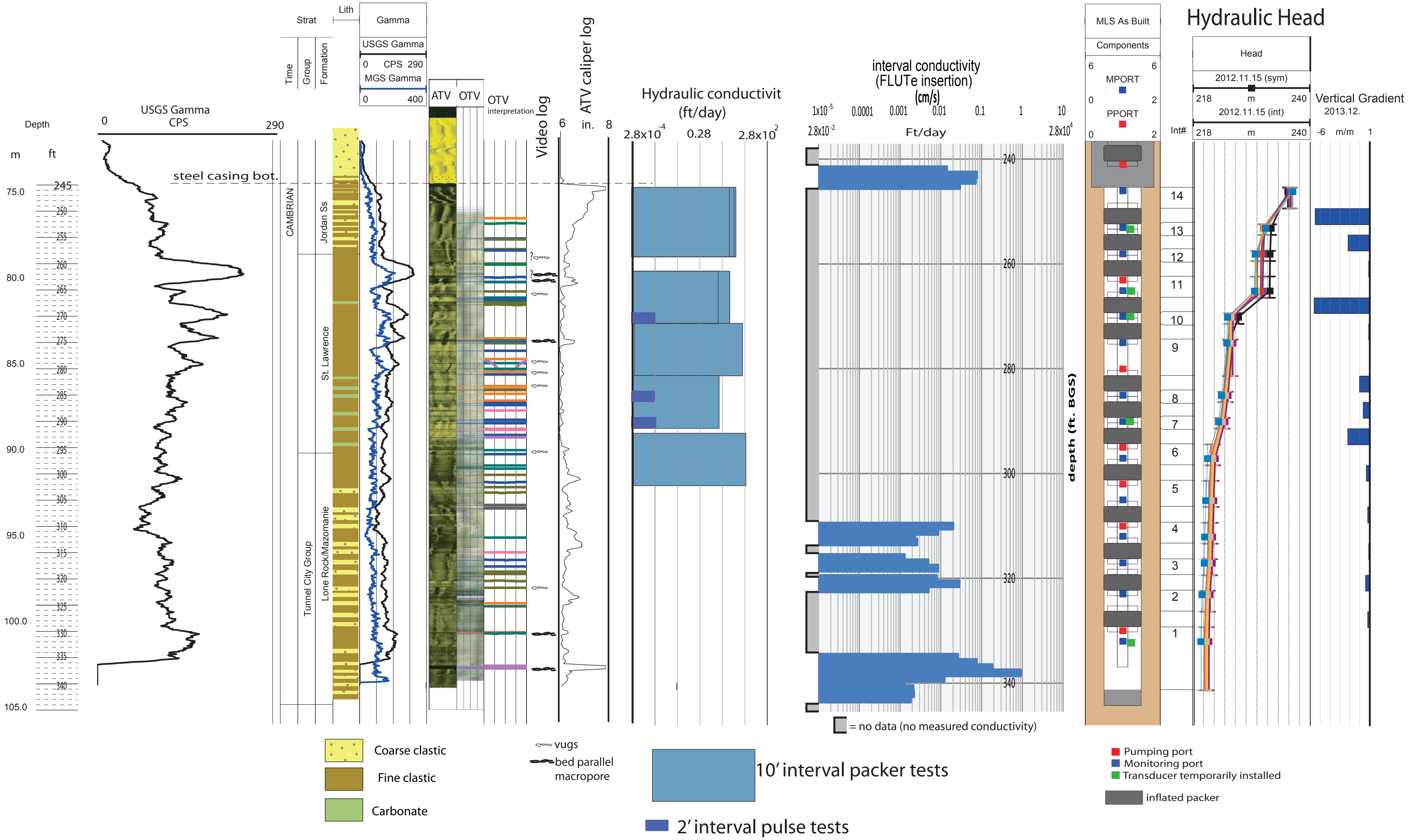

Depth
m
ft
75.0
80.0
85.0
90.0
95.0
100.0
105.0
245
250
255
260
265
270
275
280
285
290
295
300
305
310
315
320
325
330
335
340
USGS Gamma
CPS
0
290
steel casing bot.
Strat
Time
Group
Formation
Lith
CAMBRIAN
Jordan Ss
St. Lawrence
Tunnel City Group
Lone Rock/Mazomanie
Gamma
USGS Gamma
0 CPS 290
MGS Gamma
0 400
ATV
OTV
OTV interpretation
Video log
ATV caliper log
6 in. 8
Hydraulic conductivit (ft/day)
2.8x10^-4
0.28
2.8x10^2
interval conductivity (FLUTe insertion) (cm/s)
1x10^-5
0.0001
0.001
0.01
0.1
1
10
2.8x10^-2
Ft/day
2.8x10^4
240
260
280
300
320
340
depth (ft. BGS)
= no data (no measured conductivity)
MLS As Built
Components
6 MPORT 6
0 2
PPORT
0 2
Int#
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Hydraulic Head
Head
2012.11.15 (sym)
218 m 240
2012.11.15 (int)
218 m 240
Vertical Gradient
2013.12.
-6 m/m 1
Coarse clastic
Fine clastic
Carbonate
vugs
bed parallel macropore
10′ interval packer tests
2′ interval pulse tests
Pumping port
Monitoring port
Transducer temporarily installed
inflated packer

Fig 14

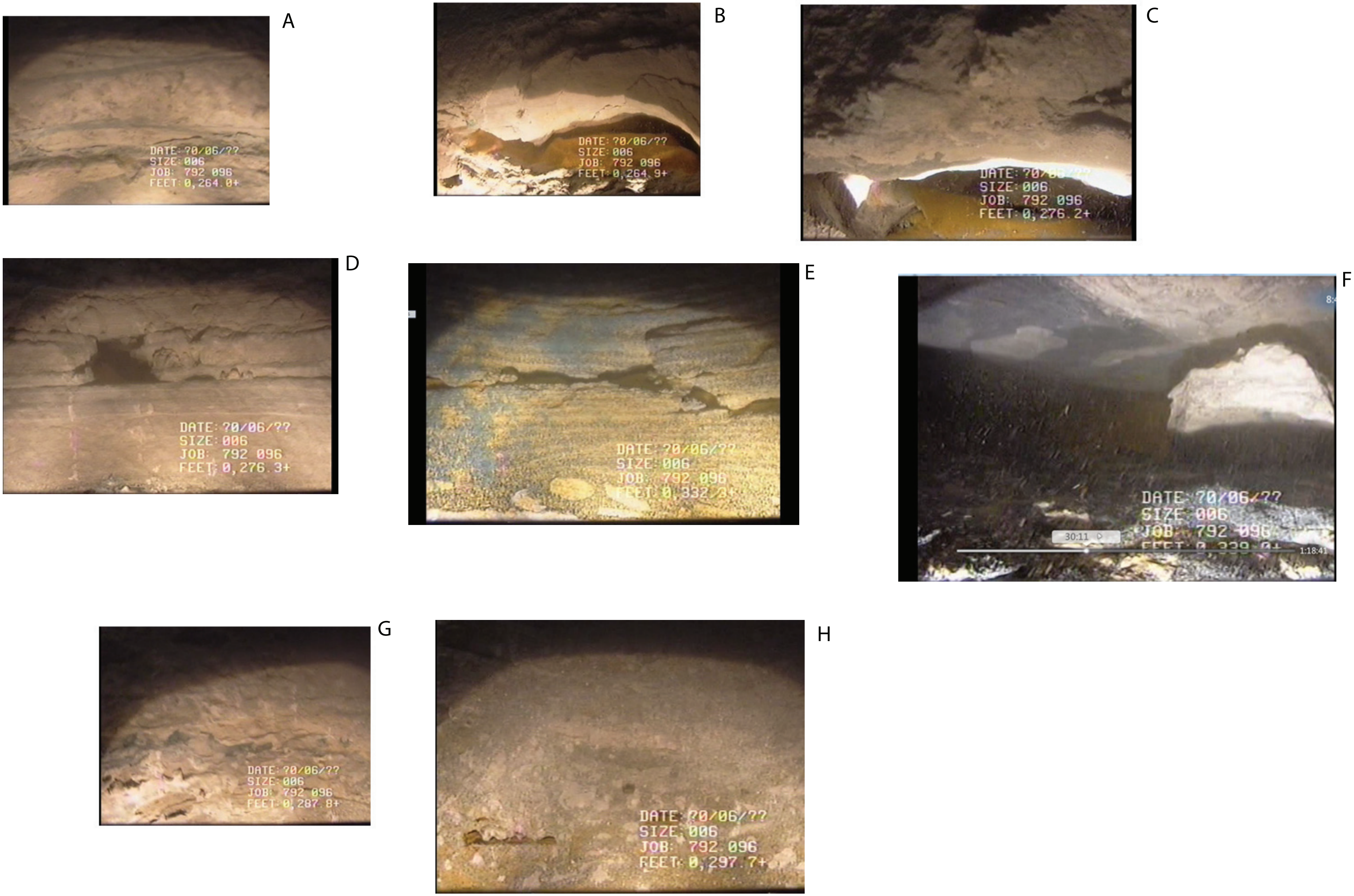
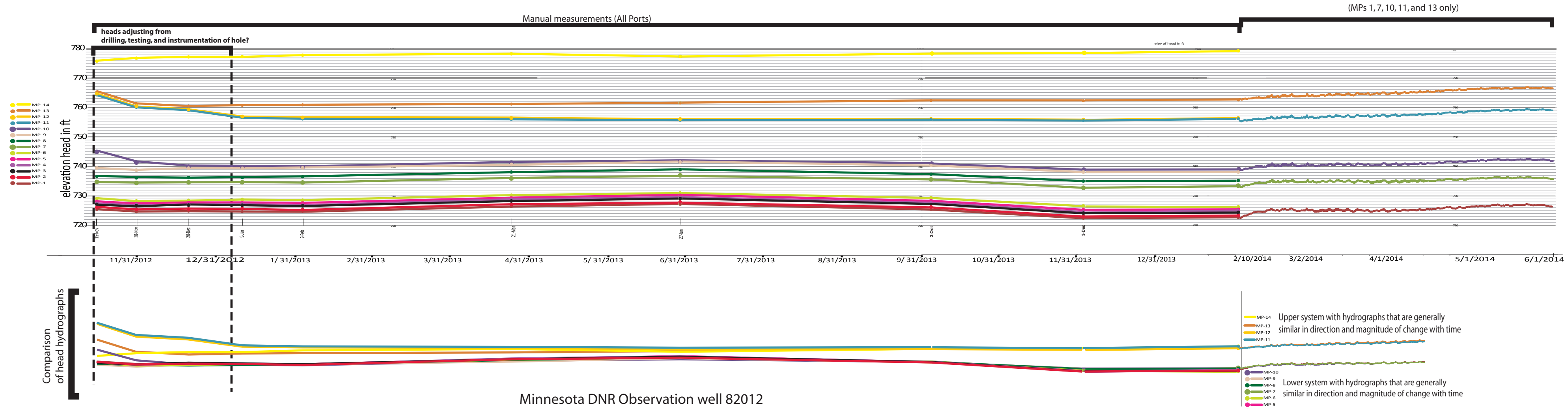

A
DATE:?0/06/??
SIZE:006
JOB: 792 096
FEET:0,264.0+
B
DATE:?0/06/??
SIZE:006
JOB: 792 096
FEET:0,264.9+
C
DATE:?0/06/??
SIZE:006
JOB: 792 096
FEET:0,276.2+
D
DATE:?0/06/??
SIZE:006
JOB: 792 096
FEET:0,276.3+
E
DATE:?0/06/??
SIZE:006
JOB: 792 096
FEET:0,332.3+
F
DATE:?0/06/??
SIZE:006
JOB: 792 096
30:11
1:18:41
G
DATE:?0/06/??
SIZE:006
JOB: 792 096
FEET:0,287.8+
H
DATE:?0/06/??
SIZE:006
JOB: 792 096
FEET:0,297.7+

Fig 15

Head data from AFTON MLS (elev in ft)



Minnesota DNR Observation well 82012

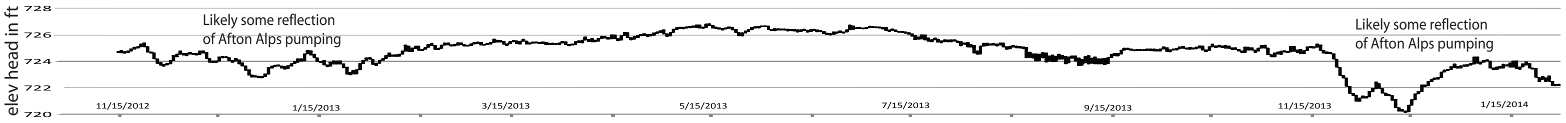


Fig 16

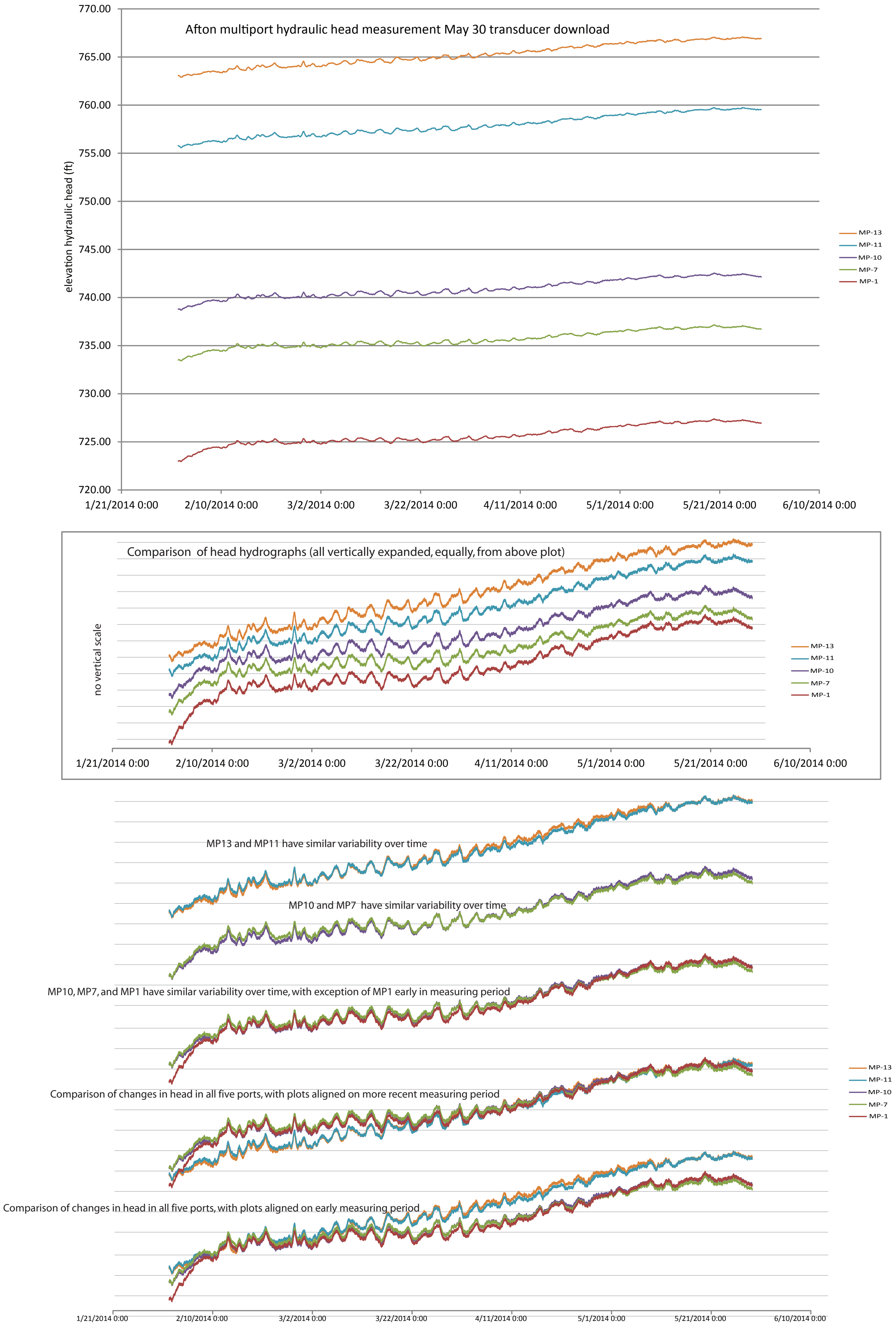
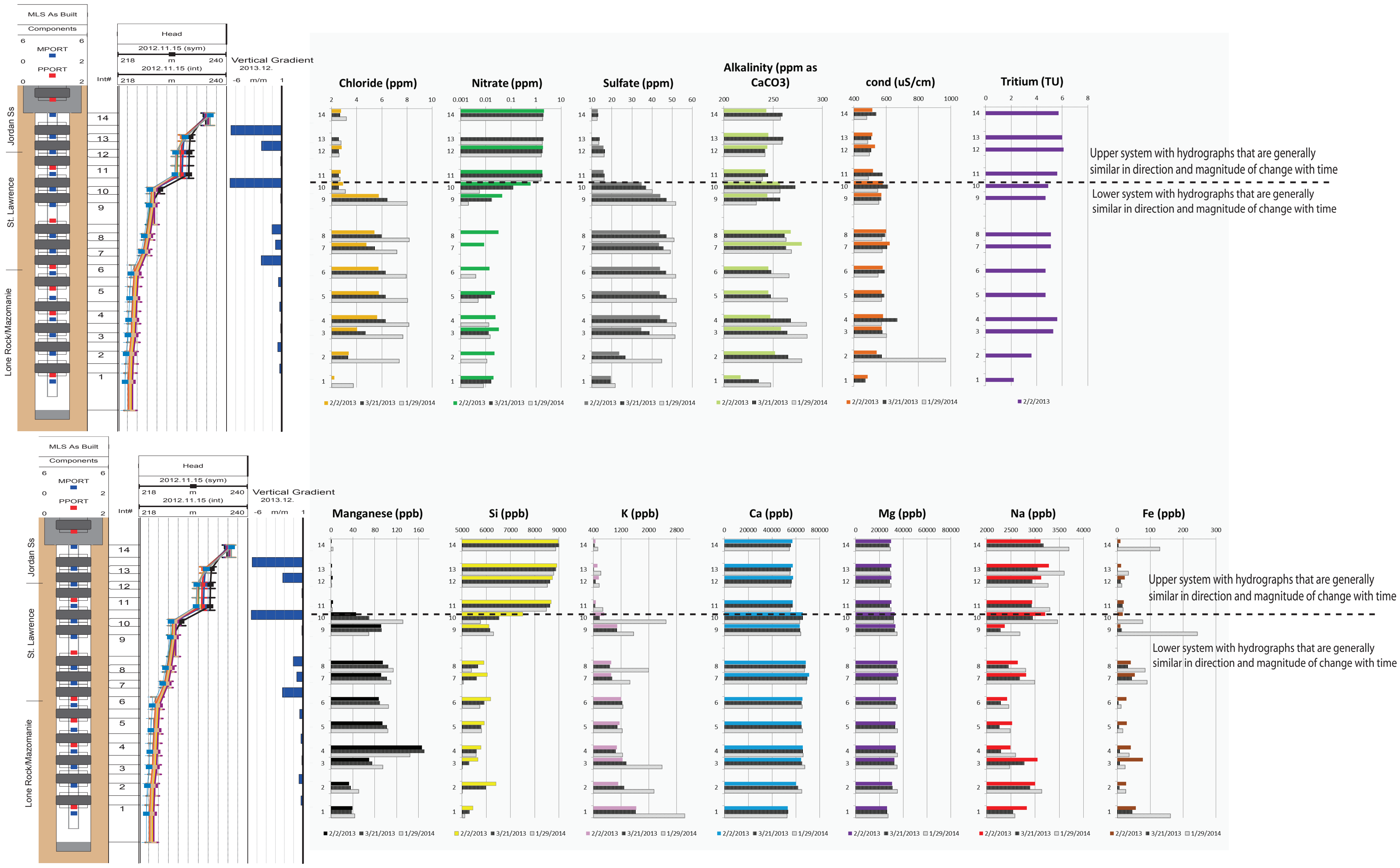

770.00
765.00
760.00
755.00
750.00
745.00
740.00
735.00
730.00
725.00
720.00
Afton multiport hydraulic head measurement May 30 transducer download
elevation hydraulic head (ft)
1/21/2014 0:00
2/10/2014 0:00
3/2/2014 0:00
3/22/2014 0:00
4/11/2014 0:00
5/1/2014 0:00
5/21/2014 0:00
6/10/2014 0:00
MP-13
MP-11
MP-10
MP-7
MP-1
Comparison of head hydrographs (all vertically expanded, equally, from above plot)
no vertical scale
1/21/2014 0:00
2/10/2014 0:00
3/2/2014 0:00
3/22/2014 0:00
4/11/2014 0:00
5/1/2014 0:00
5/21/2014 0:00
6/10/2014 0:00
MP-13
MP-11
MP-10
MP-7
MP-1
MP13 and MP11 have similar variability over time
MP10 and MP7 have similar variability over time
MP10, MP7, and MP1 have similar variability over time, with exception of MP1 early in measuring period
Comparison of changes in head in all five ports, with plots aligned on more recent measuring period
Comparison of changes in head in all five ports, with plots aligned on early measuring period
MP-13
MP-11
MP-10
MP-7
MP-1
1/21/2014 0:00
2/10/2014 0:00
3/2/2014 0:00
3/22/2014 0:00
4/11/2014 0:00
5/1/2014 0:00
5/21/2014 0:00
6/10/2014 0:00

Fig 17



Upper system with hydrographs that are generally similar in direction and magnitude of change with time

Lower system with hydrographs that are generally similar in direction and magnitude of change with time

Upper system with hydrographs that are generally similar in direction and magnitude of change with time

Lower system with hydrographs that are generally similar in direction and magnitude of change with time

Fig 18

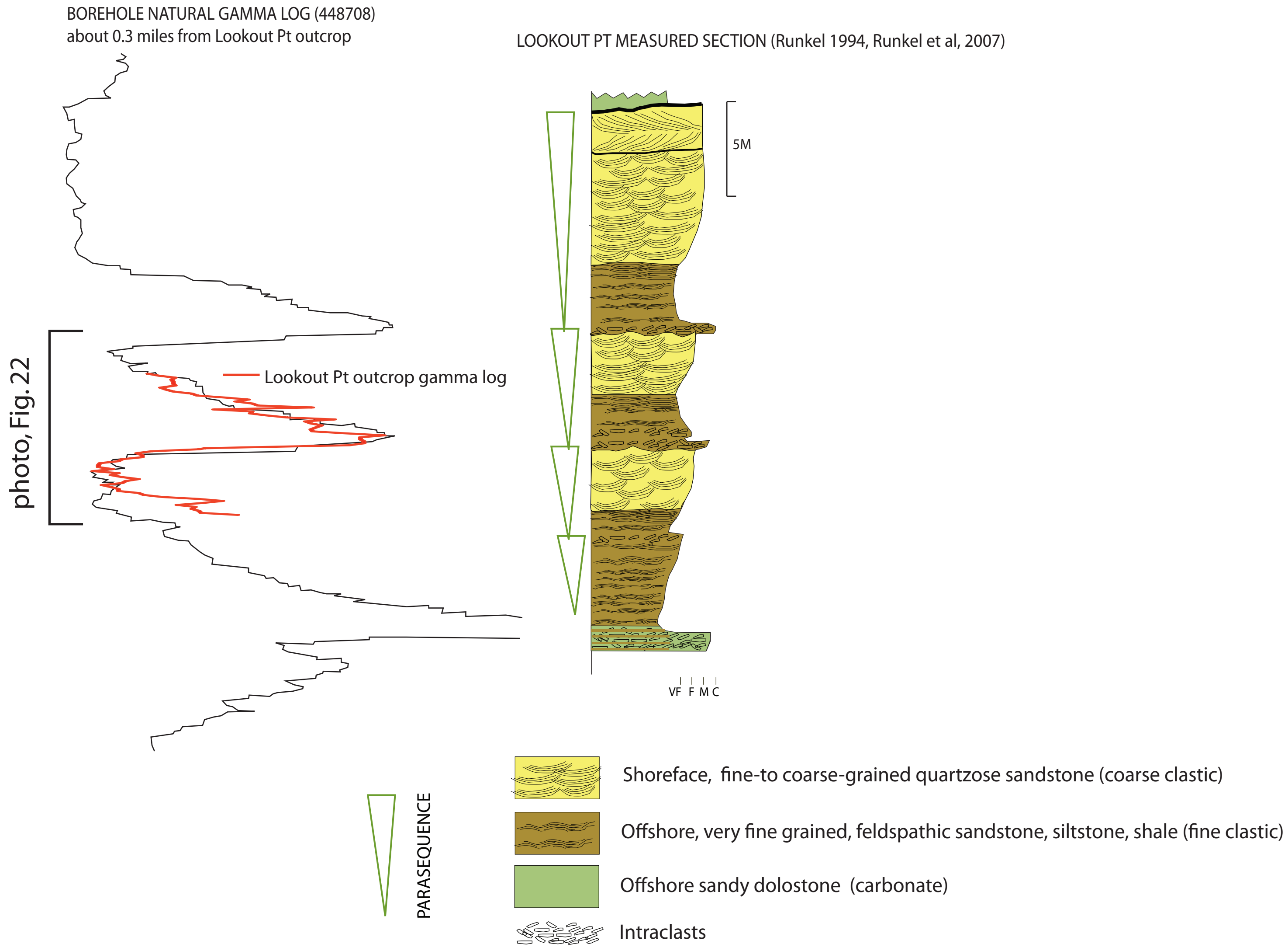

BOREHOLE NATURAL GAMMA LOG (448708)
about 0.3 miles from Lookout Pt outcrop
LOOKOUT PT MEASURED SECTION (Runkel 1994, Runkel et al, 2007)
5M
photo, Fig. 22
Lookout Pt outcrop gamma log
VF F M C
PARASEQUENCE
Shoreface, fine-to coarse-grained quartzose sandstone (coarse clastic)
Offshore, very fine grained, feldspathic sandstone, siltstone, shale (fine clastic)
Offshore sandy dolostone (carbonate)
Intraclasts

Fig 19

Lookout Point, south face

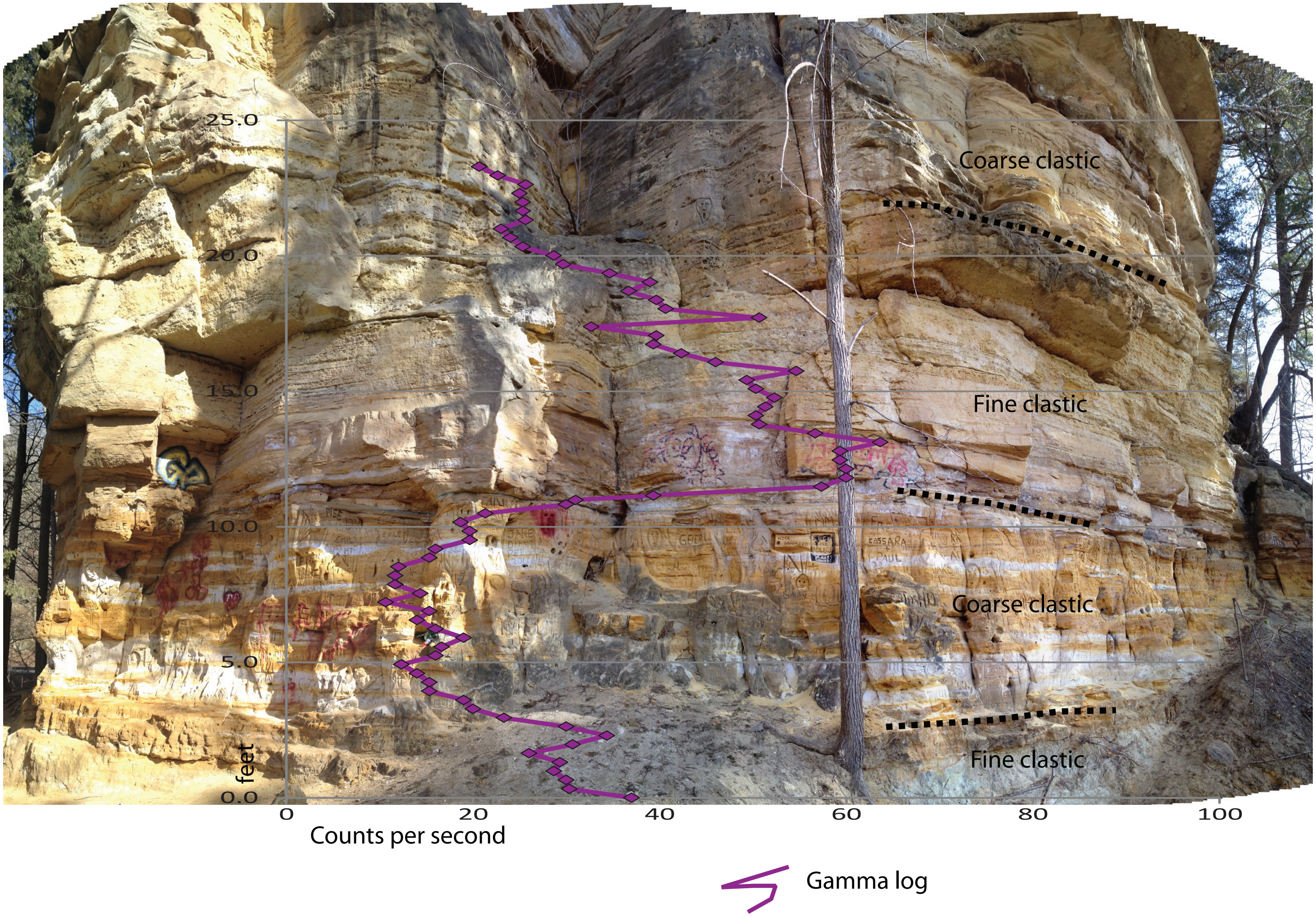


Fig 20

Lookout Point south outcrop face

Fig 21

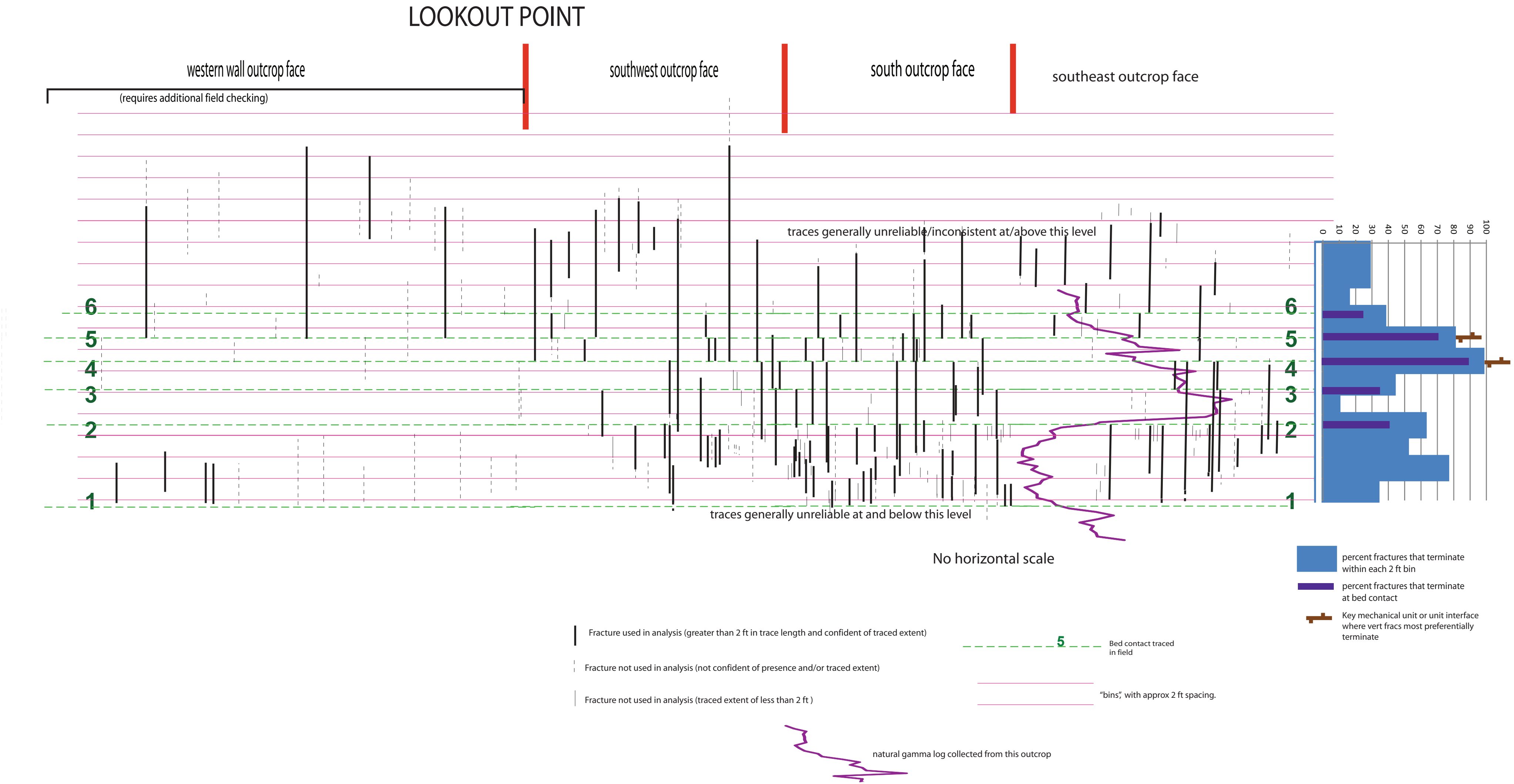

LOOKOUT POINT
western wall outcrop face
(requires additional field checking)
southwest outcrop face
south outcrop face
southeast outcrop face
traces generally unreliable/inconsistent at/above this level
traces generally unreliable at and below this level
6
5
4
3
2
1
0
10
20
30
40
50
60
70
80
90
100
No horizontal scale
percent fractures that terminate within each 2 ft bin
percent fractures that terminate at bed contact
Key mechanical unit or unit interface where vert fracs most preferentially terminate
Fracture used in analysis (greater than 2 ft in trace length and confident of traced extent)
Fracture not used in analysis (not confident of presence and/or traced extent)
Fracture not used in analysis (traced extent of less than 2 ft )
5
Bed contact traced in field
"bins", with approx 2 ft spacing.
natural gamma log collected from this outcrop

Fig 22

Fairy Glen

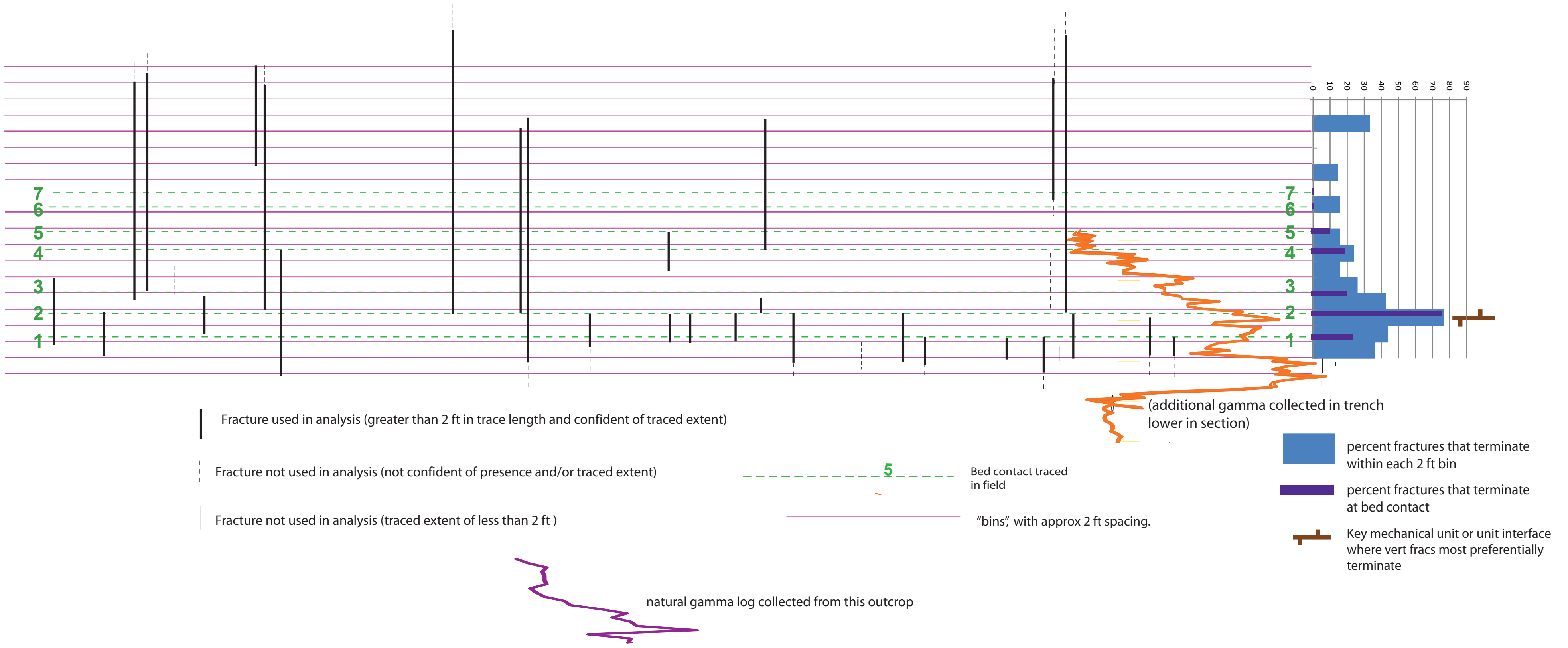


Fig 23

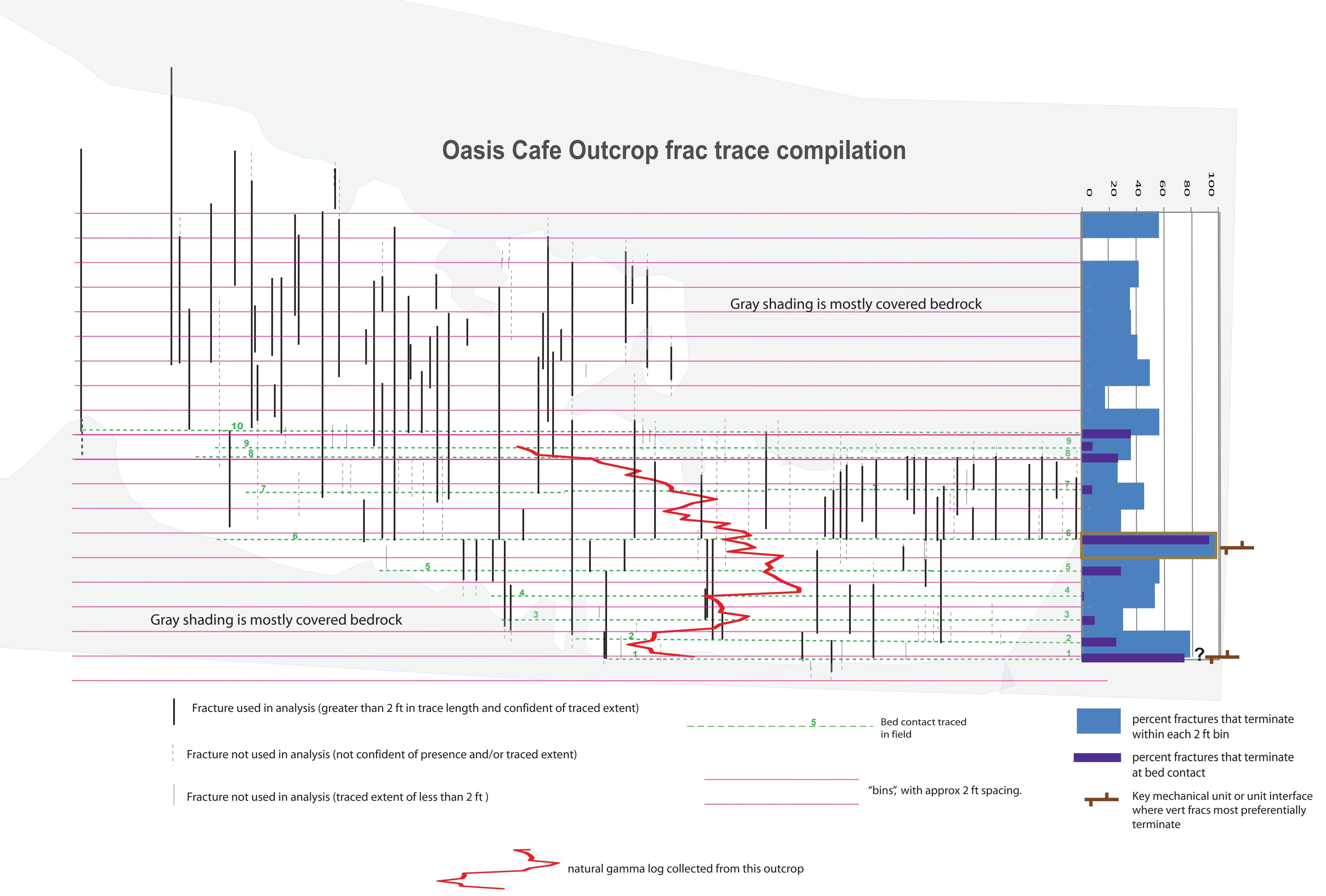

Oasis Cafe Outcrop frac trace compilation
0
20
40
60
80
100
Gray shading is mostly covered bedrock
Gray shading is mostly covered bedrock
10
9
8
7
6
5
4
3
2
1
?
Fracture used in analysis (greater than 2 ft in trace length and confident of traced extent)
Fracture not used in analysis (not confident of presence and/or traced extent)
Fracture not used in analysis (traced extent of less than 2 ft )
5
Bed contact traced in field
"bins", with approx 2 ft spacing.
percent fractures that terminate within each 2 ft bin
percent fractures that terminate at bed contact
Key mechanical unit or unit interface where vert fracs most preferentially terminate
natural gamma log collected from this outcrop

Fig 24

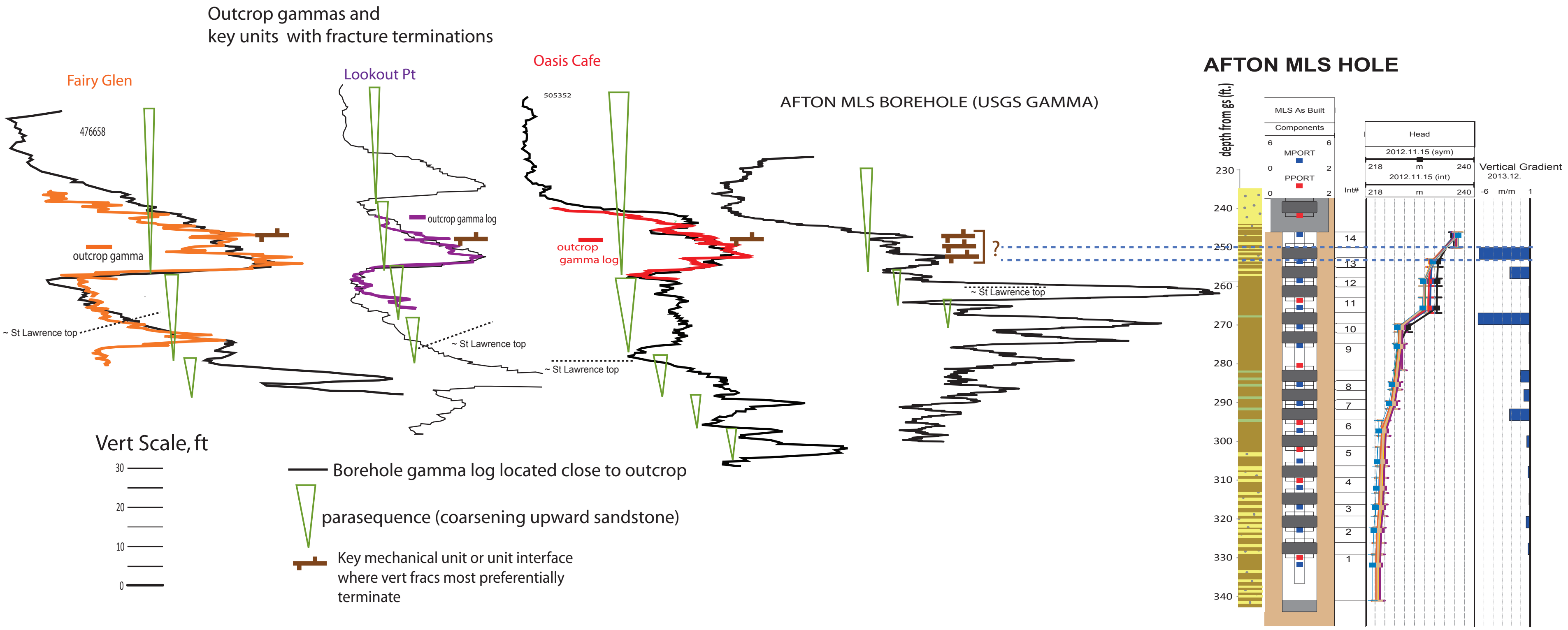

Outcrop gammas and
key units with fracture terminations
Fairy Glen
476658
outcrop gamma
~ St Lawrence top
Lookout Pt
outcrop gamma log
~ St Lawrence top
Oasis Cafe
505352
outcrop
gamma log
~ St Lawrence top
AFTON MLS BOREHOLE (USGS GAMMA)
?
~ St Lawrence top
AFTON MLS HOLE
depth from gs (ft.)
230
240
250
260
270
280
290
300
310
320
330
340
MLS As Built
Components
6
6
MPORT
0
2
PPORT
0
2
Int#
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Head
2012.11.15 (sym)
218
m
240
2012.11.15 (int)
218
m
240
Vertical Gradient
2013.12.
-6
m/m
1
Vert Scale, ft
30
20
10
0
Borehole gamma log located close to outcrop
parasequence (coarsening upward sandstone)
Key mechanical unit or unit interface
where vert fracs most preferentially
terminate

Fig 25

Afton MLS hole gamma and cuttings
Jordan Sandstone and upper St Lawrence Formation

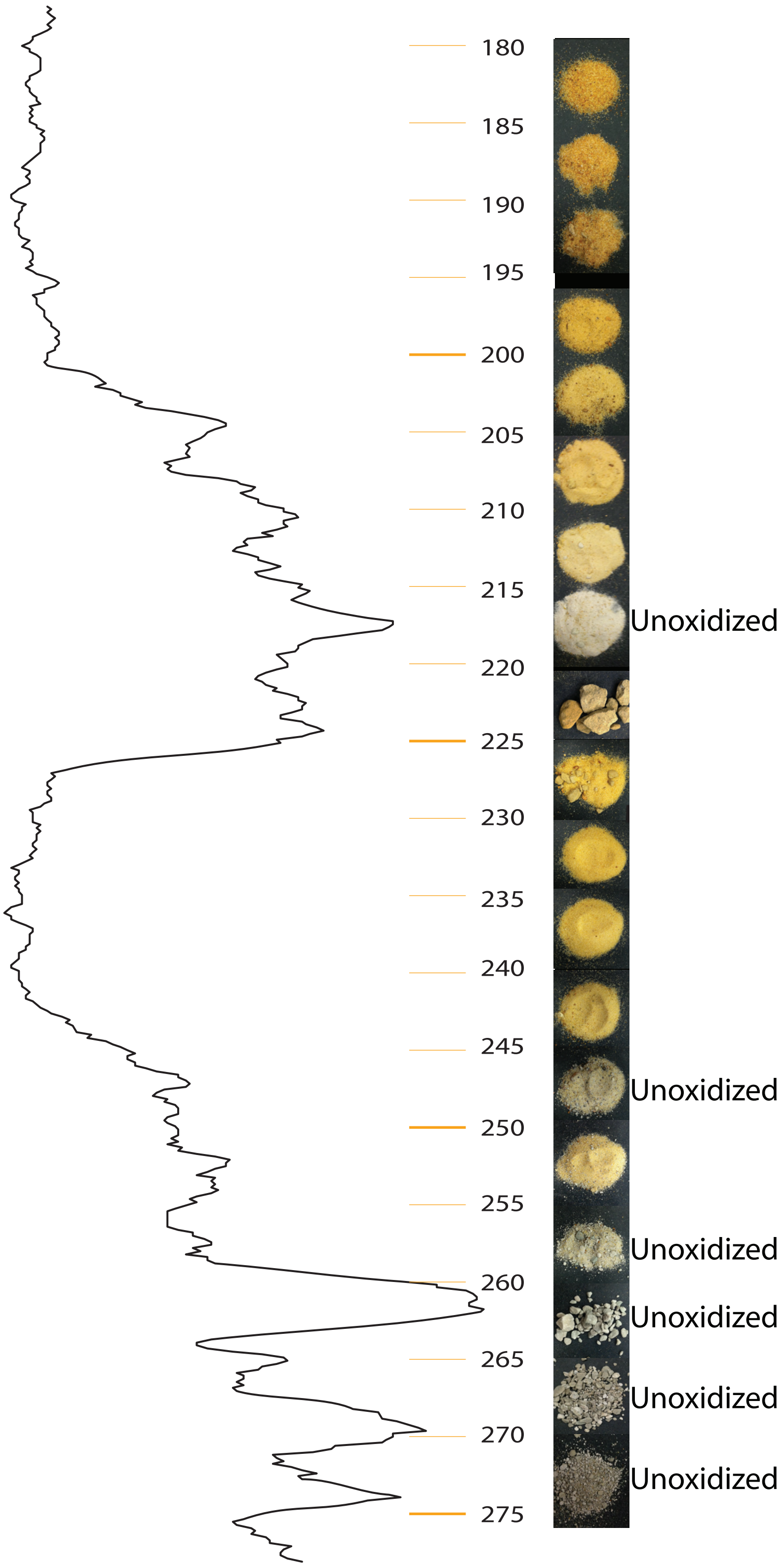


Fig 26

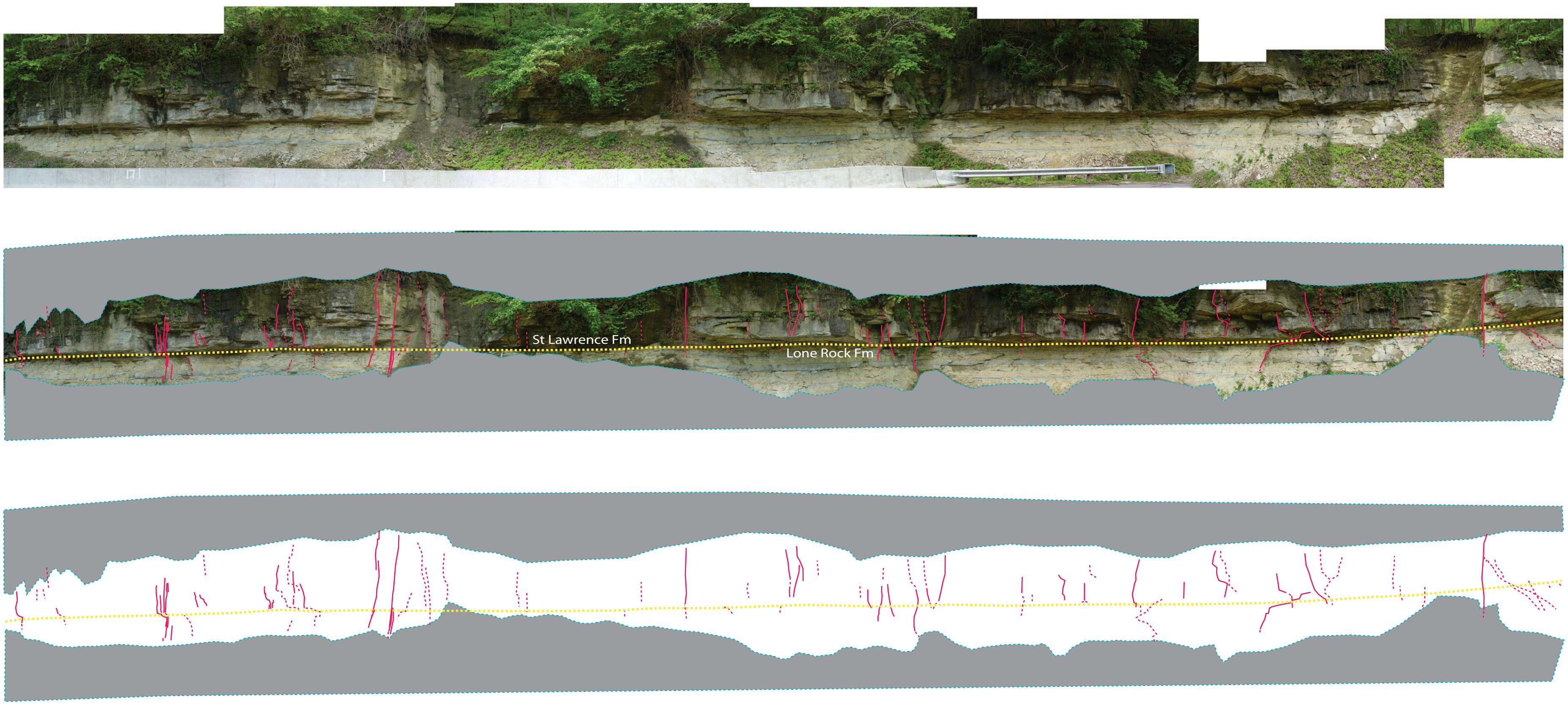


Fig 27

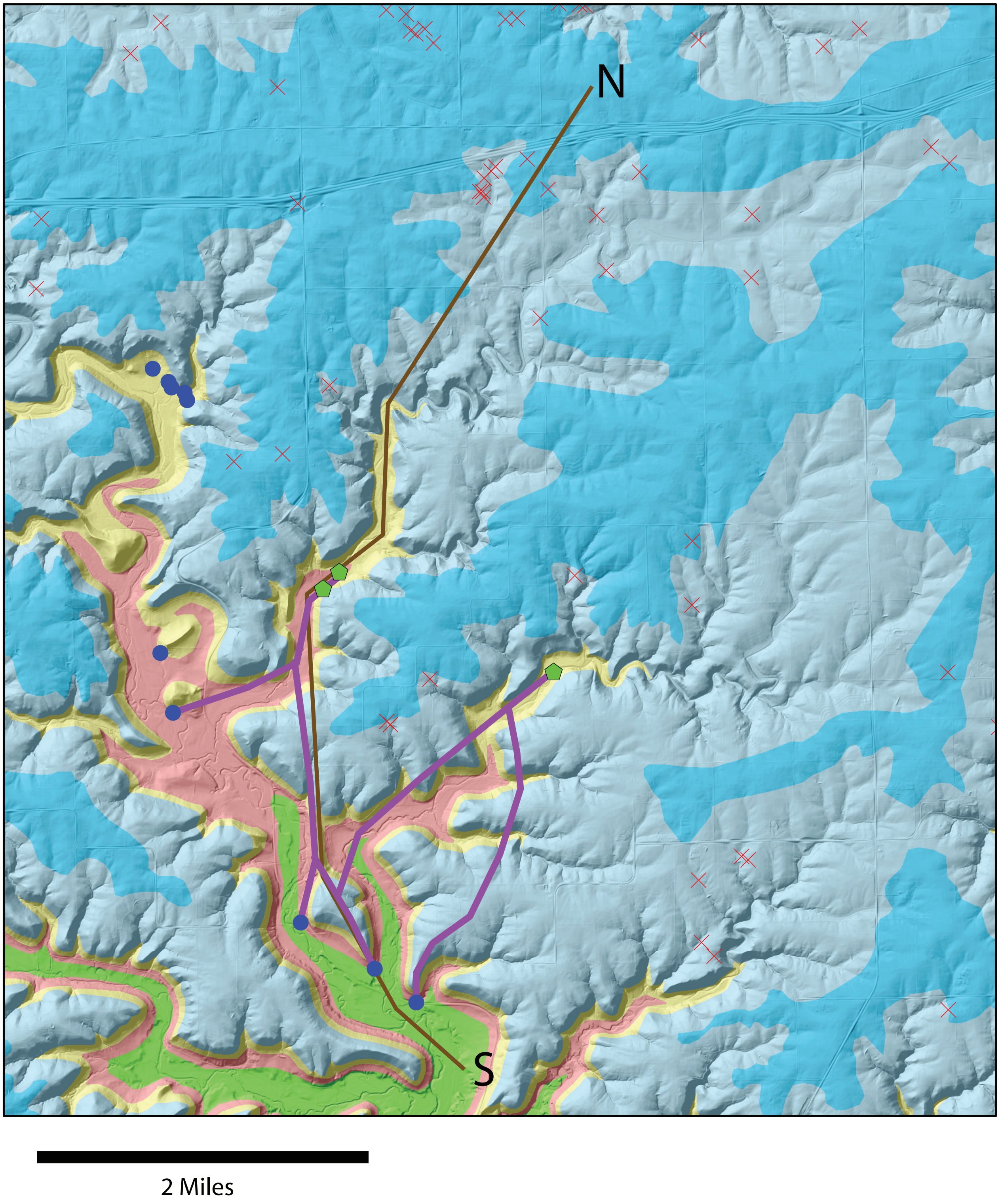

N
S
2 Miles
Legend
Dye vector
Dye input points
Spring
Sinkhole
Cross Section
Bedrock Geology
Shakopee Formation (Ops)
Oneota Dolomite (Opo)
Jordan Sandstone (Cj)
St. Lawrence Formation (Cs)
Tunnel City Group (Ctc)

Figure 28

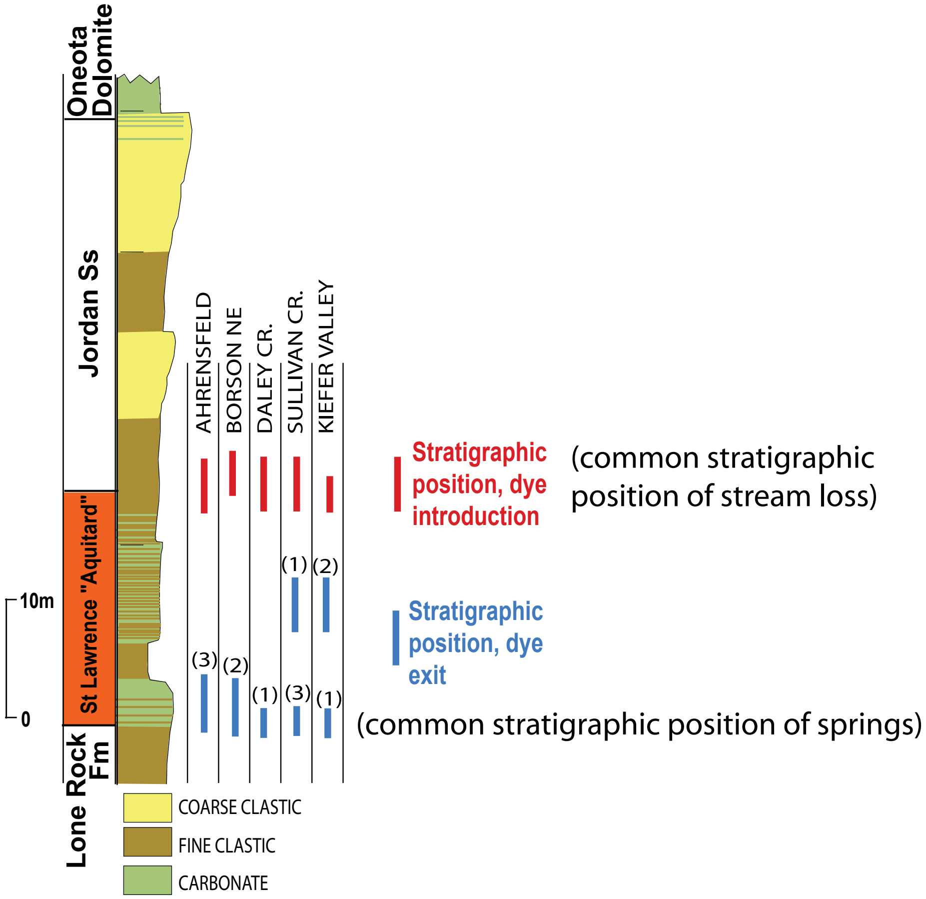

Oneota Dolomite
Jordan Ss
St Lawrence "Aquitard"
Lone Rock Fm
10m
0
AHRENSFELD
BORSON NE
DALEY CR.
SULLIVAN CR.
KIEFER VALLEY
(3)
(2)
(1)
(3)
(1)
(1)
(2)
Stratigraphic position, dye introduction
(common stratigraphic position of stream loss)
Stratigraphic position, dye exit
(common stratigraphic position of springs)
COARSE CLASTIC
FINE CLASTIC
CARBONATE

Fig 29

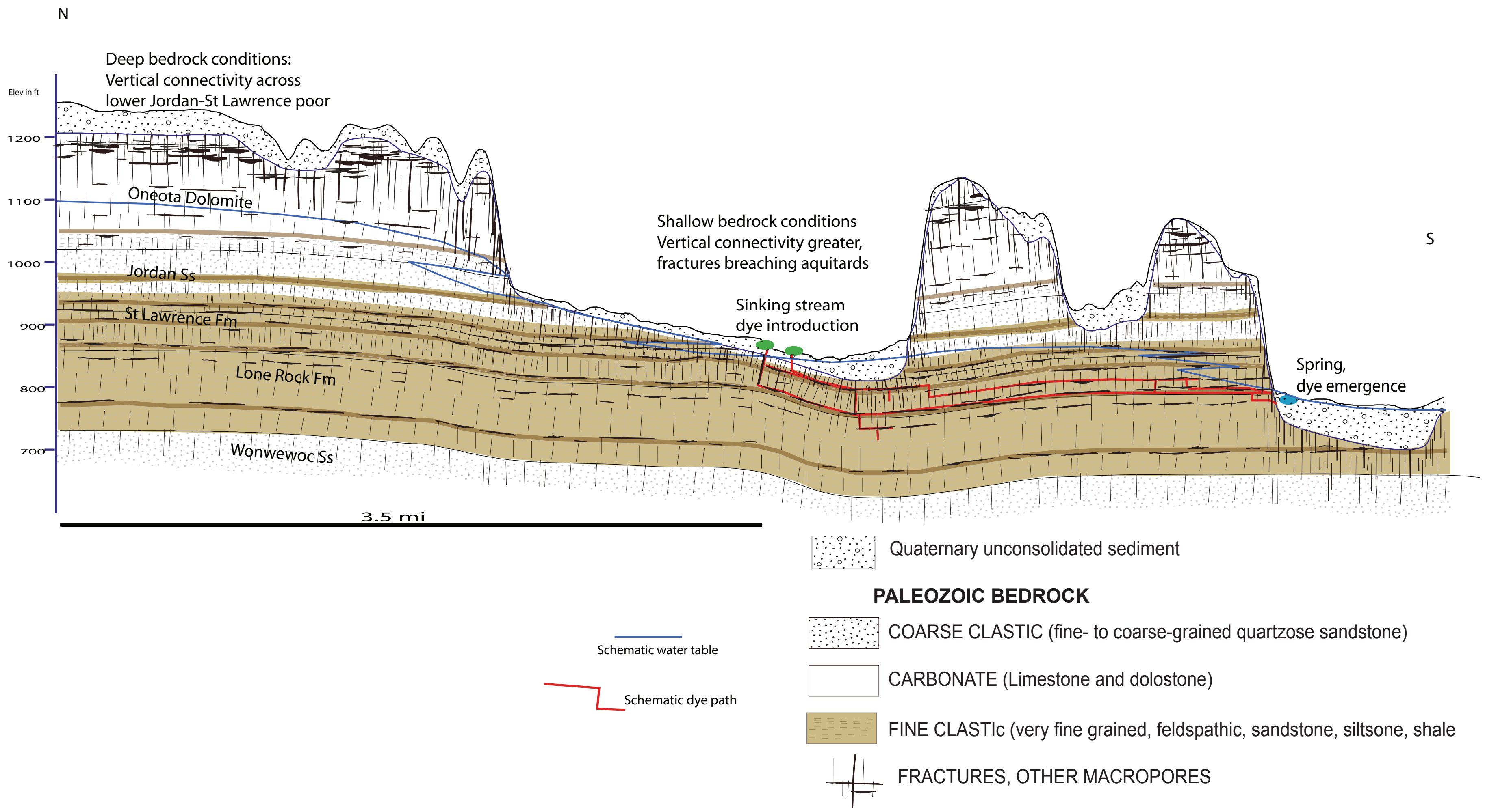

N
Deep bedrock conditions:
Vertical connectivity across lower Jordan-St Lawrence poor
Elev in ft
1200
1100
1000
900
800
700
Oneota Dolomite
Jordan Ss
St Lawrence Fm
Lone Rock Fm
Wonwewoc Ss
3.5 mi
Shallow bedrock conditions
Vertical connectivity greater, fractures breaching aquitards
Sinking stream dye introduction
S
Spring, dye emergence
Quaternary unconsolidated sediment
PALEOZOIC BEDROCK
COARSE CLASTIC (fine- to coarse-grained quartzose sandstone)
CARBONATE (Limestone and dolostone)
FINE CLASTIc (very fine grained, feldspathic, sandstone, siltsone, shale
FRACTURES, OTHER MACROPORES
Schematic water table
Schematic dye path

Figure30

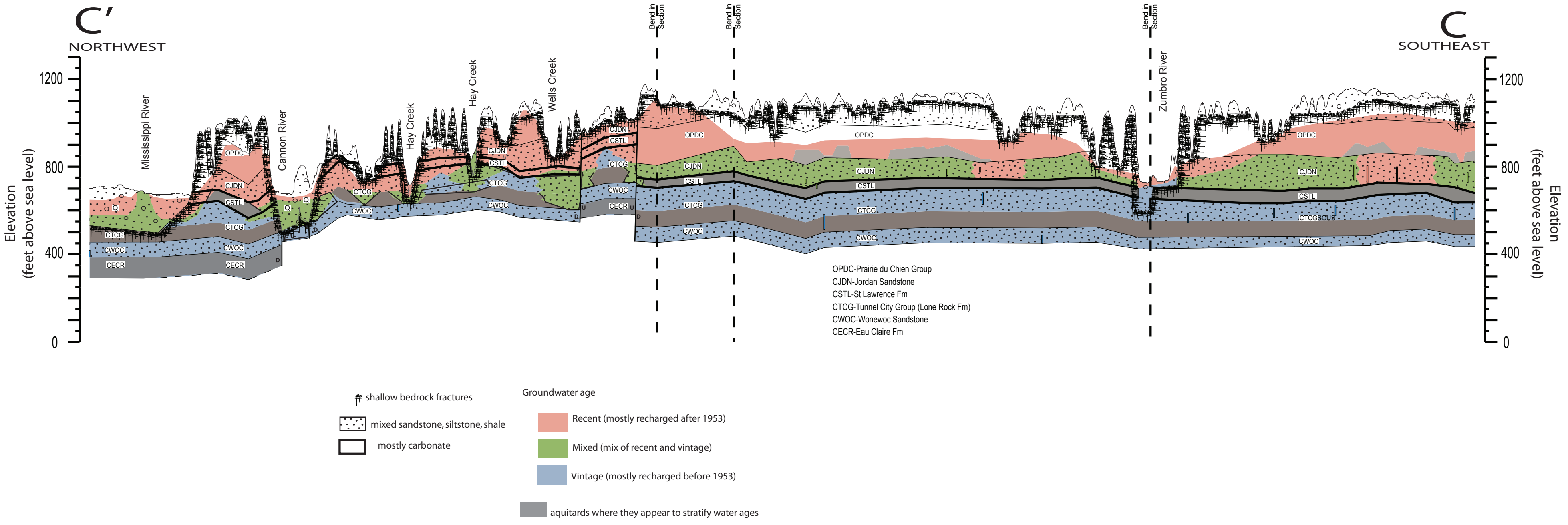

C'
NORTHWEST
C
SOUTHEAST
Elevation
(feet above sea level)
1200
800
400
0
Mississippi River
Cannon River
Hay Creek
Hay Creek
Wells Creek
Bend in Section
Bend in Section
Bend in Section
Zumbro River
Q
OPDC
CJDN
CSTL
CTCG
CWOC
CECR
CTCGSOUS
U
D
OPDC-Prairie du Chien Group
CJDN-Jordan Sandstone
CSTL-St Lawrence Fm
CTCG-Tunnel City Group (Lone Rock Fm)
CWOC-Wonewoc Sandstone
CECR-Eau Claire Fm
shallow bedrock fractures
mixed sandstone, siltstone, shale
mostly carbonate
Groundwater age
Recent (mostly recharged after 1953)
Mixed (mix of recent and vintage)
Vintage (mostly recharged before 1953)
aquitards where they appear to stratify water ages

Figure 31

# APPENDIX A SUMMARY US GEOLOGICAL SURVEY BOREHOLE GEOPHYSICS AND PACKER TESTING

U.S. Geological Survey (USGS)

Minnesota District

Quarterly Project Progress Report

Quarter ending 31 December, 2012

January 25, 2013

Project Name: Characterization of the Hydrogeologic Properties and Groundwater-Flow Conditions in the St. Lawrence Formation

Project Number: 8607EAM Begin Date: July 2010 End Date: September 2013

Project Chief: Perry M. Jones

Cooperator: Minnesota Geological Survey (MGS)

## Objective

To characterize the hydrogeologic properties and groundwater-flow conditions of the St. Lawrence Formation

## Progress During FY11

The project chief and USGS hydrologists worked with a geophysicist from the USGS Branch of Geophysics to analyze and archive data collected during borehole geophysical surveys in a borehole and a monitoring well at Afton State Park near Afton, Minnesota. The following geophysical logs were collected in the borehole and the monitoring well: 1) natural gamma, 2) electromagnetic induction, 3) optical televiewer, and 4) acoustic televiewer (See attached geophysical logs). Electromagnetic flow meter, fluid conductivity, and fluid temperature logs were conducted under ambient and stressed (pumped) conditions in the borehole, while heat-pulse flow meter, fluid conductivity, and fluid temperature logs were collected under ambient and stressed (pumped) conditions in the monitoring well.

The project chief and a hydrologist worked with hydrologists from the USGS Wisconsin Water Science Center to analyze data collected during packer tests in the borehole at Afton State Park near Afton, Minnesota. Static water levels were measured (table 1) and slug tests were conducted in five isolated intervals in the borehole. Hydraulic conductivity values were determined from water-level data collected from the 8 slug tests (table 2) Following completion of the packer tests on September 9, the packers were left in the borehole until October 29, when they were removed to install a multiport monitoring system. USGS Log Archiver System entry forms for the borehole geophysical surveys conducted in the borehole and monitoring well were completed.

On October 29, the project chief and hydrologists from the USGS Wisconsin Water Science Center (WWSC) (Jim Rauman and Jason Smith) conducted a slug test in a packed-off interval within the borehole and pulled the packers from the borehole.

## Problems

None.

## Plans for Next Reporting Period

The project chief will work with a MGS geologist and a MGS hydrogeologist to summarize results from the borehole geophysical surveys and packer tests in a MGS/USGS report or journal article. Figures, tables, and text will be developed for the report. A hydrologic technician will complete archiving the collected geophysical logs into the USGS Log Archiver System (http://logarchiver.usgs.gov/).

## Significant Results Since Last Reporting Period

Results from the geophysical logs did not indicated flow in the St. Lawrence Formation in the borehole or the monitoring well, but ambient vertical flow occurred in the open portion of the borehole from the Jordan Sandstone downward to the Tunnel City Formation (See Borehole Geophysical Log for USGS site 445218092470101 and USGS site 445219092465801). The televiewer logs indicated only three low-angled fractures or bedding planes and one steep fracture in the St. Lawrence Formation in the borehole. No fractures were identified in the televiewer logs in the monitoring well. The electromagnetic flow meter log indicated an ambient vertical downward flow of approximately 60 gpm from the Jordan Sandstone to the Tunnel City Formation. Little change in ambient vertical flow occurred in the borehole when water in the borehole was pumped at a rate of 1.6 gpm. No ambient flow was measured in the St. Lawrence Formation in the monitoring well. An upward vertical flow of approximately 0.85 gpm was measured in the monitoring well when the well was pumped at a flow rate of 0.7 gpm. Water was flowing out of the lower part of the St. Lawrence and upper part of the Tunnel City Formation during this pumping. Only minor changes were measured in the fluid conductivity and temperature under ambient and stress conditions in the borehole and the well.

Static water levels in the packed-off intervals across the St. Lawrence Formation in the borehole ranged from 721.61 to 724.87 feet above NGVD29 datum (table 1), with water levels decreasing from the Jordan Sandstone to 281 feet below the land surface in the St. Lawrence formation. Between 281 and 302 feet, the static water levels rose approximately 1.2 foot with depth in the packed-off intervals. Water levels in the open borehole above the packers decreased with depth. A 10-foot drop in water level in the open borehole above the packers occurred between 271 and 281 feet below the land surface, potentially indicating a point of outflow from the borehole between those depths. The decreasing trend in water levels with depth in the open borehole above the packers correlates with the downward flow of water from the Jordan Sandstone to the Tunnel City Formation measured in the open borehole.

Water levels measured during eight slug tests conducted between packed-off intervals within the Jordan Sandstone, St. Lawrence Formation, and Tunnel City formation were analyzed to produce hydraulic conductivity estimates (table 2). Estimates for the lower 13 feet of the Jordan Sandstone were 7.2 and 10.9 feet/day, while estimates for the St. Lawrence Formation ranged from 2.0 to 22 feet/day. The highest values in the formation occurred between 271 and 281 feet below the land surface, where the 10-foot decrease in water level above the packers occurred. Estimates for the lower 4 feet of the St. Lawrence Formation and upper 6 feet of the Tunnel City Formation were 30.0 and 32.1 feet/day.

## Other Activities

None.

## Supervisor's Comments

## References

Bouwer, H. and R.C. Rice, 1976. A slug test method for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, Water Resources Research, vol. 12, no. 3, pp. 423-428.

Table 1. Static water levels in 5 packed-off intervals in a borehole (USGS site 445218092470101), Afton, Minnesota.

[ --, no data, values in parentheses are in feet below land surface]

| Packer Interval Number | Date | Time | Open Interval Between Packers (feet below land surface) | Geologic Unit | Static Water Levels (feet above NGVD29 datum) | | |
|---|---|---|---|---|---|---|---|
| | | | | | Above Open Interval Between Packers | In Open Interval Between Packers | Below Open Interval Between Packers |
| 1 | 9/4/2012 | 21:30 | 245 - 258 | Jordan Sandstone | 773.87 (196.13) | 728.14 (241.86) | -- |
| 2 | 9/6/2012 | 11:22 | 261 - 271 | St. Lawrence Formation | 774.01 (195.99) | 724.87 (245.13) | 731.31 (238.69) |
| 3 | 9/6/2012 | 16:45 | 271 - 281 | St. Lawrence Formation | 769.92 (200.08) | 721.61 (248.39) | 735.59 (234.41) |
| 4 | 9/7/2012 | 4:31 | 281 - 291 | St. Lawrence Formation | 759.77 (210.23) | 722.37 (247.63) | 739.26 (230.74) |
| 5 | 9/9/2012 | 8:37 | 292 - 302 | St. Lawrence Formation/Tunnel City Formation | 759.06 (210.94) | 722.8 (247.20) | 726.48 (243.52) |

Table 2. Hydraulic conductivity values determined from slug tests conducted in packed-off intervals in a borehole (USGS site 445218092470101), Afton, Minnesota.

| Slug Test Number | Date | Time | Open Interval Between Packers (feet below land surface) | Geologic Unit | Hydraulic Conductivity (ft/day)[1] |
|---|---|---|---|---|---|
| 1 | 9/4/2012 | 21:30 | 245 - 258.3 | Jordan Sandstone | 10.9 |
| 2 | 9/5/2012 | 8:46 | 245 - 258.3 | Jordan Sandstone | 7.2 |
| 3 | 9/6/2012 | 11:22 | 261 - 271 | St. Lawrence Formation | 2.4 |
| 4 | 9/6/2012 | 11:44 | 261 - 271 | St. Lawrence Formation | 5.5 |
| 5 | 9/6/2012 | 16:45 | 271 - 281 | St. Lawrence Formation | 22.0 |
| 6 | 9/7/2012 | 4:31 | 281 - 291 | St. Lawrence Formation | 2.0 |
| 7 | 9/9/2012 | 8:37 | 292 - 302 | St. Lawrence Formation/Tunnel City Formation | 30.0 |
| 8 | 10/29/2012 | 14:30 | 292 - 302 | St. Lawrence Formation/Tunnel City Formation | 32.1 |

[1] values determined using the Bouwer-Rice method (1976)

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# BOREHOLE GEOPHYSICAL LOG

**English/Metric units** E

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **SiteID (C1)** | 445218092470101 | **Station name (C12)** | Afton 028N20W34ADACBA01 0000792096 | **Other ID** | MGS-STL | **Log date** | 08/28/2012 |

**County** Washington | **State** MN | **Project** NQ00EAM00 | **Recorded by** PMJ,JB | **Observed by** JAA

**Location description** Northern part of Afton State Park | **Owner** Minnesota Dept. of Natural Resources

**Latitude** 44 52 19.4 | **Longitude** 092 47 00.0 | **Lat/Long datum** NAD83 | **Log measurement point (LMP)** LS

**Height LMP** 0.0 | **Altitude LMP** 974 | **Altitude datum** NGVD88 | **Description of LMP** Land surface

**Borehole depth** 345 | **Borehole diameter** 6 | **Casing bottom** 245 | **Casing diameter** 6 | **Casing type** steel

**Source of data** USGS-MGS | **Logging unit** USGS-MGS | **Log orientiation** MN | **Magnetic declination**

**Software non-ASCII logs** Century Display, Matrix | **Fluid type** Water | **Fluid depth below LMP** 231.78 **at time** 14:23

**Hydrologic conditions** Ambient, pump 1.6 gal/min start pump at 14:34 stop at 15:55. Drawdown=0.21ft | **Type of log** ZZ

**Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check**

**Tool run 1** Acoustic televiewer-dev, 8/28-10:43, Mount Sopris - ABI40, SN#020906, log up, depth error=0.15ft, acoustic image and wellbore deviation in deg-in hole cal check.

**Tool run 2** Optic televiewer-dev, 8/28-11:40, Mount Sopris - OBI40, SN#073612, log up, depth error=1.90ft, optical image and wellbore deviation in deg-in hole cal check. depth corrected in Wellcad

**Tool run 3** EM flowmeter-fluid, 8/28-amb troll 13:03 stationary 13:45-pmp troll 15:47 stationary 15:00, depth error=0, fluid temp in Deg F -fluid res in ohm-m-wellbore flow in gal/min, in hole cal check.

**Tool run 4** EM induction-gamma, 8-30-16:45, log up, depth error=0.11ft, formation conductivity in mmho/m- gamma in CPS, cal check at surface.

**Tool run 5** Hydraulic head data collected using single and straddle packers collected by USGS on 9/4/12.

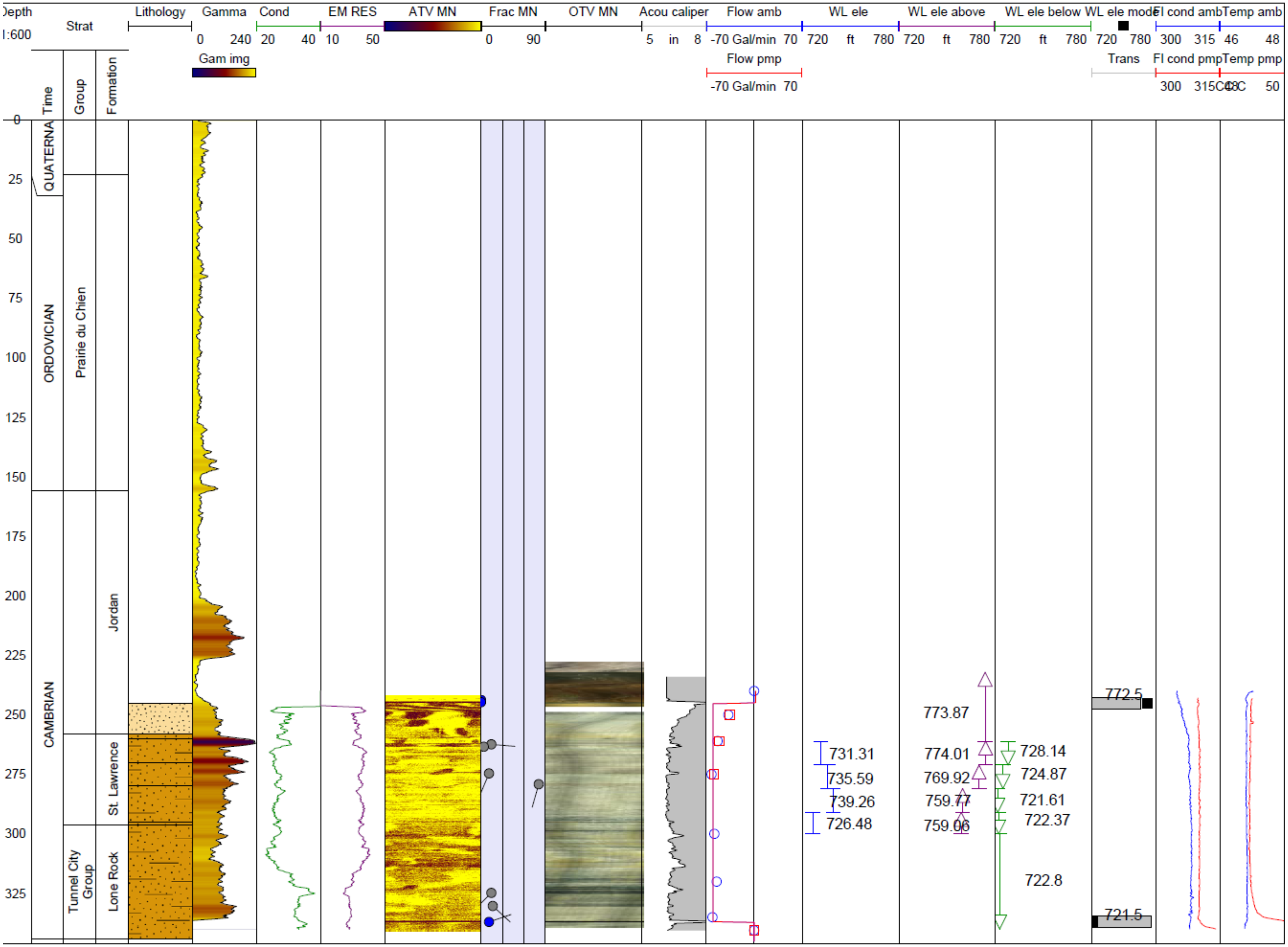
**Tool run 6**

**Tool run 7**

**Tool run 8**

**Tool run 9**

**Remarks** Casing stickup =2.5ft ALS. EM res log Calculated from Cond log, Fl cond logs Calculated from Fl res logs. Strat and litho logs from MGS. WL ele = water level elevation between packers- WL ele above = water level elevation above packers- WL ele below -= water level elevation below packers.



Depth
1:600
Strat
Time
Group
Formation
Lithology
Gamma
0 240
Gam img
Cond
20 40
EM RES
10 50
ATV MN
Frac MN
0 90
OTV MN
Acou caliper
5 in 8
Flow amb
-70 Gal/min 70
Flow pmp
-70 Gal/min 70
WL ele
720 ft 780
WL ele above
720 ft 780
WL ele below
720 ft 780
WL ele mode
720 780
Trans
Fl cond amb
300 315
Fl cond pmp
300 315
Temp amb
46 48
Temp pmp
48 50
C C
0
25
50
75
100
125
150
175
200
225
250
275
300
325
QUATERNA
ORDOVICIAN
CAMBRIAN
Prairie du Chien
Jordan
St. Lawrence
Tunnel City Group
Lone Rock
731.31
735.59
739.26
726.48
773.87
774.01
769.92
759.77
759.06
728.14
724.87
721.61
722.37
722.8
772.5
721.5

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# BOREHOLE GEOPHYSICAL LOG

**English/Metric units** E

**SiteID (C1)** 445219092465801 | **Station name (C12)** 028N20W34ADA 01 000024459 | **Other ID** MDNR Obwell 82012 | **Log date** 8/29/2012

**County** Washington | **State** MN | **Project** NQ00EAM00 | **Recorded by** PMJ,JAB | **Observed by** JAA

**Location description** Northern part of Afton State Park | **Owner** Minnesota Dept. of Natural Resources

**Latitude** 42 52 19.5 | **Longitude** 092 47 00.0 | **Lat/Long datum** NAD83 | **Log measurement point (LMP)** LS

**Height LMP** 0.0 | **Altitude LMP** 970.81 | **Altitude datum** NGVD88 | **Description of LMP** Land surface

**Borehole depth** 306 | **Borehole diameter** 4.5 | **Casing bottom** 277 | **Casing diameter** 4.0 | **Casing type** steel

**Source of data** USGS-MGS | **Logging unit** USGS-MGS | **Log orientiation** MN | **Magnetic declination**

**Software non-ASCII logs** Century Display, Matrix | **Fluid type** Water | **Fluid depth below LMP** 231.40 **at time** 10:21

**Hydrologic conditions** ambient, pump 0.7 gal/min.  Start pump at 12:30-stop pump at 13:02, drawdown = 5.04 ft | **Type of log** ZZ

**Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check**

**Tool run 1** Acoustic televiewer, 09:16, Mount Sopris-ABI40, SN#020906, log up,depth error=0.1ft, acoustic image in deg and caliper in inches-wellbore deviation in deg, in hole cal check

**Tool run 2** Optical televiewer, 09:58, Mount Sopris-OBI40-MK4, SN#073612, log up,depth error=0.0ft, optical image and wellbore deviation in deg, in hole cal check

**Tool run 3** Electromagnetic flow-fluid,amb at 10:41- pmp at16:15, Century 9721, SN#1162, troll down 20ft/min, depth error amb =0.02-pmp=0.13, fluid temp in deg- F-res in ohm-m, cal check at surface.

**Tool run 4** Heatpulse flowmeter ,amb at 14:24- pmp at 15:32, Mount Sopris, SN#2060, stationary, wellbore flow in Gal/min, in hole cal check.

**Tool run 5** Electromagnetic induction-gamma,8/30/12-16:03, Century 9510, SN#756, log up, depth error 0.11, formation conductivity in MMHO/M-gamma in CPS,conductivity cal check at surface.

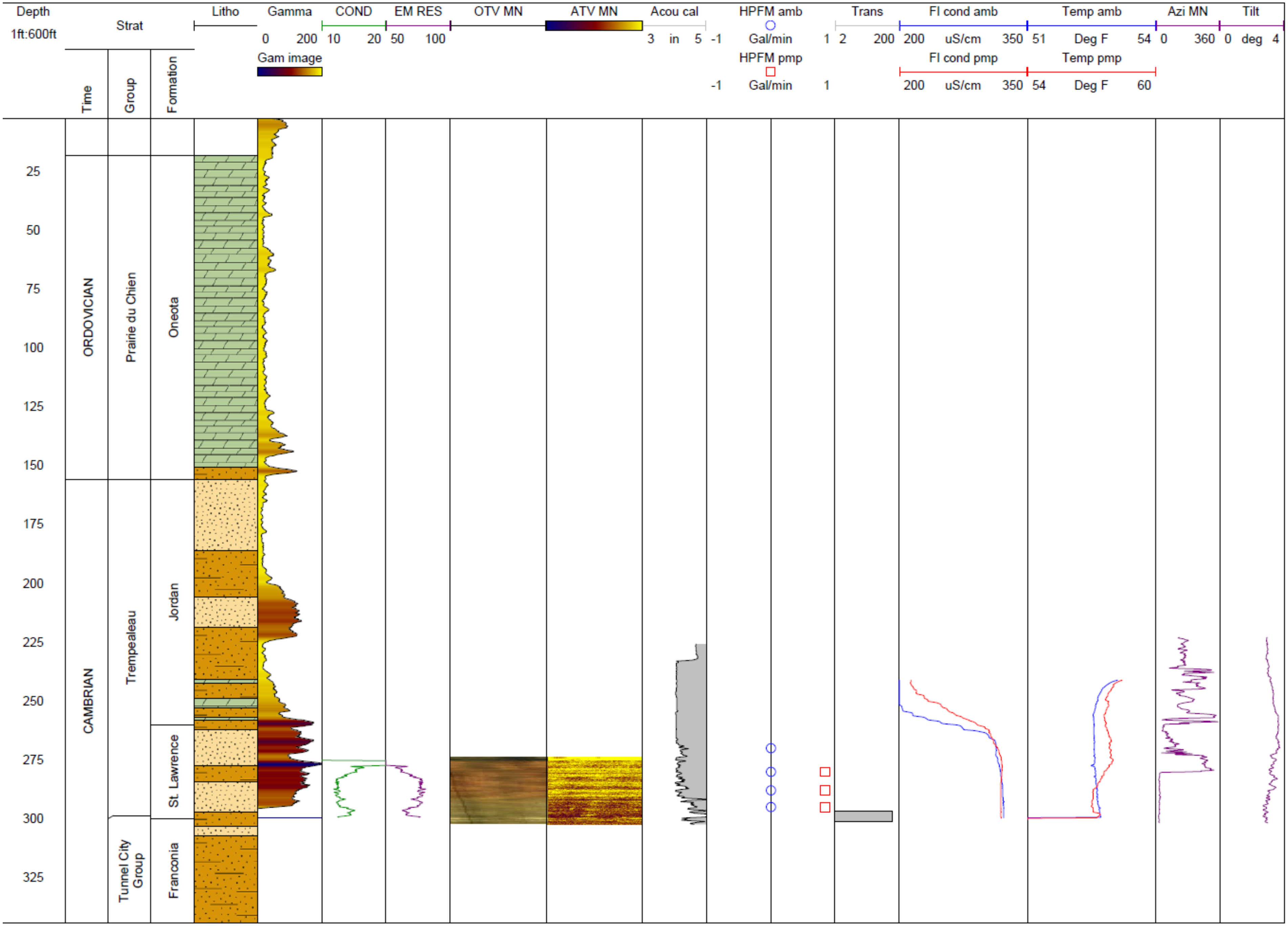
**Tool run 6**

**Tool run 7**

**Tool run 8**

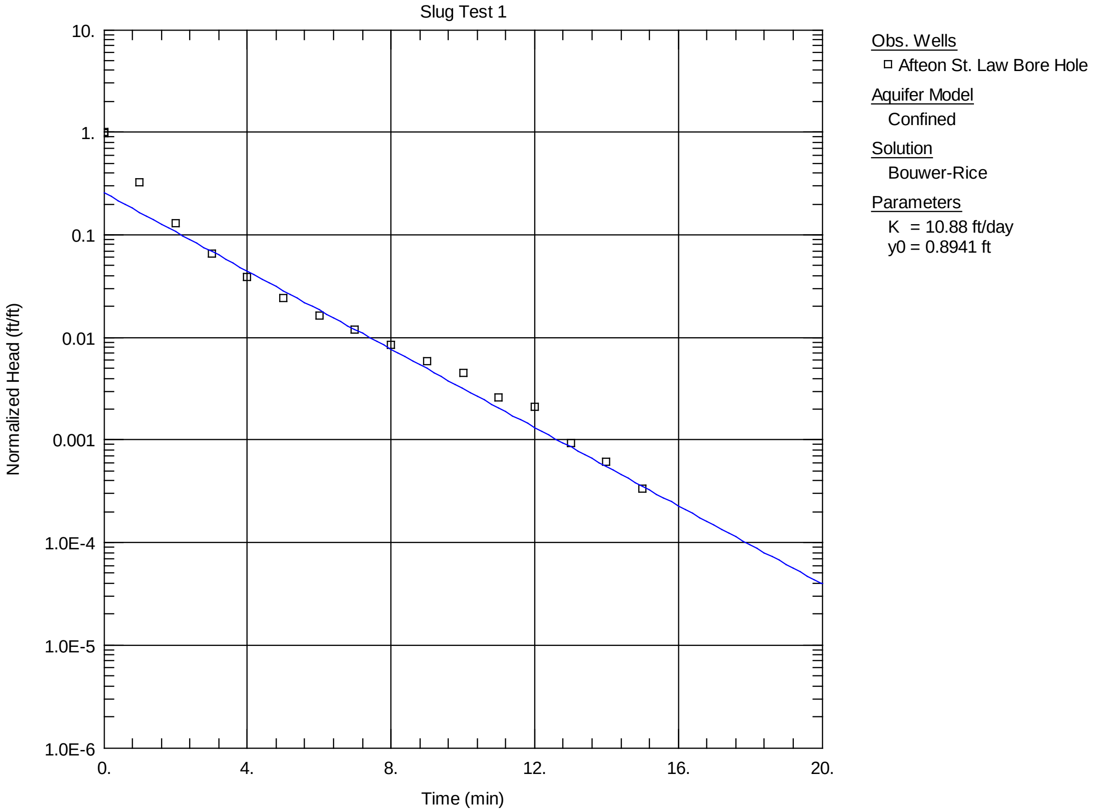
**Tool run 9**

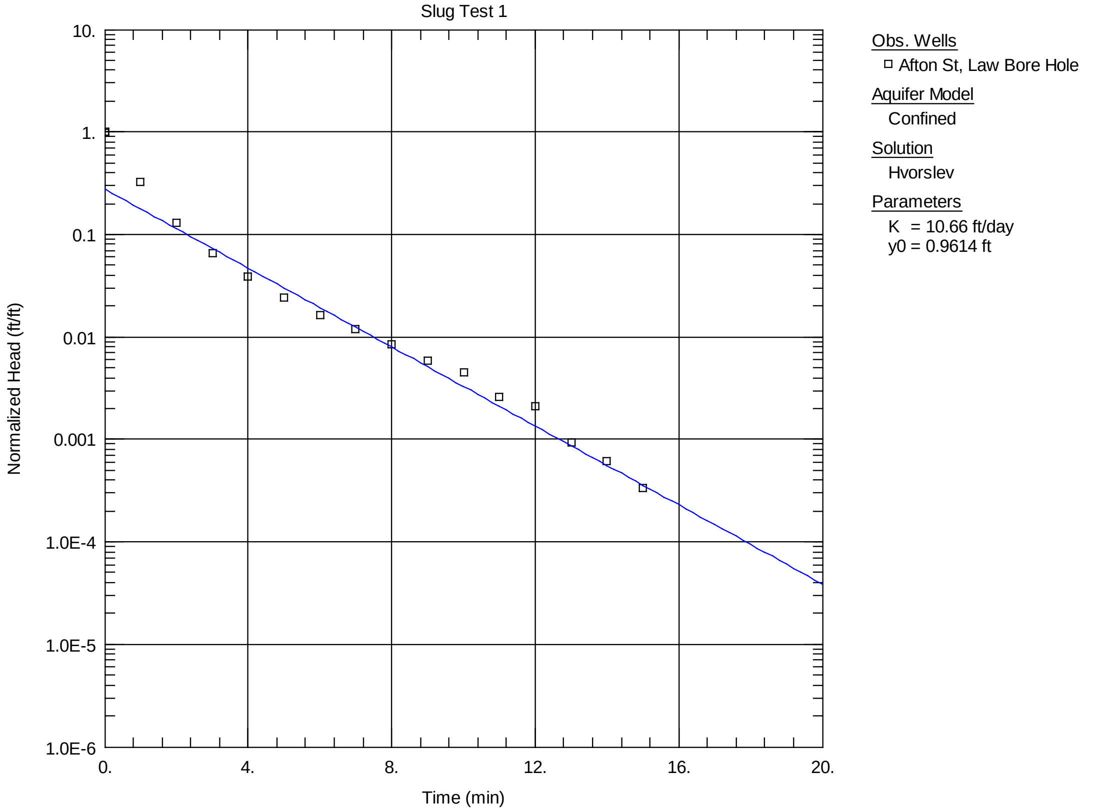
**Remarks** casing stickup= 1.0ft ALS.  EM res log derived from Cond log, Fl cond logs derived from Fl res logs.  Strat and litho logs from MGS


Depth
1ft:600ft
Strat
Time
Group
Formation
Litho
Gamma
0 200
Gam image
COND
10 20
EM RES
50 100
OTV MN
ATV MN
Acou cal
3 in 5
HPFM amb
-1 Gal/min 1
HPFM pmp
-1 Gal/min 1
Trans
2 200
Fl cond amb
200 uS/cm 350
Fl cond pmp
200 uS/cm 350
Temp amb
51 Deg F 54
Temp pmp
54 Deg F 60
Azi MN
0 360
Tilt
0 deg 4
25
50
75
100
125
150
175
200
225
250
275
300
325
ORDOVICIAN
CAMBRIAN
Prairie du Chien
Trempealeau
Tunnel City Group
Oneota
Jordan
St. Lawrence
Franconia

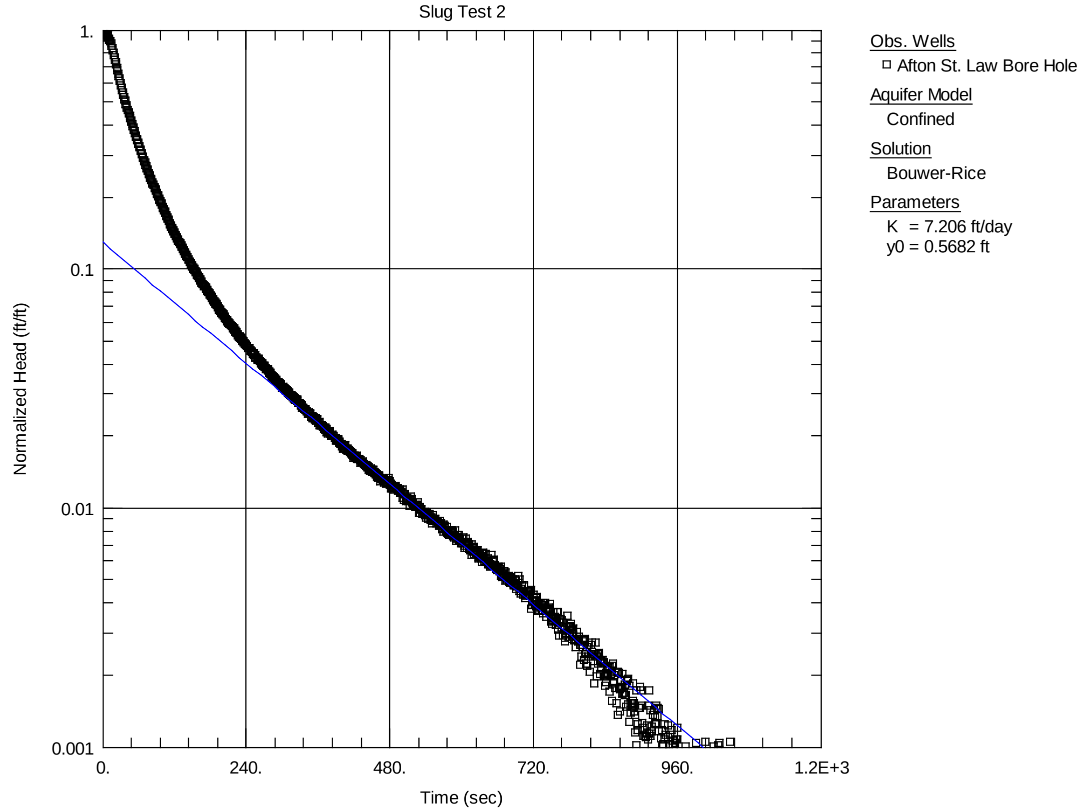
# SLUG TESTS, AFTON MLS HOLE, DATA FROM US GEOLOGICAL SURVEY

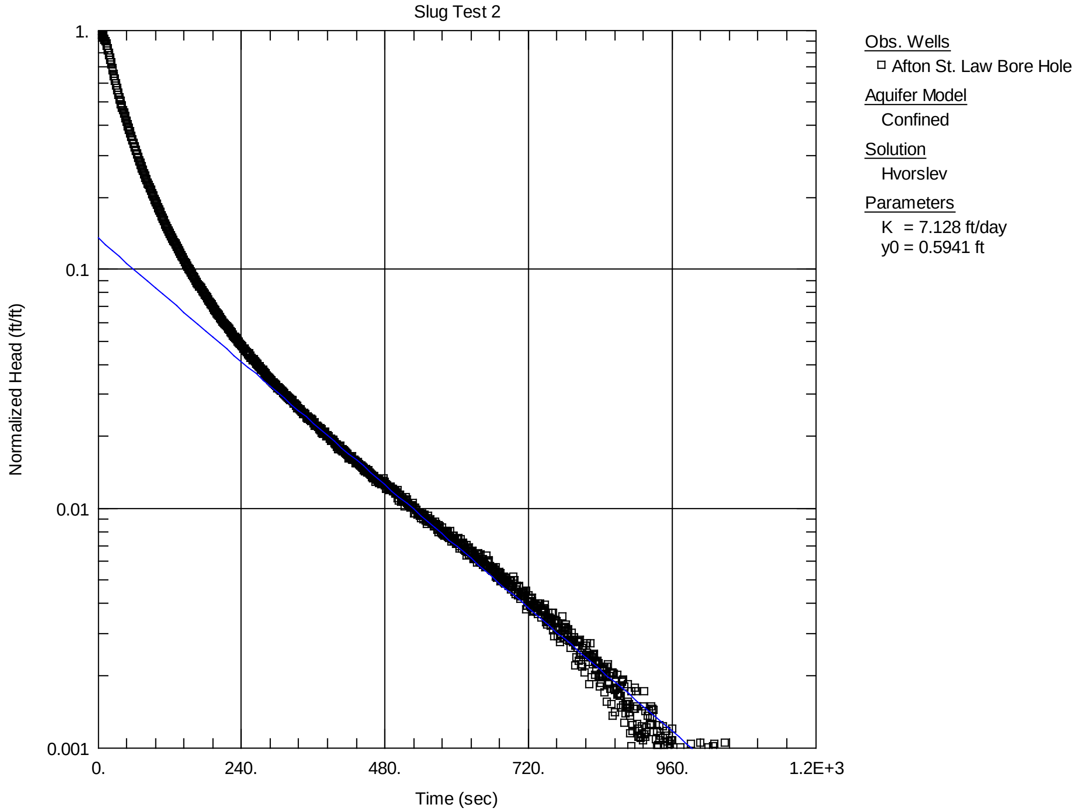
## Slug Test 1



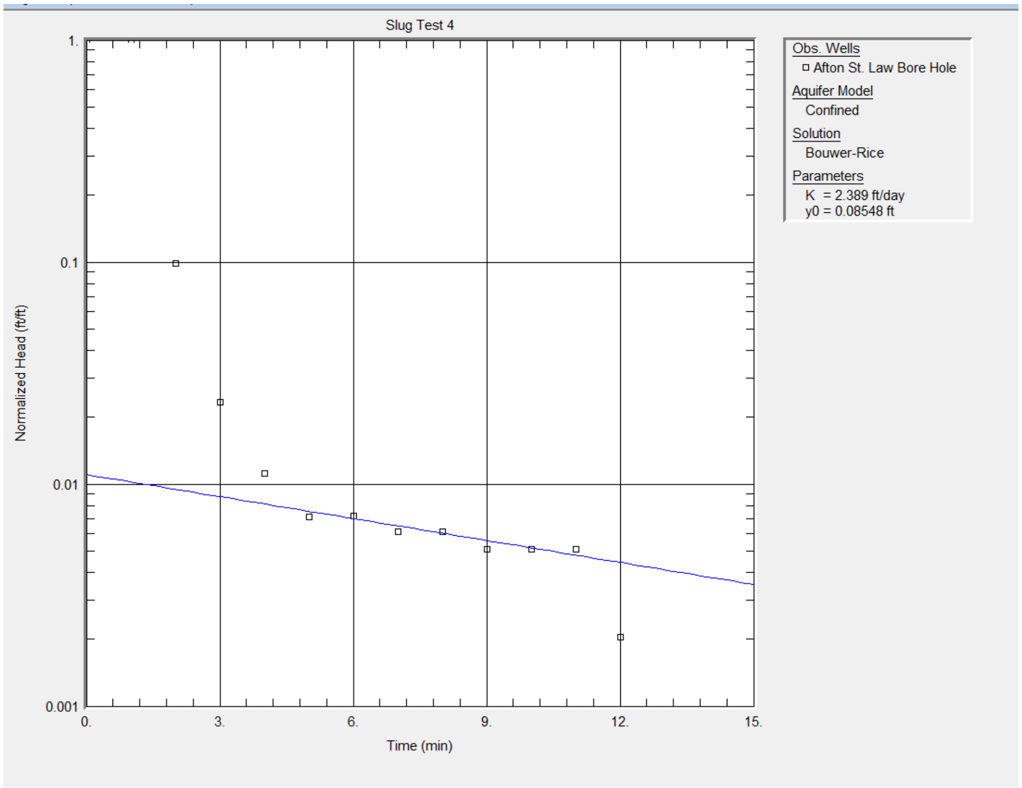


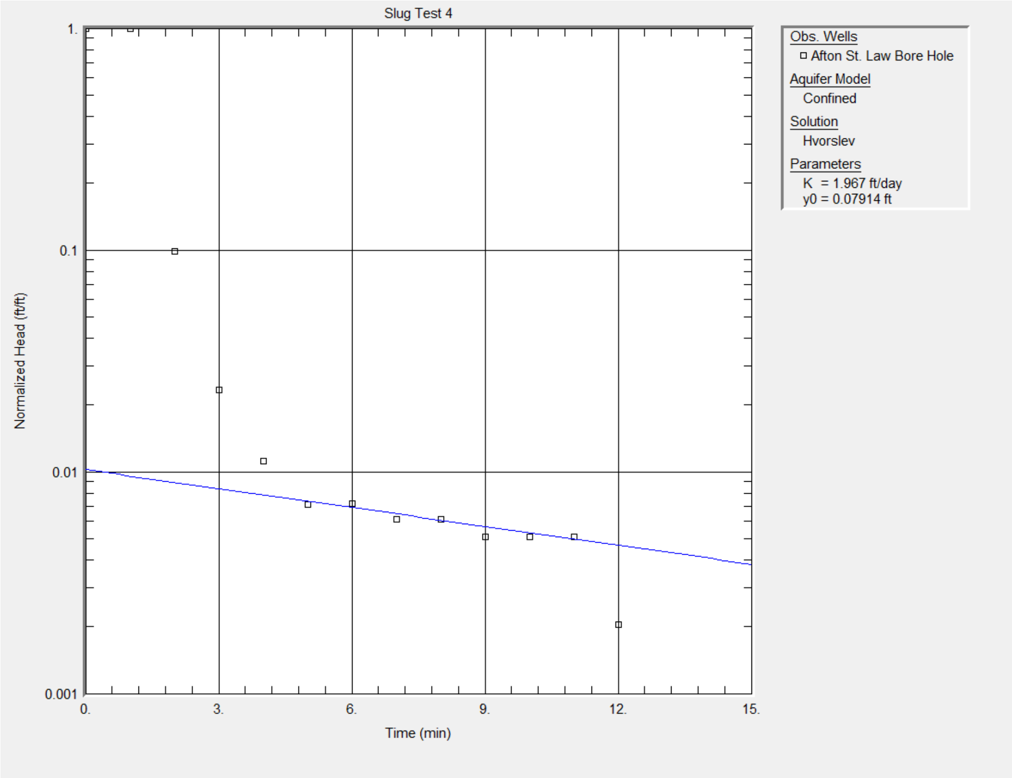
## Slug Test 2


Slug Test 2
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
240.
480.
720.
960.
1.2E+3
Time (sec)
Obs. Wells
□ Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Bouwer-Rice
Parameters
K = 7.206 ft/day
y0 = 0.5682 ft

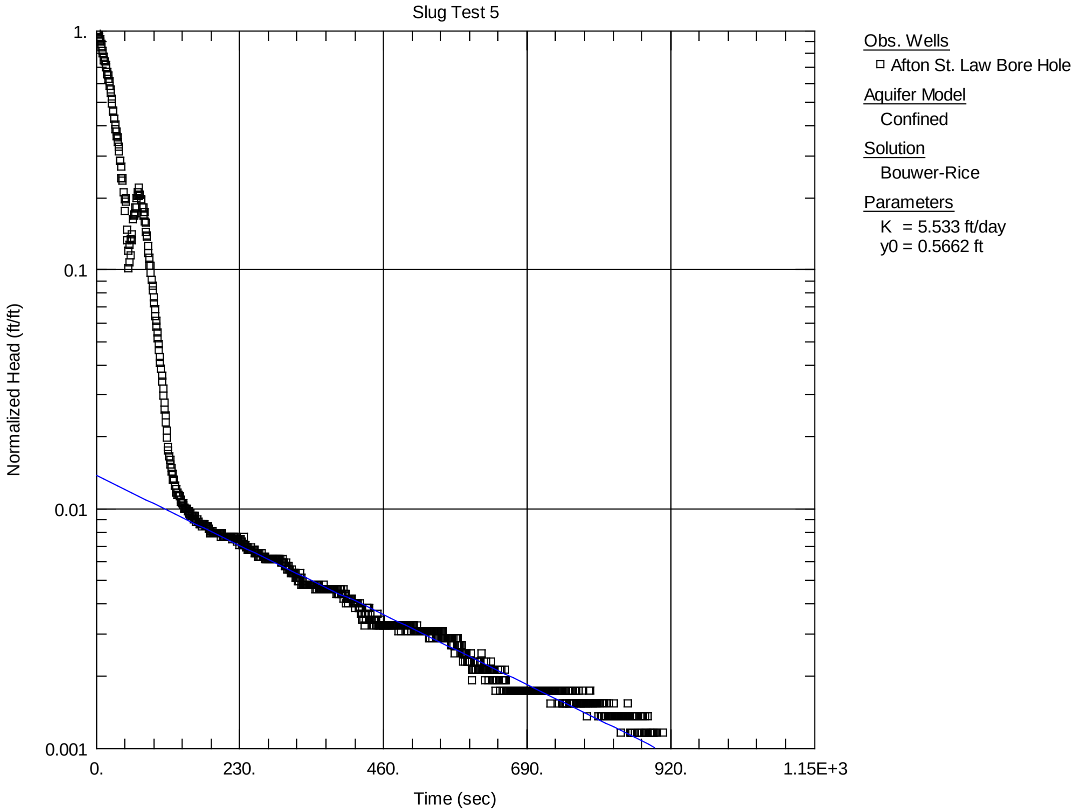

Slug Test 2
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
240.
480.
720.
960.
1.2E+3
Time (sec)
Obs. Wells
□ Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 7.128 ft/day
y0 = 0.5941 ft

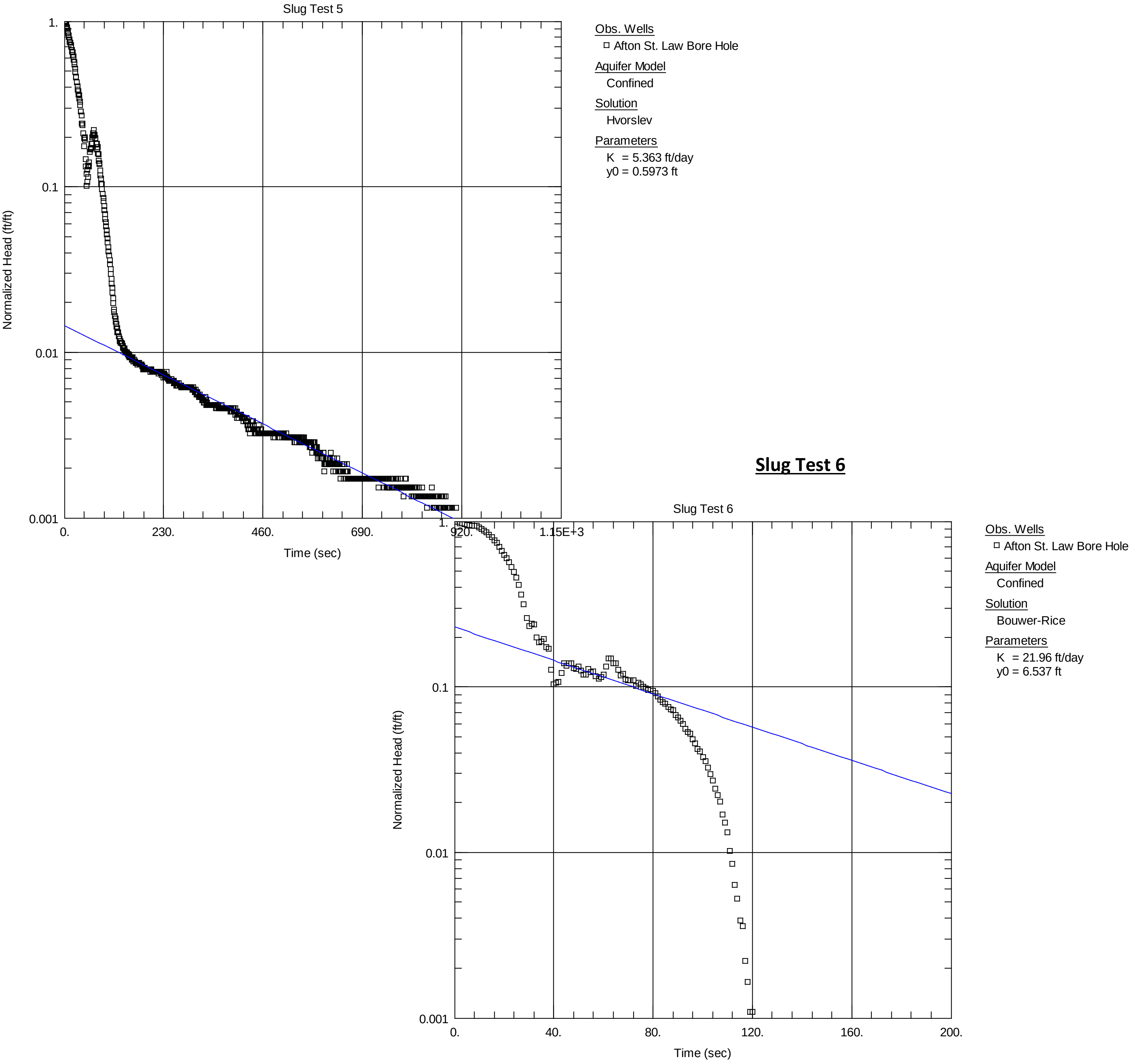
## Slug Test 4


Slug Test 4
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
3.
6.
9.
12.
15.
Time (min)
Obs. Wells
Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Bouwer-Rice
Parameters
K = 2.389 ft/day
y0 = 0.08548 ft

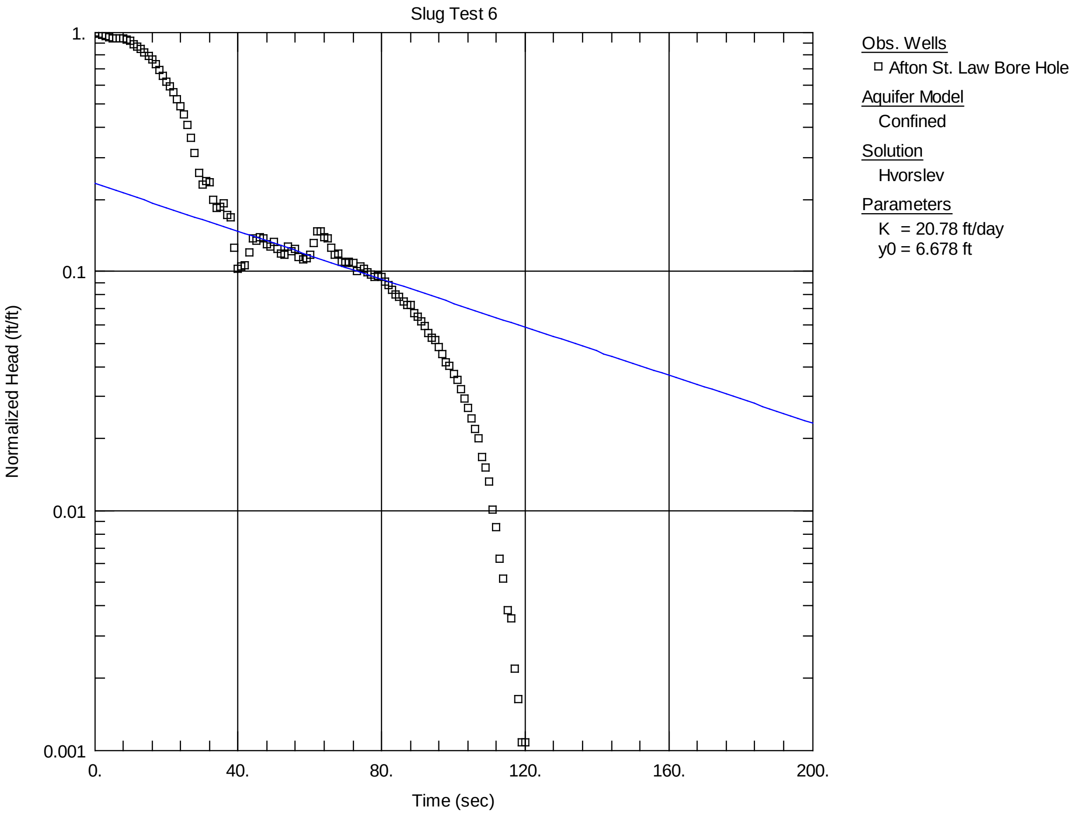

Slug Test 4
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
3.
6.
9.
12.
15.
Time (min)
Obs. Wells
Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 1.967 ft/day
y0 = 0.07914 ft

## Slug Test 5

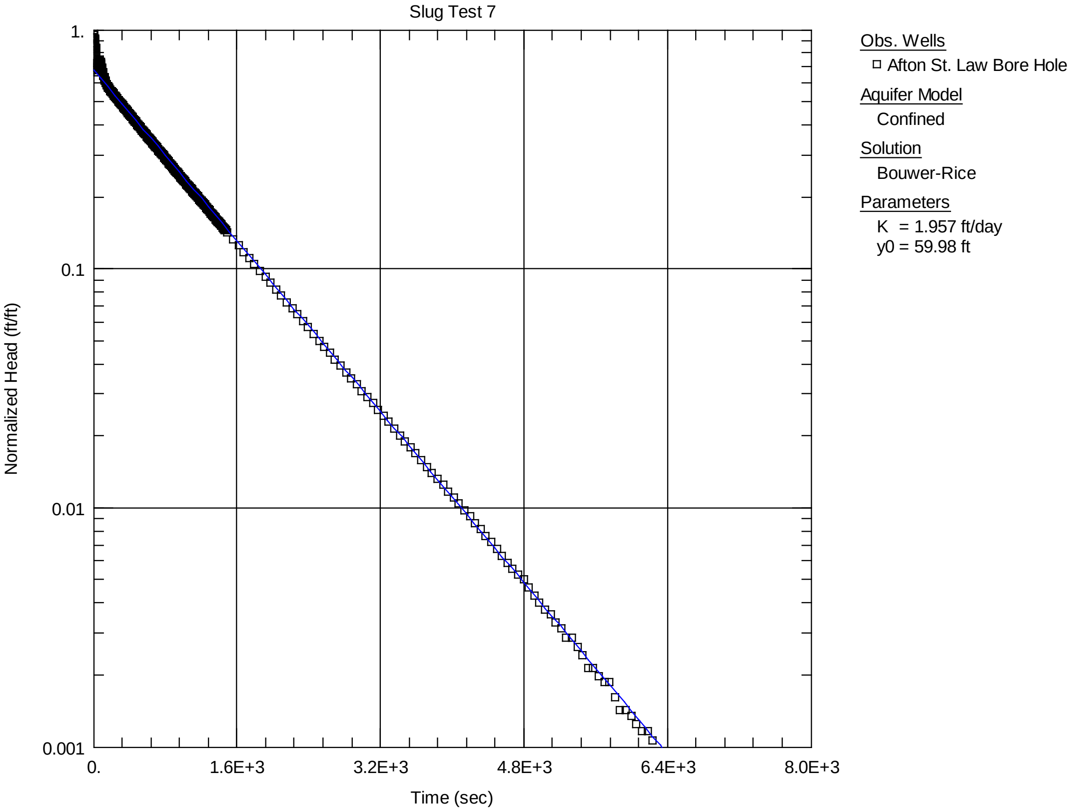

Slug Test 5
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
230.
460.
690.
920.
1.15E+3
Time (sec)
Obs. Wells
Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Bouwer-Rice
Parameters
K = 5.533 ft/day
y0 = 0.5662 ft

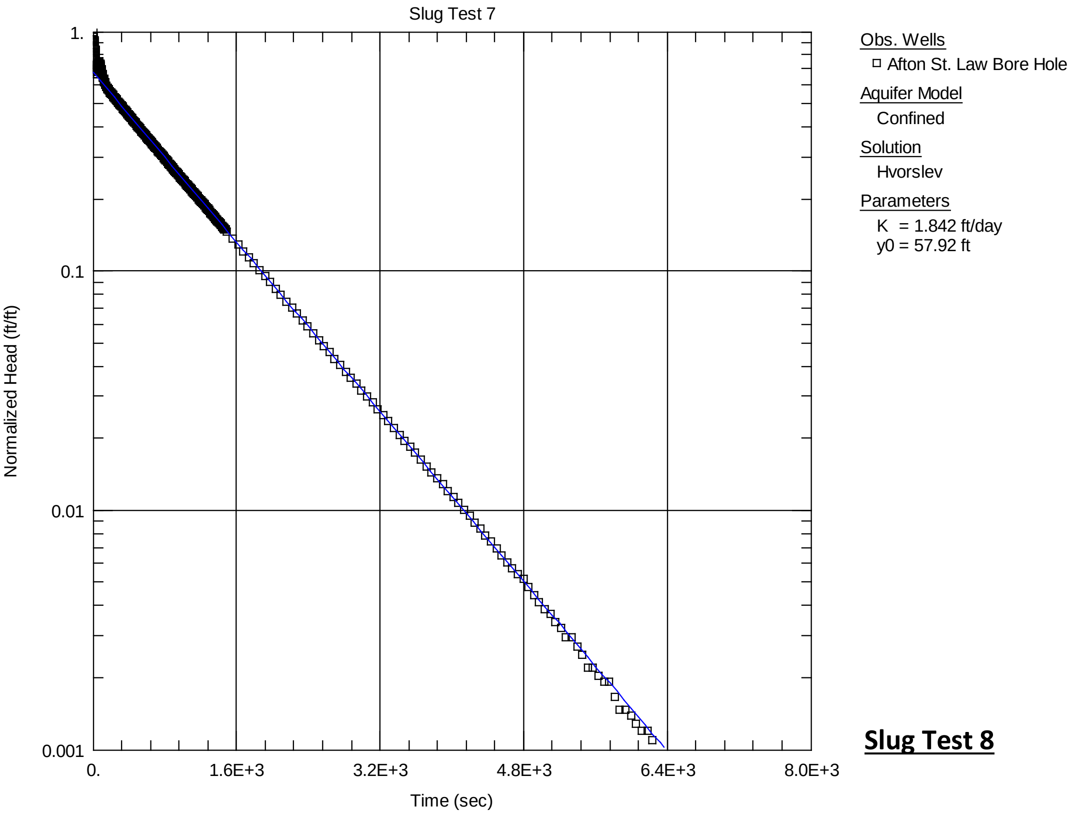

Slug Test 5
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
230.
460.
690.
920.
1.15E+3
Time (sec)
Obs. Wells
Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 5.363 ft/day
y0 = 0.5973 ft
Slug Test 6
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
40.
80.
120.
160.
200.
Time (sec)
Obs. Wells
Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Bouwer-Rice
Parameters
K = 21.96 ft/day
y0 = 6.537 ft

## Slug Test 6

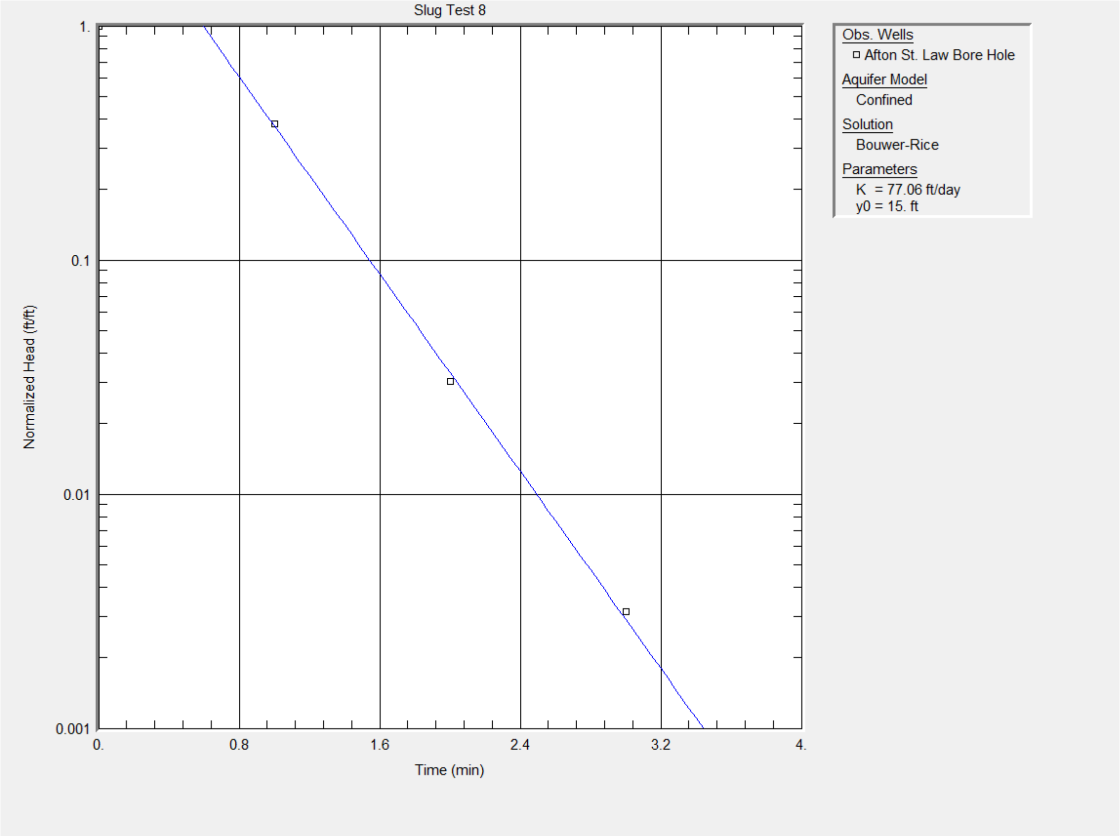

Slug Test 6
1.
0.1
0.01
0.001
Normalized Head (ft/ft)
0.
40.
80.
120.
160.
200.
Time (sec)
Obs. Wells
□ Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 20.78 ft/day
y0 = 6.678 ft

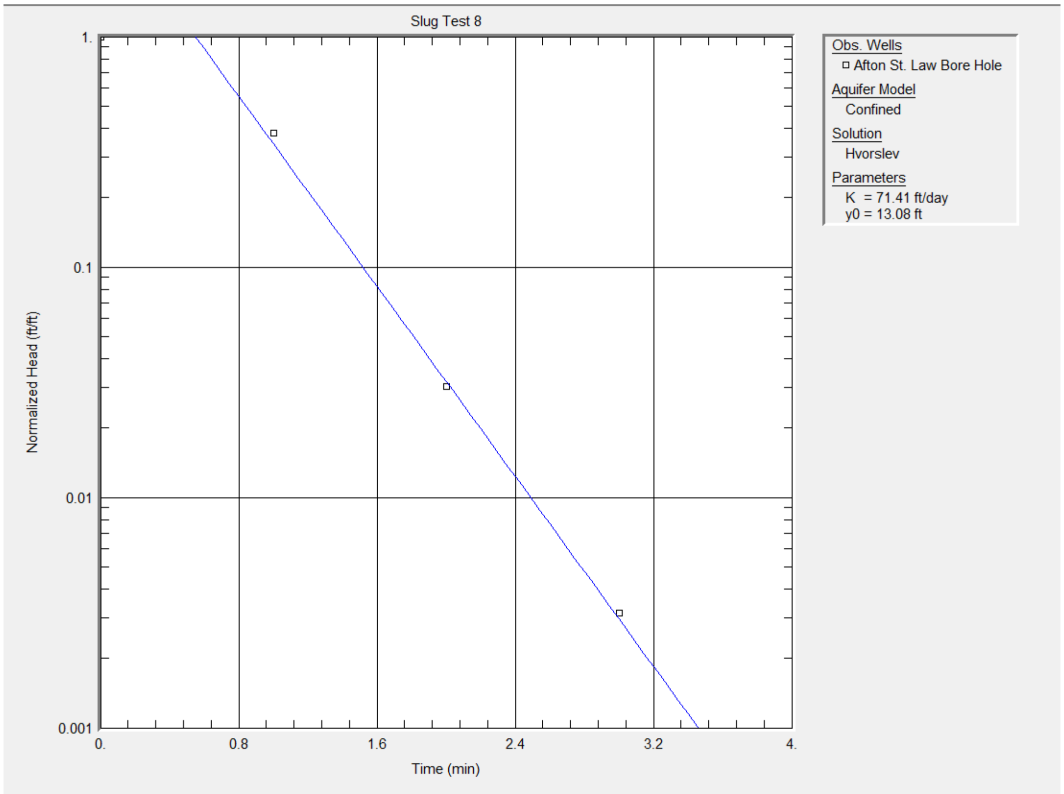
## Slug Test 7


Slug Test 7
1.
0.1
0.01
0.001
Normalized Head (ft/ft)
0.
1.6E+3
3.2E+3
4.8E+3
6.4E+3
8.0E+3
Time (sec)
Obs. Wells
□ Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Bouwer-Rice
Parameters
K = 1.957 ft/day
y0 = 59.98 ft

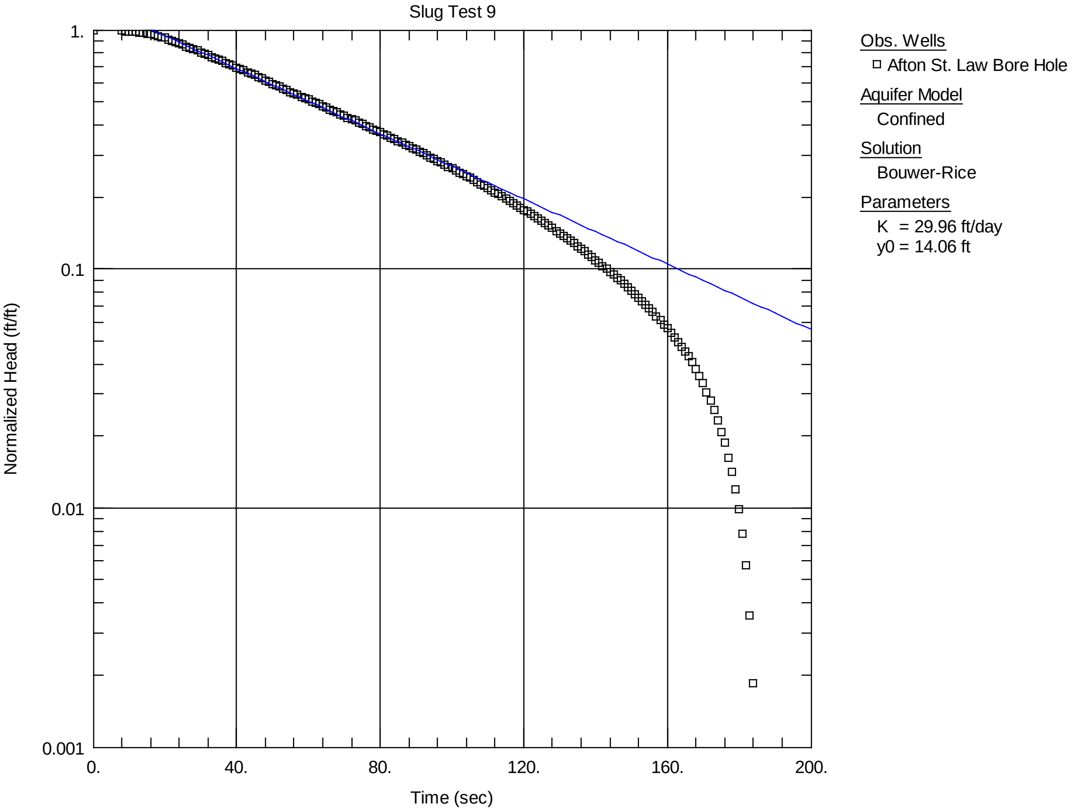

Slug Test 7
1.
0.1
0.01
0.001
Normalized Head (ft/ft)
0.
1.6E+3
3.2E+3
4.8E+3
6.4E+3
8.0E+3
Time (sec)
Obs. Wells
Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 1.842 ft/day
y0 = 57.92 ft

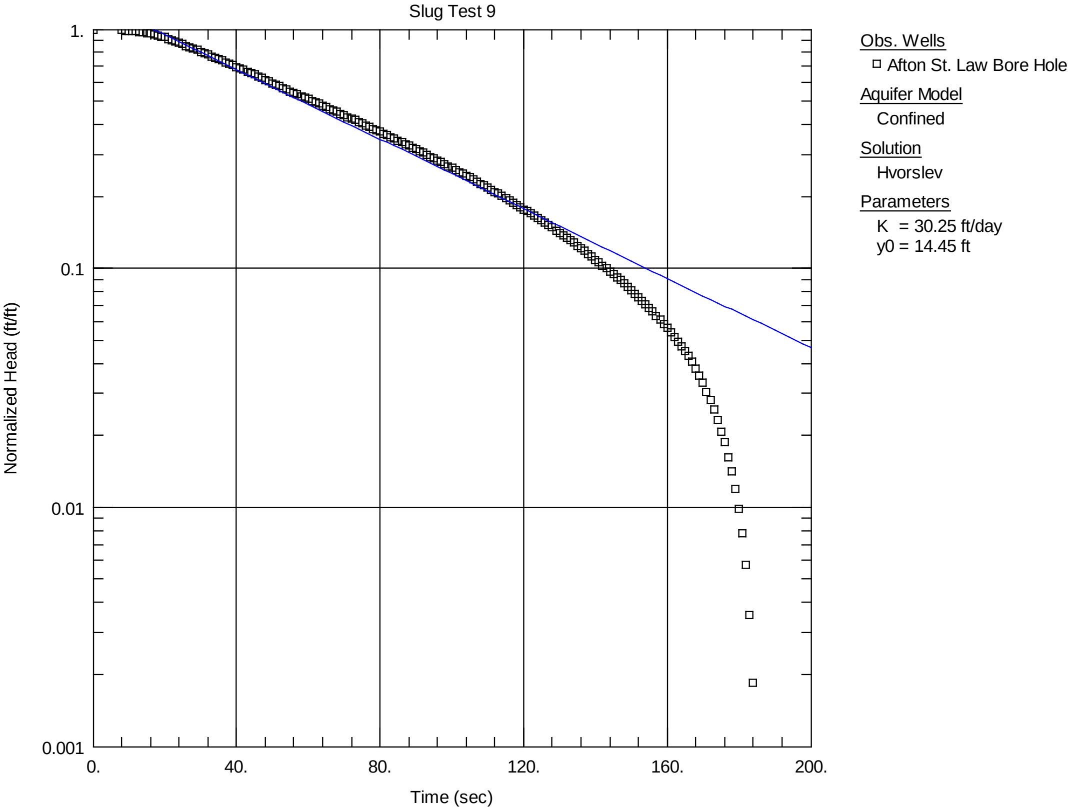
## Slug Test 8


Slug Test 8
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
0.8
1.6
2.4
3.2
4.
Time (min)
Obs. Wells
□ Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Bouwer-Rice
Parameters
K = 77.06 ft/day
y0 = 15. ft

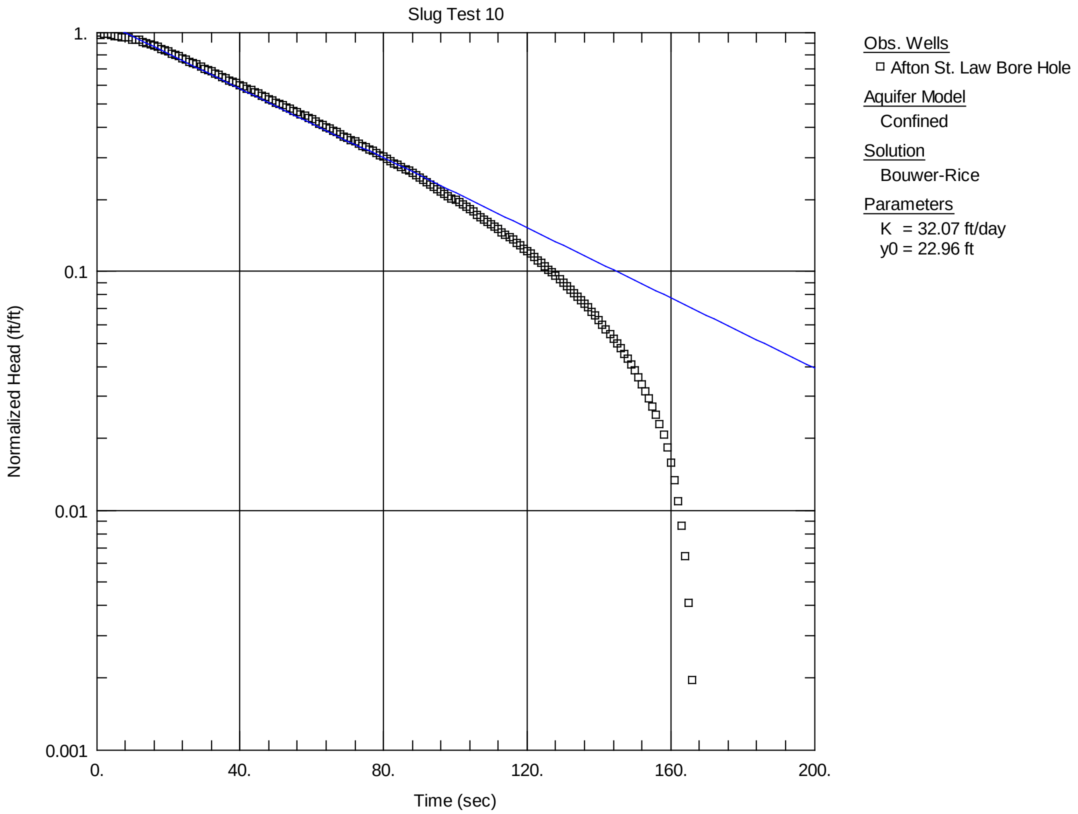

Slug Test 8
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
0.8
1.6
2.4
3.2
4.
Time (min)
Obs. Wells
□ Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 71.41 ft/day
y0 = 13.08 ft

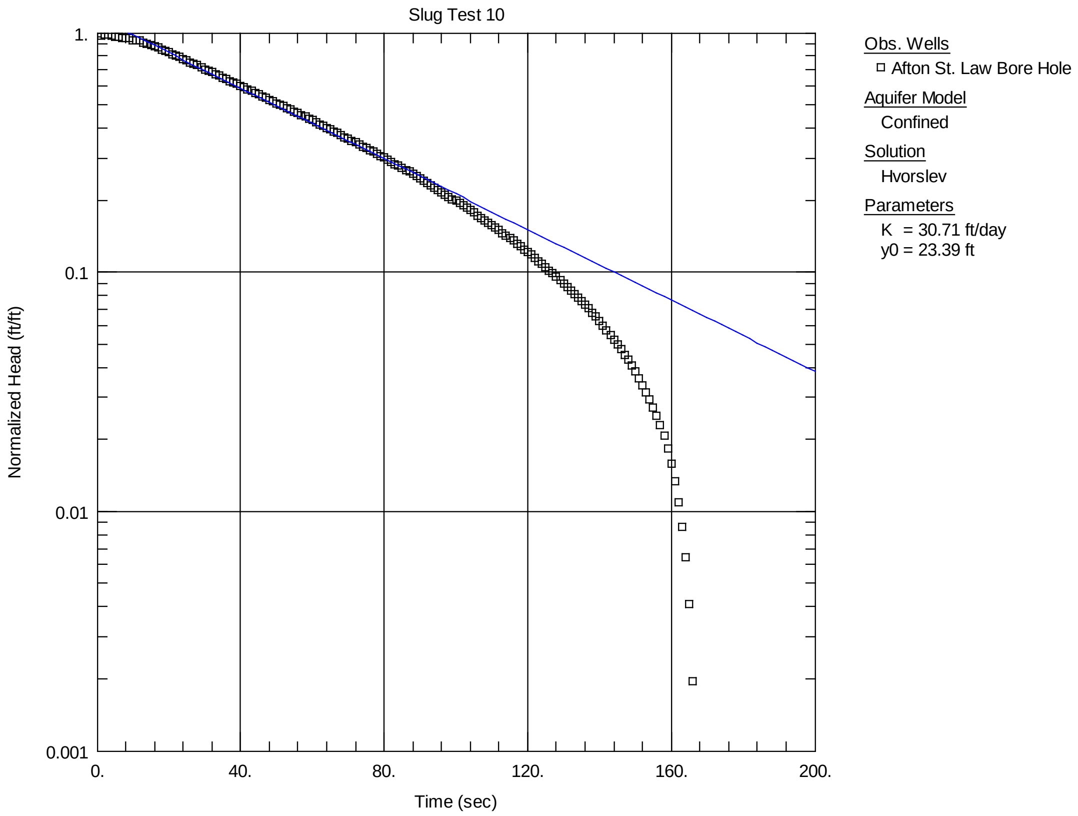
## **Slug Test 9**


Slug Test 9
1.
0.1
0.01
0.001
Normalized Head (ft/ft)
0.
40.
80.
120.
160.
200.
Time (sec)
Obs. Wells
□ Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Bouwer-Rice
Parameters
K = 29.96 ft/day
y0 = 14.06 ft


Slug Test 9
1.
0.1
0.01
0.001
Normalized Head (ft/ft)
0.
40.
80.
120.
160.
200.
Time (sec)
Obs. Wells
□ Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 30.25 ft/day
y0 = 14.45 ft

**Slug Test 10**

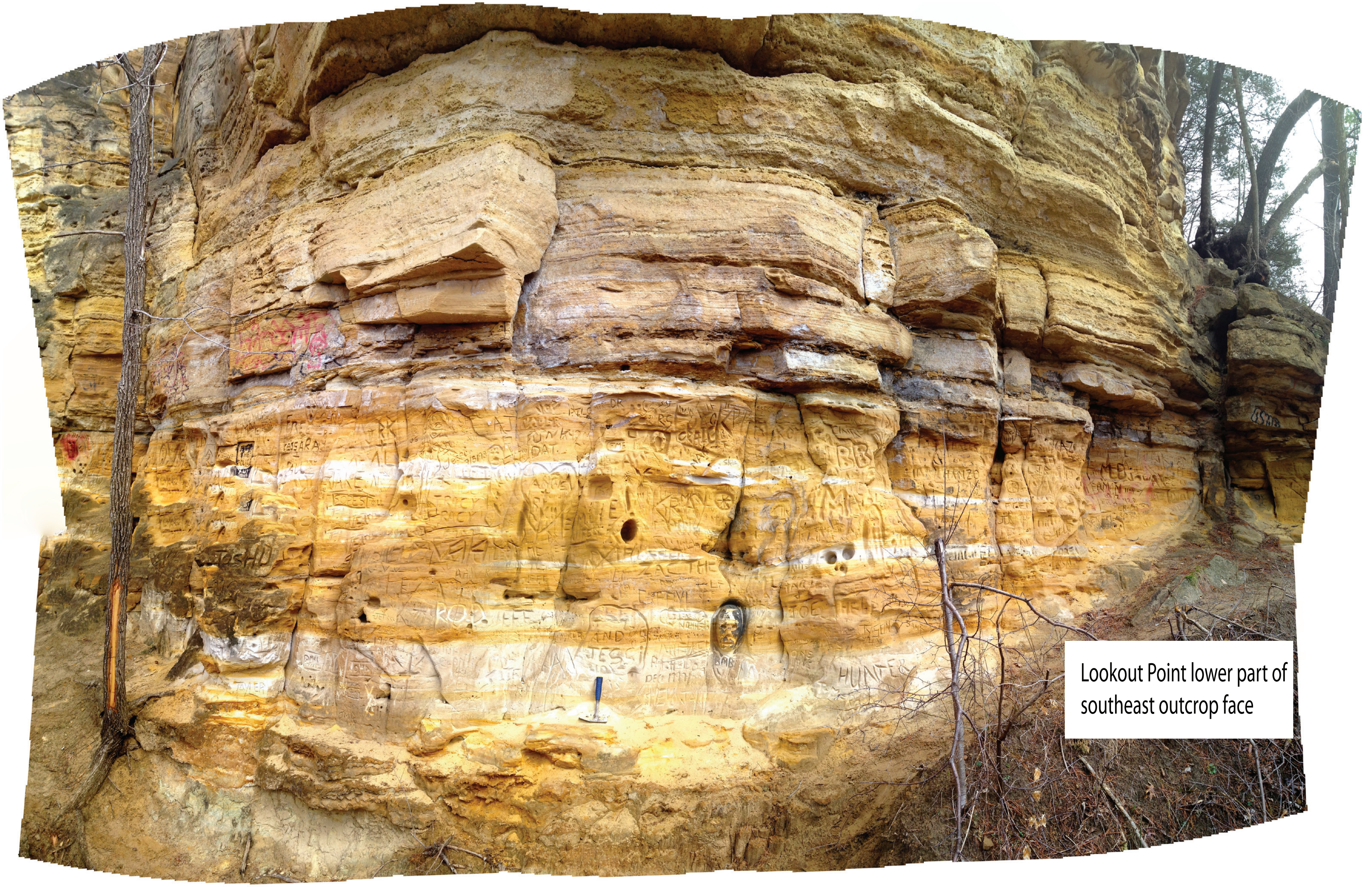

Slug Test 10
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
40.
80.
120.
160.
200.
Time (sec)
Obs. Wells
Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Bouwer-Rice
Parameters
K = 32.07 ft/day
y0 = 22.96 ft


Slug Test 10
Normalized Head (ft/ft)
1.
0.1
0.01
0.001
0.
40.
80.
120.
160.
200.
Time (sec)
Obs. Wells
Afton St. Law Bore Hole
Aquifer Model
Confined
Solution
Hvorslev
Parameters
K = 30.71 ft/day
y0 = 23.39 ft

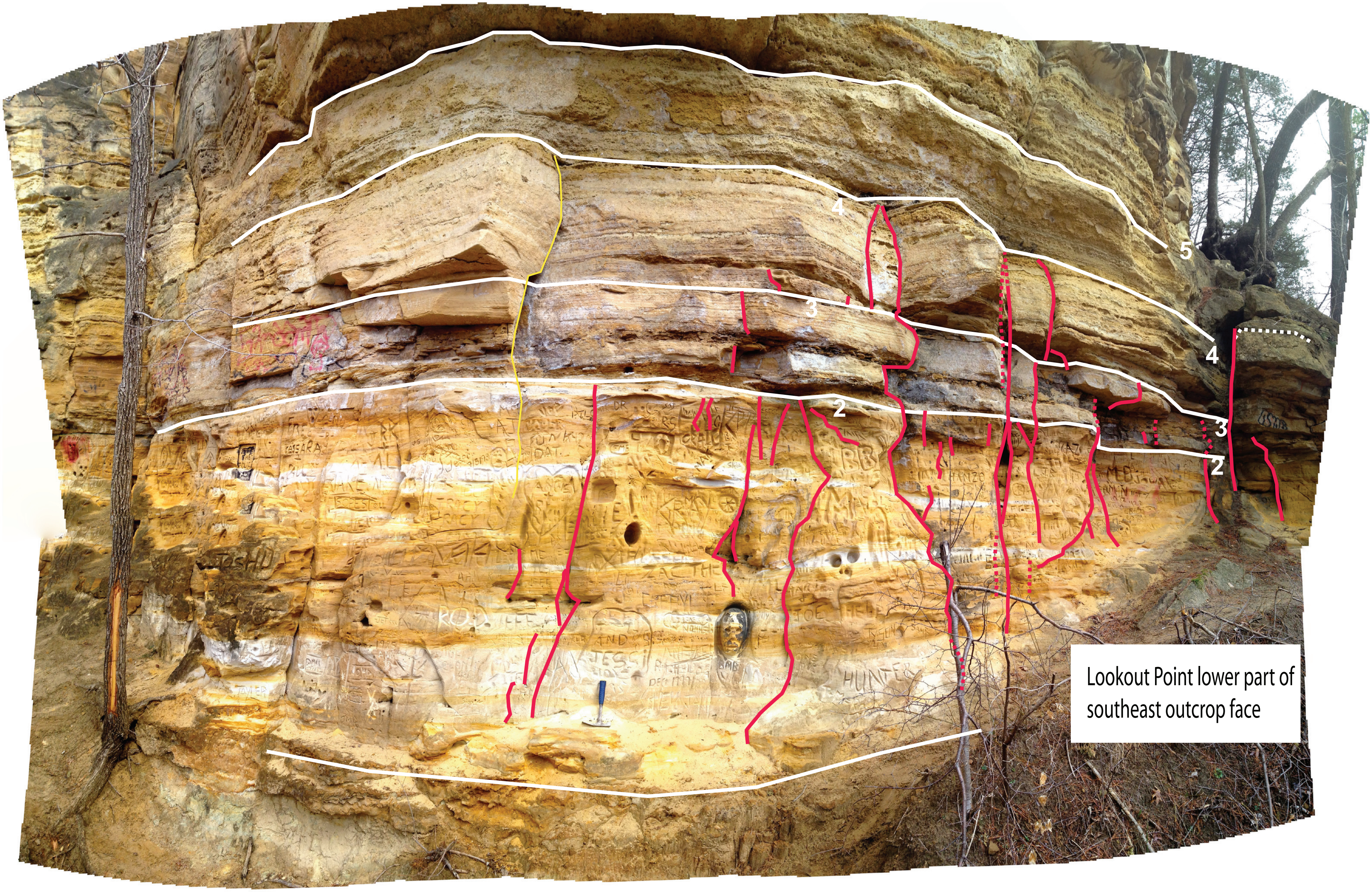
Fairy Glen traced fractures and bed contacts

# Fairy Glen

Fairy Glen traced fractures and bed contacts

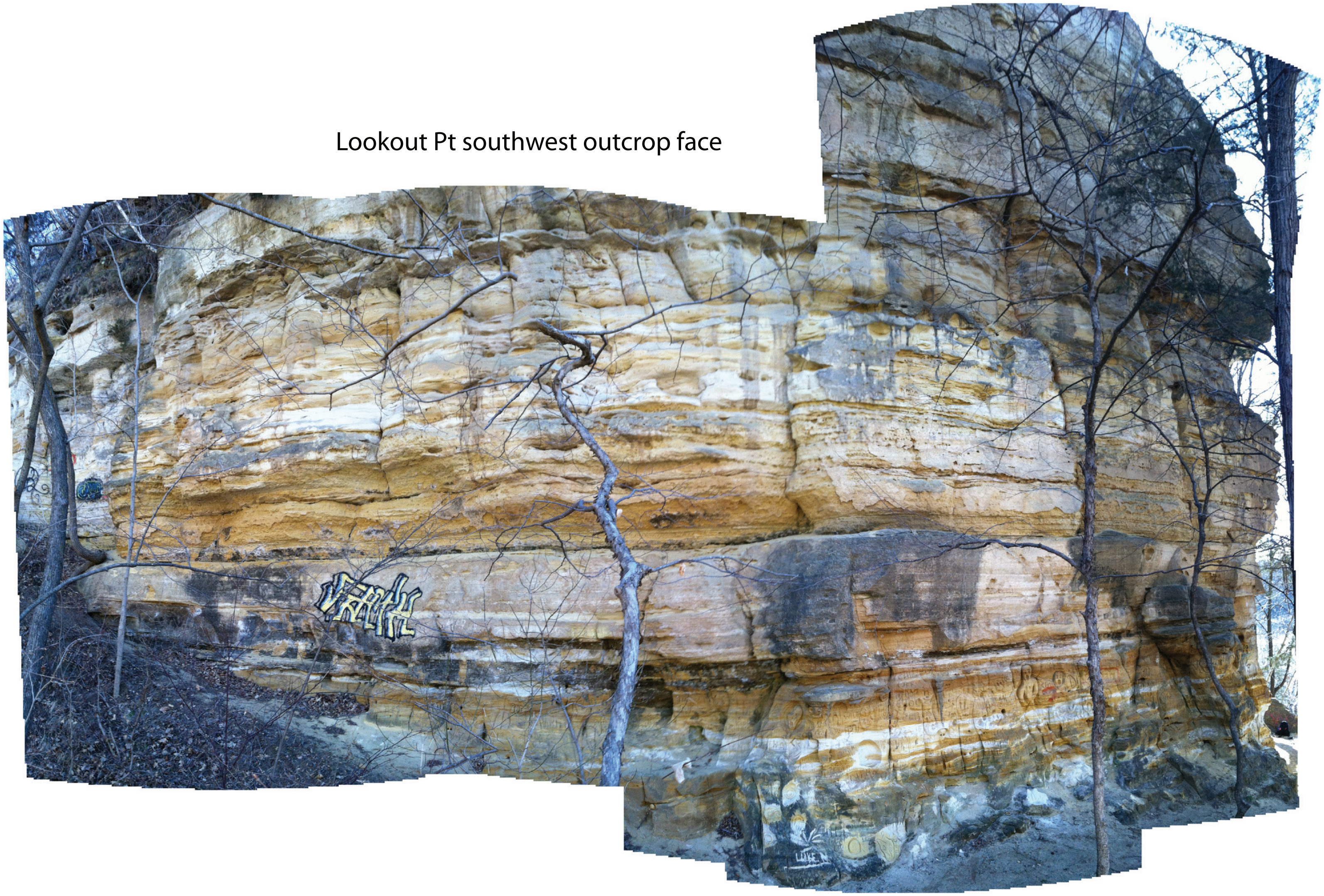


Lookout Point lower part of southeast outcrop face

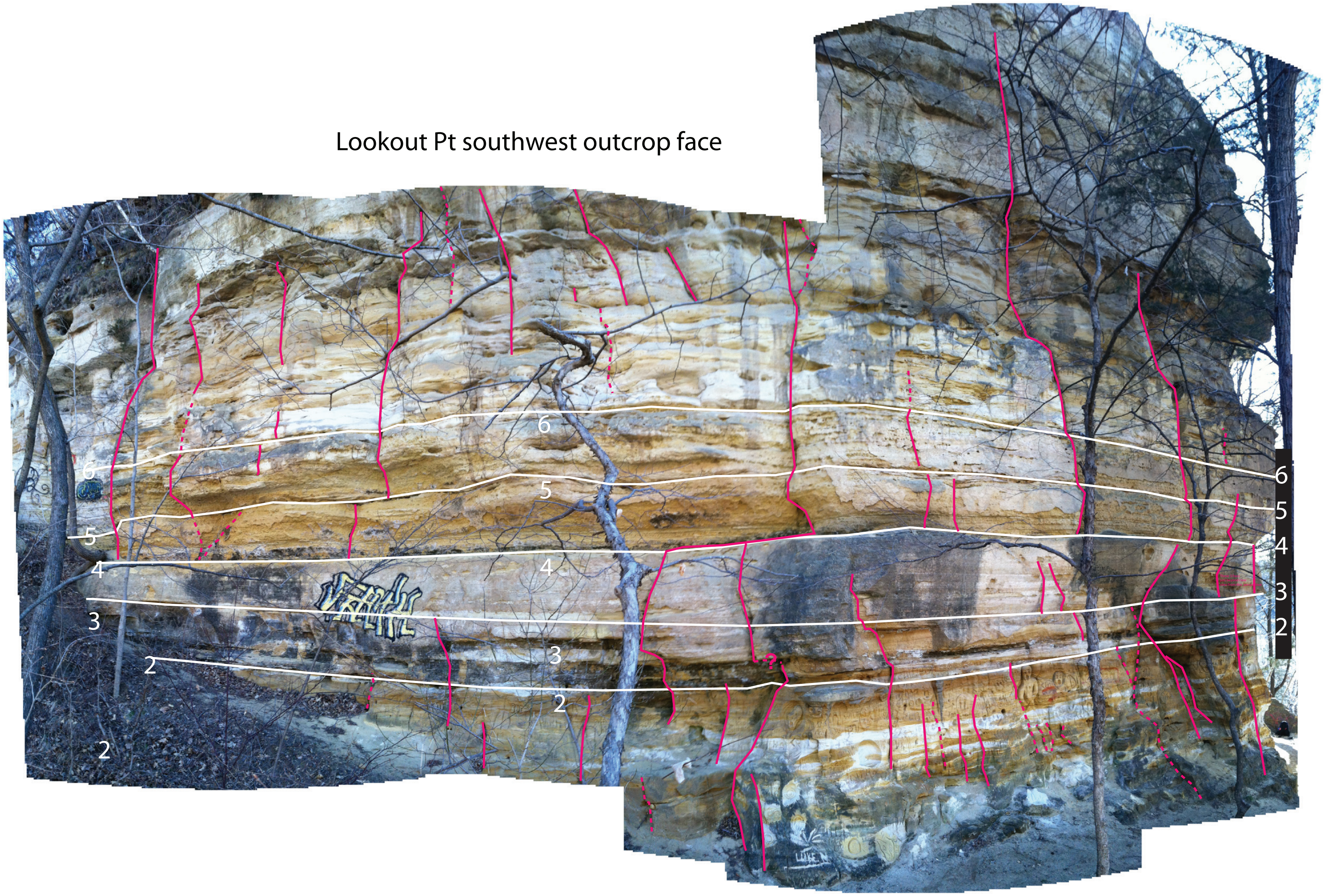


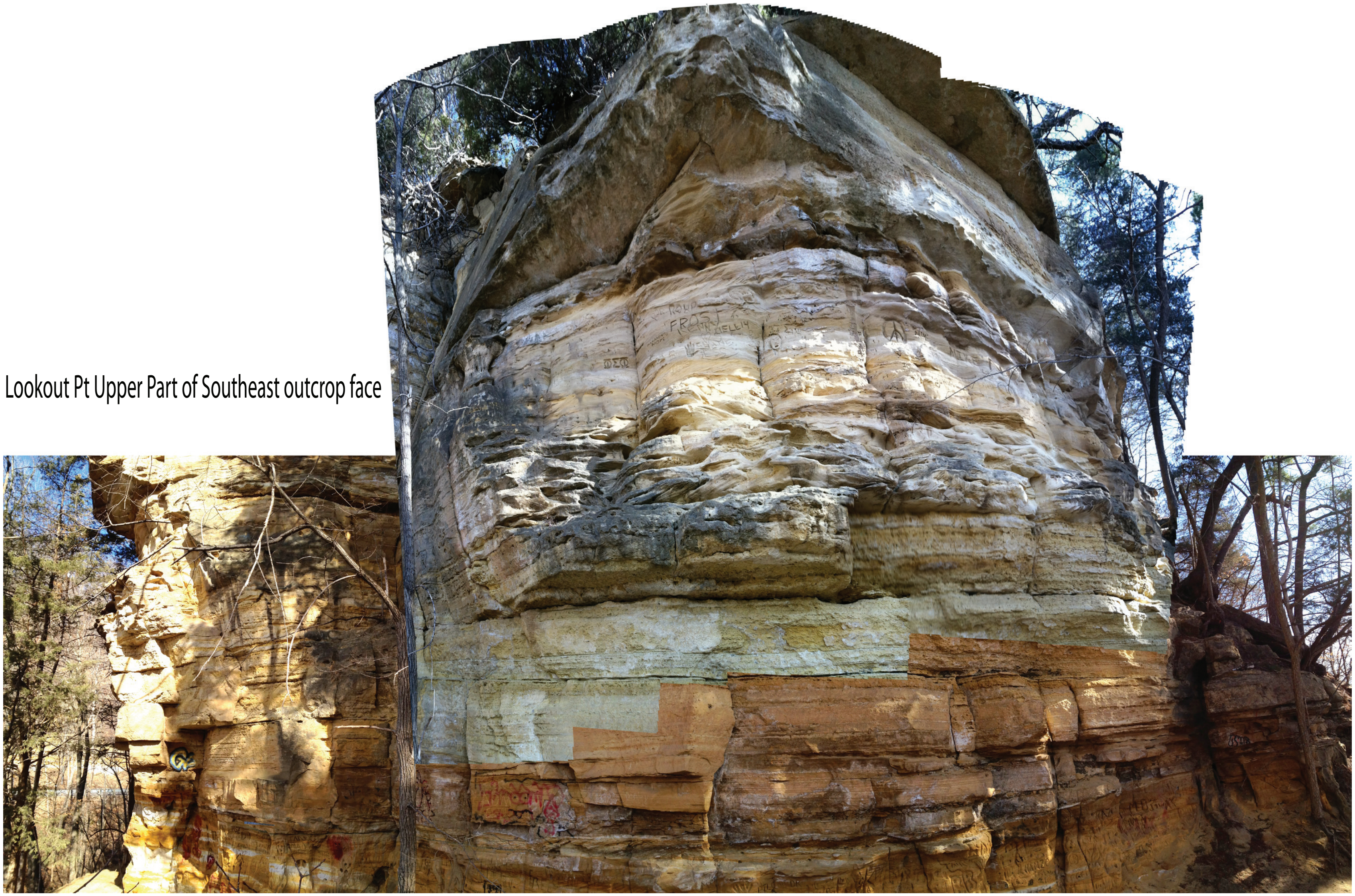
Lookout Point lower part of southeast outcrop face

Lookout Pt southwest outcrop face



Lookout Pt southwest outcrop face

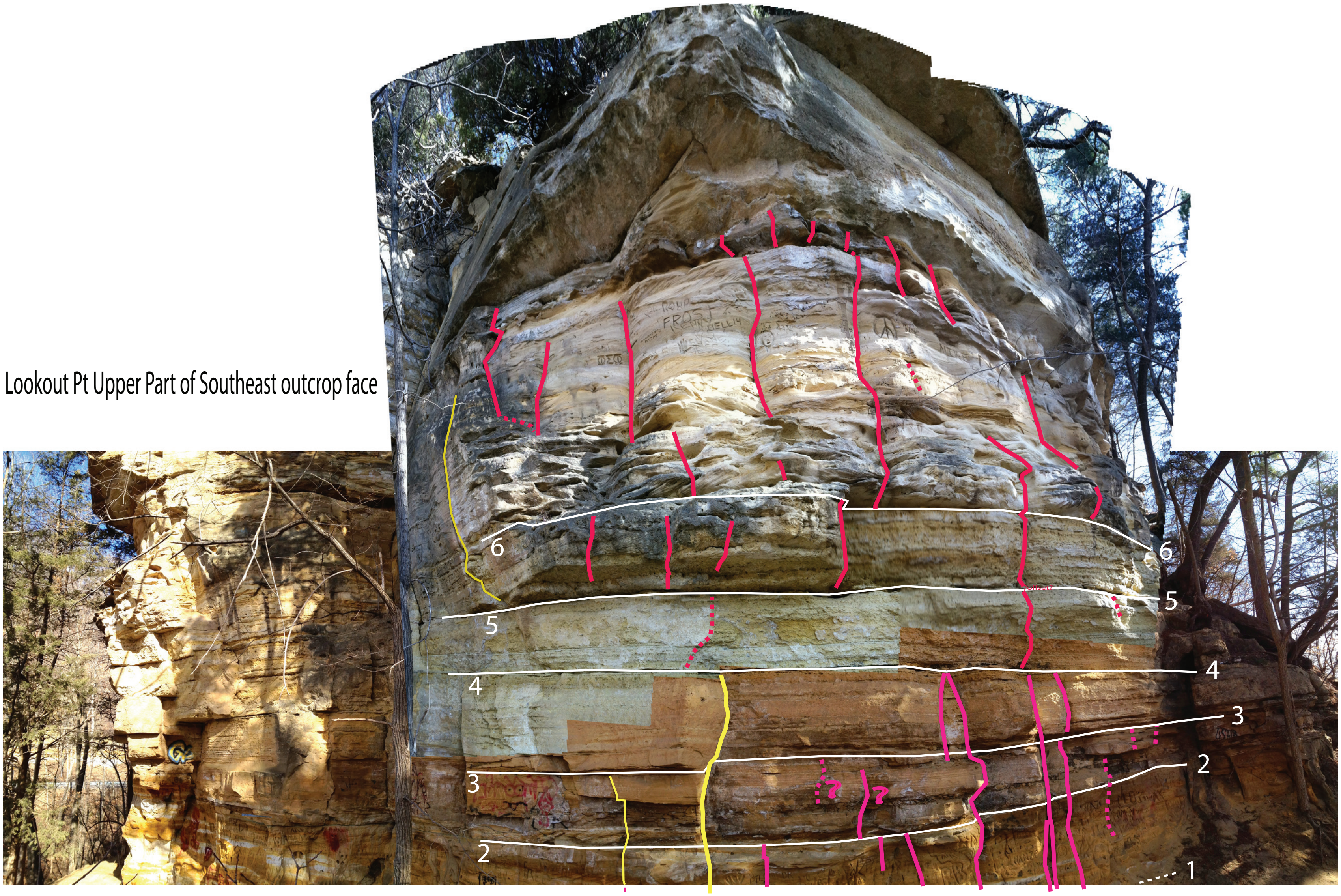




Lookout Pt Upper Part of Southeast outcrop face

Lookout Pt upper part of southeast face

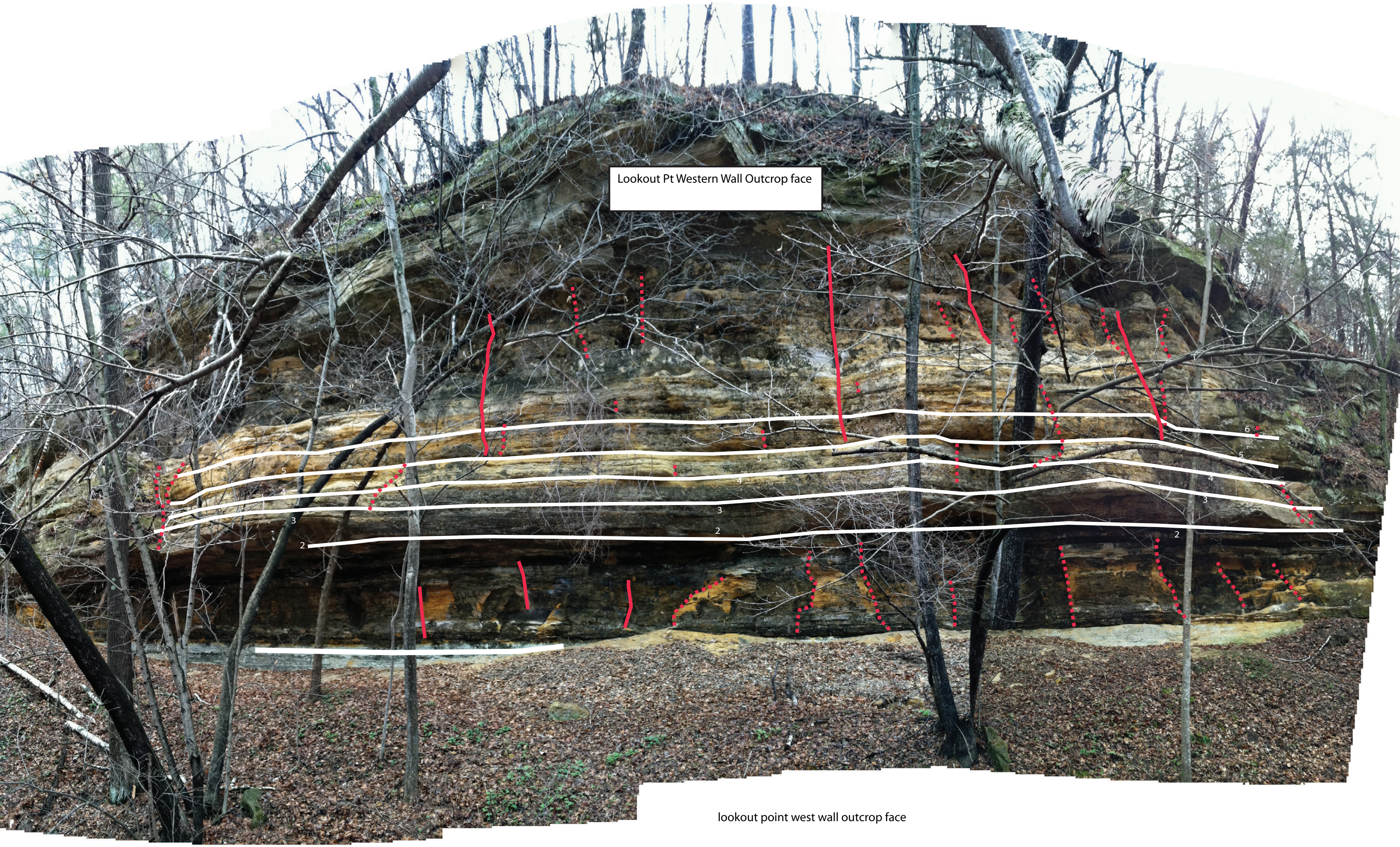
Lookout Pt Upper Part of Southeast outcrop face



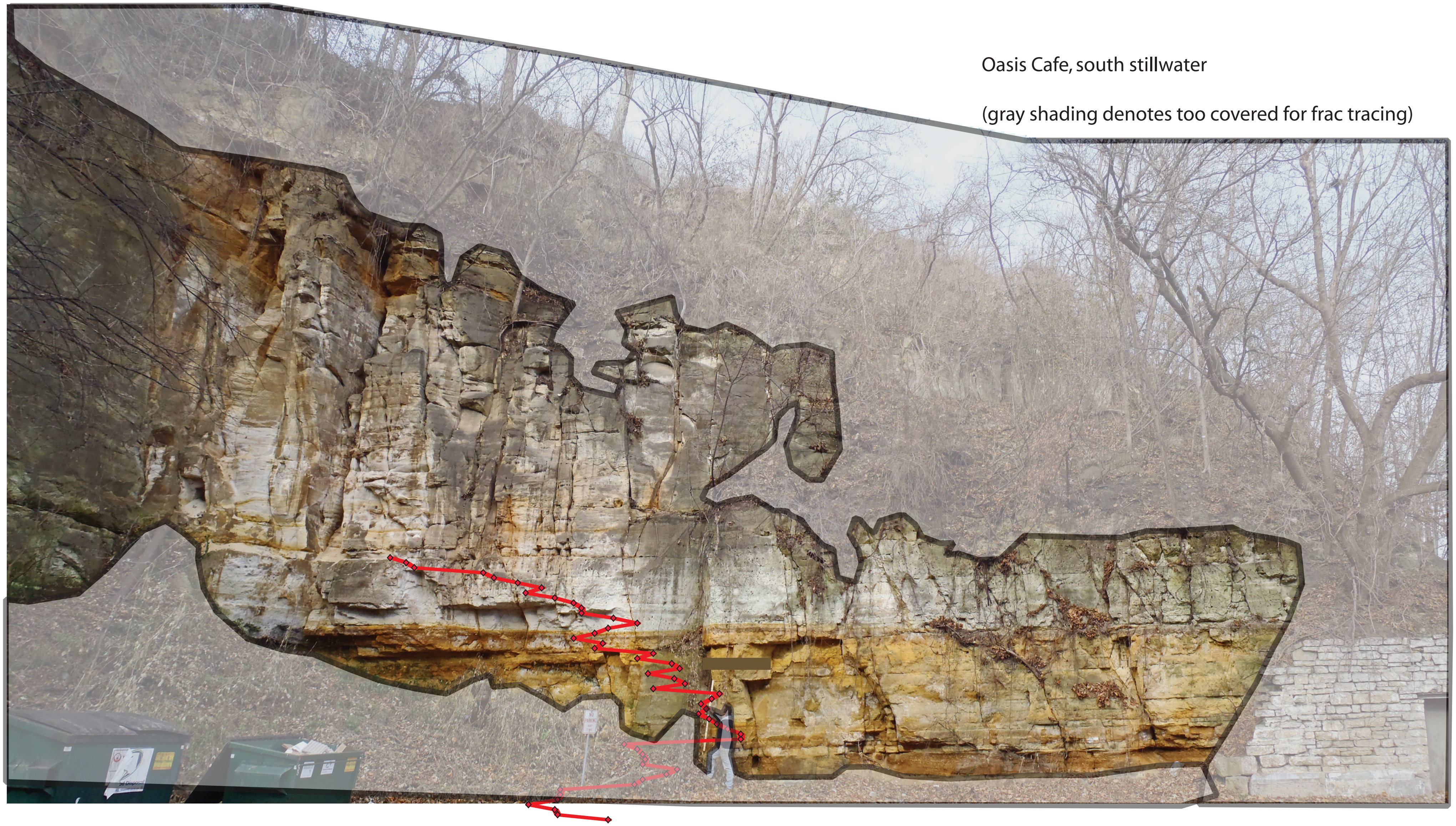
yellow traces are overlap with south face photo collage

Lookout Pt upper part of southeast face

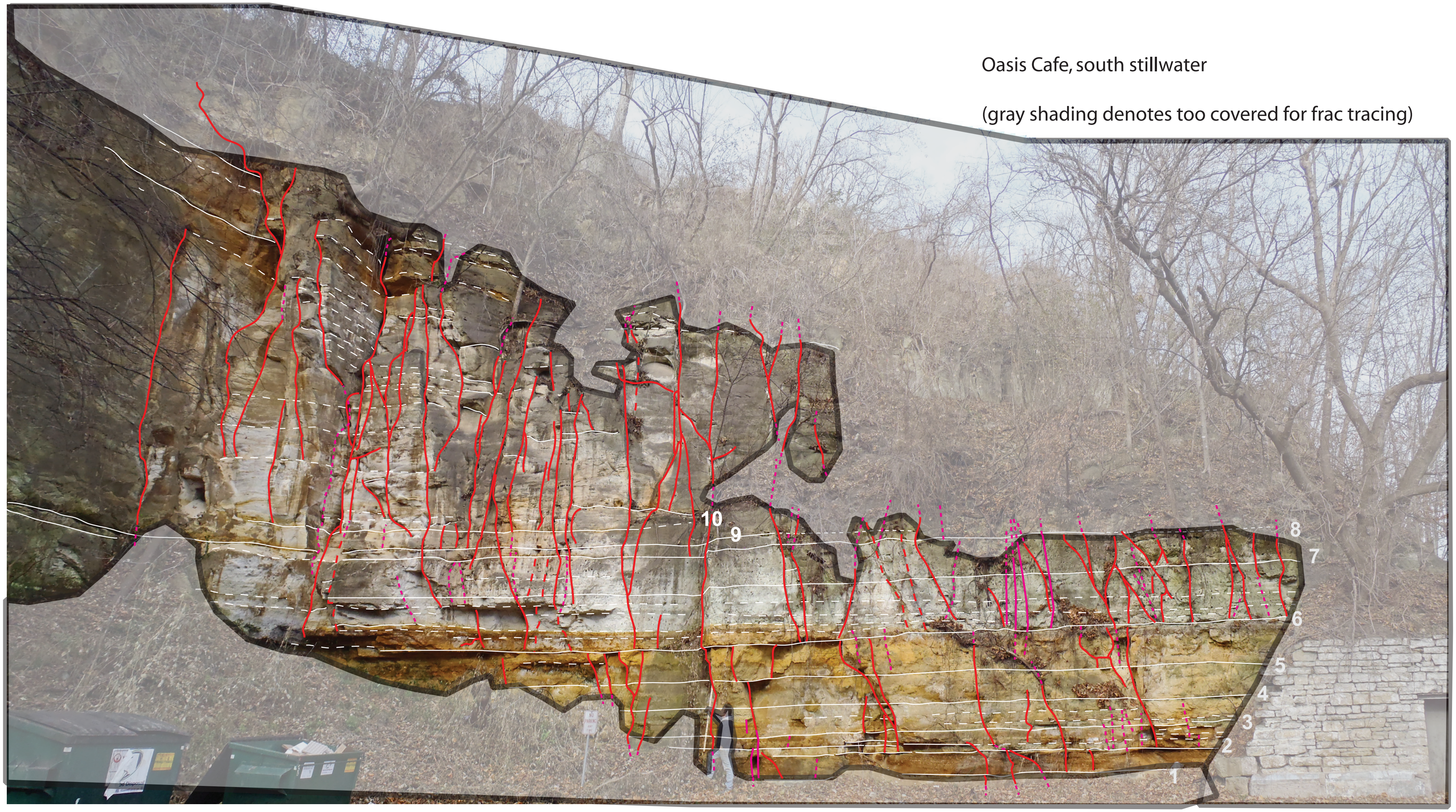
lookout point west wall outcrop face



lookout point west wall outcrop face



Oasis Cafe outcrop with traced bed contacts and fractures


Oasis Cafe, south stillwater

(gray shading denotes too covered for frac tracing)

Oasis Cafe outcrop with traced bed contacts and fractures